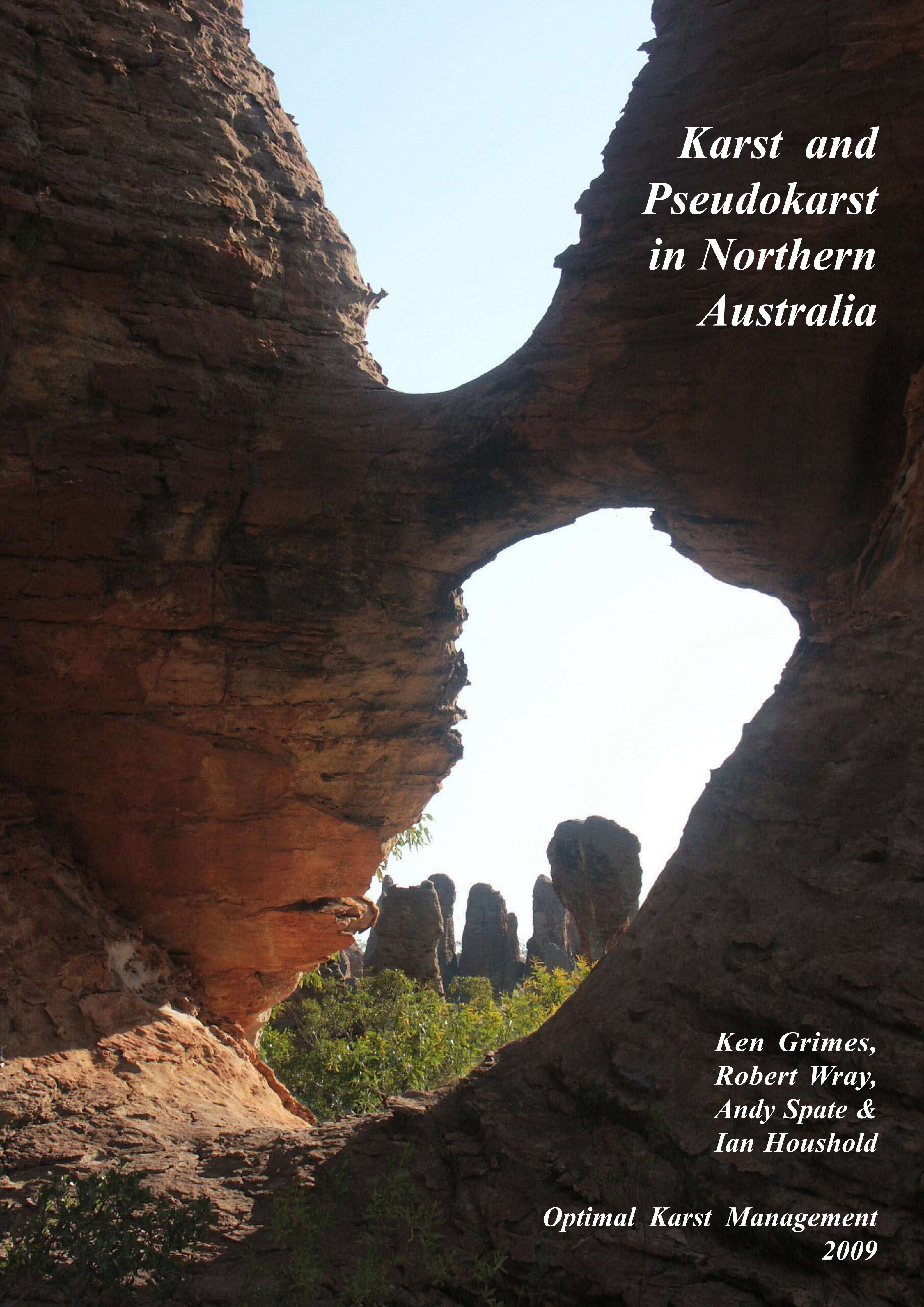


Karst and Pseudokarst in Northern Australia

Ken Grimes, Robert Wray, Andy Spate & Ian Houshold

Optimal Karst Management 2009

Karst and Pseudokarst in Northern Australia

Report on the field study of June-August 2008

compiled by

Ken Grimes, Robert Wray, Andy Spate & Ian Houshold

Stone city at Abner Range, NT. KG080552

A Report to

Department of the Environment, Water, Heritage and the Arts

by

OPTIMAL KARST MANAGEMENT

Suite 2, 10 Victoria Street, Hall, ACT 2618.

August 2009

Cover photograph is of a sandstone arch in an isolated block at Abner Range, with large pinnacles in distance. Photo KG080538a.

CONTENTS

Index to Figures and Photos

Figures

Tables

Photos (sorted by filename)

Photos & Figures for each Site

Western Australia

Northern Territory

Queensland

EXECUTIVE SUMMARY

This report arises from two workshops dealing with the natural heritage values of the karst and pseudokarst resources, respectively, of Australia. The (now) Department of the Environment, Water, Heritage and the Arts hosted the workshops. It became clear that the pseudokarst resources of northern Australia were almost unknown and had not been widely studied in any systematic manner. The authors presented a proposal for a field reconnaissance to DEWHA with the result that the Department partially funded desktop studies, field and laboratory work in 2008. This report provides the results of that work.

Pseudokarsts and similar landforms are found in a variety of rock types across northern Australia – chiefly in sandstones and quartzites but also in laterite and granites, and share many features with the more fully studied limestone karsts. The report discusses concepts underlying the term ‘pseudokarst’ and similar terms, as these are used in varying ways in the scientific literature. We have adopted the more generic term ‘karst-like’ in this report, together with the term ‘ruiniform’ for structurally controlled features that are not specifically ‘karst-like’. The processes that produce these karst-like landforms are also briefly discussed.

Around 30 sites were visited over a nine-week period – some only by aerial reconnaissance. Observations arising from published literature and fieldwork in earlier years are also included in the report. Results are discussed in two ways. Firstly, the ruiniform and karst-like landforms we observed on sandstone, laterite, granite and, to a lesser extent, limestone are discussed at all scales and in degrees of complexity related to type of features and landscape elements.

Secondly, the report discusses the characteristics of each site visited in the Northern Territory (15 sites), Queensland (11) and Western Australia (3). Some of these were quite small and relatively complete appraisals were possible. Others, such as Kakadu and Bunju need far more thorough assessments and more detailed studies.

The report goes on to provide an initial assessment of the natural heritage significance of each of the sites visited. We state that the karst-like landforms of northern Australia have a much greater level of significance than has been previously recognised and that a serial World Heritage nomination linking the existing Purnululu and Kakadu World Heritage properties with others in the Northern Territory such as the Abner Range, Limmen and East Arnhem Land would be justified. Many sites are worthy of listing on the new National Heritage List – others should be recognised at state level.

The report is accompanied by a comprehensive series of appendices listing the detailed laboratory and field results as well as an illustrated glossary and some relevant recently produced materials relating to northern karst-like landforms

An isolated block of pinnacles, Abner Range KG080568

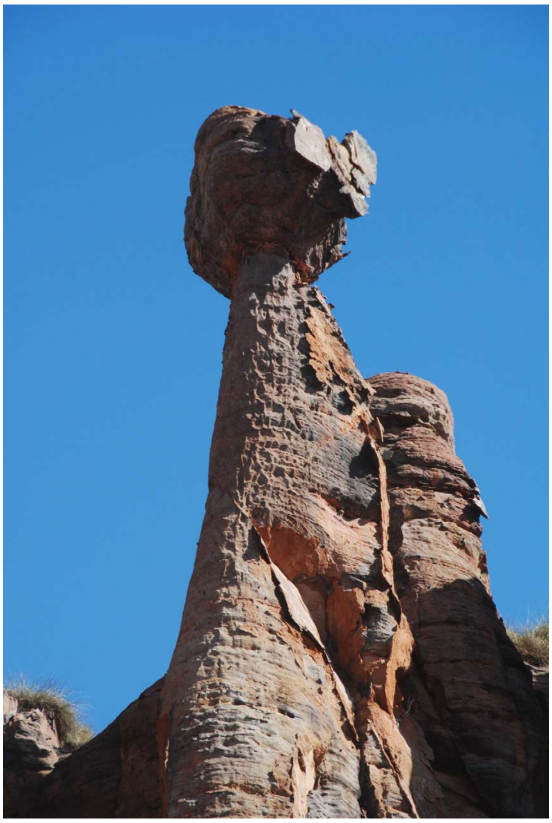
ACKNOWLEDGMENTS

A long and complicated fieldwork exercise across northern Australia in a variety of tenures has required input from many outside the team. Chief among these were:

- Jayne Thomas and Jenny Dyring who participated in the fieldwork in many ways as assistants, companions, cooks and drivers;
- Paul Swifte and Byron Arnold of Forest Contracting Services (Tas) Pty Ltd who provided the necessary insurance work compensation and financial administration in a highly competent and friendly manner;
- Jane Ambrose of the Department of Environment Water, Heritage and the Arts who facilitated and supported the project from its inception;
- Others, including Jennifer Carter, of the Department;
- The University of Wollongong School of Earth and Environmental Sciences for laboratory analysis support;
- The Land Conservation Branch of the Tasmanian Department of Primary Industries and Water for use of field equipment, communications and providing leave time for one of us (IH);
- Various officers and offices of Parks Australia North, the Conservation Commission of the Northern Territory, the Northern Land Council and the Queensland Environment Protection Agency;
- Ian Withnall of the Geological Survey of Queensland, for providing access to air photos of various Queensland sites, and information on Cobbold Creek;
- Jenny Dryling, who discussed development of geomorphic systems at Limmen and elsewhere;
- Bobby Nungumajbaar of the Northern Land Council at Ngukurr for facilitating access to Bunju;
- John Green for access to Glen Osmond and ultimately to Whalemouth Cave;
- Simon Terry at Cobbold Station for access to the Cobbold Creek hinterland; and
- many others.

- Satellite images are from Google Earth.
- Base maps in figures 19, 21, 22, 24, 26, & 27 are copyright to the Commonwealth of Australia.

We are very grateful to all of these people and institutions and extend our thanks to them for making this work a reality.



Capped pinnacle, Limmen West. RW082873

Karst and Pseudokarst in Northern Australia

Report on the field trip of June-August 2008

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1: INTRODUCTION

1.1: Background

This is the report of a reconnaissance survey of selected karst, parakarst and pseudokarst sites in northern Australia commissioned by the Natural Heritage Assessment Section of the Commonwealth Department of Environment, Water, Heritage and the Arts.

The Department requires information on Australian pseudokarst and karst sites and features for the comparative assessment of sites that may have potential national heritage significance. The Department's 2006 karst and 2007 pseudokarst workshops clearly identified that the geomorphology of the karst and pseudokarst of northern Australia is under-surveyed, often poorly researched, and under-represented in the literature when compared with sites that are located in the more populous areas of southern Australia.

A field study to gather further data was therefore proposed, involving four earth scientists. As the Department had limited funds for a study of the scope required, the four scientists and two field assistants involved freely donated their time, with the exception of a small per diem to cover personal field costs and food, and provided their own 4WD transport. The Department funded the field, laboratory and reporting costs, and paid for some of the air photographs and maps – others were drawn from existing personal collections.

1.2: Objectives

The objectives were to study the extent and nature of non-limestone karst, parakarst and pseudokarst in northern Australia, and in particular, to collect data and compare sites for assessment of their potential heritage significance. This was to be done by a reconnaissance field survey of many of the known or suspected karst and pseudokarst sites in the northern parts of Queensland, the Northern Territory and Western Australia, followed by a laboratory study of samples collected in the field. Field observations concentrated on the geology and geomorphology of sites, although observations on soils, water quality and subterranean fauna were also recorded. Although the prime emphasis was on non-limestone systems, some limestone karst areas were also to be visited for comparison and where special karst features were known to exist.

1.3: Scope and limitations

The field work lasted 9 weeks between June and September 2008 and involved a significant amount of travelling time with the field time at individual sites ranging from one hour (e.g, Mt Price and Castle Rock) to three days (Limmen South and Kakadu). Light aircraft and helicopters were used for access and aerial inspections at several sites. The four scientists involved were A.P. Spate (Optimal Karst Management), K.G. Grimes (Regolith Mapping), I. Houshold (Tasmanian Department of Primary Industries and Water), and Dr R.A.L. Wray (University of Wollongong). Two field assistants, J. Dyring and J. Thomas, also participated.

This report also draws on our previous field work, air-photo and satellite interpretation, and information derived from the literature. Dr Wray at the University of Wollongong carried out the laboratory studies.

The sites to be visited were selected from information provided at the karst and pseudokarst workshops, together with additional research, including remote sensing images and a scan of tourism sites. Some additional sites were added during the field trip on the basis of local information, and serendipitous observations.

Whilst a limited number of important carbonate karst systems were examined, the majority of sites were located in non-carbonate lithologies (primarily sandstones/quartzites, laterites and granites). As fieldwork progressed it became obvious that, whilst investigations were necessarily restricted to areas with reasonable road access, there are likely to be many additional sites remote from roads as these terrains cover a substantial proportion of northern Australia.

Assessment of the significance of the sites was somewhat restricted by a lack of published, comparative research into the nature of landforms and associated environmental processes. This reconnaissance has highlighted important avenues for future research into

Table 1: Sites studied in this project.

Site		Location	Size	Status	Character	Comment
WA	Whalemouth Cave	17°16.4’S, 128°15.7’E	S	P/A? *	Sstn: Large stream cave at edge of plateau	Also Literature
	Osmond Range	17° 17t’S, 128° 18’E area	M	NP/ WH?	Sstn: Plateau with karstic drainage features, ruiniform terrain, & possible caves	Aerial inspection only
	Purnululu	17° 25’S, 128° 25’E area	VL	WH	Sstn: Ruiniform terrain, Pinnacles etc	Aerial & Ground inspection.
Northern Terrirory	Keep River	15° 46’E, 129° 04’E area	M?	NP	Sstn: Ruiniform terrain, large towers	Brief visit only
	Gregory Karst	16° 3’S, 130° 24’E area	L	NP	Limestone karst: grikefields etc	For comparison
	Litchfield	13°13.0’S, 130°44.2’E	S	NP	Sstn: Small ruiniform area, also laterite karst	
	Darwin area	12° 27’S, 130° 50’E area	M	mixed	Laterite karst features	Features in coastal cliff, and within and near the city
	Kakadu Ubirr	12°24.5’S, 132°57.5’E	S+	WH	Sstn: Varied ruiniform features, karren, caves	
	Kakadu Nourlangie	12°51.6’S, 132°48.8’E	M	WH	Sstn: Caves, ruiniform features.	More work needed!
	Kakadu misc	12° 36’S, 133° 2’E area	VL	WH	Sstn: Sinkholes, arches and ruiniform features on the main plateau	Aerial inspection only
	Mt Price	14° 54.9’S, 133° 42.6’E	S-	P?	Sstn: Small cave	small accidental discovery
	Yulirienji Cave, Old St. Vidgeon	15° 2.3’S, 134° 42.0’E	M	NP	Sstn: Cave & ruiniform features	Also Literature
	Bunju (Boorlungu)	14° 17’S, 134° 55’E area	VL	A	Sstn: Ruiniform features, caves, ...	Aerial inspection, limited ground work, Literature.
	Bath Range	13° 20’S 135° 45’E area	L	A	Sstn: Large sinkholes scattered over a broad area	Aerial inspection & remote sensing
	Limmen S	15° 50’S, 135° 27’E area	L	NP	Sstn: Ruiniform terrain	
	Limmen W	15° 46.4’S, 135° 21.6’E	S+	NP	Sstn: Ruiniform terrain	
	Nhumby Nhumby	15° 58.6’S, 136° 4.2’E	S	A	Sstn: Two large sinkholes in plain	Remote sensing & Literature
	Caranbirini	~16° 17’S, 136° 5’E	S+	CP	Sstn: Ruiniform features	
	Abner Range (Cape Crawford)	16° 42’S, 135° 49’E area	L	P, T	Sstn: Ruiniform features	Helicopter access only
	Sturt Plateau	16° 39.7’S, 132° 55.2’E	S	P	Laterite sinkholes	Also Literature
	Castle Rock	18°21.0’S, 033°491’E	S	P	Laterite mesa, pipes.	
	Barry Caves	20° 2.9’S, 136° 40.7’E	S	P	Laterite + sstn: caves	

Site		Location	Size	Status	Character	Comment
Queensland	Lawn Hill (Boodjamula)	118°41'S, 138°29'E	S	NP	Sstn: Significant caves, underground drainage.	Also previous study by KGG
	Tobeys Waterhole	18° 45.6'S, 139°32.1'E	S	P	Laterite karst	Also previous study by KGG
	Cobbold Creek	18° 50'S, 143° 24'E area	L	P,T	Sstn: Ruiniform features, gorge, caves.	Also literature
	Chillagoe Metal Hills	17°6.5'S, 144°30.5'E	S	P?	Granite boulder caves	Small area, substituted for Black Mountain
	Mt Mulligan	16° 50'S, 144° 50'E area	M	A	Sstn: Table mountain with ruiniform features	Access unobtainable, aerial inspection only. Previous study by APS
	Black Mountain	15° 39.2'S, 145° 13.3'E	M	A	Granite boulder caves	Access refused. Remote sensing. Previous study by APS
	Pelican Lakes	19° 52.5'S, 144° 15.7'E	S	P	Laterite: Closed depressions of uncertain origin	Also previous study by KGG
	White Mountains, Denna Plain region	20 43'S, 145° 13'E area	S	NP+P	Laterite karst pinnacles & pans	Also has ruiniform sandstone features
	Salvator Rosa	24° 45'S, 147°10'E area	M	NP	Sstn: Large towers, pinnacles, caves	Also previous study by RAW
	Mt Moffatt	25° 00'S, 147° 55'E area	M	NP	Sstn: Large towers, caves.	Also previous study by RAW

Size refers to the area occupied by ruiniform or karst-like features, not the whole park. S, Small; M, Medium; L, Large; VL, Very Large.
Status: WH, World Heritage; NP, National Park; P, Private land; A, Aboriginal land; T, Tourist operation on private land.
* Note: Location of Whalemouth Cave is about 1km outside the boundary of the Purnululu Conservation Reserve.

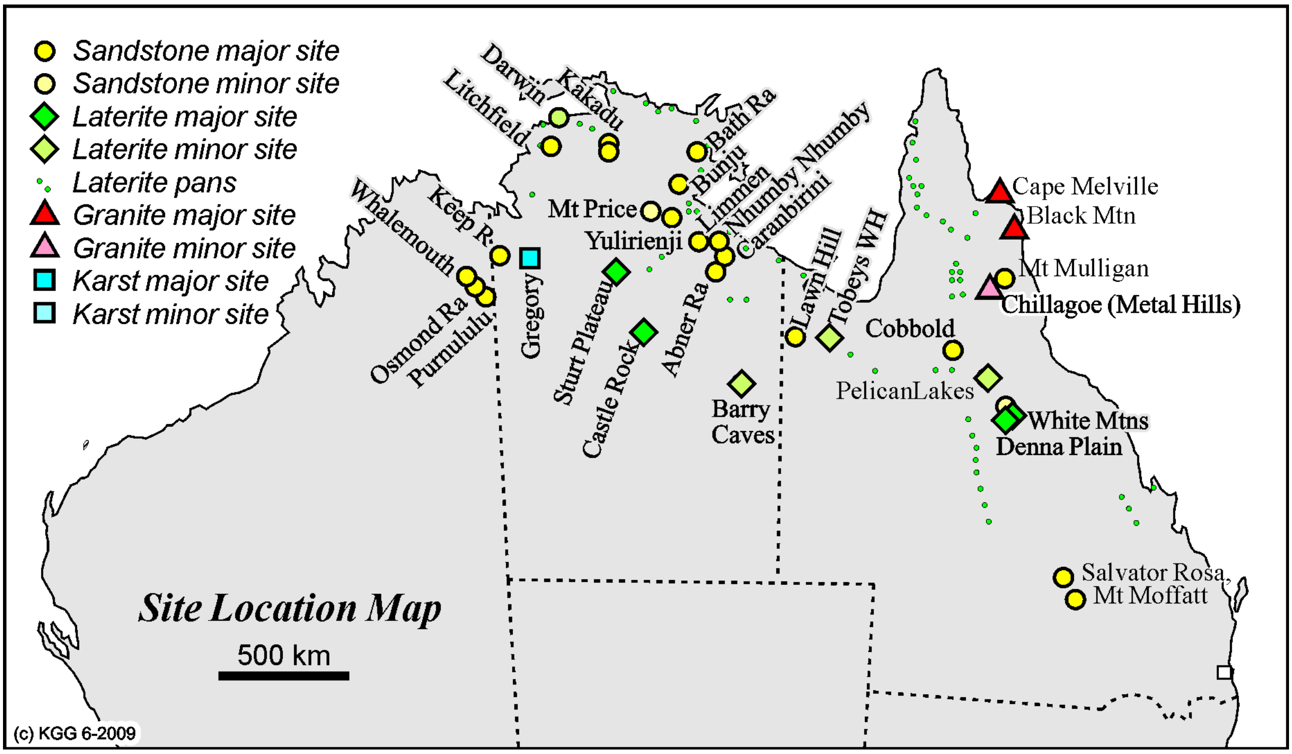


Figure 1: Location of sites described in this report.

landscape evolution and groundwater/surface water interactions in northern Australia. The lack of theoretical development in this field is underlined by the absence of an accepted classification and terminology of silicate, laterite and granite landforms that have developed through varying proportions of solutional and mechanical processes. For this reason, we refer to these landforms as "karst-like" (see section 3, Terminology). We have also used the term "ruiniform" for sandstone terrains which are not strictly karst-like but which have significant scenic and scientific interest.

Land access restrictions, together with problems in contacting the Traditional Owners of several areas and in obtaining their services as guides hampered the field work in certain areas, including Arnhem Land, parts of Kakadu National Park, Black Mountain and Mt Mulligan. Work within Kakadu National Park was also constrained by a lack of clear information on what areas could be visited and what activities were permitted – or not permitted.

Although access during the dry season simplified logistics, it restricted potential insights into critical hydrological and geomorphic processes, which are most active during the wet. A far better understanding of the range of environmental systems and processes would be possible if a seasonal comparison could be made.

However, although both time and finances were limited, a far better understanding of the nature and distribution of non-limestone karst and similar landforms in northern Australia has been gained. The Bunju sandstone site, in particular, is undoubtedly world-class and deserves further study in cooperation with its Traditional Owners.

1.4: Sites visited

Table 1 lists the 32 sites studied during the program, including several that we were unable to inspect on the ground but for which we gained information from aerial views, air-photo interpretation or previous studies. Figure 1 shows the site locations. In the main text we use **bold** text to highlight the names of sites studied.

1.5: The Format of this Report

This report presents a brief outline of the region (section 2), followed by a discussion of the terminology and processes involved on karst, parakarst and pseudokarsts (section 3, with a Glossary as Appendix 2).

Section 4 first discusses and illustrates the nature and nomenclature of the main features of interest found during the study (4.1) and then summarises the features found at each site, and their significance (4.2). Specific data collected and the results of laboratory studies are summarised in 4.3, but the details are in the appendixes and will be provided on the CD-ROM. A list of samples collected is in Appendix 1 as an Exel file on the CD-ROM.

The accompanying CD-ROM provides a selection of photos of the features together with digital versions of associated data and reports. A subset of the photos are printed within the report and an index (page iv-vi) gives the page numbers where these appear. Note that, as per section 5 of the contract, copyright for the photographs and other intellectual property is retained by the authors, but the Commonwealth has non-exclusive licence to use these.

Throughout the text of the report the names of the sites studied are shown in **bold print** and terms that are defined in the Glossary are indicated by *italics*.

A wall of pinnacles at Limmen South, NT. RW08_Limmen-Pan3

2: The Nature of the Region

Most of northern Australia currently has a monsoon climate with pronounced wet and dry seasons (Figure 2). Rainfall varies from high near the northern and eastern coasts, to arid in the inland. Central Queensland is cooler and the rainfall has a less seasonal distribution. However, the weathering of the rocks, that was an essential precursor to the style of erosion that has developed or exposed the karst-like features, extends back tens of millions of years into the Tertiary and even earlier, and possibly even into the Proterozoic (several hundreds of millions of years) in some areas. Past climates have been quite varied, but for much of the early to mid-Tertiary at least are believed to have been slightly wetter. But there has been a progressive drying to the present (particularly inland) as Australia has drifted northwards away from Antarctica, with the opening of the Southern Ocean and coming under the influence of the sub-tropical high pressure systems and tropical monsoon (White 1994).

The geological formations of most interest to this study are quartzose sandstones (including the hard pure quartzites), granites, and carbonates (limestone and dolomite). However, karst-like features are also found in the deep weathering profiles (laterites etc) that are common across northern Australia formed on a broad range of rock types.

The sandstones have a very broad range of ages, from the Proterozoic to the Jurassic, but are all quartzose and are undeformed or have been only mildly folded.

The landscapes hosting the karst-like landforms are quite varied, but frequently involve old land surfaces, and are especially well developed around dissected plateau margins, where denudation rates are fastest. The laterite karst features are invariably related to old land surfaces of Tertiary age, but these have also been dissected to varying degrees. The granite caves are in distinctive boulder hills.

Many of the sites are in national parks or similar reserves; some are in world heritage areas (**Kakadu** and **Purnululu** (Bungle Bungles)). Others are on Aboriginal land, and some on private land used as cattle stations etc. Two of the private sites have well-organised tourist access to the features (**Cobbold Creek** and **Abner Range**).

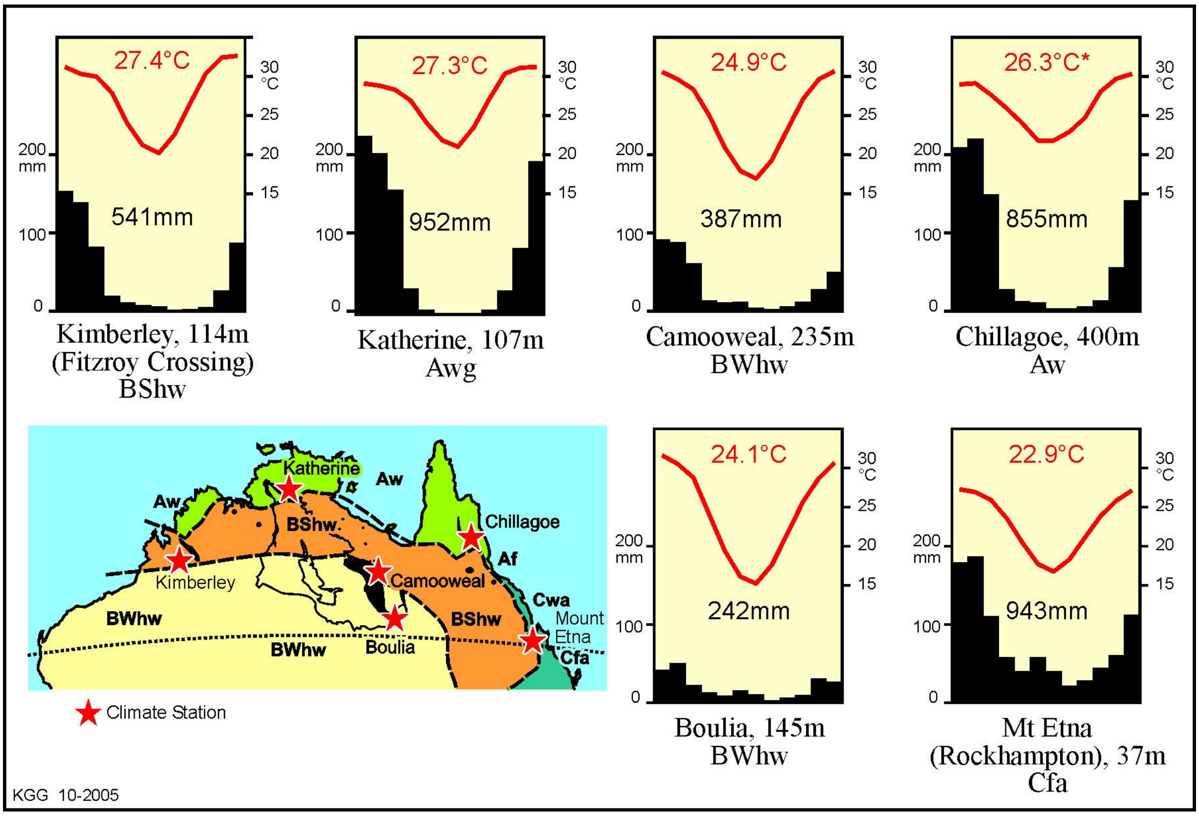


Figure 2: Climates of northern Australia. The map shows the Köppen climates (Green, Humid monsoon; Brown, Semi-arid monsoon; Cream, Arid; Blue, Humid with even rainfall). Monthly mean rainfall and temperatures of selected climate stations are from the Australian Bureau of Meteorology.
From Grimes (in press a)

Pinnacles and a small arch at Abner Range. KG080540

3: TERMINOLOGY

The terminology of the karst, parakarst and pseudokarst features we are describing is complicated by many duplicate terms from different regions or language groups around the world; coupled with a lack of precise definition in many cases. Many of the terms have been used quite broadly and their meanings overlap with each other. We, however, need a set of precise terms for this report, including subtle distinctions that others have not attempted. Thus, some of the terms used here are existing ones but used in a more specific sense, others we have created ourselves.

Part of the problem is that many named features are part of a gradational series with no well-defined boundaries. For example there is commonly a continuous gradation from a high-level plateau *pavement* with small *grikes* through *giant grikes* to *stone city* to *stone forest* and eventually to a low-lying *pavement* with small *grikes* – illustrated by Figure 3. The cut-off between these variants is often quite subjective.

A **glossary** (Appendix 2) defines our meaning of the terms we use in this report for the features seen in the region. Within the main text we use *italics* to highlight terms that are defined in the glossary.

Here we will concentrate on discussing the broader terms used to describe the classification and the associated processes. A detailed discussion and description of the different types of features found in the area follows in section 4.1.

3.1: The classification of Karst - parakarst - pseudokarst - non-karst sandstone weathering.

The definition and coverage of what is meant by the terms 'karst' and 'pseudokarst' are probably one of the most complex and highly argued in modern geomorphology and there is still no universally agreed definitional limits. The problem has been compounded by the recognition of similar forms on rocks other than the limestone on which karst was first recognised, such as the quartz sandstones and laterites studied here.

A wide variety of solutional, weathering and mechanical processes, and many rock types are now known to be involved in the production of landforms traditionally associated with carbonate terrains.

Karst has been defined in general terms as "a terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed secondary porosity" (Ford & Williams, 1989).

However, in nature a continuum exists between predominantly solutional landforms and processes, and systems combining varying proportions of solutional and mechanical processes. This continuum is reflected by the terms *karst*, *parakarst* and *pseudokarst.* Traditionally, a distinction has been made between karst *landforms* or features, the karst *process* that forms them and the *rocks* they can form on (Grimes, 1997; Wray, 1997b; Kemp & Halliday, 1997; Doerr & Wray, 2004). .

Karst landforms can be defined by the distinctive features involved – (a) on the surface: various types of closed depressions, stream sinks, springs, towers and pinnacles, a variety of karren (small-scale sculpturing of the rock), and a general lack of integrated surface drainage; and (b) below the surface: caves and a well-organised underground drainage.

The definitive ***karst process*** can then be referred to as solution. However, it must be noted that even in the carbonate karsts solution is not always the dominant process, so much as a necessary "critical" or "initiating" stage that may later be dominated by other processes, for example hydraulic erosion once large stream passages are formed. In defining the nature of karst, Jennings (1985, p.1) noted that "Solution is not always the most prevalent process in karst, nor is it necessarily the dominant one, but it does play a more important role here than in other kinds of landscape". Other authors, e.g. Young 1987, Young & others, 2009, have also argued that solution can be a "critical" stage even though not dominant in forming karst-like sandstone landforms.

The most extensive ***karst rocks*** are the carbonates (limestone, dolomite, and minor magnesite, and possibly carbonatites) that are particularly soluble in natural waters. However other rocks are also highly soluble, in particular gypsum and halite formations (both rare in Australia, but extensive elsewhere in the world). The silicates (including the quartz sandstones) are soluble to a lesser degree and solution of silicates can form karst landforms if given enough time and suitable conditions.

Having made that distinction, it is the differences in the process, and in the rock chemistry involved, that lets us apply a three-way division (karst, parakarst, and pseudokarst) which was first suggested by Anelli (1963), Cigna (1978) and other European workers, and was supported by Grimes (1997). This approach distinguishes between ***true karst*** (CO_2 influenced solution of carbonates), ***parakarst*** (solution of non-carbonate rocks) and ***pseudokarst*** (processes other than solution) – all three share a common set of landforms such as caves, sinkholes etc.

This three-way division has the advantage of providing a middle ground (the parakarsts) between the (carbonate) karsts and the pseudokarsts, although some authors (eg. Ford & Williams, 2007) argue that the highly soluble gypsum and halite formations should also be regarded as karst, based on their solubility. Cigna

Terminology used in this Report.

To clarify the terminological discussion, In this report we will use the following terms:

Karst: as a general term for solutional landforms (regardless of the degree to which solution has contributed)

Pseudokarst: as a general term for karst-like features in which solution has not been a factor.

Karst-like: describes features that are similar to karst (caves, dolines, underground drainage), without regard to their genesis.

Ruiniform: for erosional features dominated by structural control (grikefields, stone cities etc) regardless of whether solution is involved.

(1978) noted that Maximovitch (1975) had suggested the adjectives "tachy" (fast) and "brady" (slow) to distinguish the high and low solubility types.

However, there is another group of scientists who prefer to restrict the classification to a two-way division, with karst incorporating all karst-like landforms where solution (of any type) is dominant, or if not dominant then "critical" at some stage of the process (e.g. Wray, 1997b, Doerr & Wray, 2004 and Kemp & Halliday, 1997). In this approach most parakarsts would be classed as karst. Given that Grimes and Wray are both involved in the present study, this has caused some debate within the team!

However, most authors are agreed that the *pseudokarsts* are characterised by processes other than solution; and for the present study the main pseudokarst processes involved in producing karst-like features in sandstones, granites and laterites are: chemical weathering in general (i.e reactions other than simple solution), piping, mass movement, granular weathering (tafoni etc), surface stream erosion and wind erosion, among other, generally minor processes.

One problem with the silicate parakarsts studied in this project is that the processes producing the landforms involve both solution and other (pseudokarst) processes and it is not easy to decide which should be considered dominant. Many of the landforms we actually see have been fashioned by other (pseudokarst) processes, albeit guided by a stage of solutional preparation that is either focussed in certain areas which are then eroded to form karst-like pipes, grikes, stone cities and pinnacles; or that produces a soft sandstone which is easily eroded by flowing water, but can support steep faces (enabling the development of deep grikes and steep-walled pinnacles or towers.

An alternative approach, suggested by Houshold, is to consider the amount of insoluble residue involved. In the highly soluble rocks (carbonates, gypsum and halite) this residue is relatively small and does not greatly influence the landforms. However in the sandstones, granites and laterites it is considerable and so for them the final landform relies largely on the type and efficiency of the processes that follow a possible "preparation" stage of chemical weathering, including solution. Using this approach, we could perhaps redefine "parakarst" to cover cases where solution is a critical initiating process, but the bulk of the material is removed (and the landscape sculptured by) other (pseudokarst) processes.

In this approach the main determinant of karst/parakarst/pseudokarst would be the process of *mass transport* of the weathered rock - ie the *proportion* mechanically rather than solutionally *transported* - rather than the rock type or its inherent solubility.

3.2: Usage for this study

Given that this report is primarily concerned with describing and cataloguing landforms rather than analysing geomorphic processes, a simplified terminology is adopted which provides a consensus of the most widely accepted approaches. Hence, the terms *karst* or *karst-like* encompass many of landforms studied, regardless of the processes involved in their formation. Lithological adjectives are used to distinguish landforms developed in limestone (or other carbonates), sandstone, laterite and granite. Some of the spectacular sandstone landscapes described here are not even truly karst-like, but are structurally controlled weathering features, but they have definite heritage values! For these, we use the additional term *ruiniform.*

This report addresses the following broad groups of *karst, karst-like* and *ruiniform* landform assemblages (which are described in section 4):

- **Carbonate landforms** (limestone and dolomite) – true *karst* landforms primarily included for comparison with the non-carbonate systems.
- **Silicate landforms** – which include *karst*, *karst-like* and *ruiniform* landforms developed on:
- **Sandstone** – this is the main focus of the present study, and has the most spectacular landscapes.
- **Laterite** – developed in deep weathering profiles on a broad variety of silicate rocks.
- **Granite pseudokarsts** – *karst-like* landforms, primarily boulder piles and mountains with boulder cave systems and enclosed surface depressions.

Some landforms and features are common to all those groups; others are restricted to one or two only.

The terminology we use for the features ranges from broad group terms or composite features down to specific forms. The terms are defined in the Glossary and discussed in more detail in the following section (4.1). Within the main text we use *italics* to highlight terms that are defined in the glossary, but many of those are also discussed below in section 4.1.

3.3: Some broad terms used for particular landscapes:

Ruiniform: is a general term (Mainguet, 1972) referring to a sharply dissected, "ruin-like" landscape, found mainly on sandstones, which is characterised by numerous vertical-faced blocks of rock which show obvious joint control – particularly good examples occur at **Bunju** and **Abner Range**, and it is extensive at **Kakadu**, but many of the sites visited have areas that fall into this broad class. It is most common at the dissected margins of plateau where the stronger relief has enhanced mechanical erosion. Some, but not all, of the ruiniform components are karst-like. However, one could equally say that karst landforms mimic ruiniform ones – the important factor is strong structural control of localised weathering and erosion, not necessarily the presence or absence of solution.

Here we will use "ruiniform" to indicate the sandstone landforms that exhibit strong structural control, especially that of jointing.

Ruiniform landscapes can be divided into a progressive and gradational sequence from minor *grikefield* to *giant grikefield* to *stone city* to *stone forest* to isolated *pinnacles* (see glossary, and section 4.1.1.1 for details of those terms).

Photo KG080565a, at **Abner Range**, illustrates the progressive change and Figure 3 suggests possible cut-offs between the terms based on the relative widths of the low areas (streets) to the high areas (blocks or pinnacles). However, this simplistic approach ignores the visual influence of the vertical relief and also the confusing visual effect of smaller scale dissection of the tops of the blocks to form smaller grikes, pinnacles etc (photo KG080567Rx). The essential consideration is whether (a) the upstanding blocks dominate over the incised lines (a *giant grikefield*) or (b) the blocks and incised lines have equal dominance (a *stone city*) or (c) the low ground dominates over the blocks & pinnacles (a *stone forest*).

Stone cities, in turn contain a number of features, for which we have adopted a "city" oriented nomenclature: *streets*, *plazas, blocks*, *villas* etc - see Figure 4 and "*Stone City*" in the Glossary. Details are in the following section 4.1.1.1.

Photo KG081180, **Bunju.** Ruiniform terrain – stone city and stone forest.

3.4: Processes

Arenisation and the formation of karst-like features in quartz sandstones

In most of the sandstone terrains studied, the karst-like features have formed by a combination of silica solution and mechanical erosion, a process known as *arenisation* (Martini, 1979, 1987, 2000; Jennings, 1983). However, whereas in carbonates 80% or more of the material is removed in solution, in quartz sandstones it is much lower, perhaps only 10-20% of the rock bulk (Martini, 1979). Much material therefore needs to be excavated by mechanical means, and Martini suggested the term 'arenisation' for this interaction of chemical and physical processes that can lead to karst development in quartzose rocks. This process entails:

- Slow chemical dissolution of quartz, especially along crystal boundaries,
- Freeing of individual grains, leaving the rock less coherent and more susceptible to physical erosion,
- Mechanical removal of sand grains by flowing water and piping.

Piccini (1995) noted that arenisation acts most effectively along the joints. In these joints water is moving slower than that flowing across the rock surface and has a greater time for reaction. On the surface, runoff waters do not have enough time to dissolve the silica cement of the arenite, and the alternation of wet and dry conditions often leads to the formation of hard crusts of silica and iron oxides that protect the rock surface.

The effects of mechanical erosive processes are strongest where the potential energy is highest and water flow is fastest; along streams, and particularly near plateau edges.

As well as producing the karst-like features (*caves, dolines, stream-sinks*), arenisation also contributes to the joint-controlled development of *ruiniform* relief.

The localised solution of the rock has formed many fine gaps between grains. However, because, in many cases, the grains are still (at least partially) interlocking the rock maintains a medium to high compressive strength. This allows the rock to stand in steep faces and form cliffs. However, when a tensional or shear force is applied (such as by running water), the lack of cement binding the rock together allows the grains to be easily detached and the rock is quite easily eroded.

Photo AS.Bunju031P, **Bunju**. The "Blasted Tower" – A lightning strike has shattered a tower to rubble and loose sand; illustrating the friable nature of "arenised" sandstone.

4: RESULTS

4.1: Overview of the Features seen

This section provides an illustrated summary or overview of the most significant findings of this research organised by broad landform type. Section 4.2 of this report describes the individual sites and summarises the landform features and their significance at each.

Note: terms in *italics* are also defined briefly (and illustrated) in the Glossary (Appendix 2).

4.1.1: Sandstone landforms

4.1.1.1 Composite landscapes:

The sandstone landscapes are mainly characterised by a spectacular set of composite *ruiniform* landforms that show strong *structural control* of the erosional patterns. They include *grikefields* (giant or smaller), *stone cities*, *stone forests* or isolated *pinnacles* and *towers*.

In a well-developed *ruiniform* area (eg Photo KG080565a, Figure 3) one can often see a gradational sequence of erosion that starts at the edge of a high plateau, commonly an old erosion surface, with a bare or thinly soil-covered sandstone *pavement* which has narrow eroded *grikes* and *clints* that follow the joints or weaknesses in the rock. With ongoing erosion the grikes deepen and widen to become a *giant grikefield* (photo AS.Roper198), after which the grikes become progressively wider to form a *stone city* in which the streets and city blocks have equal visual dominance (photo RW083223). Further erosion widens the streets and narrows the blocks, which then break up into groups, or individual, pinnacles that now become the dominant visual character – we call this a *stone forest* (photo KG081182x). With further erosion the *pinnacles* become isolated, and these eventually are destroyed to leave a low-level rock *pavement* (or *pediment*) at the base level of the erosion. This, at close quarters looks similar to the original pavement at the plateau surface – it may have small grikes and clints, and the process may cycle again.

A less common form, seen only at Bunju, is a high-level pavement containing a field of circular to elongate

Photo KG080565a. From the air at **Abner Range**, shows the progressive change in ruiniform character from a high-level pavement (foreground), through giant grikes and stone city to a distant low-level pavement with scattered pinnacles.

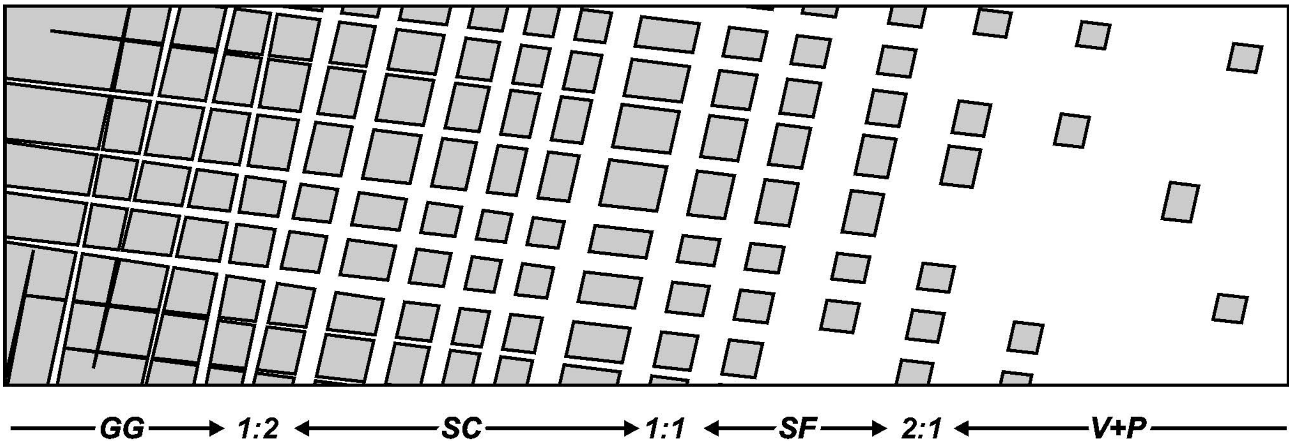


Figure 3: Gradations between *Giant Grikefield* (GG), *Stone City* (SC), *Stone Forest* (SF) and *Pavement* with scattered *Pinnacles* (V+P). Ratios are those between the width of the streets (or low ground, shown in white) and the blocks (high ground, shown in grey)

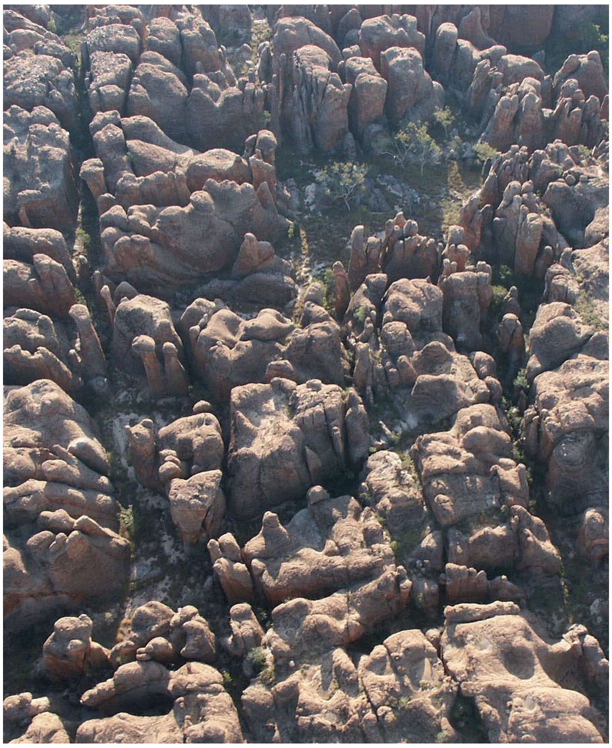


Photo KG080567x, **Abner Range.** Aerial view shows *giant grikes* and *stone city* blocks with dissected tops, narrow *streets* and a *plaza* in the top right.

Photo RW083223, **Bunju**. Aerial view of a *stone city*, showing variety of sizes of smooth-topped *blocks* and *lanes*, *streets* and *avenues*.

Photo AS.Roper198, **Bunju**: *Giant grikes* from air.

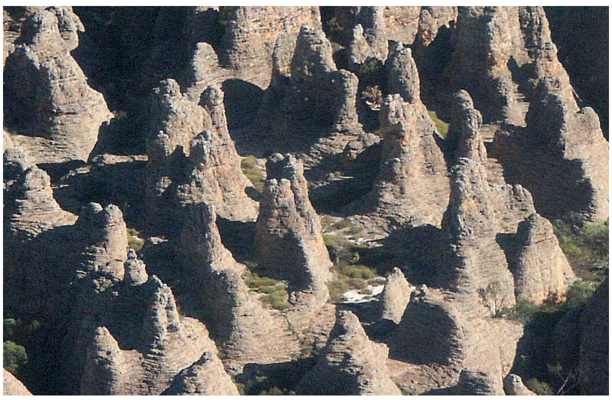
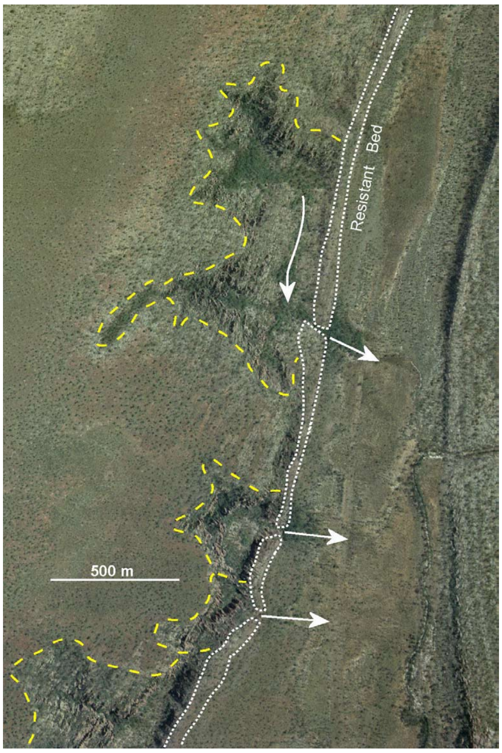


Photo KG081182x. **Bunju**. Aerial view of a *stone forest* of conical *pinnacles.*



Air photo, **Abner Range** NT. Scarp-marginal basins. Yellow lines outline the basins. White dotted line is the resistant bed. Arrows show drainage.

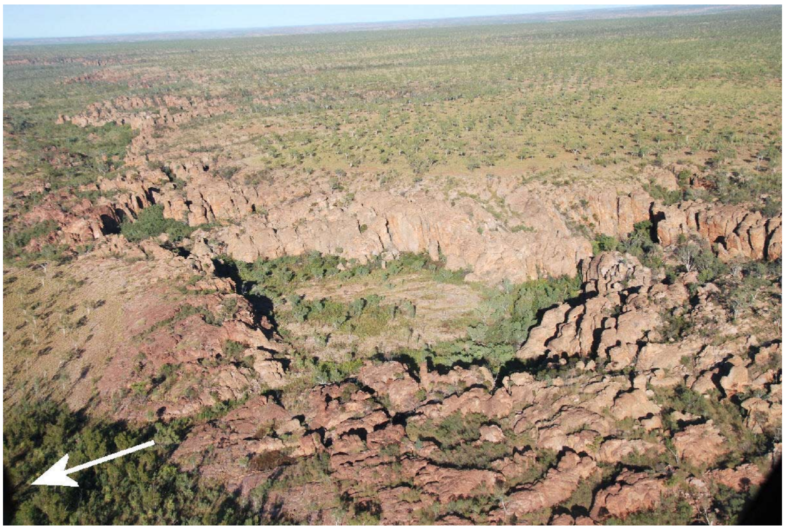


Photo RW081870, **Abner Range**. Scarp-marginal basin. Arrow shows drainage exit line through the resistant bed, with erosional basin expanded behind it.

Photo KG081467, Jabiru Dreaming near Ubirr at **Kakadu**. A broad *tower* or *bornhardt* in sandstone has steep sides, a large *rock shelter* and a smaller *cave* entrance.

dolines (closed depressions) and having a completely underground drainage (photo KG081222).

However, some sites lack the full sequence and show only one form (eg pinnacles and towers only).

Scarp-marginal basins: In the gently dipping belts of sandstone, such as seen at **Abner Range** and **Limmen**, we found distinctive enclosed basins with jagged outlines forming at intervals along the strike line (see air photo above). We will refer to them here as "scarp-marginal basins" – there being no previous name available. These erosional basins typically have a narrow exit, through an apparently more resistant sandstone bed, but widen out upstream of the breach and are eroding back into the plateau or a flat-topped ridge, to form a small-scale more-or-less circular, ruiniform sequence of joint-controlled stone cities etc surrounding a flat-floored *plaza* (photo RW081870, AS.Abner047). The difference from the more usual stone city formation at a plateau edge is that here the erosion is all focussed into a single narrow outlet, rather than as a series of streets opening out onto the marginal pavement. At **Abner Range** they form discrete basins along the belt of *Pra* sandstone west of the main "Lost City" (see air photo). At **Limmen South** we see the discrete narrow exits, but the basins have mostly merged into a continuous belt of ruiniform terrain and are less distinctive. The exit points are often marked by springs or seepage areas that produce a patch of dense vegetation (arrowed on the photos), and these tend to be spaced regularly along the strike line. The stream profiles upstream of the initial plaza are commonly convex, suggesting that subsurface erosional processes are important in these systems.

These basins demonstrate the process of headward erosion and spring sapping as being a major factor in the development of the ruiniform terrain and stone cities. The scarp-marginal basins are the first step in that process.

4.1.1.2 Large-scale features:

Large isolated features are steep-sided *towers*, and round-topped domes similar to *beehives* or *bornhardts*

Photo KG081222, **Bunju.** A field of dolines – circular and elongate; shallow and deep; with possible cave entrances at the base of the cliffs. The flat-floored depression in the centre resembles a *polje* and has a stream channel crossing its floor, so would be better called a *karst window*.

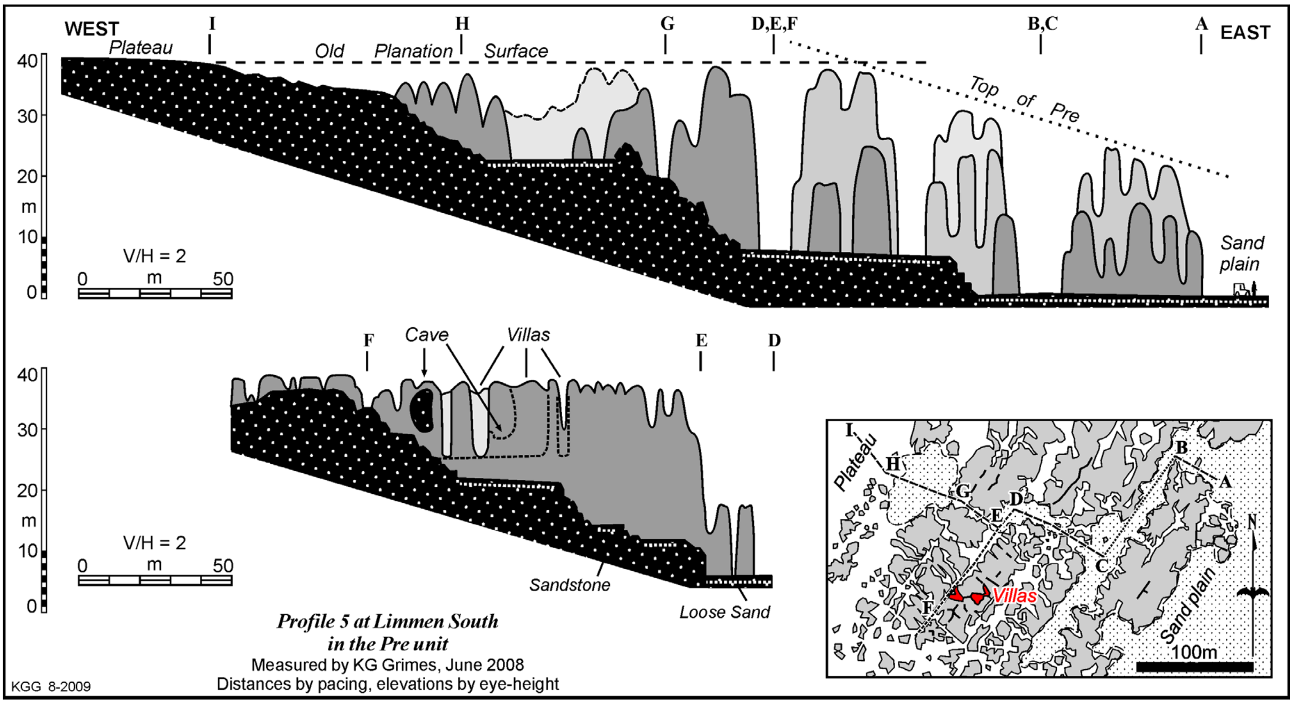


Figure 5: Profile across stone city at Limmen South, showing stepped nature of street floors: flat sandy sections alternate with steep rocky rises. The smaller profile shows projections of several villa courtyards, and a part of the narrow street that is roofed over to form a small cave. Note vertical scale is exaggerated x2.

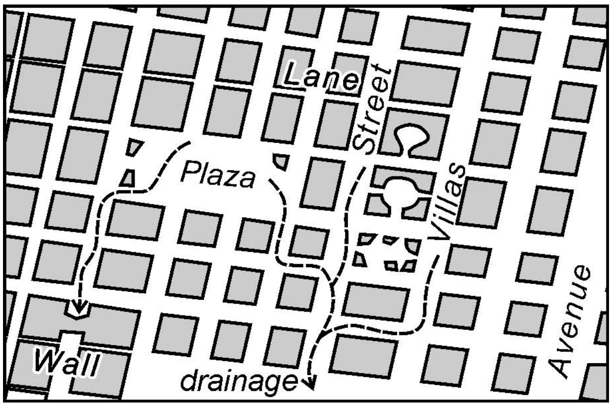


Figure 4: Components of a stone city. Grey is blocks.

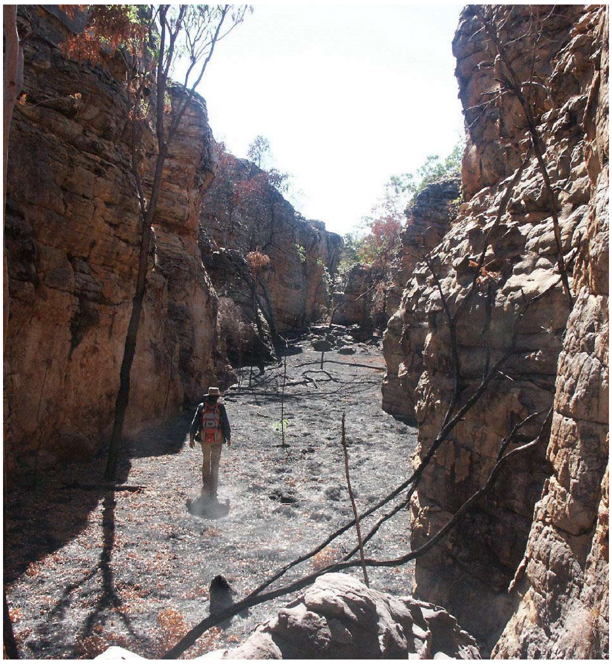


Photo KG080733, **Limmen South**: *street* in a *stone city* (after a fire).

(photos KG082382 (**Keep R**), KG081467 (**Ubir** at **Kakadu**)).

Within the *ruiniform* systems (*grikefields*, *stone cities*, *stone forests*) we find a variety of large features (Figure 4). The city *streets* are typically flat-floored and steep walled (Photo KG080733), with occasional piles of rubble where an adjoining block has collapsed. There is commonly an abrupt (often 90°) break-of-slope at the cliff base. They vary in width, and typically there is a wider set following one joint direction and a narrower set of cross-cutting *lanes*. Occasional broader streets we call *avenues* – they may indicate a fault or major joint, or a group of close-spaced joints, which has produced a wider band of weathered sandstone than is usual. The larger streets are typically floored by white sand with small stream channels, the smaller ones may be rock floored. Occasionally a street may be barred by a *barrier wall* of solid rock through which the stream flow is restricted to a small cave or a narrow *fissure*. Where one or more city

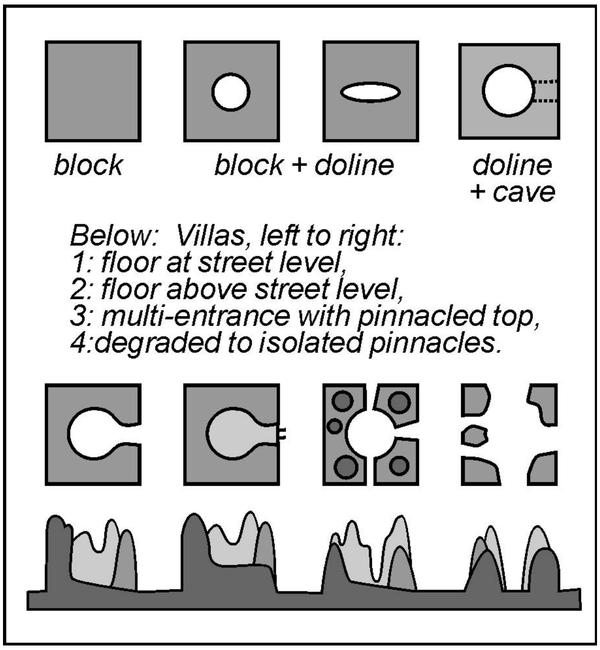


Figure 6: Modifications to a city block.

Photo KG080693, at **Limmen South:** Inside a *villa*. The only entry is the fissure at top left, and the floor level is several metres above the city street outside.

blocks have been destroyed by erosion, flat-floored areas may appear – we call these *plazas* (photo KG081188).

The *city blocks* are initially flat topped or domed (photo RW083223, 7958), but ongoing erosion dissects them further, creating clusters of smaller pinnacles separated by shallow grikes or high-level lanes (photo KG080566x & 0567Rx). In several areas erosion has hollowed out the centre of a block to form a *villa* (a name derived from the Roman villas, which had a central courtyard with one or several entrances from the surrounding streets). The villas in the stone cities have a central courtyard that is up to 15 m across, and commonly 1-5 m above street level (Figure 5, photo KG080693), but in a few cases, seen from the air (photo KG080567Rx), villas can be perched at the top of a city block with only a low parapet around them. The villa

Photo KG081188, **Bunju**. Aerial view of a large *plaza*, within a giant grikefield. There is a small *cave* in an orange bed in the cliff behind the plaza that leads to a large circular *doline* (top middle).

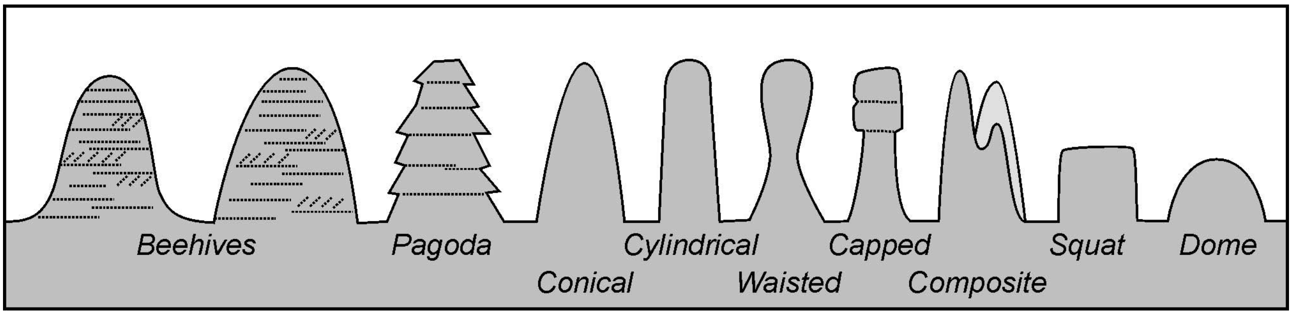


Figure 7: Types of pinnacle

Photo KG082661, **Purnululu**: a *beehive pinnacle.*

Photo KG080608, **Limmen South**: Tilted pinnacles are perpendicular to tilted bedding.

courtyards may have a flat sandy floor, or a bare basinal form eroded into the rock. Some degraded villas are rimmed by isolated pinnacles rather than a thick wall with occasional entry lanes. Note that the mapping of individual villas is difficult as they are commonly at the limits of resolution of the air photo or satellite image, and one needs stereo images to discriminate the villas from shadows cast by pinnacles on top of a solid block.

Pinnacles come in a variety of shapes and sizes, extending from large down into the medium-sized category. Figure 7 illustrates the various named types. The term "*beehive*" refers not only to the domed or bell-shaped outline, but also to the intricate patterns of etched bedding or *tessellations* on their sides (photo KG082661). An interesting effect seen at **Abner** and **Limmen**, where the beds are dipping at up to 20° is that because the pinnacles are formed by removal of

Photo RW084921, **Kakadu.** Large *arch* from air.

Photo KG084392, **Mt. Moffatt**. The thin Marlong *Arch.*

weathered material along the joint planes, which in turn are usually perpendicular to the bedding, the tilted beds and their joints result in tilted pinnacles! Photo KG080608, taken looking along the strike, shows a group of pinnacles all dipping at a similar angle.

Blind valleys 2-3 km long feed into *stream sinks* leading to **Whalemouth** and Widdallion (**Lawn Hill**) Caves (see Figures 12 & 13). Several apparently blind valleys are shown on the topographic map of the **Osmond Range** and two were confirmed from the air. At **Cobbold Creek** a broad basinal blind valley in the middle of a *giant grikefield* feeds through two small caves and a *doline* (or *karst window*) before entering the main gorge. At **Bunju** several valleys are crossed by *bridges*.

Photo AS.Roper185, **Bunju:** Collapse(?) *doline* associated with a cavernous orange bed.

4.1.1.3 Medium-sized features:

Medium-sized features associated with most stages of ruiniform development are *arches* and *bridges* (photos KG080538a, 4392; RW084921), *villas* (see above) *dolines* and *caves.*

Dolines are generally rare in sandstones and were only common at **Bunju** where they were visible on the air photos and confirmed from an aircraft. A few dolines were also seen from the air on the **Kakadu** plateau. In addition to the discrete dolines (or sinkholes) we suspect areas of closed drainage occur within the streets of some stone cities. Some of these are blocked by *barrier walls*. Unfortunately, these are difficult to map from air photos because of problems in estimating the elevations of the narrow street floors.

The **Kakadu** dolines were steep sided and probably collapse type. One elongated example, visited on the plateau margin near Jim Jim Falls, was essentially a giant

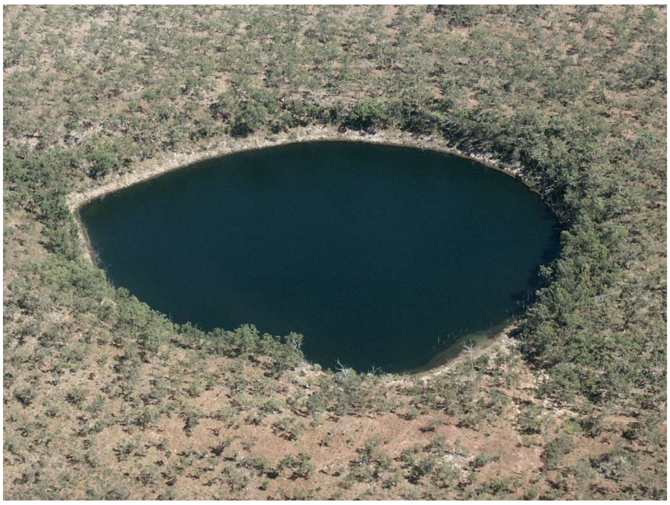


Photo KG081248, **Bath Range:** *Cenote* (water-filled collapse doline) about 260 m wide.

grike with closure at each end. Other circular dolines were viewed from the air (photo RW084929T), but we only got a brief look and ground access would be very difficult.

At **Bunju**, there is an area of high-level pavement (a stratigraphic unit) in the eastern sector (Map, Figure 19, photo KG081222) with a variety of dolines ranging from fields of small, shallow, elongated hollows (10 m wide, but up to 50 m long) with soil and vegetation fill (photo KG081226a - foreground), to less common larger, deep, steep-sided holes up to 10-30 m across and possibly 10 m deep (photo KG081225, RW083498). There was also a larger closed depression 30 x 150 m, and about 10 m deep with a flat floor and stream channel that was reminiscent of a *polje* (photo AS.Roper156) but would be better classed as a *karst window*. There were overhangs and rock shelters in the cliffs at the edge of this plateau, some quite close to the deep dolines and very likely connected to them by caves (photo KG081223). The cliffs were in an orange to yellow unit, which was seen to have numerous overhangs and rock shelters elsewhere in the area (Photo RW083544b, 3492, AS.Roper185 & 202).

Elsewhere at **Bunju** there were isolated large deep dolines, some with possible cave connections to adjacent streets or plazas (photos AS.Roper185, 202 & RW083492 show deep circular dolines up to 20 m across), and smaller elongate shallow and deep hollows.

The large collapse dolines at **Bath Range** and **Nhumby Nhumby** occur in sandstone, but are of uncertain origin and we have not been able to observe them on the ground. Several have permanent water-table lakes and would be classed as *cenotes* (photo KG081248). The sandstones at Bath Range might have a carbonate content that could dissolve, making them true karst, and the sandstones at Nhumby Nhumby overlie a dolomite bed, so those dolines could be a type of *subjacent karst* collapse.

Photo KG082374, **Keep River**: *Rock Shelter*.

Large collapse dolines also occur in *laterite karst* on the **Sturt Plateau** (see 4.1.2).

4.1.1.4 Caves:

Complex *caves* that penetrate for any depth into the rock, as opposed to simple *rock shelters*, are quite rare in most quartz sandstones. However, they are more

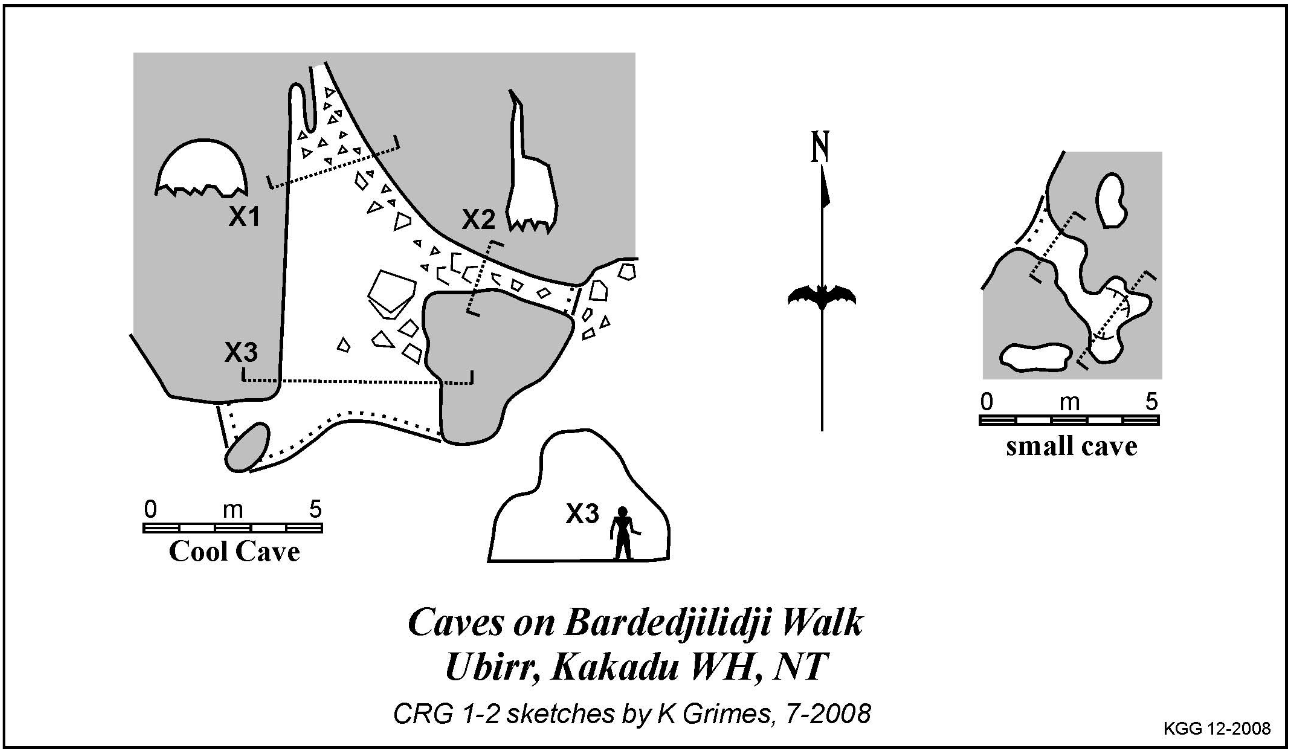


Figure 8: Two small caves on the Bardedjilidji Walk, Ubur, **Kakadu**: Left "Cool Cave", Right "small cave".

Photo KG080635J, **Limmen South**, Small tunnel cave connecting two villas.

Photo KG081553P, Ubirr, **Kakadu**, Rear chamber of small cave with "phreatic" looking sculpture that may in fact be tafoni. (Feet for scale. see map, Fig 8)

Photo IH08072008_33. Coralloid speleothems in Cave "No.2" at Nourlangie, **Kakadu**. Probably silica, but not analysed.

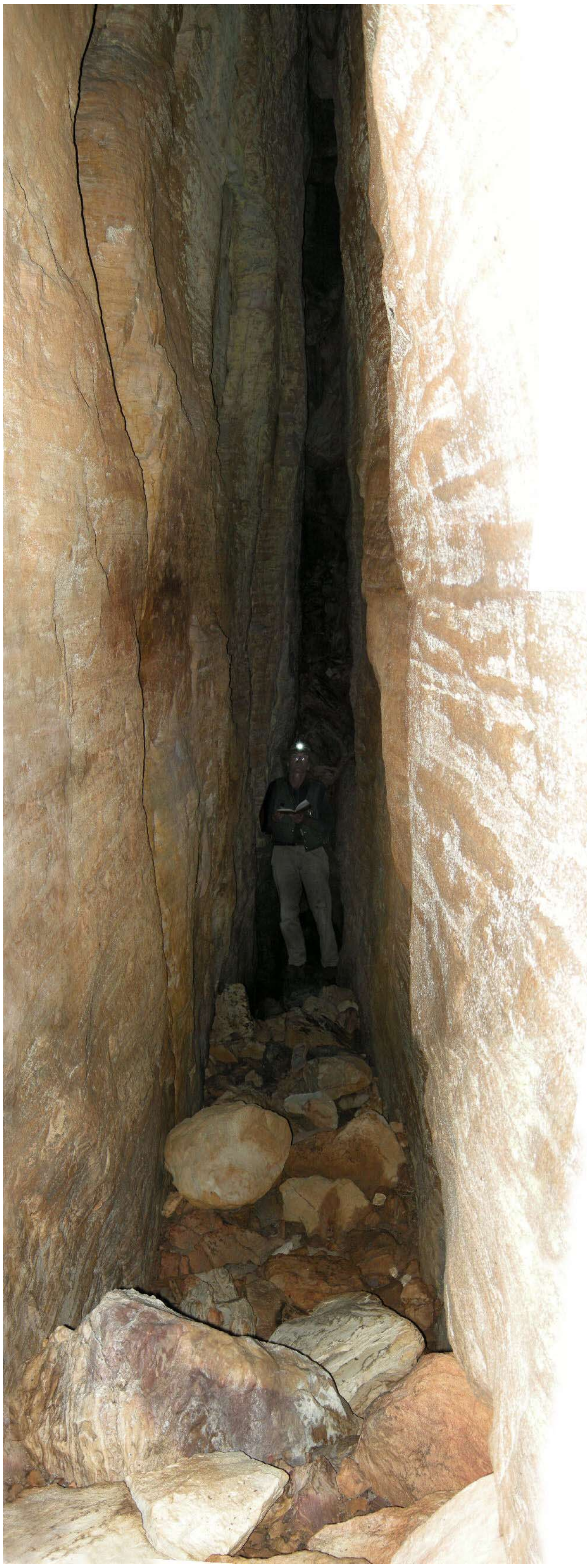


Photo IH08072008_04P3Jb.
Tall fissure passage in cave "No 2" at base of the main scarp at Nourlangie Rock, **Kakadu**, NT. See Map in Fig 9 (section X5). The ceiling reaches to daylight. The floor is water-washed rubble.

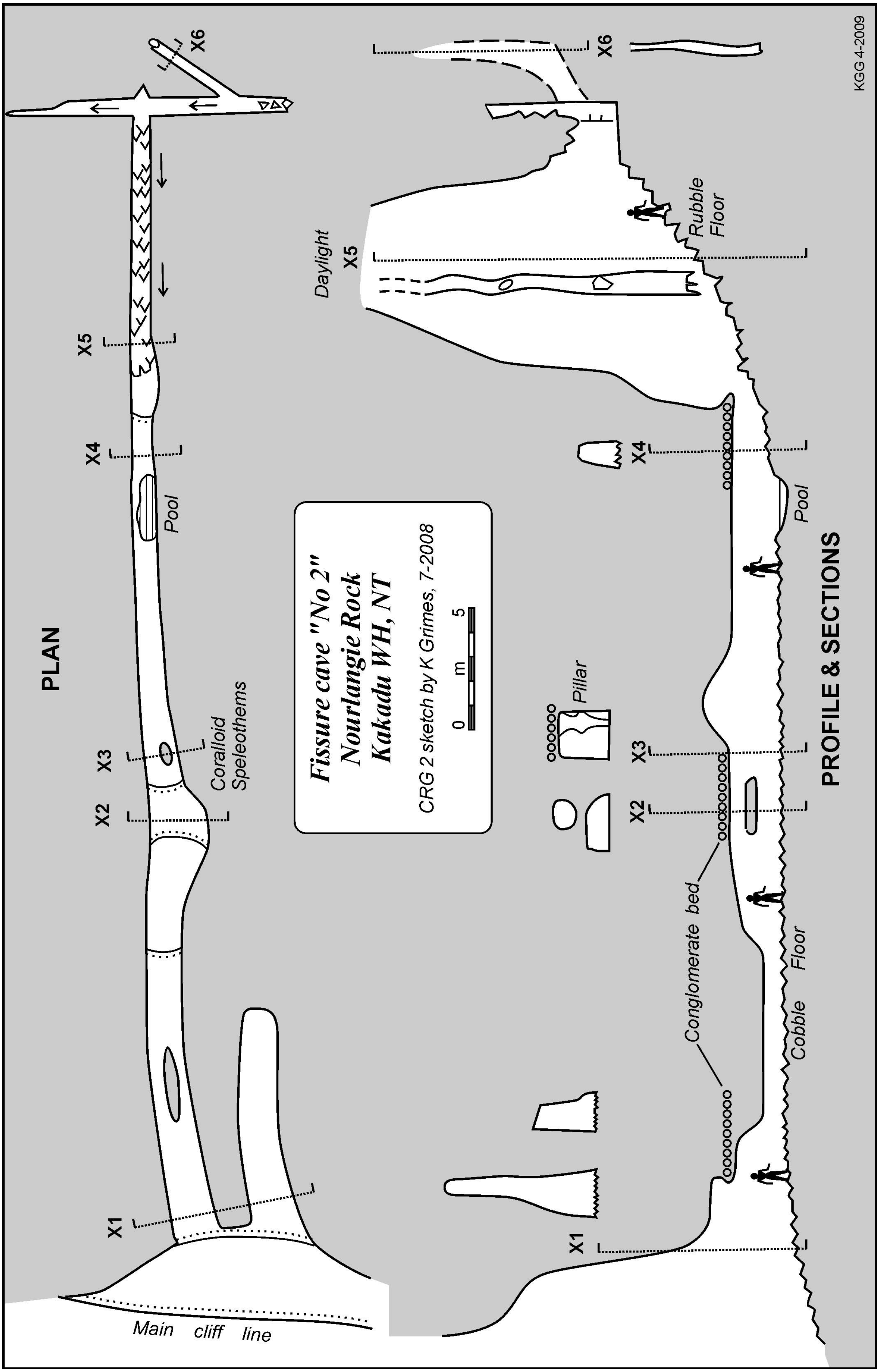


Figure 9: Map & Profile of "Cave No 2" at base of big cliffs at Nourlangie Rock, Kakadu,

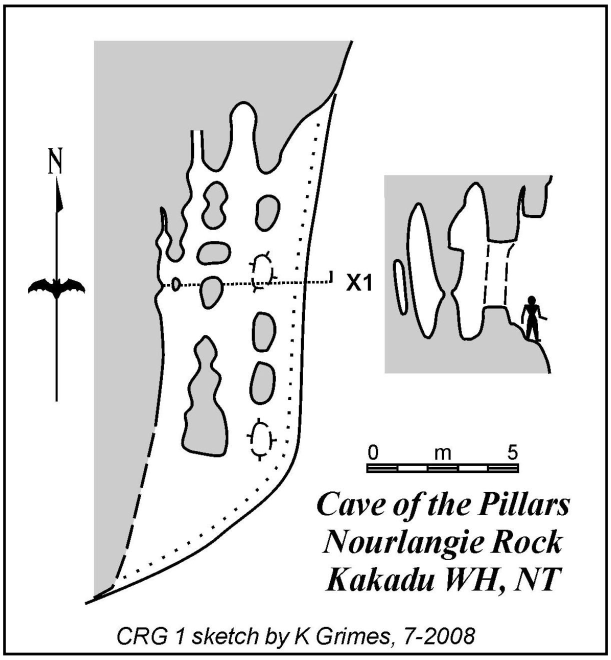


Figure 10: Cave of the Pillars. On the plateau top at Nourlangie Rock, **Kakadu**.

Photo RW084570bx, Nourlangie, **Kakadu**: Cave of the Pillars, entrance (See map, Figure 10).

common in some places, such as tropical Venezuela and Brazil (see Wray,1997a and Young & others, 2009), for detailed reviews), but to date little research has been done on the sandstone caves of northern Australia. The caves inspected varied from simple rock shelters (*cavernous weathering*) at cliff-bases (photo KG082374); to short connecting passages between giant grikes (photo KG083821Pa) or between city streets and villas (photo KG080635J); to simple *fissure* systems (Figure 9, photo KG081763P, IH08072008_04P3Jb); to significant through-flowing stream systems (**Whalemouth Cave**, north of Purnululu and Widdallion Cave at **Lawn Hill**) and a relict stream cave (**Yulirienji Cave** at Old St Vidgeon); to extensive and complex *mazes* seen at **Nourlangie**, and potentially **Jim Jim** in **Kakadu**. These stream and maze caves are the largest known in sandstones in Australia and undoubtedly rank internationally among the world's large sandstone cave systems and therefore hold very important national heritage significance.

***Kakadu Caves**:*

At **Kakadu** we found a variety of caves. Rock shelters are very common and well known, often holding important cultural and archaeological heritage. Other small to medium caves are moderately common in all parts of this region. Several large fissure caves and one extensive maze cave were visited at Nourlangie Rock, and there are undocumented reports of other, smaller but significant cave systems at Nourlangie (G.C Nanson and S. Short, pers. comm. to RW), and possibly also near Jim Jim Falls.

The Australian Karst Index (Matthews, 1985) lists four caves in the Jabiluka area (8J-1 to 4) with passage lengths up to 100m. Little detail is given, but 8J-3 is named “Jigsaw in Tubes” and described as a “complex joint-controlled passage” with a total passage length of 70 m and a vertical range of 40 m. That area was not visited on this trip.

Ubirr has well-known rock shelters with Aboriginal art. A large, unvisited, cave entrance was seen part way up the sides of a large sandstone dome (photo KG081467) near the East Alligator River boat landing.

At **Bardedjilidji** south of Ubirr, two caves are worth describing (Figure 8). Cool Cave, on the main walking track, is a single chamber, 10 m long and up to 4 m high, with three entrances. At the rear it narrows to a fissure in a strongly jointed area. A smaller, but interesting, cave (Figure 8) has its entrance 2.5 m up the side of a small sandstone tower (photo RW084442a), and is developed mainly in a single thicker bed within a thin-bedded sequence. The 4 m long entry tunnel has an irregular, but smoothly-rounded cross-section (photo KG081550a) and the small (1.5 m long) terminal chamber has many pockets (large and small) that might be *phreatic* in character, although one must be careful not to confuse such things with *tafoni* hollows (photo KG081553P). There were numerous small silica *coralloids*, stalactites, and flowstone in this cave.

At **Nourlangie Rock**, a suite of large caves were visited, comprising high level, horizontal maze systems developed not far below the plateau surface; deep fissure systems, some of which presumably drain these systems in the wet season; and a variety of *rock shelters*,

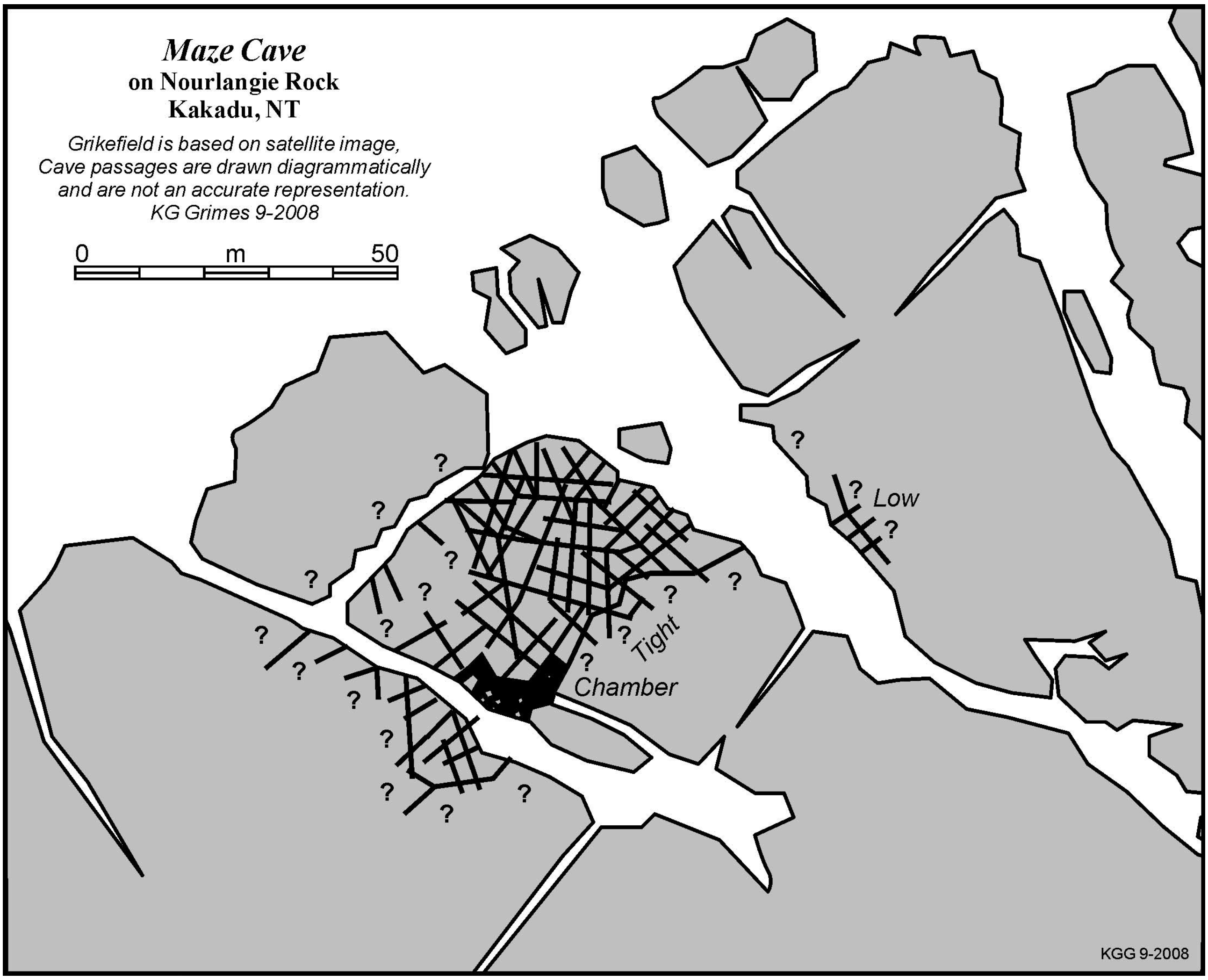


Figure 11: Large maze cave at Nourlangie Rock, **Kakadu**. Grey is sandstone blocks, white is floor of giant grikes. See photos on facing page. Note that the cave has not been surveyed, the passages are just shown diagrammatically.

generally at the main cliff base, containing highly significant Aboriginal art.

The three fissure caves comprise tall vertical *fissures*, in places reaching to the surface, that intersect to form simple mazes. One at the base of the main cliff ("cave No 2", AMG ~629773) went in about 50 m (Figure 9). At the start it was low roofed, even a crawl, but further in the ceiling rose at least 10 m out of sight and there was some daylight. It ends at a T-junction and a final narrow fissure doubles back (see Figure 9, photo IH08072008_04P3Jb). This cave contained deposits of rounded to sub-angular fluvial cobbles and gravels, suggesting that it provides a significant underground flowpath during the wet season. The upper level may connect to a system of horizontal cave and tube development reported (G.C Nanson and S. Short, pers. comm. to RW) at a major bench not far below the plateau surface.

On the top of the plateau two *fissure* caves occurred behind a local scarp running north from the main cliff-line west of the waterfall. These were both tall narrow fissures, up to 12 m high, with some cross-fissures (photo KG081763P).

Nearby was the small but distinctive "*Cave of the Pillars*" (AMG ~630775, Figure 10, photos KG081729Pax, RW084570bx) that was a daylight system with several rows of *pillars* rather than solid walls. These pillars were at two levels, and were strongly sculptured by a combination of etched bedding and vertical *pseudo-karren* flutings (photo KG081737). Pillars of this type are a distinctive feature of many of the caves at Kakadu.

To the northwest a chaotic area of degraded stone city at AMG 629777 had numerous collapsed blocks and pinnacles and some remnants of cave passages (photos KG081796, RW084659) which suggested the prior existence of a horizontal maze cave, but at a higher stratigraphic level to that of the main maze cave described below.

The ***big maze cave*** found during this study (at AMG 628778) so far remains unnamed and because of its complexity and potential significance requires further

Photo KG081833P, part of maze cave at Nourlangie, **Kakadu**: Panorama of the big chamber, showing flat roof, *pillars*, *bollards* and fallen blocks. Daylight in distance is entrance from giant grike. (see map, Fig 11)

Photo KG081820a, maze cave at Nourlangie, **Kakadu**: Two fissure passages combined by loss of a thin wall. Note roof *pendant* left behind, and water-washed cobbles on floor – evidence of strong wet season stream flow.

Photo KG081859, maze cave at Nourlangie, **Kakadu**: Small passages at south-eastern end of cave. Notebook is 19cm high.

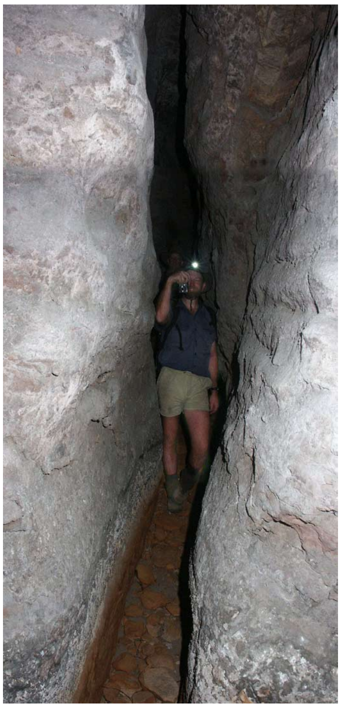


Photo KG081846P (above), Giant grike cutting the maze cave at Nourlangie, **Kakadu**.

Photo KG081823Px (left), Fissure passage in maze cave at Nourlangie, **Kakadu**.

study. It is extremely significant for several reasons, including geomorphic and, possibly, cultural national heritage values. This is the first recorded case of a large maze system in sandstone in Australia and it is of sufficient size and complexity to rank internationally among the world's large sandstone caves. We had limited time, so this cave remains unsurveyed but has an estimated total passage length of at least 1500 metres. It occurs about 20 m beneath a gently dipping sandstone pavement with well-spaced giant grikes, which descend to the level of the cave and intersect some of its passages. A second, less extensive, pavement occurs at the floor-level of the cave and grikes and forms a bench along the main scarp. Individual grikes vary from 1-20 m wide and 15-20 m deep (photo RW084701, 4742). The cave is a dense maze of horizontal joint-controlled passages (Figure 11).

The passages are typically spaced 3-5 m apart and are 0.2 to 2 m wide and 0.5 to 3+m high (photo KG081859). Some are very tall fissures (photo KG081823P). Wider passages are often a coalescence of two closely-spaced passages, as indicated by *pendants*, *bollards* or relict pillars (photo KG081820a). The passages become smaller and tighter to the SE (away from the main cliff-line). The passage floors are generally flat and formed of sand, gravel or sub-round to sub-angular cobbles, with occasional boulders – the cobbles appear to armour the floor against erosion by the strong wet-season streams (eg photo KG081820a).

Adjacent to the giant grikes, enlargement of close-spaced passages often results in the formation of distinctive cylindrical and hour-glass *pillars* (photo KG081846P, RW084768, 4786).

A big chamber is located adjacent to the SW bounding grike, and is also connected to a second grike parallel to that one (see Figure 11 and photo KG081833P). *Pillars*, *bollards* and roof *pendants* indicate that the chamber formed by the enlargement and coalescence of a maze of passages.

The caves at Nourlangie Rock strongly suggest two main phases of development at this part of the Arnhem Land Escarpment at least. Firstly, an extensive series of largely phreatic(?) maze systems was developed at no great depth below the present Arnhem Land Plateau surface (although there may have been substantial surface lowering since their original formation – as seen in the decayed horizontal maze described above). Secondly, as local relief increased due to lowering of the surrounding land through lateral extension of the Koolpinyah surface (c.f. Nott & Roberts 1996), a series of vertical fissures developed, draining the maze systems. It is likely that both are currently connected by substantial subsurface flows during the wet season. Weathering caves (rock shelters) at cliff bases are likely to be relatively young features, developed through slow groundwater *exsudation* near present base level.

At **Jim Jim Falls**, ground and aerial observations of the edge of the sandstone plateau indicates structures similar to those seen at Nourlangie, and there appears to be strong potential for maze cave systems in that area also. The Jim Jim Falls track passes near an elongated doline, from which a large maze cave appears to radiate at shallow depth below the surface. Passages lead to vertical drops into fissure caves, which were not investigated further during a very brief reconnaissance. The form of this cave potentially mirrors the two-phase development documented at Nourlangie. Further detailed examination would be strongly warranted, as this system is likely to be extensive, and incorporate many features typifying caves on the Arnhem Land Escarpment.

Similar potential exists elsewhere at Kakadu, along much of the escarpment, its sandstone outliers, and the plateau surface. Because of the importance of such sandstone caves, research in this area should be actively encouraged.

Caves at other sites:

At **Bunju** our aerial and ground inspections, and local reports (Jennings, 1979a) suggest that there are extensive sandstone cave systems (see discussion above of the *dolines* there). The presence of caves was suggested by Jennings (1979) from comments made to him by an Aboriginal guide, but he was unable to visit any such caves. Many large entrances were seen from the air in the "orange" beds (see discussion of dolines above, and photos AS.Roper185, KG081225, RW083492, 4269a).

Photo IH27122008_18PJ, **Whalemouth Cave**, Looking out of the big downstream chamber.

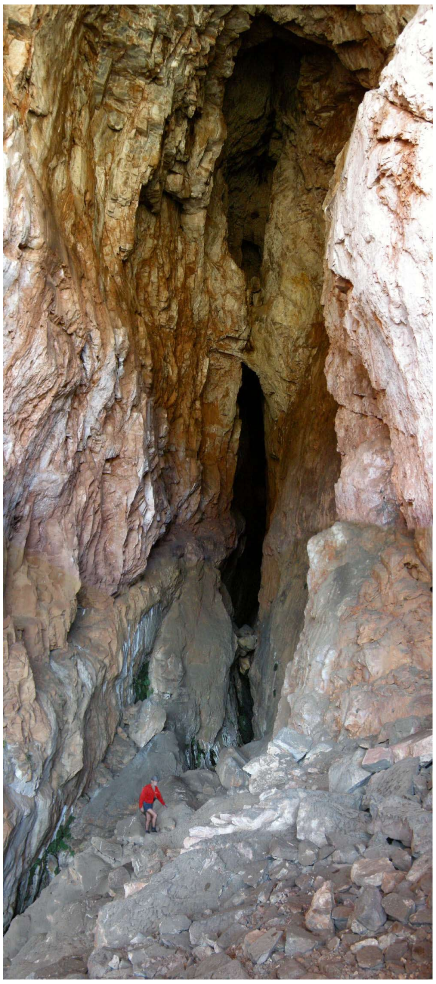


Photo IH17072008_07PJx.
Whalemouth Cave. Stream fissure passage behind big exit chamber.

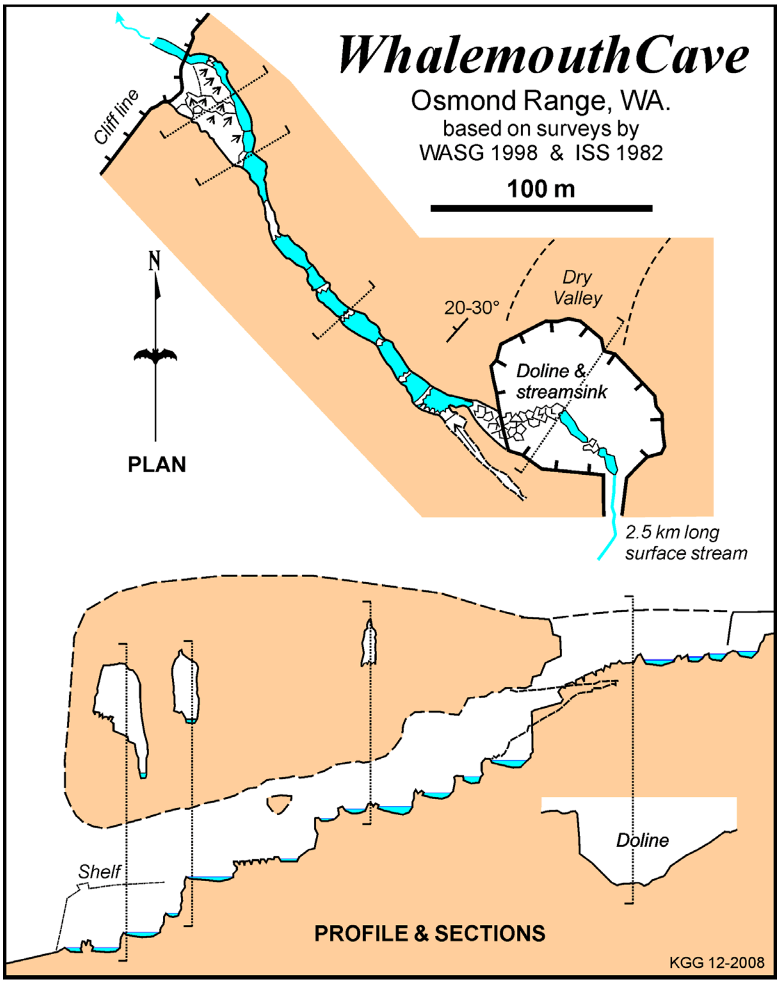


Figure 12: Map and profile of **Whalemouth Cave**. From Grimes (2008).

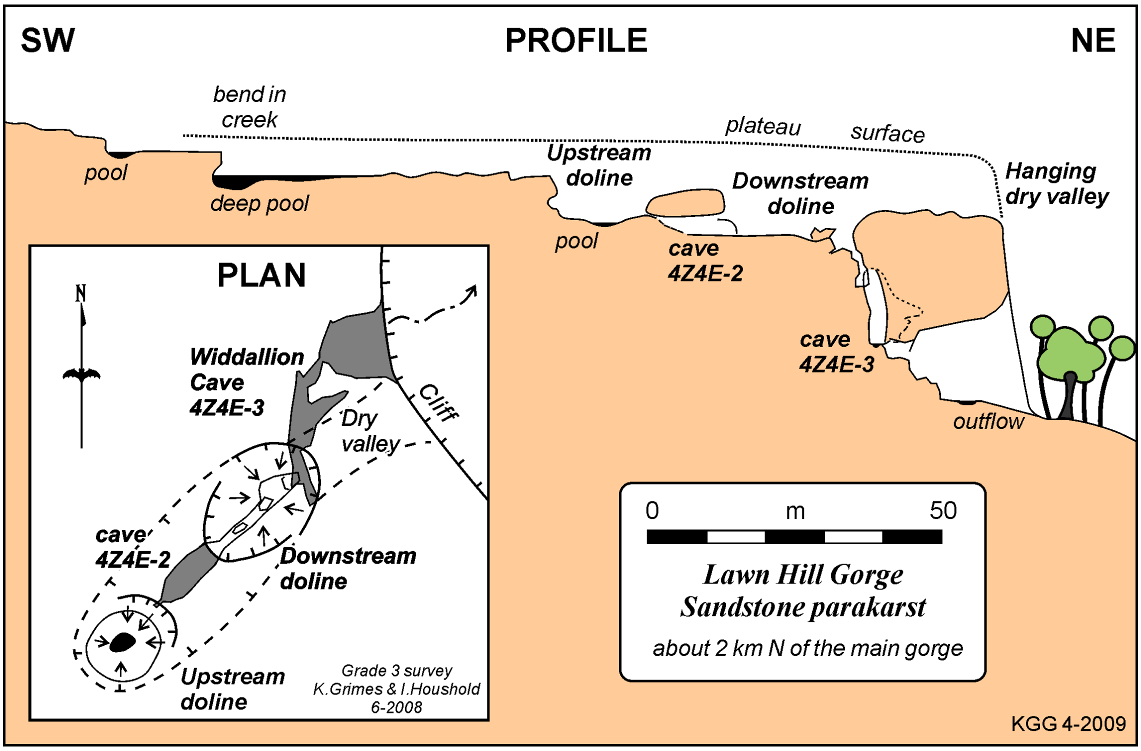


Figure 13: Profile & map of blind valley and Widdallion Cave, at edge of plateau, **Lawn Hill Gorge** area, Qld.

Photo KG081019P, **Yulirienji Cave**. Looking north along the old stream passage. NB Aboriginal art on walls.

Two significant stream caves formed at plateau margins were visited (**Whalemouth Cave** in WA, and Widdallion Cave at **Boodjamula (Lawn Hill)**, Qld). See those sections for details. These both have sizable streams sinking into them on the plateau surface and they descend as a series of vertical fissures to an exit at the base of the scarp (Figures 12 & 13 & photos KG080116a, KG082429ax, IH27122008_18PJ). Widdallion Cave also had unusual orange and grey speleothem deposits (see below, 4.1.5).

Yulirienji Cave, south of Roper Bar, has been known for some time (e.g. Tindale, 1925). It is unusual for its geomorphic character and setting (Jennings,

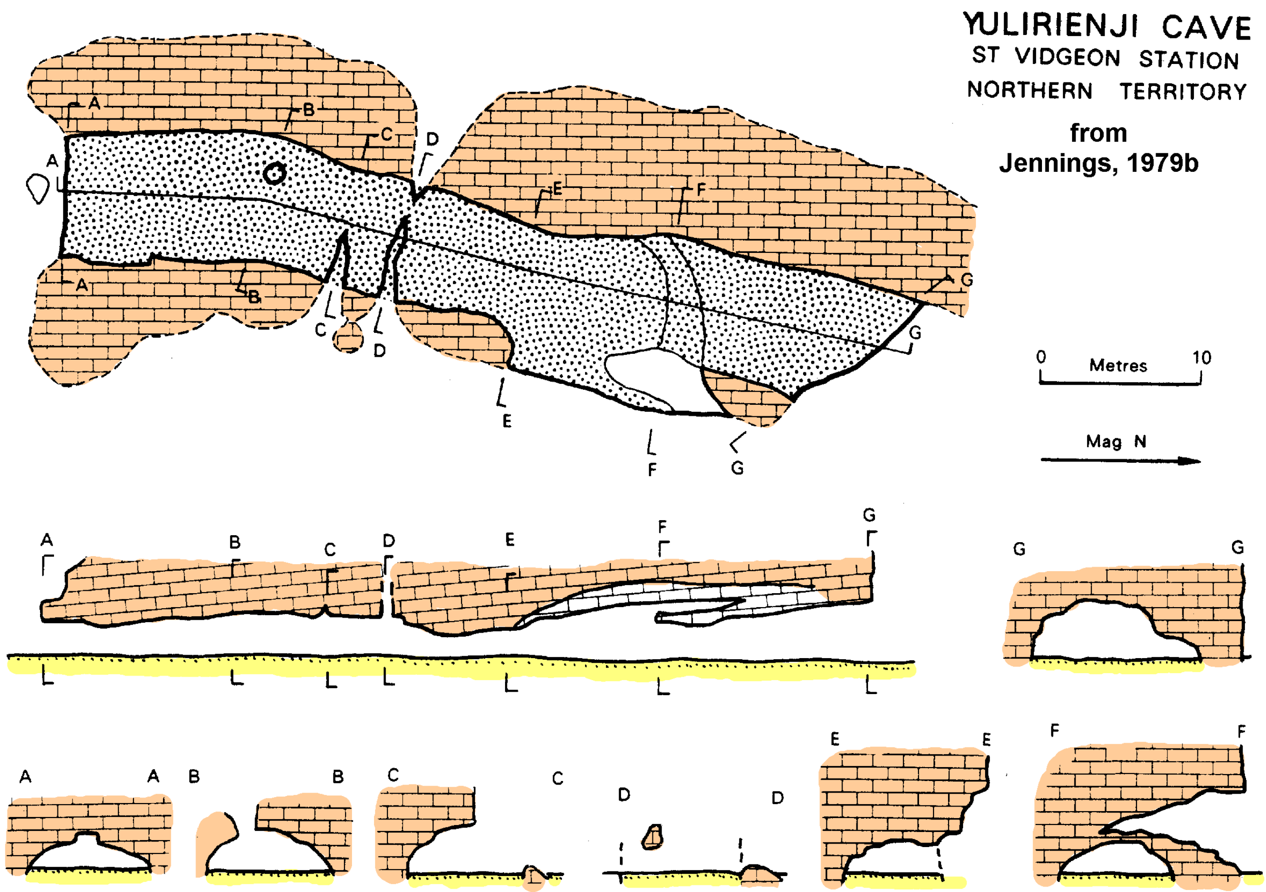


Figure 14: Map of **Yulirienji Cave**, from Jennings (1979b)

Photo KG083634Pb, short stream cave at **Cobbold Creek**, Qld.

1979b, Figure 14), but more so for its Aboriginal heritage (Mountford & Brandl, 1967). It is a horizontal broadly-arched tunnel, 50 m long and 8 m wide (photo KG081019P, RW083051a) that runs beneath a stone city block, and is perched 13 m above the level of the present stream. This cave appears to be very old, and of uncertain genesis – further study is needed. The cave has extensive rock art, grinding hollows and a depository of human bones.

At **Cobbold Creek** there were numerous rock shelters and some partly-roofed grikes (photo KG083826Pb), and also a set of small stream caves taking flow from a broad irregular blind valley on the plateau top. This comprised two low but broad caves (photo KG083634Pb). A well-formed wet-season stream channel (photo KG083728) runs from the blind valley westward through the first cave then across a smooth-walled doline (or *karst window*) and through the second cave. The stream drops 7 m from the far end of the cave system into a side gorge of the main Cobbold Gorge.

In the Carnarvon Ranges (**Salvator Rosa** and **Mt. Moffatt** sites), rock shelters and large tafoni cavities grade to small tunnel-caves up to 10 m long, which in turn intersect sets of horizontal *tubes* 0.1-1 m in diameter and with circular to elliptical sections (Wray, 2009; and see Figure 15, photos KG084396, 4562, 4622). These small straight tubes intersect to form inaccessible mazes. Coalescence of tubes can form small caves (see Figure 15 for maps of SR-4, MM-5 & MM-6 and photos KG084333j, & 4562). SR-4 comprises a rock-shelter with pillar and a network of small tubes. Some caves and rock shelters have archaeological significance (QPWS, 2005, Mulvaney & Joyce, 1965, Robins & Walsh, 1979).

At **Mount Moffatt** a variety of small caves includes some of significance for both geomorphology and archaeology. The small caves are mostly found at the foot of the cliffs. Larger tubes are transitional to small "tunnel" caves. At Marlong Arch, there were several tubes and tunnels up to 1 m diameter that drilled part or all the way through the wall beside the arch (e.g. photo KG084393) and one small cave was a walk-sized passage that followed a joint in and then turned left to follow a cross-joint parallel to the cliff face (photo KG084396).

At Cathedral Rock there were two small but interesting caves. Cave MM-5 (Figure 15 and associated photos) had two short horizontal branches. The right branch was a double tube (photo KG084562) and the main branch was a single horizontal tube but with a cavity in the ceiling that might have been the beginning of a higher cross tube. Outside there were two other tubes in the cliff at this higher level. Cave MM-6 (Figure 15 and associated photos) was a set of partly-connected small (impenetrable) horizontal tubes at different levels.

Slightly larger caves are mainly the result of cavernous weathering, though this may have commenced beside a tube. One in the ridge to the NE of Cathedral Rock had a narrow, joint-controlled, entrance (photo KG084674Pa) but opened out into a low-roofed twilight chamber, about 4 m across and less than 1 m high (photo KG084668) with a short joint passage continuing into the ridge.

There are also the archaeological caves at The Tombs (photo KG084464P) and Kenniffs Cave, described by Mulvaney & Joyce (1965), Robins & Walsh (1979) and QPWS (2005).

Mulvaney & Joyce (1965) describe Kenniff Cave as a joint controlled rectangular loop in plan with a central pillar that slopes inwards and much collapsed rubble. Total passage length is about 90 m, and roof height averages 3 m but with some very low sections less than 0.3 m. Bedding and joints control the detailed form and the ceiling is a hard quartzite. Wray reports some smaller tubes leading off from the main passages. The excavation was 3 m deep in fine sand & gravel with some rubble.

The Tombs has medium-sized shelters & caves at the base of the cliff with some tafoni and horizontal tubes (photo KG084464P). The tubes also occur concentrated in bands along susceptible beds higher up (photo KG084446P). Mulvaney& Joyce 1965 report that the main archeological cave is 35' (10 m) long and 15' (5 m) wide and 1-3' (0.3-0.9 m) high.

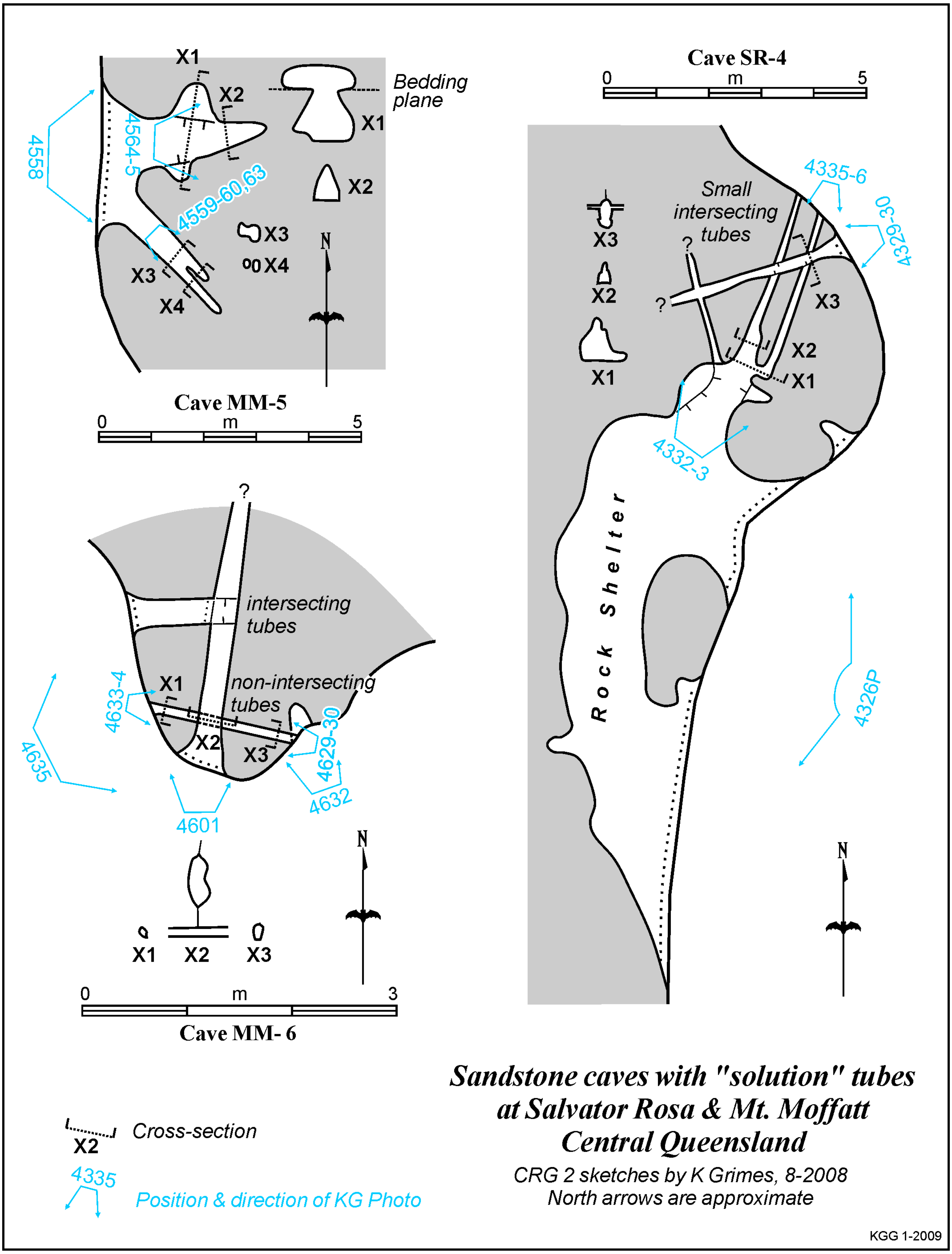
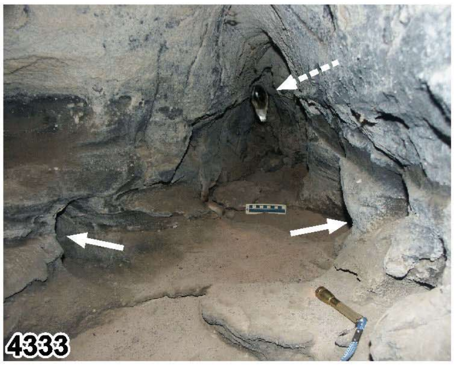


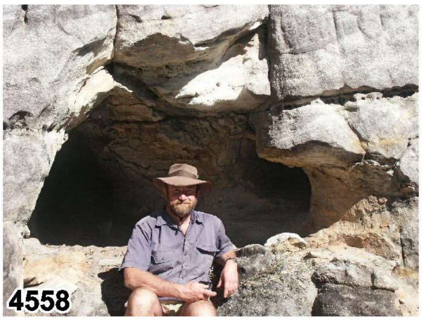
Figure 15: Caves with tubes at **Salvator Rosa** and **Mt. Moffatt** - see also photographs on facing page.

Photos for cave maps SR-4, MM-5 & MM-6.

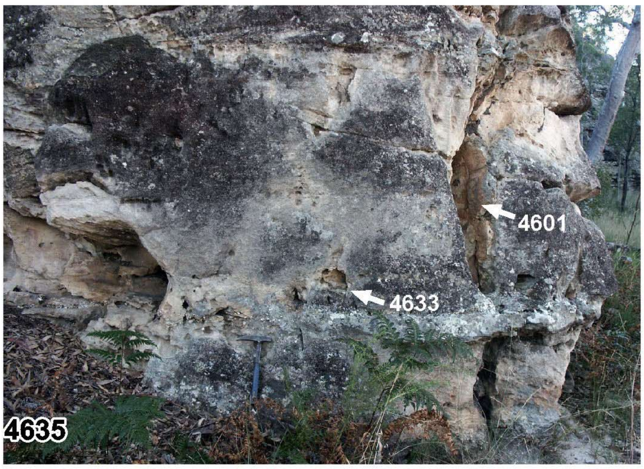
SR-4: to left
4326P: Panorama of main section of cave, tubes are in sandstone block at right.
4333: Inside cave - looking down one tube and arrows indicate side-tubes. Dotted arrow shows light from cross-tube
4329: Main cross tube
4336: Small tube



MM-5: below L to R
4558: Entrance
4564: Rear of left tube, high-level tube above (arrow)
4563: Double tube



MM-6: Below L to R
4635: View of west side with three tubes.
4601: Main tube entrance, with vertical controlling joint
4633, 30, 32: 3 views of small cross-tube. NB cemented rim & light from far end.



Photos to accompany Figure 15 (facing page). Caves and tubes at **Salvator Rosa** and **Mt. Moffatt**.
All photo files have a KG08 prefix.

Caves in *laterite karst* and *boulder caves* in granite are described in separate sections below (4.1.2 & 4.1.3).

Speleothems and other chemical deposits are discussed later (4.1.5).

4.1.1.5 Small-scale features:

Case-hardened surfaces are common on the sandstones, and these, in turn, control much of the local character of *stone cities*, *cavernous weathering* effects and *tafoni*. Sandstone *pillars* are a distinctive feature within maze caves, at some cave entrances and at the base of pinnacles at Litchfield. At a smaller scale the rock surfaces may be sculptured by *karren* (especially *kamenitza* (solution basins) and linear *runnels*), *pseudo-karren*, an array of *tafoni* hollows, and *tessellations*; or be penetrated by vertical solution *pipes* or horizontal *tubes*, and networks of thinner *tubelets*.

Case hardening results from cementation of a surface layer of a rock (or possibly softening of the core behind the surface), by various processes and various materials (see Dorn, 2004). The most common form is the precipitation by either evaporation or changing chemical conditions of silica and iron minerals dissolved from within the underlying rock. In the study area it occurs in three settings:

1: a thin (1-10 cm) sharply terminated cemented zone on exposed surfaces (photo RW088066, KG083820);
2: thin (1-10 cm), sharp, cemented zones on both faces of an open joint (photo KG080233, KG080424). In places one side of a case-hardened joint appears to have been removed during the expansion of a *stone city* street.
3: less commonly, a thicker (1-2 m) zone with a more diffuse outer boundary adjacent to a joint (photo KG084268a, KG084263P). This form can produce *cemented walls* such as The Wall at **Salvator Rosa** left behind after the erosion of surrounding sandstone.

The surface type 1 would be subaerial (Dorn, 2004). Type 2 would be mainly developed underground, prior to exhumation, through deposition of silica from groundwater penetrating the joints. This may have been in the *vadose* zone, with repeated cycles of wetting and drying at the air-rock contact, or in a permanently wet *phreatic* zone.

The thicker more diffuse zones (type 3) would be *phreatic* and formed by water diffusing out of the joint into the rock.

These case-hardened layers, with associated *cavernous weathering*, appear to provide an important control on the formation of landforms in north Australian sandstones and more study is needed on both the development of case-hardening and its subsequent influence on erosional sculpturing of the rocks. A case hardened surface is more resistant to surface erosion than a non-hardened surface. In many areas we can see evidence for multiple cycles of case-hardening and erosional breakdown of the hardened surfaces (photo RW088066).

Photo RW088066, **Cobbold Creek.** Case-hardened surfaces in a rock shelter (Type 1). Cavernous weathering is removing the softer rock behind the surface.

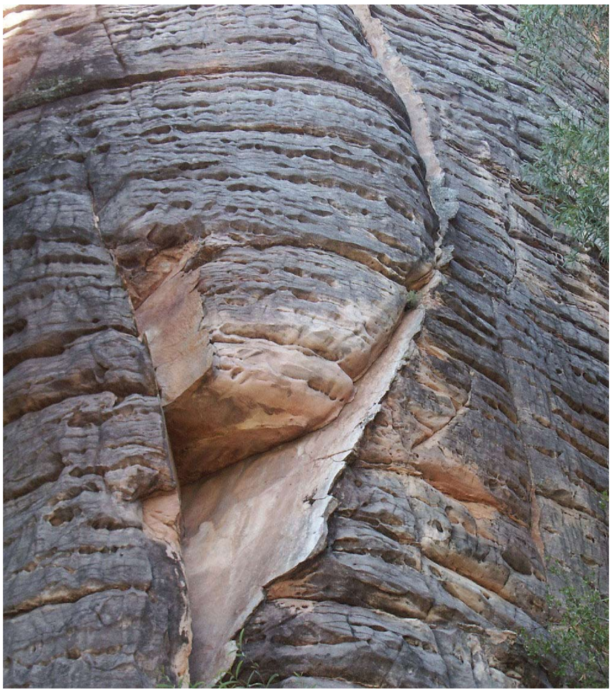


Photo KG080233, **Caranbirini.** Case-hardening along a joint (Type 2).

Cavernous weathering results from chemical and mechanical weathering on a cliff face, in which grains and flakes are loosened so as to enlarge hollows and recesses. It is frequently, but not always, associated with the breaching of a case-hardened shell on the surface of a cliff (photos: KG083326, 3819). In this report we use *cavernous weathering* as a broad term for the process and *tafoni* for all sizes of the individual hollows (photos KG082336, 4357) and *honeycomb weathering* for regular patterns of close-spaced small tafoni (photos KG082337, 3611).

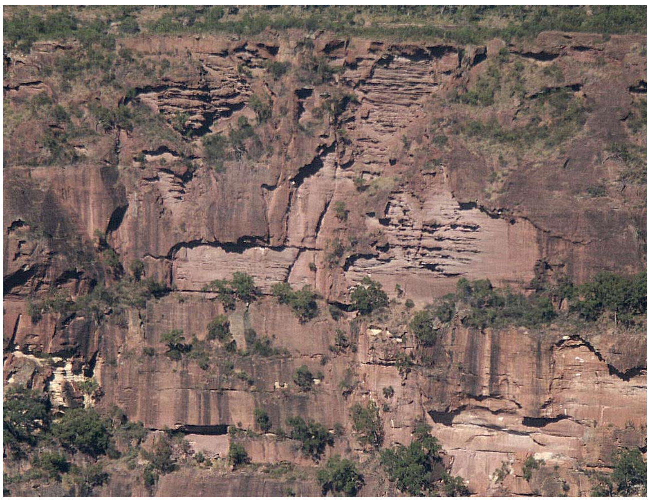


Photo KG083326, **Mt Mulligan**. Cavernous weathering on a cliff face.

Photo KG082337, **Keep River.** Honeycomb weathering at the back of a rock shelter.

Photo IH07072008_36, **Kakadu**. Pillars in a cave may indicate focussed cementation by vertical water flow. Notebook is 18 cm high.

Pillars or *half-pillars* were a feature at some sites (eg **Kakadu** & **Litchfield**) where they occur within caves and at the cave entrances, or in the base of larger pinnacles. Those in cliffs or pinnacles start as vertically elongated hollows cut into the base of the face (photo KG082065), but develop by leaving a half pillar between them (KG080687), and eventually a free-standing cylindrical pillar of sandstone, with cavernous erosion continuing behind it (photo KG082028). They are commonly confined to a specific susceptible bed and may be a result of an earlier stage of localised cementation by 'fingers' of focussed vertical water flow through the porous sandstone (Aubrecht & others, 2008) The walls may be sculptured by *pseudo-karren*. At **Litchfield** some extreme examples resulted in pinnacles standing on a pillared base (photo KG082026). At **Kakadu** the pillars were often found within and beside cave entrances (Figure 10, photos RW084570bx, 4768; KG081729P,; IH07072008_36). Broken pillars can leave *bollards* or roof *pendants*. The capped pinnacles seen at **Mount Moffatt** (photo KG084494) may be a related form in which the thin roof over the pillars has been destroyed to leave individual pinnacles. Photo RW082834 shows a pair of capped pinnacles/pillars which are still connected to form a small arch.

Karren such as *kamenitza* (photo KG081408) and *runnels* (photos KG080378, 0407) are formed by the dissolution of either standing or running water. They were not particularly common across most of the sandstones and were best developed in **Kakadu**, particularly at **Ubir Rock**. These features seem to need a fairly resistant rock for their preservation and growth to any reasonable size. Spate & Wray (2008) discuss the nomenclature and nature of *kamenitza* in sandstone and other rocks.

Pseudo-karren: We use this term for the vertically elongate grooves found on sandstone faces and *pillars* (especially close to the ground-level or in sheltered places). See photos KG080268, 0782, 3291. At **Limmen South** vertical grooves appear to have formed beneath a soil cover at the base of scarp margins and were then locally exposed by fluvial or wind erosion. These strongly resemble the rundkarren common on carbonate karsts and may be part of a process solutionally undercutting cliff margins adjacent to sand plains in similar contexts (see section 4.1.1.1). When pseudo-karren form on *pillars*, the result looks remarkably like that of a speleothem column (photos KG081740, KG082098). Faint vertical striations (1-2 mm wide) also occur at **Limmen West** and resemble *microkarren*. The origin of pseudo-karren is uncertain, but they are possibly a type of elongate *tafoni*, influenced by vertical flow of sheets of water. Some may have been initiated beneath a prior soil cover.

Tessellations (tessellated surfaces) are patterns of superficial cracks, which penetrate no more than 10 cm into the rock, and which may be partly opened up by

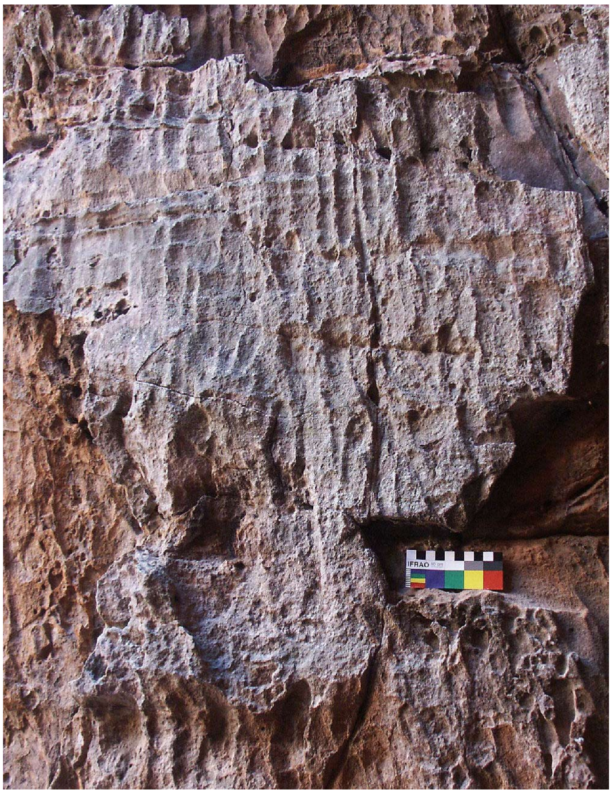


Photo KG080268, **Caranbirini.** Pseudo-karren on a case-hardened wall.

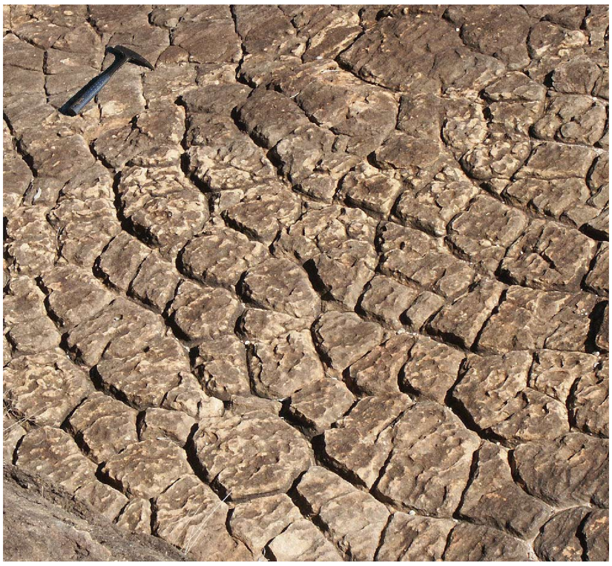


Photo KG083777J, **Cobbold Creek.** Polygonal tessellations

weathering (Branagan, 1983; Young & others, 2009). The pattern may be polygonal (eg photos KG083630, 3665, 3777J on gently rounded slopes at **Cobbold Creek**) or rectangular (photos KG084556, 4572, 4638 on steep slopes at **Mount Moffatt**).

Pipes, tubes and tubelets: These small *conduits* are generally too small for human entry (<30 cm wide, tubelets are only 1-2 cm), but are important indicators of the origin of the karst-like features – they indicate focussed weathering (including solution) followed by excavation of the weathered material by *piping* erosion or other proceses. We use *tube* as a general term for small conduits in any direction, and *pipe* (or *solution pipe*) for the vertical ones – see Glossary. Both are relatively straight and smooth-walled.

Tubes can be cylindrical or oval in section (Figure 29), and commonly, but not always, follow joints or bedding planes (photo KG084624). They are found throughout the tropical region, but particularly good examples of straight horizontal tubes occur in the Carnarvon Ranges at **Salvator Rosa** & **Mount Moffatt** (e.g. Photo KG084329b). The horizontal tubes at those two sites may intersect to form cross-cutting mazes (see Figure 15). Where the inner end could be seen, the tube narrowed down to an abrupt or hemispherical end (photo KG084562, 4624) . This suggests piping headwards from an exit point at a cliff face (Wray, 2009).

Most *tubes* are sub-horizontal with roughly elliptical cross-sections (photos KG084329b, 4603, 4624, 4661). Some tubes are obviously located along (or just above or below) a bedding plane (photos KG080430, 4209), but others are in the middle of a massive or cross-bedded bed. Some have a plan direction aligned with an obvious joint, others have no obvious joint but most tend to be fairly straight or gently sinuous (see Figure 15) but less regular and branching forms also occur (Wray, 2009). Photo 4329b shows a tube aligned on both a bedding plane & a vertical joint.

Some tubes had cemented rims a few cm thick (photo KG084632, 4663).

Vertical *solution pipes* are best developed in the *laterite karsts* (photos KG083071, 3098), as at **Castle Rock**, and show an analogy to those in the *syngenetic karsts* (Grimes, in press). Vertical pipes are generally cylindrical, 0.1 to 0.5 m diameter and can be several metres deep.

Tubelets are very small tubes (less than 2 cm wide), usually in sets, that may run parallel to bedding or a joint, or be irregular 3-D networks in a mass of sandstone. Many have smooth coated surfaces or thin cemented rims. These appear to be true dissolution features, and are equivalent to the proto-conduits of limestone karst. Branching forms along a bedding plane can resemble the anastomosing tubes seen in limestones (cf photo KG080255 with photo KGS921213 which shows a pattern of anastomosing tubes on the surface of a limestone bed). They are therefore significant as indicators of the degree of solution that has occurred. Good examples occur at **Caranbirini** (photo KG080255), **West Limmen** (0841), **Abner Range**, **Mt Moffatt** (Ph KG084616, 4620), **Bunju** and **Purnululu**. They also occur in *laterite karsts* (e.g. photo KG083061 in a sinkhole at **Sturt Plateau**, and KG088060 at **Darwin**) where some authors attribute them to termite burrows (Eggleton & Taylor, 2008).

Photo KG080255, **Caranbirini.** Parallel vertical tubelets with cemented rims

Photo KG080841, **Limmen West**. An array of tubelets.

Photo KG084620, **Mt. Moffatt**. three-dimensionally branching tubelets.

Photo KGS921213, Nullarbor. Anastomosing tubelets following a bedding plane in limestone.

4.1.2: Laterite karst-like landforms

Laterite karst features form within a *deep weathering profile* (up to 100m deep. but generally ~30m) that can develop on a broad range of rock types (Grimes & Spate, 2008). The chemical and physical processes involved in the formation of laterites, and deep weathering profiles in general, are quite complex and involve much more than simple solution (see chapter 2 of Thomas, 1994).

Deep weathering involves the intensive chemical weathering of the minerals in a rock over a long period of time (Thomas, 1994), and north Australian landforms are renowed for their great age. The minerals are converted to new forms which may be soluble, and can be removed in solution; or may be softer, such as clay minerals, or crumbly, such as residual sand grains, and can be washed out of the rock by flowing water – termed *piping*. Both processes produce cavities and other karst-like forms. Localised cementation by iron, silica or aluminium compounds forms hard bands known as duricrusts – these are responsible for many of the mesas seen in inland Australia, and provide a solid roof that caves can form beneath.

The nature of the original rock is generally largely destroyed by the weathering and replaced by a weathering profile which comprises a hard, cemented, cap (the duricrust) and a softer underlying zone that grades down to the original rock (Figure 16). Karst-like features form in the weathering profile because of the removal of material in solution or by piping.

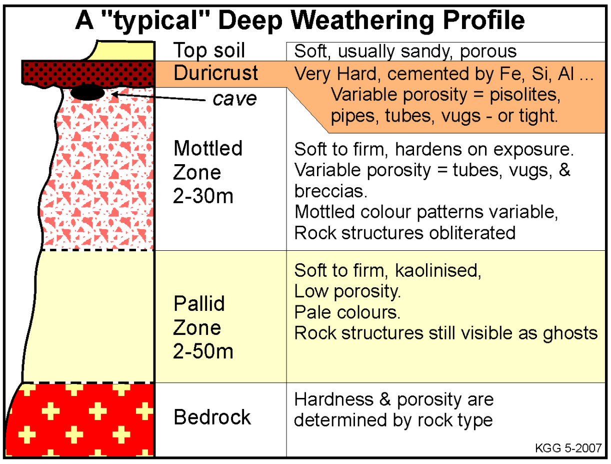


Figure 16: The typical components of a deep weathering profile.

Deep weathering profiles (DWPs) form also on quartzites, but are not as distinctive because of the lack of *labile* minerals. There is less iron and aluminium available to form a distinctive ferricrete or bauxite layer, and the iron rich mottles. A lack of original or secondary clay also makes the profile less distinctive. Instead, one typically finds a silcrete crust with only faint mottling in the sandstone below. However, given time, deep chemical weathering does occur by solution and the "arenisation" process discussed in section 3.4.

Satellite Image: Detail of laterite pans and a dambo (bottom) on Cape York Peninsula, Qld.

Laterite karst landforms show a stronger analogy with the *syngenetic karsts* (in soft porous calcarenites) than with the classical "hardrock" karsts. This is because laterites and syngenetic karsts both have formed by simultaneous solution and cementation and show the influence of caprocks (duricrusts) on cave development.

The resulting landforms vary from broad-scale (shallow dolines, or "pans" up to 2 km across) through a variety of meso-scale features such as solution pipes and pinnacles to smaller-scale tubelets, vughs and breccias (Grimes & Spate, 2008).

4.1.2.1: Large-scale Laterite Karst features.

Broad but shallow *pans*, up to 2 km across, with intermittent lakes, are a distinctive feature of many flat tropical plains that overlie lateritic deep weathering profiles in northern Australia (satellite images & photo RW083632). These pans are sometimes associated with shallow flat-bottomed and unchannelled valleys that are called "dambos" in Africa. The hollows are assumed to be dolines resulting from the removal of underlying material in solution, together with resulting subsidence of the topsoil. But once they have formed, deflation (wind erosion) of seasonally dry pan surfaces may help to deepen and extend them. Other processes can also form shallow lakes and pans, and although the large **Pelican Lakes** overlie a laterite DWP, their origin is uncertain.

Large collapse *dolines* occur in laterite on the **Sturt Plateau**. (photo KG083069, RW087278P, and see McFarlane & Twidale, 1987, Twidale, 1987). Twidale

Satellite Image: Laterite pans and dambos on Cape York Peninsula, Qld.

(1987, figure 4) maps the evolution of one sinkhole during 1981-1982; it did not appear to have evolved much further when we visited it in 2008.

4.1.2.2: Medium-scale features.

Caves typically occur in the softer weathered material beneath the duricrusts, which provide a hard roof. Solution, *piping* and other weathering processes remove the soft material to form small caves (photo KG083129P), most of which are better termed *rock shelters*, but some had lengths much longer than their entrance width (eg the **Barry Caves**). The study did not find any complex mazes, such as the one known at Chittering, WA (Lefroy & Lake, 1972, Grimes & Spate, 2008).

As well as caves, medium scale laterite karst features include smaller solution and subsidence *dolines*, subsoil *grikes,* vertical *solution pipes*, *pinnacles*, and *polygonal walls* (photo KGS841404) associated with pipes or very large scale mottled patterns. These can produce an irregular *epikarst* surface beneath a soil cover (photo KG088054P).

Photo KG088054P, **Darwin**. Epikarst surface in a deep weathering profile.

Solution pipes in laterite are analogous to those found in the *syngenetic karsts* (Grimes, 2004, in press b). They are small smooth-walled vertical cylinders, typically 0.1 to 1 m wide, and one or more metres deep, which may be isolated or in dense fields (photo KG083098). They may be empty or filled with breccia, rubble, nodules or soil. The hollow ones have probably had a prior soft fill removed since exposure at the surface. They are thought to form from focussed vertical flow of water that dissolves or erodes the rock

Laterite *pinnacles* are also analogous to those in the syngenetic karsts (Grimes, in press b) and are **not** related

Photo KG083098, **Castle Rock**. Solution pipes in a laterite duricrust.

Photo KGS780511, **White Mountains.** Laterite pinnacles. 50% of these had hollow cores.

to the pinnacles described in the sandstone sites. They are typically 1-2 m wide and 2-3 m high but reach 4 m wide and 5 m high. They include both solid and hollow forms (photos KGS780512, KG083189), and probably result from a focussed vertical flow of water that first dissolved a solution pipe, then cemented a rim around it. This is the third type of *case-hardening* discussed in 4.1.1.5. In a few hollow pinnacles, the pipes have a hard sandy lining which is quite different to the usual red mud fill (photo KG083222). This would seem to be a younger fill, of sandy topsoil, into an empty pipe. At **Castle Rock** a dense field of coalescing solution pipes has left irregular pinnacles between them (KG083106) – this is a different type of pinnacle to the smoother-walled and hollow ones at **White Mountains** which are more likely to comprise the *case-hardened* rims of solution-pipes.

4.1.2.3: Small-scale features.

Small-scale laterite karst features include three-dimensional networks of small solution *tubelets* and *vughs*, which may be infilled with nodules, clay, silica (opal) or left open (photos KG083061, 8060, KGS880107, KGS900317). These are analogous with the “anastomosing tubes” which are the first stage in the formation of limestone caves (c.f. photo KGS921213). However, some of these tubelets could be termite tunnels (e.g. Eggleton & Taylor, 2008).

Pockets or bands of *brecciated* (broken up) material (photo KGS860510) can occur adjacent to cavities formed by solution or piping. This is analogous to the formation of breakdown chambers in caves, but at a smaller scale (photo KGS830437). Examples were seen at **Darwin**, the **Sturt Plateau** dolines and **Barry Caves**.

Photo KGS880107a, Charters Towers, Qld. A network of solution tubelets in laterite.

Photo KGS860510, Lake Buchanan, Qld. Brecciated material in a coarse mottled DWP.

4.1.3: Granite karst-like features

Talus or *boulder caves* are widely known across Australia and around the world, although, as Halliday (2004) points out, most are in-valley type deposits of boulders topographically low in the landscape. Granite rocks, in particular, weather into large accumulations of rounded boulders – *tors*. Where the weathered materials in the joints are eroded by vertically moving waters a jumble of spherical, woolsack or mattress shaped blocks may result. The toppling of cliff faces and columnar volcanic rocks and landslides can produce other jumbles of boulders.

Strieble (1999; cited in Halliday 2004, p 722) has identified a number of types of talus caves and the specific processes that formed them. Among them are caves formed by several types of erosion, frost-splitting, and rock movement. Specific types included:

- "woolsack" and "mattress" caves in tors and other features resulting from the spheroidal weathering of granite;
- "gorge bottom caves"; and
- "erosion boulder caves" or "boulder fragment caves" (gorge bottom caves in which a labyrinthine conduit has been eroded between boulders).

Sjoberg (1989, cited in Halliday 2004, pp721-22) describes four types of talus caves as follows:

- glacial boulder caves;
- abrasive boulder caves;
- one boulder caves formed by frost wedging; and
- neotectonic boulder caves.

Sjoberg goes on to further divide neotectonic boulder caves (from Archean rocks in Sweden) into split *roche mountonnées* and talus caves in collapsed mountain slopes.

None of these types (or indeed the classifications generally) adequately describe the landforms of **Black Mountain**, Cape Melville, Chillagoe or other boulder piles in Far North Queensland, although the woolsack/mattress category fits best.

The north Queensland within-mountain boulder caves differ significantly from the in-valley granite boulder caves reported elsewhere in Australia, such as at Labertouche, Britannia Creek and Mount Buffalo in Victoria (Finlayson, 1981), along the Pinch and Jacobs Rivers in Kosciuszko National Park, New South Wales and the large Blyth Valley system in Tasmania (Houshold, 2007a,b). Similarly, Melville's Caves in western Central Victoria in no way compare, as these are largely just spaces between individual, albeit large, granite tors. A similar comment applies to the granites of the Girraween/Bald Rock National Parks that lie astride the New South Wales/Queensland border (Webb, 2007, Finlayson, 1982).

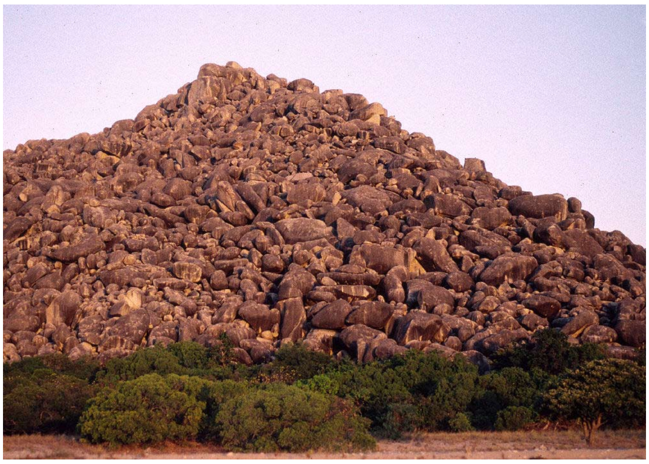


Photo ASCapeMel2, **Cape Melville**. Cavernous granite boulder hill.

Photo KG083422J, **Metal Hills, Chillagoe**. Looking out from a cave in granite boulders.

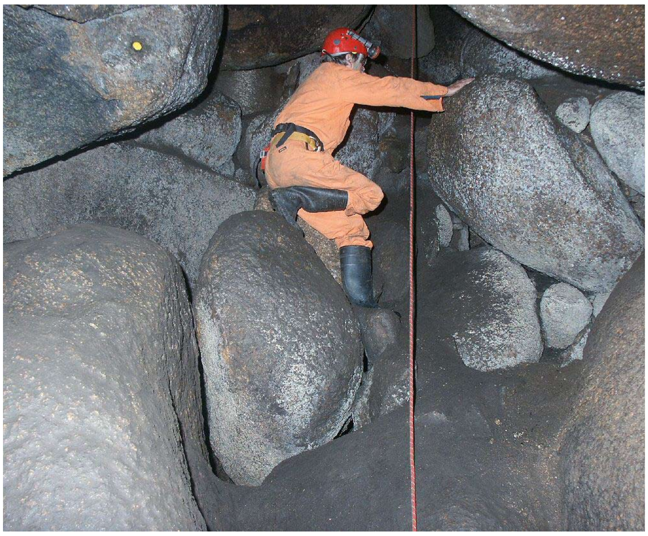


Photo KG070884, Labertouche Cave, Victoria. A granite boulder cave developed within a valley.

4.1.4: Limestone karsts

We studied the tropical limestone karsts mainly in order to make comparisons and draw analogies to the karst-like landforms found on the silicate rocks.

The most obvious difference between the carbonate karsts and the quartz sandstones we studied is a consequence of the solubility differences. Although quartz will dissolve in time, the solution is mainly of the cement between the grains (*arenisation*) and the usual situation results in a large mass of undissolved loose sand that has to be removed by physical processes in order to produce karst-like landforms (see section 3.4). It is only the smallest tubelets (<2 cm diameter) in the sandstone that appear to be formed entirely by solution. With a few exceptions, the intermediate tubes and larger caves all seem to require piping or other mechanical processes to remove the sand.

Carbonates (especially the impure ones) do generate insoluble residues, but these seldom dominate the system to the extent seen in the sandstone karsts.

At the Gregory Karst, NT, the zoning of the karrenfields is analogous to that seen in the ruiniform sandstones – with a progression from a (recently exposed) smooth pavement, through grikes to giant grikes and pinnacles and then isolated blocks in a stone city or stone forest pattern and a lower-level pediment (see Figure 17, Grimes, in press a).

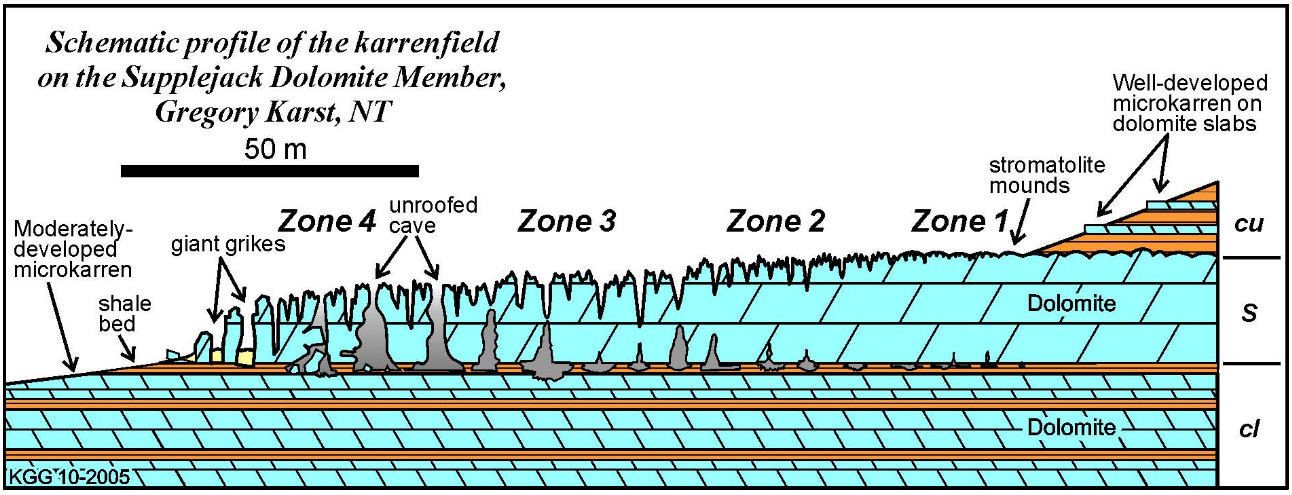


Figure 17: Schematic profile of a karrenfield in the Gregory Karst Region, Northern Territory, showing the progressive development of ruiniform character. (from Grimes, in press a)
cu, upper Skull Creek Formation; S, Supplejack dolomite member; cl, lower Skull Creek Formation.
Zone 1, Incipient karren; Zone 2, moderately-developed grikes and spitzkarren; Zone 3, deep grikes and large spitzkarren; Zone 4, giant grikes, unroofed caves, sculptured pinnacles

4.1.5: Other features:

Speleothems and other chemical deposits

Speleothems are secondary deposits in caves or rock shelters formed from material dissolved from within the host rock and re-precipitated at or near the host rock surface (Hill & Forti, 1997). They comprise stalactites and stalagmites formed by dripping water, a variety of flowstones and rimstone pools formed by running water on slopes and coralloid and other irregular formations formed from surface-tension films. Speleothems on quartz sandstones and quartzites are often composed of silica, and are much smaller and less common than the calcium carbonate speleothems found in limestone caves (Wray, 1999). *Coralloids* and flowstone structures are the most common forms on silicate rocks.

Photo RW084614. Layered silica flowstone, **Kakadu**.

A wet, red/brown flowstone structure was discovered within Widdallion Cave at **Lawn Hill** (photos KG080099, IH21062008_06). This material was analysed and found to be approximately 1/3 iron-based material, 1/3 organic and 1/3 other material.

Similar secondary chemical deposits also occur at the surface, running down cliffs, or across rock slopes (photos IH08072008_20, 33; RW084075, 4614; KG080397).

For further details see Appendix.7.

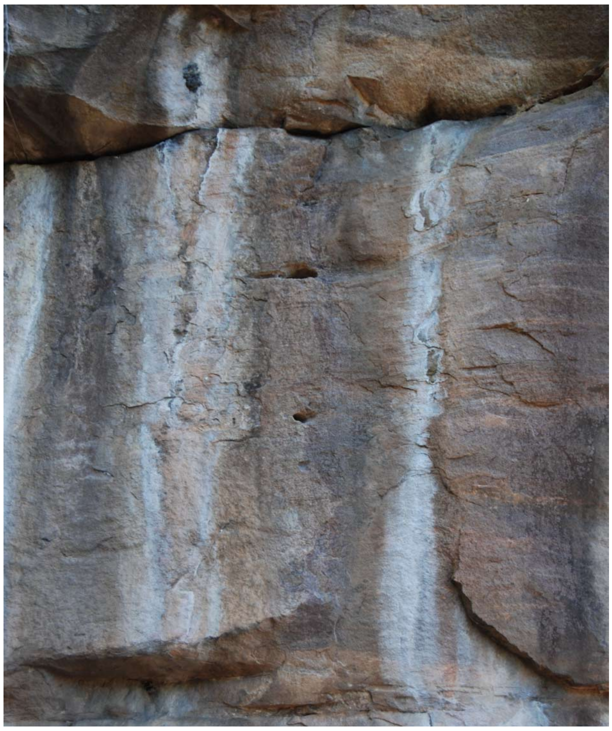


Photo RW084075. Silica coatings on rock face, **Kakadu**.

Photo IH08072008_20. Coralloid speleothems, **Kakadu.**

Giant grikefield with open plazas and pavements, **Bunju**. RW083490

Broad avenues at the edge of the stone city, **Bunju**. RW083425a

4.2: Site Descriptions

4.2.1: Western Australian Sites

4.2.1.1: Whalemouth Cave

Whalemouth Cave is on the edge of the Osmond Range, about 20 km north of Purnululu. It is currently the largest (in volume) and most spectacular of the sandstone caves in Australia. However, further exploration at Kakadu and elsewhere may change that status. Its 270 m length and 120 m vertical extent make it the longest and deepest Australian example of an underground *conduit* drainage system in sandstone (see section 4.1.1.4 and map). Its origin is probably a combination of solutional preparation and subsequent joint-controlled stream erosion of the weathered rock. The wet season flow through the system is awesome (Jolly, 1982).

The Proterozoic Mt Parker Formation (Tyler & others, 1998) is a quartz sandstone and conglomerate. At the cave it has a poorly-defined bedding that is obscured by strong and rather chaotic and variable jointing. The bedding dips 20-25° out from the cliff. It has hard surfaces but is very friable behind those case-hardened surfaces. Small-scale weathering structures (tafoni etc) are rare, as most surfaces are joint or fracture planes.

The *cave* starts on the plateau at a *stream-sink* in a large *doline* that takes water from a surface *blind valley* that is 2.5 km long (but narrow, about 0.6 km^2 catchment). The original valley continues as a *dry valley* 30-40 m above the doline floor and connects to another valley that leaves the plateau via a narrow gorge. This was the path of the original stream prior to its underground *capture* (Jennings, 1983). The cave descends as a series of waterfalls and plunge pools within a large fissure. The downstream exit is a large fissure-chamber, 30 m wide, 40 m deep and 60 m high opening at the base of a 150 m high red sandstone cliff (see map and photos KG082429ax,IH27122008_18PJ, IH17072008_07PJx). The cavern has been substantially enlarged by rockfall and surficial weathering processes – predominantly mechanical spalling of angular pebble- to cobble-sized fragments rather than granular weathering typical of less well-jointed sandstones. The cave stream emerges through a tall, narrow slot at the base of the chamber, typical of vadose incision.

There are many other springs rising along the base of the scarp, but none have known caves.

We visited only the downstream entrance chamber on the ground and viewed the upper stream-sink, blind valley and catchment on the plateau from the air. For more information see Jennings, 1983; Grimes, 2008; Figure 18.

National Heritage Significance

High: The cave, in all ways, including its *underground drainage* system. This is significant at a world scale, and

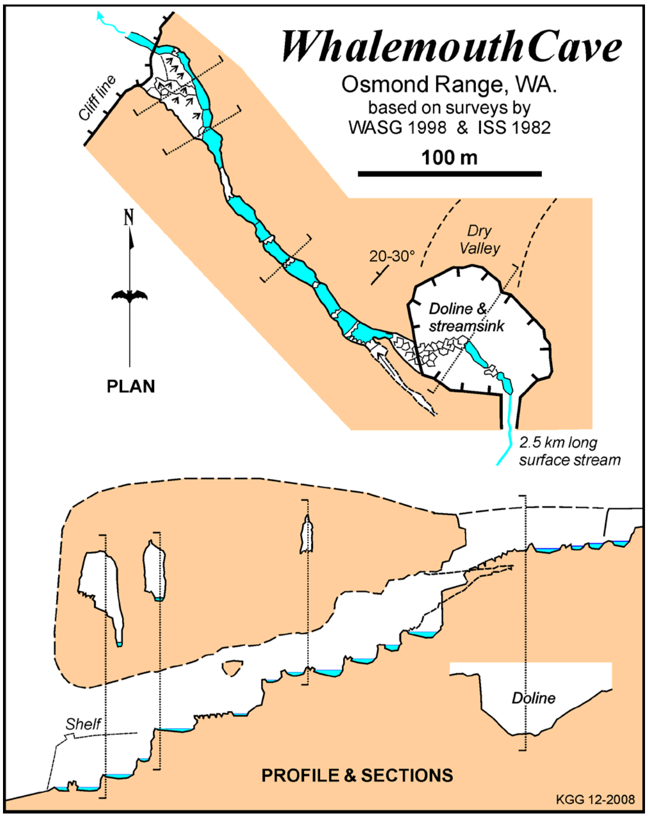


Figure 18: Map and profile of **Whalemouth Cave**. From Grimes (2008).

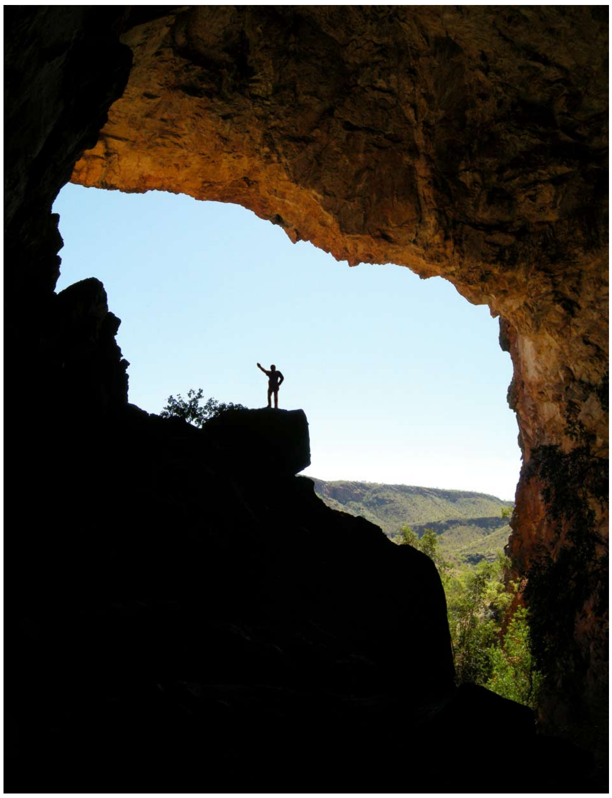


Photo IH27122008_18PJ, **Whalemouth Cave**, Looking out of the big downstream chamber.

it is one of the world's deeper sandstone caves (probably within the world top-50).

Mod-good: Blind valley; the doline and the hydrological system (stream-sink, *underground drainage* and spring).

4.2.1.2: Osmond Range:

This is the plateau behind Whalemouth Cave, and the sandstone is the same Mt Parker Formation. There are many large springs rising along the base of the northern scarp, but the only known outflow cave is **Whalemouth**. The features on the Osmond Plateau are interesting examples of small to medium scale *ruiniform* relief and underground drainage, but have only been viewed from the air. They require ground study, but this will involve difficult access. The Bungle Bungle 1:50,000 topographic map sheet (4563-2) shows four "sinkholes" and an "underground creek" in the area to the east of Whalemouth Cave. The "underground creek" was confirmed from the air as a stream-sink and spring pair with an underground separation of about 100m and one of the sinkholes also had an associated spring about 100m from it.

National Heritage Significance

Mod-Good: Blind valleys and underground drainage, ruiniform relief in general. A ground study might upgrade the significance of these and of the large springs at the edge of the range and in some other ranges in the region.

4.2.1.3: Purnululu (Bungle Bungle Range):

A well known (World Heritage property) and moderately well-studied site. It is developed in Paleozoic quartz sandstones and conglomerates of the Devonian Mahony Group (Tyler & others, 1998; Hoatson & others, 1997). There is a magnificent and spectacular array of sandstone landforms, some of which are karst-like (*beehive* pinnacles/towers, small caves) that is illustrated in detail by Hoatson & others (1997). Young (1986,1987, 1988) has described the evidence that solution of the intra-granular cement (*arenisation*) was 'critical' in the evolution of the landforms, but physical erosion is the dominant process (see section 3.4). The influence of old land surfaces and intermediate levels of denudation (Young, 1986) is interesting. Photos KG082598, 2678.

Photo KG082598, **Purnululu**. Beehive pinnacles & towers

As this is already World Heritage, and has been described in detail by Hoatson &others (1997) and its karst significance discussed by Young (1986, 1987 & 1988), we only made a quick inspection for comparison with other sites.

National Heritage Significance

High: Towers and beehive pinnacles forming stone cities and stone forests, gorges, old land surfaces.

Mod-Good: Pinnacles, arches, case hardening, tubelets, pseudo-karren.

4.2.2: Northern Territory Sites

4.2.2.1: Keep River:

This area needs a more detailed study – it was a last-minute addition to our schedule and we only did a quick inspection. These are Paleozoic sandstones of the Late Devonian Cockatoo Formation (Whitehead & Fahey, 1985) – a similar age to that of the Mahony Group which forms the beehives at Purnululu.

There is large-scale ruiniform sandstone scenery, with similarities to **Purnululu**: there are gorges and large *beehive pinnacles/towers*, with some large *rock shelters* formed by *cavernous weathering*. But, with the possible exception of the towers, there were no obvious karst-like features in the section we visited. However, based on satellite imagery, we suspect that there may be stone city and stone forest country further to the west of the main tourist track area. See photos KG082321, 2382.

National Heritage Significance

Mod-Good: Towers, stone city(?), gorges, tessellated surfaces.

4.2.2.2: Litchfield:

The sandstone is Proterozoic Depot Creek Sandstone of the Tolmer Group (Pietsch, BA., & others, 1989). There is only a small area of *stone forest pinnacles* in a sandy bench in the dissected edge of the plateau. However, distinctive features of this area are the blocky nature of the pinnacles with a clear influence of horizontal beds and vertical joints breaking the sandstone up into blocks (photo RW085149) and the presence of many basal *pillars* and hollows (photo KG082026). This formation could be regarded as an 'older', more degraded, stone forest than some of the others we inspected. There are also good examples of *pseudo-karren* sculpturing (KG082098). Elsewhere in the park there are examples of *laterite karst pans* on the plateau

Photo AS.Litch047, **Litchfield** pinnacles.

(e.g. tabletop Swamp), of isolated *towers* and there is a large *bridge* (arch) over the gorge at Tolmer Falls. A large perennial spring system resurging from the sandstone feeds Florence Creek above the Buley Rockholes.

National Heritage Significance

High: Pinnacle styles,

Mod-Good: Stone forest, pillars, pseudo-karren, bridge (arch).

4.2.2.3: Darwin (Laterite karst):

A lateritic deep weathering profile is developed on Cretaceous claystones (Doyle, 2001). This is a convenient location for looking at *laterite* and *deep weathering profiles* and their karst-like character. The sea cliffs show a variety of small solution *tubelets* etc. The surrounding coastal plain has a scatter of broad but shallow *pans* (laterite karst dolines) which have been described by Borger, & others, 2004, and McFarlane, & others,1995. An excavation in the city serendipitously revealed a section through a laterite profile, including a buried *epikarst* surface (photo KG088054P). Although a good representative example of a widespread phenomenon, none of this is spectacular.

National Heritage Significance

High: Laterite karst effects in a deep weathering profile.

Mod-Good: Dolines (pans), old land surfaces, tubelets.

4.2.2.4: Kakadu (general):

An extensive and rugged plateau developed on quartz sandstones and conglomerates of the Proterozoic Kombolgie Subgroup has high scarps overlooking a low-level alluvial plain. Although Kakadu has a huge expanse of spectacular *ruiniform* sandstone scenery, only some of the landforms are karst-like: these are some very significant *caves*, and areas of scattered arches and dolines.

The main significance at Kakadu lies in the *caves*, especially the maze systems at **Nourlangie** and possibly Jim Jim (see 4.1.1.4). The distinctive *pillar* structures need an explanation (see 4.1.1.5). Some of the smaller caves at **Nourlangie** and **Ubirr** (Bardedjilidji) had interesting “phreatic” features. The “big arch” and nearby “big doline” that we saw from the air also warrant attention (photo RW084929T). The ruiniform landscapes, such as the *stone cities* and *pinnacles* seen on Nourlangie rock and from the air on the main plateau to the east, are less distinctive than those of the Bessie Creek and Abner Sandstones at **Bunju**, **Limmen**, **Abner Range** etc, but are nonetheless quite impressive.

At a smaller scale we measured *kamenitza* at Ubirr and there were also some *runnels* there. These runnels and basins were the best developed of all the sandstones inspected during the trip. The reason for this is uncertain, possibly the sandstone is more resistant to surface breakdown (i.e. the grains are better cemented together). A few “solution” *tubes* occurred, but many were gradational to deep *tafoni*, and of uncertain genesis. There were good examples of *pseudo-karren* on some of the cave pillars at Nourlangie.

See Hoatson & others (2000); photos RW084929T, KG081960, 2006a.

Kakadu, Ubirr:

Towers and larger bodies of sandstone rise abruptly from the modern flood plain (photo KG081467). Some of these have been interpreted as being old coastal islands and stacks formed at the peak of the post-glacial transgression, 6000 years ago (Hoatson & others, 2000, p.42), but might date back to the prior interglacial coast 120,000 years ago. In the Bardedjilidji area, thin-bedded sandstone forms “pancake” or *pagoda* style pinnacles in a stone city or stone forest. Several more symmetrical pinnacles occur and may be related to the *pillars* seen elsewhere at Kakadu (photos KG081520a, 1543). These pillars seem to be restricted to certain beds. There are several small caves (see Figure 8 and detailed descriptions in section 4.1.1.4). One had a 4 m entry tunnel with an irregular, but smoothly-rounded cross-section (photo KG081550a) and the small (1.5 m long) terminal chamber had many pockets (large and small) that might be *phreatic* in character (see Figure 8). Small silica speleothems were observed in these caves and in

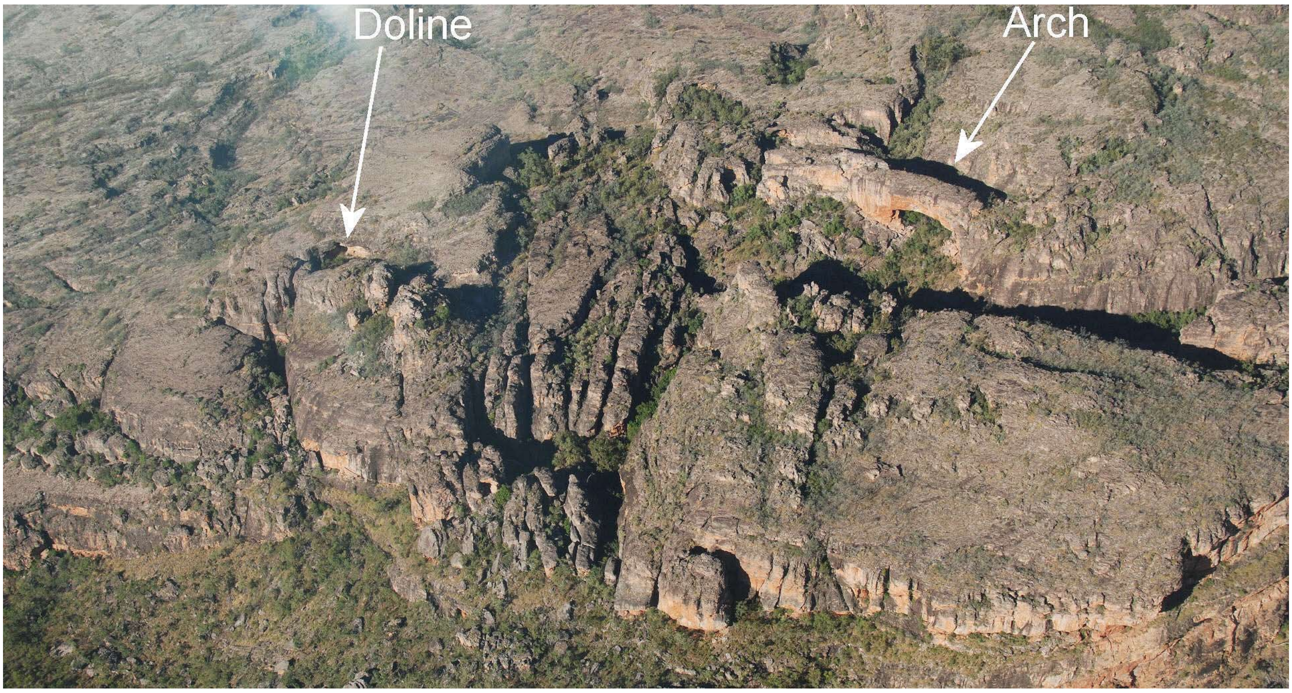
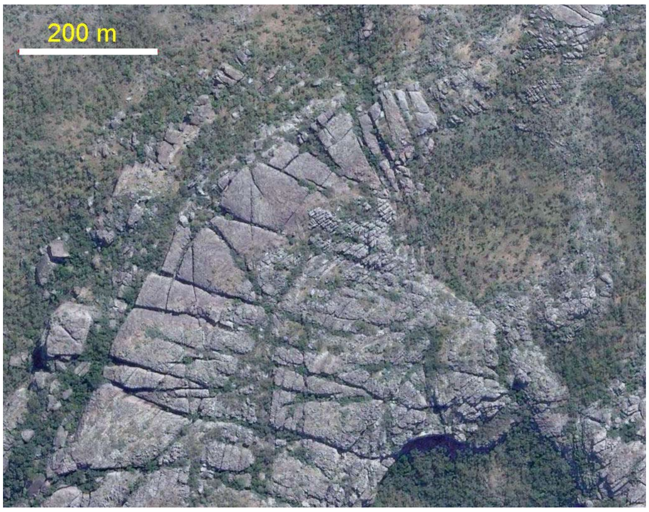


Photo RW084929T, **Kakadu.** Doline and arch on the main plateau.



Satellite image of **Nourlangie Rock**. Showing giant grikes and smaller grike fields and other ruiniform terrain.

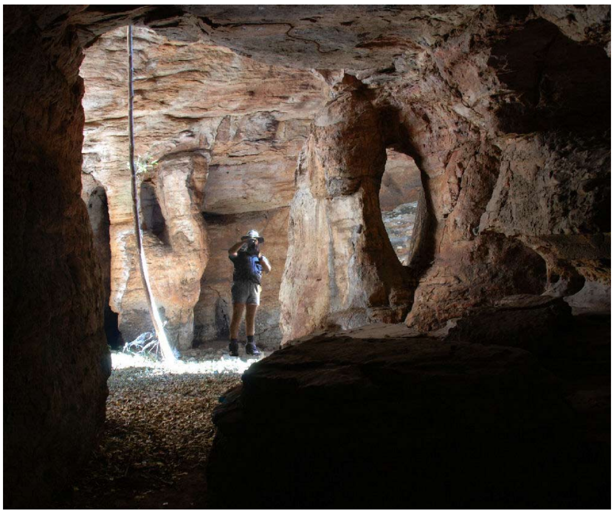


Photo RW084738Ja, Cave at **Nourlangie, Kakadu**.

many other protected locations. This area had the greatest number of speleothems of all sandstones on the trip.

National Heritage Significance

High: Karren forms (*kamenitza* and *runnels*)

Mod-Good: Small *caves*, pinnacle types (showing structural control), stone forest and larger sandstone towers, domes, speleothems.

Kakadu, Nourlangie:

Norlangie Rock is an outlying plateau, separate from the main one. The lower parts of the big cliffs bounding the plateau are mainly conglomerate. Higher up is mainly sandstone with occasional conglomerate beds. The beds dip gently to the SE. Bedding is mainly medium but varies thin to thick. Some beds are recessive and form benches and major undercuts with cavernous horizons (photo KG081581). The plateau top has alternating areas of stone city, pinnacles, vegetated valleys and some bare sandstone pavements. The thin-bedded or more densely jointed units tend to form chaotic *stone cities* of small jagged *pagoda* pinnacles (photo KG081796), whereas the thicker beds with fewer joints form *pavements* with *giant grikes* (see satellite image). There are some highly decayed maze-cave systems associated with degraded ruiniform topography (photo RW084659, KG081792).

Nourlangie had a set of very significant fissure and maze *caves*, which are described in detail in section 4.1.1.4. Many of these had distinctive *pillars* within them and at the entrances; these have been sculptured by *pseudo-karren*. The caves and pillars both seemed to be restricted to certain beds. The vertical fissures descending from some caves systems here, and possibly at Jim Jim, potentially reflect ongoing development of regional surface relief as outlined in Nott & Roberts (1996). The area is therefore highly significant for evidence for landscape evolution and integration of cave and surface landforms.

More field work is needed to map and study the caves properly, and to determine the nature of the *stratigraphic* or *structural control* on their locations.

National Heritage Significance

High: Outstanding *caves* (some probably of world status); *tubes*, *pillars*. Spectacular large-scale *ruiniform* scenery.

Mod-Good:, Giant grikes, stone cities, stone forests, and pavements – all showing structural control; pseudo-karren and chemical deposits, stratigraphic control on the locations of the caves.

Kakadu, miscellaneous:

This section refers to the main plateau, which is largely inaccessible from the ground, and which we mainly inspected from the air. It is a vast and chaotic area that has occasional large *arches* and *dolines* (photo RW084929T), and also includes areas of *ruiniform* landscape with stone cities, giant grikefields etc (photo KG081960), but also a variety of other sandstone landforms. There is good structural and lithological control of landforms. Surface topography in the Jim Jim area suggests that both high-level maze caves and vertical caves are likely to be present, mirroring those described at Nourlangie. Much more field work is needed in this area.

4.2.2.5: Mt Price rest area:

A low ridge of Proterozoic Bessie Creek Sandstone beside the road to Roper Bar had a small cave with some solution-like features.

National Heritage Significance

High: -

Mod-Good: The cave is of only limited significance, but indicates the widespread tendency for this sandstone formation to generate karst-like features.

4.2.2.6: Yulirienji Cave & Old St. Vidgeon:

A stone city and stone forest have formed in a belt of Proterozoic Abner Sandstone where it is crossed by Mountain Creek (Dunn, 1963).

The *cave* is a broadly-arched tunnel (50 m long, 2 to 3 m high, and 8 m wide) (photo KG081019P) that is described in detail in section 4.1.1.4. It is of major significance both for its geomorphology (Jennings, 1979a,b) and for its archaeological contents – the latter being outside the scope of this study (see Mountford & Brandl, 1967). In one interpretation it could be an abandoned parakarst stream cave perched 13 m above the present stream (Jennings, 1979b) – but solving the details of its formation will require further study. The height above the present stream, and the ferricretes on and beside the adjacent pavement could indicate a significant age.

The associated stone city and pinnacles seem to be only of average interest – but we concentrated on the cave and did not explore them in any detail. See Jennings 1979b; photos KG080982P4, 1019P.

Photo RW083051a, **Yulirienji Cave**. Note Aboriginal art on ceiling.

National Heritage Significance
High: Large sandstone *cave*, archaeology and Aboriginal heritage.
Mod-Good: Stone forest and pinnacles, tubelets and chemical deposits

4.2.2.7: Bunju (Boorlungu):

This is one of the most spectacular and significant sandstone areas in northern Australia. Jennings (1979a, 1983) referred to this area in Arnhem Land as Boorlungu, however we were informed the area should be more correctly know as Bunju, pronounced "boonjoo". We initially flew over the area, but were only able to make a limited ground inspection of the northern edges of the area. Figure 19 is a photo-interpreted map of the northern half of the area.

Bunju is a large, broad area (15 km long by up to 7 km across) developed on very gently dipping Proterozoic Bessie Creek Sandstone (*Pre*) and a few relict mesas of overlying lateritised Cretaceous sediments (Abbott & others, 2001). A smaller area of *ruiniform* relief occurs on the same sandstone unit 10 km to the NE (viewed from the air), and others have been reported to the west (not inspected).

Bunju has the best range of sandstone features of any site we visited (including both karst-like and ruiniform sandstone landforms, photos AS.Roper198, KG081182, 1130, 1163, 1178, RW083223, 3263, etc). As well as broad *ruiniform* areas with *giant grikefields*, *stone cities* and *stone forests*, this is the only area visited that had an extensive *doline* field (photos KG081085, 1222) and individual large dolines are scattered across the site. These dolines have strong potential for significant associated horizontal *cave* systems – large cave entrances were seen from the air in several parts of the area (photo RW083492 and see section 4.1.1.3). Many *arches* and *bridges* were seen from the air and the ground (photos RW083407x, KG081102x, KG082997).

Bunju also had the best *pavements*, which here follow gently dipping resistant beds (photo KG081193) rather than cutting across the strata, as was seen at **Abner Range**. This is a good example of *stratigraphic control*, as is the stacking of different types of structures at different stratigraphic levels within a small area (photos KG081112. RW083559 and Figure 20).

Even with our limited ground information we can see that Bunju has the most diverse development of karst-like and ruiniform sandstone features in Australia, particularly in terms of low-relief systems. It is undoubtedly of world standard.

Its location within Aboriginal Arnhem Land makes access difficult, and means that any suggestion concerning National Heritage status etc would require discussion with the landowners and careful negotiation.

See Jennings (1979a, 1983) for additional information. Much more field work is needed here – in both wet and dry seasons.

Photo KG081130, **Bunju**. General view looking NW across the northern sector; showing giant grikes, pinnacles, pavements and a large park-like plaza.

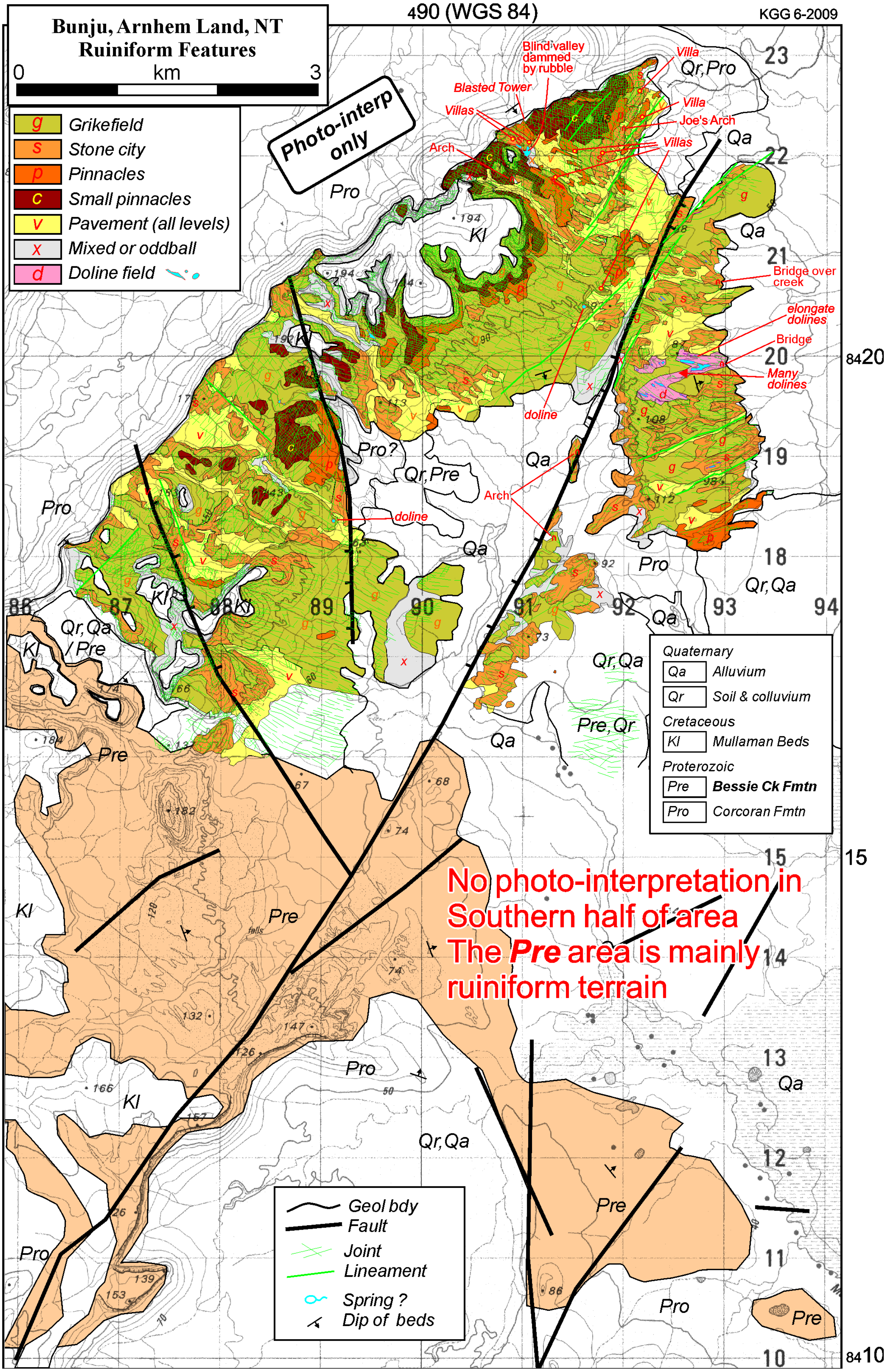
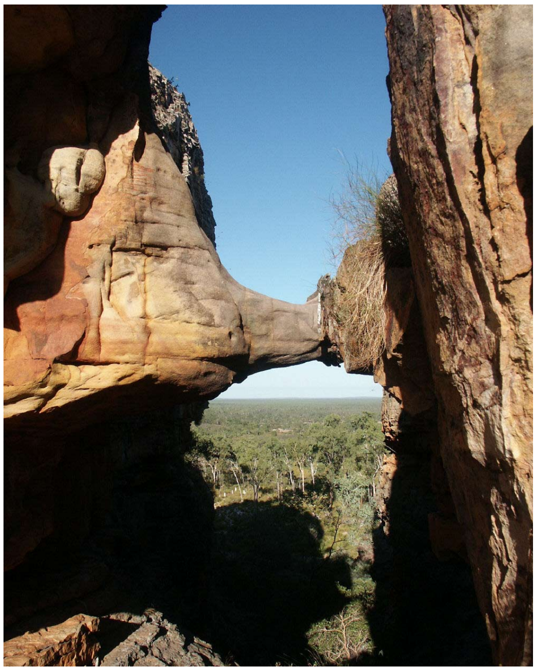
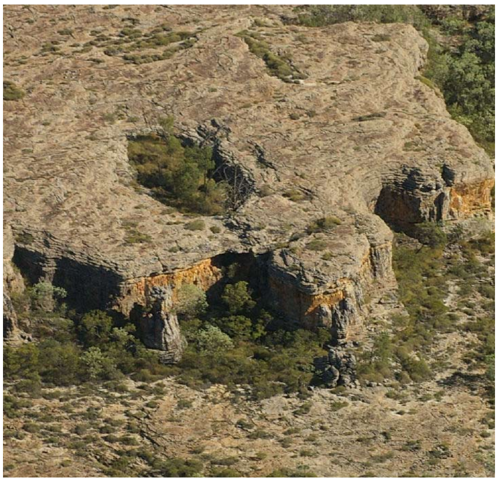
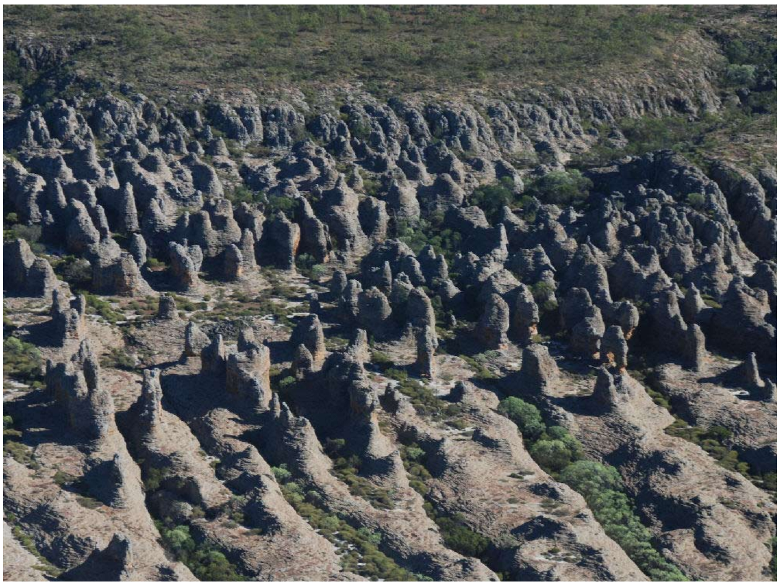


Figure 19: Landforms of the **Bunju** Area. Only the northern half has been interpreted in detail.







Bunju photos: clockwise from top left:
Photo KG081178. Joe's arch (left), pinnacles on a pedestal, and other stone city features.
Photo KG082997. Bridge across city lane.
Photo RW083559. Stratigraphic control – Cretaceous capping over pinnacled bed over a bed with giant grikes.
Photo AS.Roper185. Doline and connecting cave/arch in 'orange' unit.

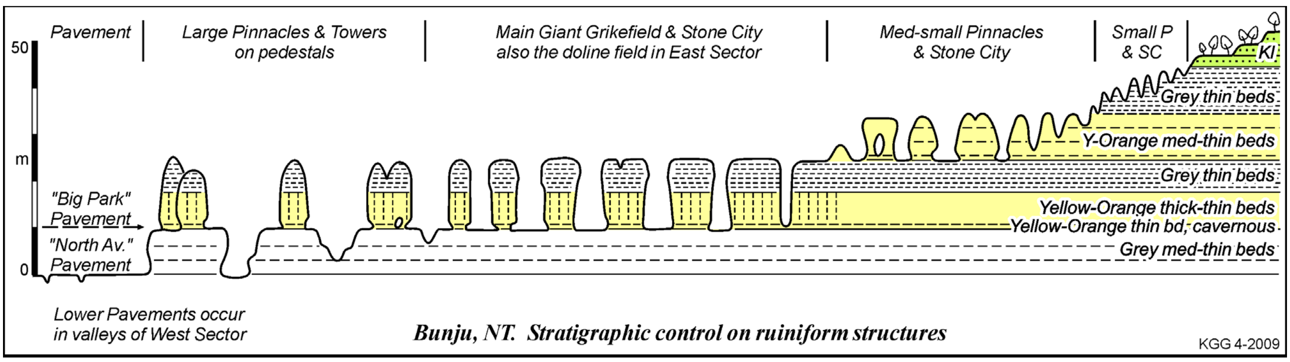


Figure 20: Stratigraphic control on topography at Bunju. Kl = Cretaceous sediments

National Heritage Significance

High: Doline field, giant grikes, stone city, pavements, towers, pinnacles, grikefields, plazas, avenues, arches, tubelets, and probably caves.

Mod-Good: Stone forest, structural and stratigraphic control, villas, caves (if not rated high). case-hardening effects and tafoni, Aboriginal heritage (level of significance uncertain but most probably very high).

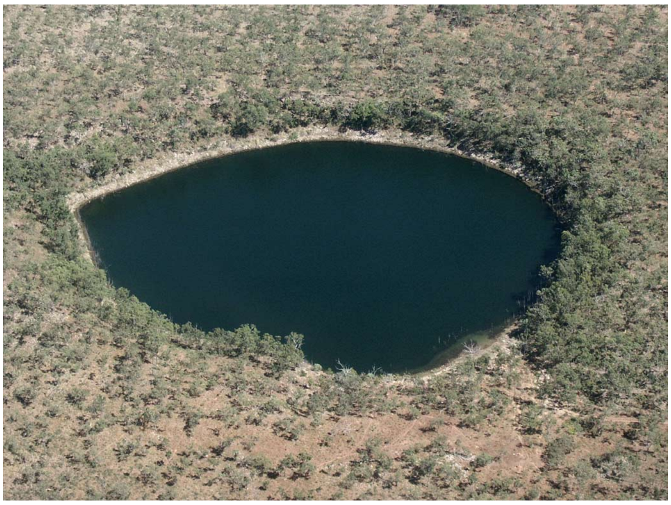


Photo KG081248, **Bath Range:** *Cenote* (water-filled collapse doline), 260 m wide.

4.2.2.8: Bath Range:

A set of large collapse *dolines* up to 260 m across are scattered across an area about 30x10 km, in a sandstone surface of relatively low relief. The depth of one dry doline could be over 50m based on spot heights on the topographic map. See Appendix 12 for details. Some of the dolines are *cenotes* with lakes that appear quite deep (eg photo KG081248). The sandstone is Proterozoic Bath Range Formation that has a variety of rock-types, but is dominantly sandstones most of which have carbonate cement (Haines & others, 1999, pp.62-64). We only did an aerial inspection, a ground study would be needed to decide whether the cavities that triggered the collapses were formed by silicate solution or by solution of the carbonate cement.

Its remote location within Aboriginal land makes access difficult, and means that any suggestion concerning National Heritage status etc would require discussion with the landowners.

National Heritage Significance

High: Collapse dolines & cenotes.

Mod-Good: -

4.2.2.9: Limmen NP - general:

The Limmen National Park has several belts of sandstone that form stone cities. The units involved are firstly the Abner Sandstone, which here is divided into the Arnald Sandstone Member (*Prax*) and the Hodgson Sandstone Member (*Prah*) separated by a soft (valley-forming) Jalboi Member (*Praj*), and secondly, the Bessie Creek Sandstone (*Pre*) We inspected the two named “lost cities” described below but there is much more both within the park, and on adjoining private land to the south and west. **Yulirienji Cave** (see 4.2.2.6) is in the western part of Limmen NP.

4.2.2.9.1: Limmen, Southern “lost city”:

This area has two belts of ruiniform relief formed on gently dipping sandstones: the Hodgson member (*Prah*) in the west and the Bessie Creek Sandstone (*Pre*) in the east; the *Prax* unit has only a narrow outcrop belt with limited areas of grikefields (see Figure 21, Haines & others, 1993). Both sandstone belts end abruptly at their southern ends where a major fault and drag fold twists them to the east and narrows them to steep dipping ridges with limited development of ruiniform features (Figure 21). Both belts have similar features, but the *box valleys* are restricted to the western *Prah*.

The sandstone belts have eroded flat tops (an *old land surface*) with the modern valleys eating into the edges of these to produce *ruiniform* landscapes (see Figure 5). This old surface has been significantly silicified to a depth of 1-3 m as a result of deep weathering in the Tertiary.

This is an easily accessed area with a broad variety of ruiniform and karst-like features, including good

Photo RW08_LS-Pan8, Pinnacles at **Limmen South** stone city.

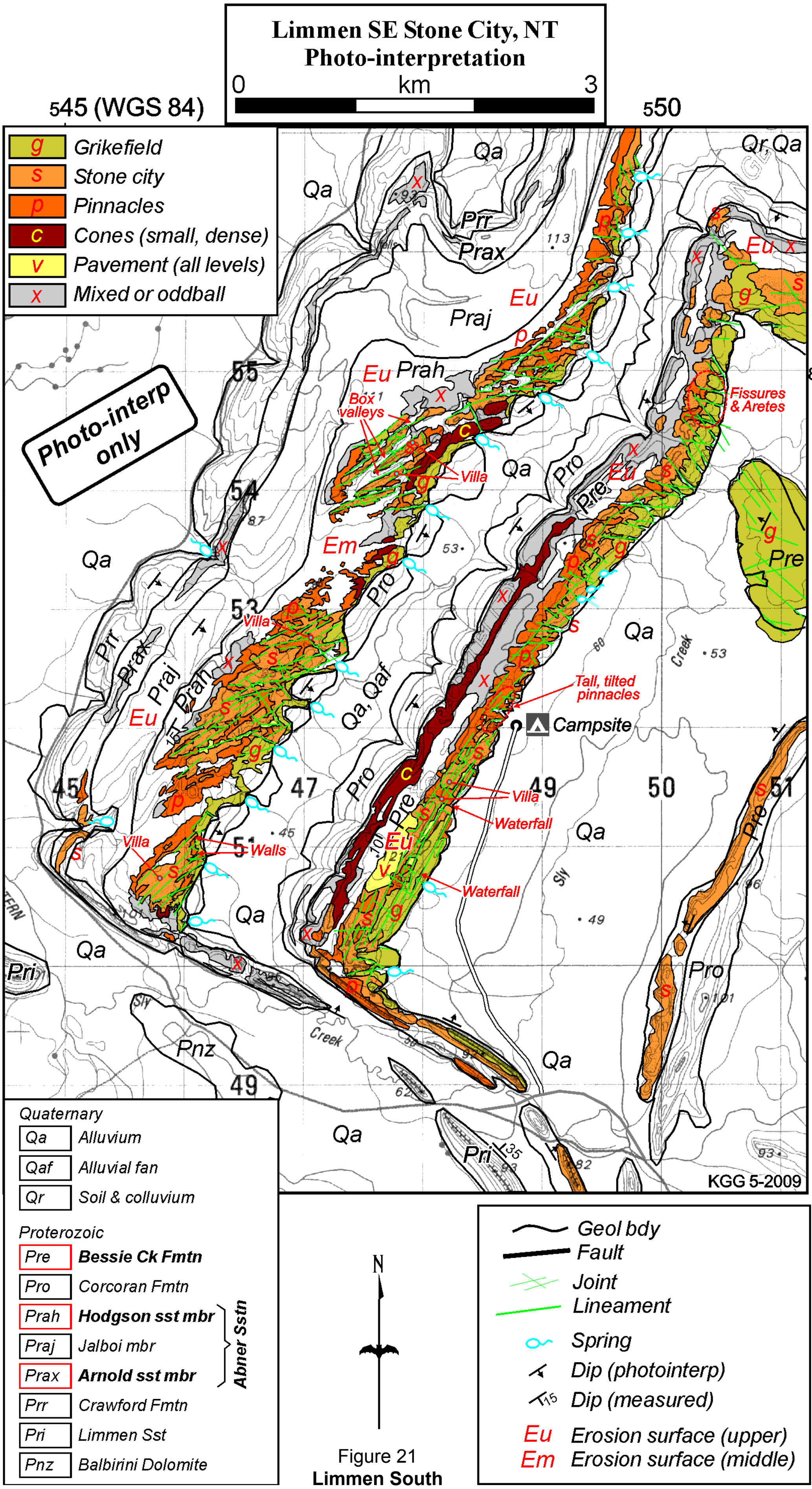
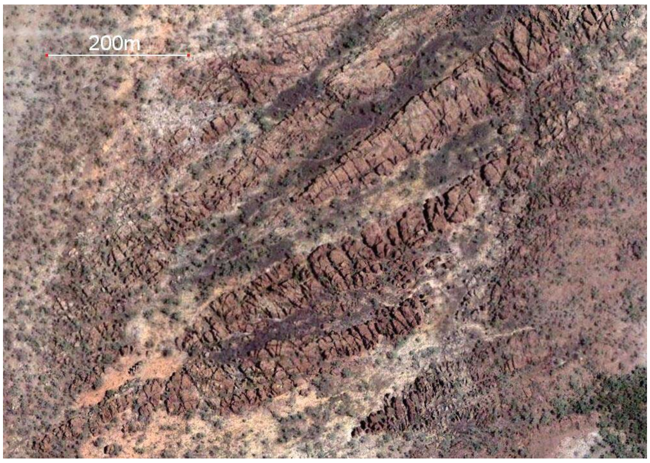


Figure 21
Limmen South



Satellite image, **Limmen South**, showing the box valley sector in the *Prah* ridge. Broad flat-floored *box valleys* (*avenues*) separate narrow belts of stone city.

examples of *stone city*, *stone forest* and *grikefields*; *villas* and *barrier walls* within the stone cities; and a variety of *pinnacles*, some tilted along with their controlling joints. *Scarp-margin basins*, with narrow outflows and springs, are eating back into the *Prah* ridge (however, these coalesce so are less distinctive than the ones at **Abner Range**). Only a few small *caves* were found, typically short tunnels connecting villas to streets or carrying water through barrier walls (photo KG080635J, 0779). The topography of the eastern belt was surveyed in some detail, with traverses of the land surface, stream profiles and associated rock hardness measurements providing insights into landscape evolution (See Appendixes 8 & 9).

Special to this site are the wide *box valleys* (or *avenues*) in a localised part of the *Prah* belt, which were not found at any other sites, and possibly the narrow *arêtes* at the northern end of the *Pre* belt.

There is a walking trail from the camp ground, about 2.5 km long, that passes through the stone forest area to the bevelled plateau top and back.

See photos, KG080603, 0676P, 0687; RW08_Limmen-Pan3.

National Heritage Significance

High: Stone city and pinnacles, tubelets.

Mod-Good: Giant grikes, stone forests, pavements, towers, grikefields, plazas, avenues, villas, box valleys, Scarp-margin basins, pseudo-karren, case-hardening, tafoni.

4.2.2.9.2: Limmen, Western "lost city":

Similar to **Limmen South**, but less extensive, yet rather more spectacular because of the larger beehive pinnacles. The two belts of sandstone at the "Western Lost City" are *Prax* & *Prah* – differing from **Limmen South** where the *Prax* was largely devoid of interest and the sandstones forming karst-like features are the *Prah* and *Pre*. The sandstone is present as a pair of east-west striking belts, but the slightly steeper, southerly, dips mean that the pinnacle and stone city belts are narrower. The flat sand-plain between them is developed on the recessive Jalboi member (*Praj*). The sandy valley ends abruptly at the eastern end where a fold turns the two sandstone belts to the south and brings them together.

The contrast between the wall of large beehive pinnacles at the edge of the two ridges and the flat sand-plain between them is particularly impressive (photo RW082849P, KG080912P), but this had been enhanced by removal of the undergrowth by a recent fire. The scattered squat pinnacles on the sand-plain were not seen at **Limmen South**, and had a different style (no solid sandstone pediments) to that seen at **Abner** (KG080909). The big arch (ph KG080837P) is quite outstanding and a smaller arch (RW082834) is rather photogenic (but there are much more impressive ones at **Bunju** and **Kakadu**). There is a very well-developed *dip-slope* on the southern side of the Prah ridge but this has not been breached to form *scarp-margin basins* as happens at Limmen South, instead the main drainage and dissection is on the northern, up-dip, side of this ridge.

There are other dissected sandstone ridges with pinnacles visible in the distance to south (*Prah*) and west (*Pre*) that warrant investigation.

Photo KG080912P, **Limmen West** stone city.

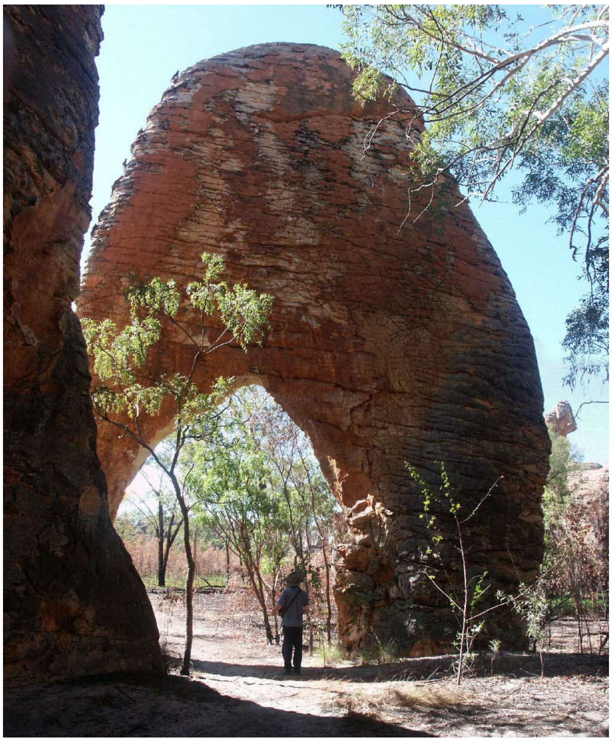


Photo KG080837P, **Limmen West**. Free-standing arch.

National Heritage Significance

High: Well developed beehive pinnacles and (small) towers with a sharp contrast to the sandplain.

Mod-Good: Stone city, tubelets, pseudo-karren, arch, stone forest on sandplain.

4.2.2.10: Nhumby Nhumby:

A pair of collapse *dolines* lie within a mildly dissected sandstone plain. They are formed in Proterozoic Stretton Sandstone (Haines & others, 1993, pp.41-42)), but are underlain by dolomites of the Yalco Formation, so they are probably *subjacent karst*. The southern doline is reported to be 30 m deep and has steep walls and a permanent lake (a *cenote*) and a system of short dendritic drainage channels feeding into it (see satellite image). The northern doline is dry and more degraded.

Satellite image of **Nhumby Nhumby** Sinkhole, a cenote.

These were not visited. Their significance appears to be similar to that of the **Bath Range** dolines, but reduced by having only two instances and only one of those particularly spectacular. Field work is needed to ascertain the genesis of these sinkholes.

National Heritage Significance

Good: Collapse dolines and cenote.

4.2.2.11: Caranbirini:

An easily accessible flat-topped ridge of flat-lying Abner Sandstone (*Prax*) has a small extent of *stone city* and large *beehive* pinnacles (Pietsch, & Rawlings, 1991; Pietsch & others, 1991). There are some narrow *giant grikes*. Small scale features of special interest are: good examples of *case-hardened* joints and younger surface case hardening; particularly well-developed sets of small solution *tubelets* in various orientations; and good examples of *pseudo-karren*.

Major joints have well-developed *case-hardened* surfaces 1-10 cm thick which form smooth surfaces contrasting with the etched bedding (photos KG080200P, 0233, 0307, 0424). A younger, quite recent, generation of case hardening also affects exposed erosional surfaces, and alternates with several generations of *tafoni* behind the hardened surfaces (eg photo KG080267).

Small (1-2 cm wide) solution *tubelets* are particularly well-developed here. They occur in parallel sets that follow horizontal bedding (photo KG080266) or vertical joints (photo KG080255) or simply run through the body of the rock. Some have irregular branching forms. Most of these have thin cemented rims (eg photo KG080266) and many project from the rock surface after erosion of the surrounding softer sandstone.

Good examples of *pseudo-karren* occur as vertical rills & elongate elliptical hollows that grade to *honycomb tafoni*. See photo KG080268.

The area clearly shows long-term movement of water through the rock and deep weathering along joints, but also and more importantly, through the rock as discrete *conduits*.

Photo RW081730, **Caranbirini.** Towers on outer wall.

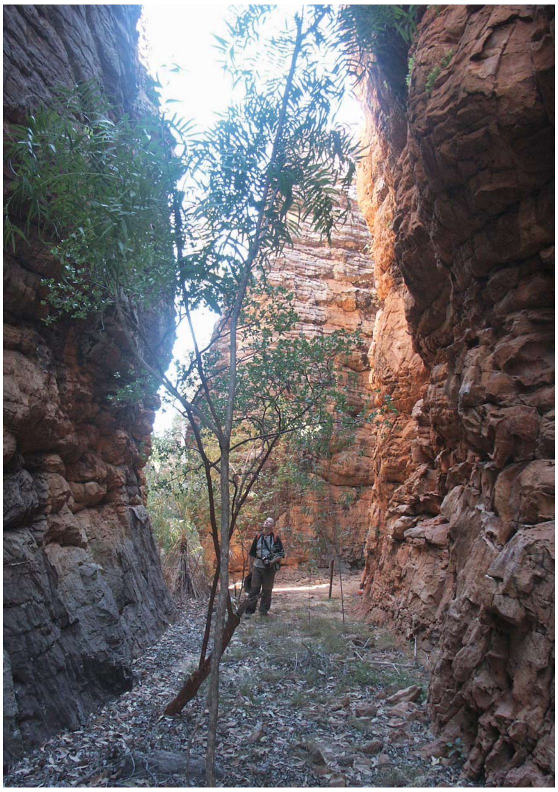


Photo KG080284, **Caranbirini**. Street of stone city.

National Heritage Significance

High: Tubelets (various types), pseudo-karren.

Mod-Good: Case-hardening effects, towers, pinnacles, tafoni, stone city.

4.2.2.12: Abner Range:

This broad plateau, with cliffed edges, has two belts of resistant sandstone on top: the Abner Sandstone (*Pra*) and the Bessie Creek Formation (*Pre*) separated by softer, recessive, formations (Pietsch & others, 1991). These are gently folded with dips up to 15° (photo KG080358P) and several anticlinal and synclinal axies producing curved belts of sandstone that have been dissected into karst-like *ruiniform* landforms (Figure 22).

The plateau has several horizontal levels (*pavements*) that cut across the dipping strata. The upper level is an *old land surface* of possible Tertiary or Cretaceous age, and a lower level is cutting back into this at the level of the modern Bessie Creek (photo KG080573). Bessie Creek, in turn, becomes incised into the lower surface towards the plateau edge and drops over the scarp as a large waterfall. Between the two plateau levels there is commonly a gradation from high-level pavements, through *grikefields*, *giant grikefields*, *stone city*, *stone forest* to low-level pavements (also griked) – see photo KG080565a. This context differs from that at **Limmen**, where the lower surface is generally a sand-plain graded to regional base-level of erosion. At Abner, the lower surface forms a pediment (or pavement) sitting some 50 m above the regional base-level. It also differs from **Bunju** where the pavements are stratigraphically controlled dip slopes.

The main area (the "Lost City") is a stone city with high city blocks and pinnacles. The tops of larger blocks are sculptured into smaller blocks and lanes etc (photo KG080566-7). Within the stone city the more protected

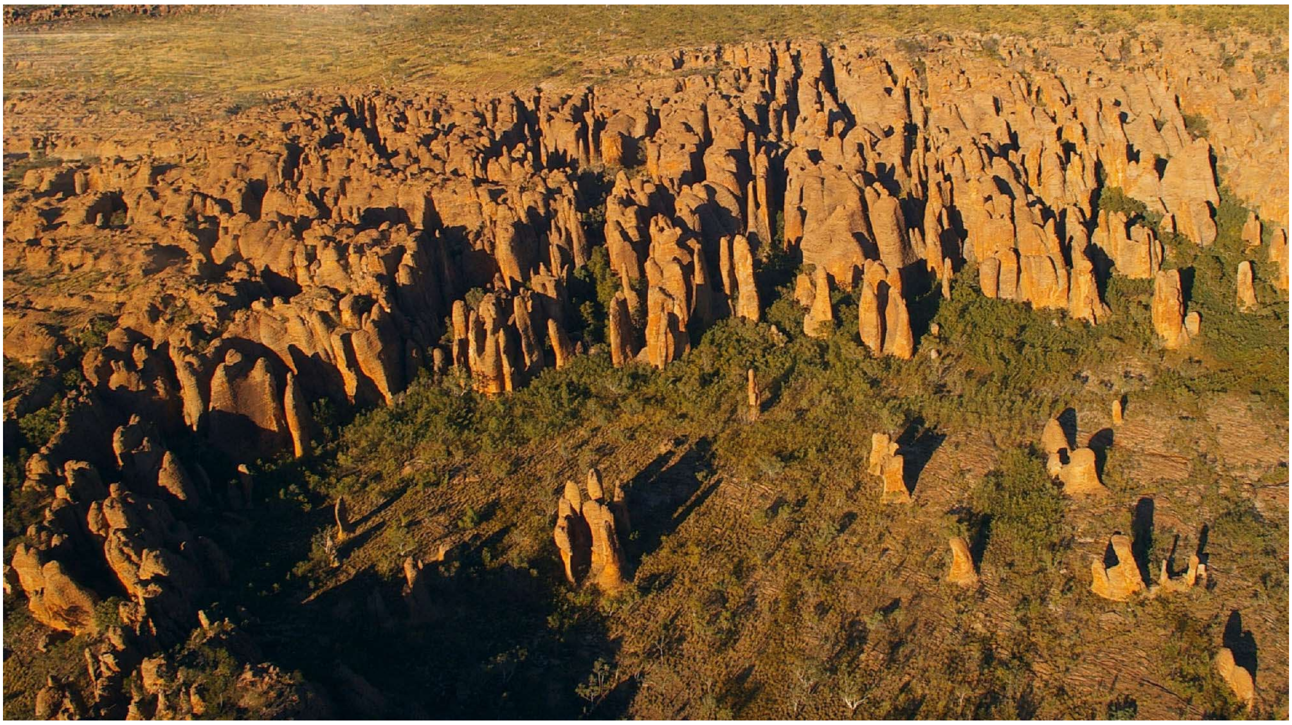


Photo AS.Abner064, **Abner Range.** Tourist section of stone city in *Pre* belt.

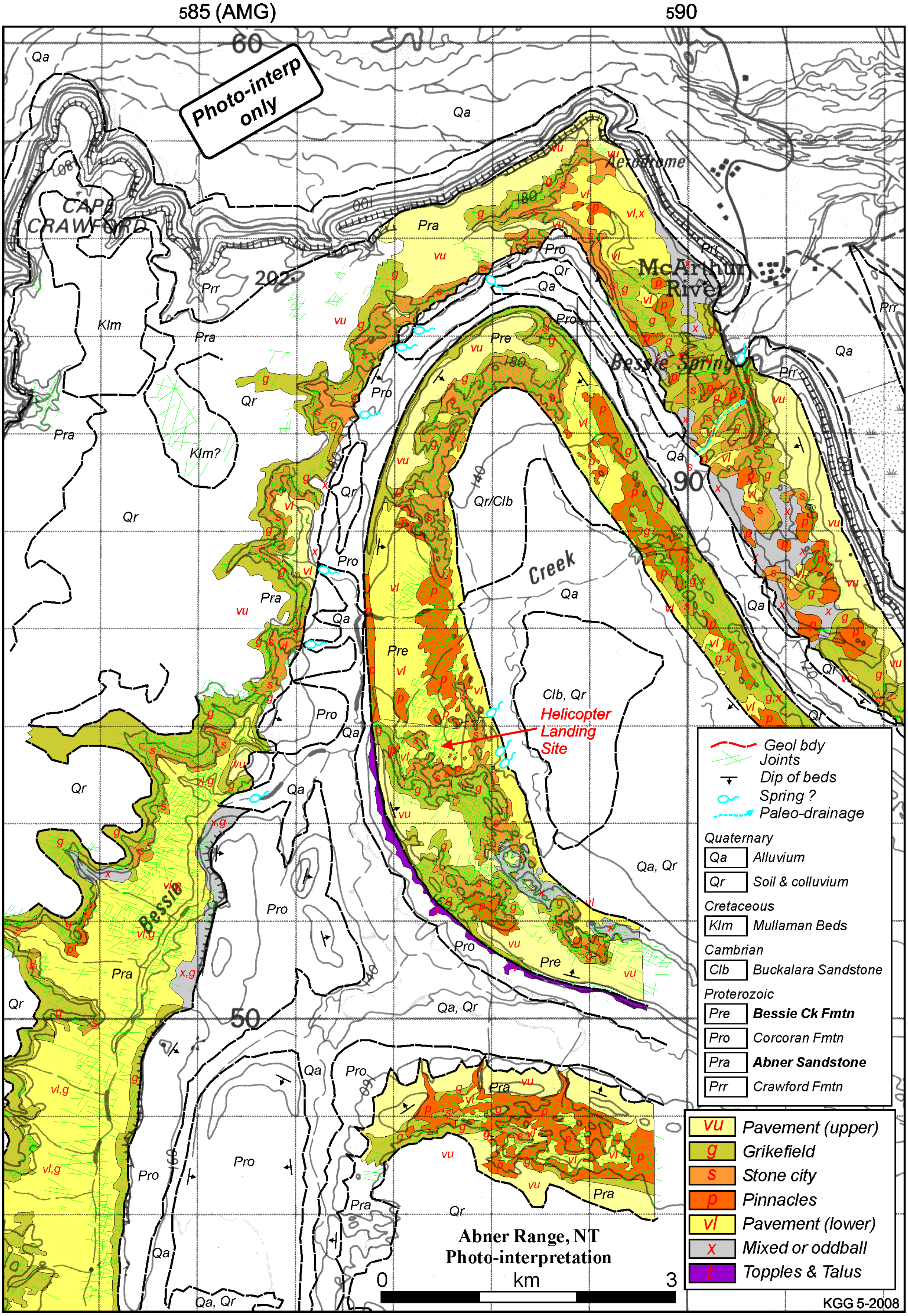


Figure 22: Map of part of the **Abner Range** area.

Photo KG080456P, **Abner Range** stone city, from the helicopter landing site. Sandstone pavement in foreground.

parts of the streets have dense vegetation verging on rainforest. This might be biologically interesting.

The tall, narrow pinnacles are commonly tilted 10-15° to the vertical (photo KG080527), being perpendicular to the dipping bedding as discussed in section 4.1.1.2. This is an interesting type of *structural control* that is also seen at **Limmen**. There are a few examples of fallen or toppled pinnacles or blocks, but not many. Fallen blocks tend to disintegrate to sand quite quickly.

Well-developed *scarp-marginal basins* are scattered through the area, especially in the western *Pra* belt (Air-photo on p.13, Photo RW081870.T).

One gently-dipping outcrop had unusual small shallow meandering *runnels* that are moist and fed from small *tubelets* (Ph KG080378, 382). The runnels are 1-4 cm wide and 1 mm deep with flat but rough (etched) floors and thin 'levees' of *chemical deposits* of white opal. Few other chemical deposits were seen.

Significance: A spectacular array of large pinnacles and blocks in sharp contrast to the flat pediment below, in particular the isolated tall narrow pinnacles and stone forest that stand out on the pediment with abrupt or flared bases. There are also good examples of stone cities and giant grikes. The main site is on *Pre*, but there are also belts of stone cities etc on the *Pra* unit, these latter include well-developed *scarp-margin basins*. The area has particularly good examples of small solution runnels fed from tubelets (photo KG080382), and of pedimentation style denudation. It has spectacular examples of isolated tall pinnacles scattered across a pediment (photo KG080568, the cover photo (KG080538a) was taken from inside this group).

National Heritage Significance

High: Stone city and pinnacles, towers, old land surfaces and evidence of regional landscape evolution.

Mod-Good: Giant grikes and grikefields, pavements, old land surfaces (plateau, pediment etc), scarp-margin basins, tubelets, runnels; stone forest, villas, tafoni, case-hardening effects, chemical deposits.

Photo KG080358P, **Abner Range**. Dipping beds of Bessie Creek Sandstone in foreground form squat pinnacles and blocks. The main stone city and a high-level Tertiary planation surface in background.

4.2.2.13: Sturt Plateau (laterite karst):

A broad lateritic plain has localised clusters of collapse *dolines* (sinkholes). See Twidale (1987) & McFarlane & Twidale (1987) for details of the area and its sinkholes. There are 9 sinkholes in the Hidden Valley area (Daly Waters map sheet, Brown, 1969) beside the Buchanan Highway that we visited during this study. The lateritic *deep weathering profile* (DWP) is on Cretaceous claystone (or sandstone elsewhere in the region) but the Cretaceous is underlain by Cambrian limestones, so there is a possibility of carbonate solution at depth causing *subjacent karst* dolines. However, Twidale and McFarlane both argue for the originating solution cavities being within the DWP.

The spectacular, large, steep-walled dolines beside (and beneath!) the highway collapsed progressively over 7 months in the wet season of 1981-82 (see figure 4 in Twidale, 1987, and the photo in his figure 9). At the time of our visit, 25 years later, the dolines were still vertical sided and did not appear to have evolved greatly in that time, although active fissures and exposed roots in the one on the old highway suggested that some movement and erosion was still occurring (photo RW087278P).

The largest doline visited was about 70 m across with vertical walls up to 14 m high (photo KG083069) and a total depth of about 19 m.

Significance: The site has the best example seen of large collapse dolines in a laterite DWP. Marred by some uncertainty as to the influence of limestone at depth, beneath the Cretaceous claystone, but there are arguments for the collapse originating in solutional cavities within the DWP. The site also has examples of small-scale solution features (tubelets, and solution-induced brecciation, photo KG083061).

National Heritage Significance

High: Laterite karst, collapse dolines

Mod-Good: Tubelets.

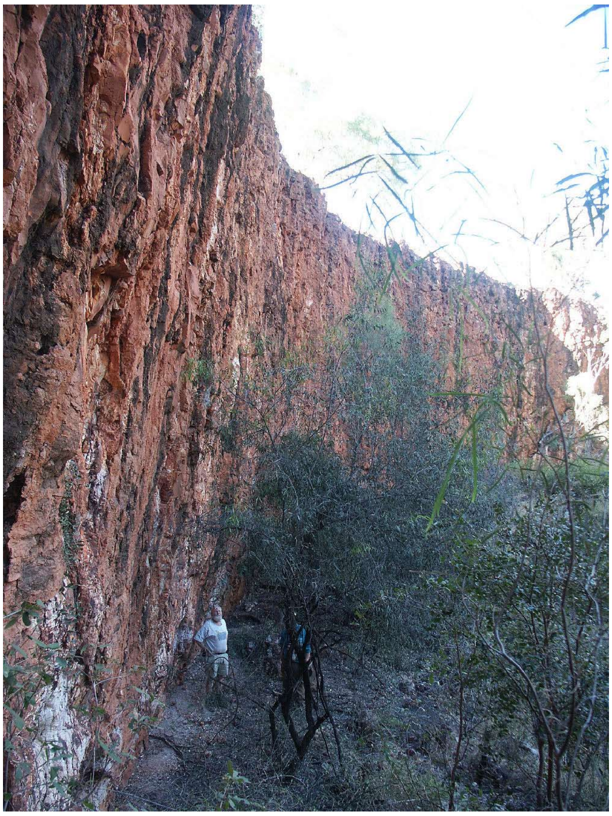


Photo KG083069, **Sturt Plateau**, wall of a deep collapse doline in laterite.

4.2.2.14: Castle Rock (laterite karst):

This isolated mesa is right beside the Stuart Highway, about 3 km south of Renner Springs. Its *laterite karst* features were briefly described by Twidale (1987, p.47). It is a strongly ferruginised and lateritised, medium to fine-grained quartz sandstone of the Cambrian Muckaty Sandstone Member of the Helen Springs Volcanics (Hussey & others, 2001). The top and cliffs of the mesa are riddled with vertical *solution pipes*, 0.1 to 2 m wide and up to 2.5 m deep (photo KG083098). These have irregular, lumpy, sides and coalesce to form fissures that isolate walls, *pinnacles* and cones of ferruginised sandstone (photo KG083106). There are also some horizontal or inclined tubes that combine in places with the pipes to form a large-scale spongework.

Significance: A conveniently located small outcrop is a good example of *laterite karst*, showing well-developed karst-like solution pipes with pinnacles left between them.

Photo KG083106, **Castle Rock**. Man engulfed by deep coalescing solution pipes, with residual pinnacles left between them.

Photo KG083129Pxb, One of the **Barry Caves**.

National Heritage Significance

High: Old land surface with laterite karst, solution pipes.

Mod-Good: coalescing pipes form pinnacles.

4.2.2.15: Barry Caves (laterite karst):

These caves are in a *silcrete* capped *mesa* near the Barkly Highway which has a *deep weathered profile* (DWP) developed on the Cambrian Wonarah Formation (Randal, 1966). The caves are in a thin-bedded very-fine grained quartz sandstone, but the unit as a while is reported to be mainly silicified limestone and dolomite with minor siltstone and sandstone. Possibly the fine-grained sandstone is an insoluble residue left after loss of the carbonate content of a sandy limestone – as is seen at Split Rock Waterhole, east of Camooweal (Grimes, 1985, p.17 & 29).

There are several small low-roofed *caves* at the base of the mesa cliff-line (photo KG083129P). The largest had two entrances and three low but broad chambers (Figure 23).

The DWP has disrupted the sandstone bedding and there are pockets and vertical pipes of brecciated and nodular material. There are also small solution tubes and pits (2-4 cm) in the walls of the caves and cliff.

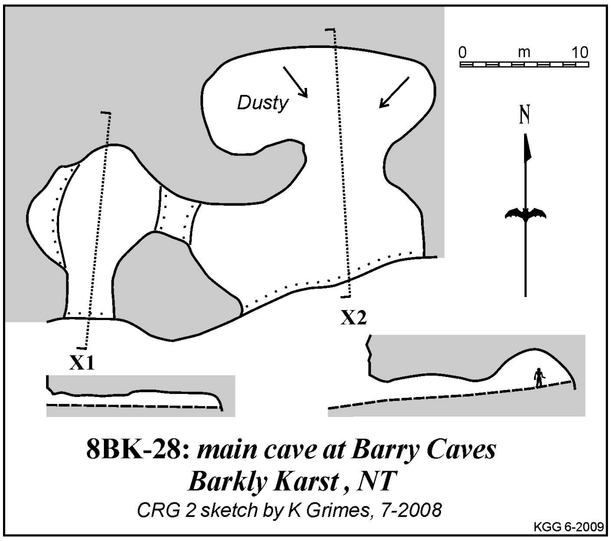


Figure 23: Map of the largest of the Barry Caves.

This is *laterite karst* in that the sandstone (and original limestone) has been affected by a DWP (including solution, as evidenced by the breccia pockets) and the caves are forming in the softer weathered rock beneath a silicified *duricrust* cap, but the actual excavation would be by mechanical (pseudo-karst) processes – wind, water and gravity.

The main value of this small site is in providing a conveniently accessible representative example of a laterite karst cave developed by erosion beneath a duricrust caprock.

National Heritage Significance

High: Laterite karst

Mod-Good: cave, old land surface, solution pipes with breccias, deep weathering profile.

4.2.3: Queensland Sites

4.2.3.1: Lawn Hill (Boodjamula) and Widdallion Cave

The sandstone is Proterozoic Constance Sandstone (*Psc*), a quartz sandstone and conglomerate that dips gently to the west (Carter & Opik, 1961). The plateau to the north of the main gorge has elements of both Cambrian and Tertiary *old land surfaces* (Grimes,

Photo KGS740636t, Cliff face at Widdallion Cave, **Lawn Hill Gorge,** showing hanging part of dry valley (arrowed). Cave exit is behind trees at base.

1974, p.13-16; 1979). The Cambrian surface comprises exhumed valleys that had been buried by the Cambrian marine sediments. The Tertiary surface is an erosional peneplain. A stream channel runs across this plateau for 2.5km, becoming incised towards the edge as a *blind valley* with several dolines and finally sinks into a fissure cave (Widdallion Cave) 20 m before the cliff at the edge of the plateau (see Figures 24 & 25). The cave opens at the base of the cliff beside Widdallion creek (photo KGS740636t). There is also a small area of *stone city*.

Widdallion Cave (Figure 25) comprises a series of descending fissures, initially running parallel to the main cliff (350° mag), but swinging to the NE as they descend as an alternation of steep drops and short horizontal sections with boulders and pools (photos KG080116a, 0103). The final fissure opens through a small window (photo IH21062008_11) into the back of a large daylight chamber at the base of the cliff. The fissures are enlarged joints, seen also in a small stone city to the northwest, which would have been *arenised* and then mechanically excavated by the water flow.

Unusual *speleothems* include soft orange "mud" flowstones (photo KG080099, IH21062008_06) that may be a combination of organic material and amorphous iron minerals (section 4.3 & Appendix 7).

The valley floor between the two sinkholes is an iron cemented gravel-boulder-block pile, which predates the cave formation (photo IH21062008_02). The stream

Photo IH21062008_06, Fissure in **Widdallion Cave**, with orange flowstone.

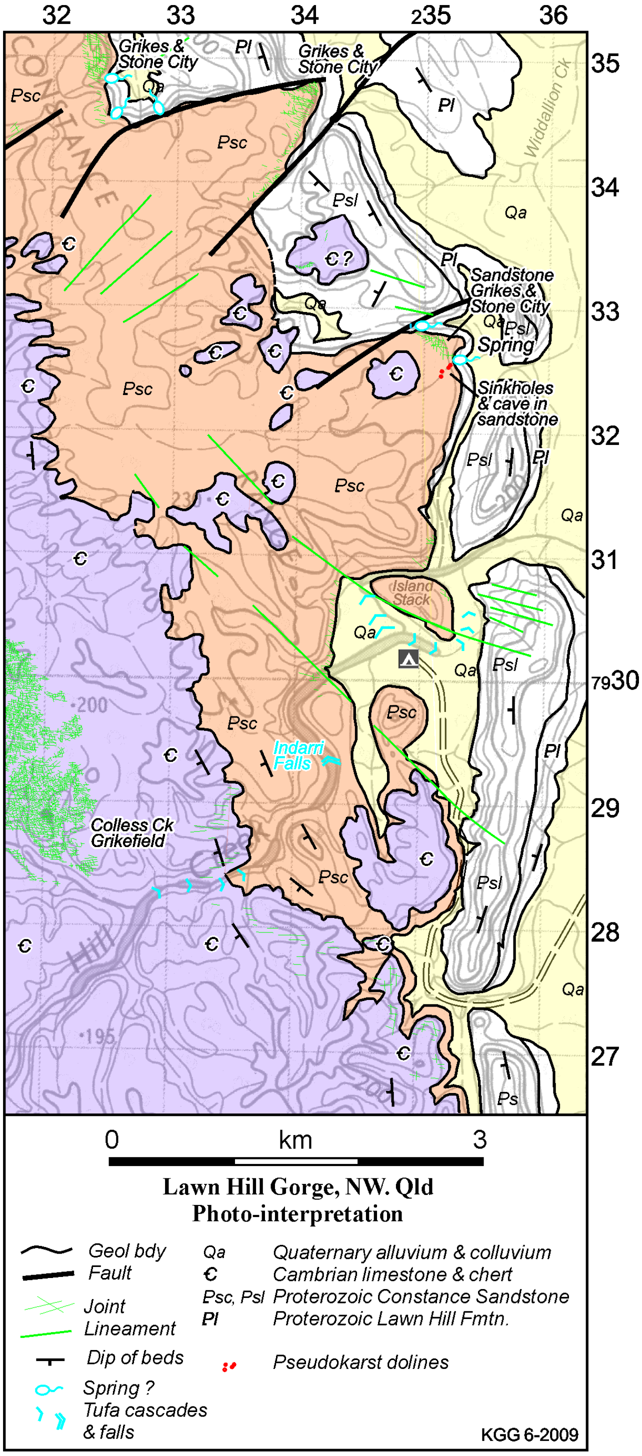


Figure 24: Sandstone karst-like features at **Lawn Hill Gorge**.

flows through a small cave (4Z4E-2) beneath this material before it sinks into the main Widdallion Cave. (photo RW081410).

Significance: The main interest is in the *stream-sink* and associated *dolines*, *dry valley* and *caves*, which are a small scale version of **Whalemouth Cave**, WA. In this case, the cave follows joints sub-parallel to the cliff, whereas at Whalemouth they are roughly perpendicular to the cliff. The cemented rubble story adds interest, but is probably not relevant to karst *sensu stricto*.

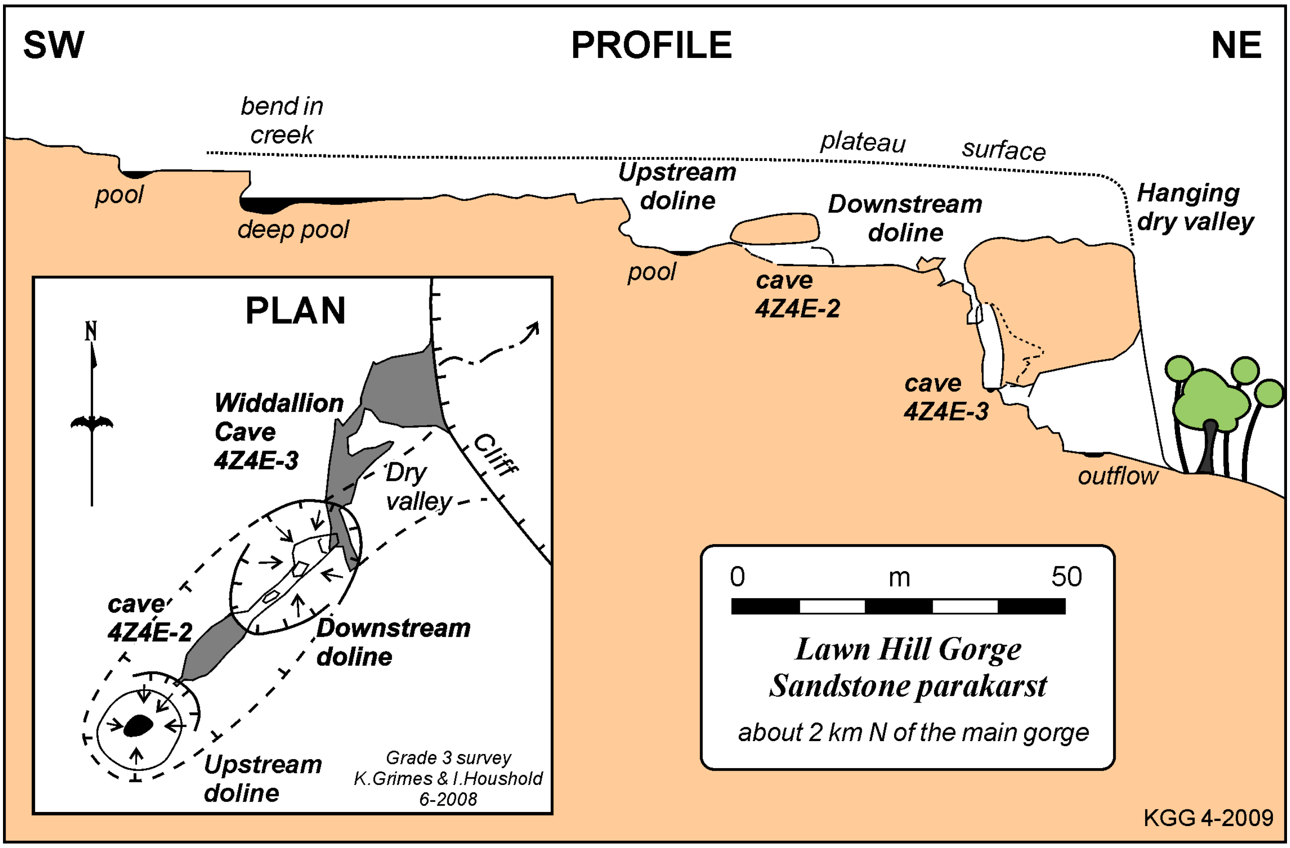


Figure 25: Profile of blind valley and map of the sandstone caves, **Lawn Hill Gorge**.

National Heritage Significance

High: Blind valley & stream cave.

Mod-Good: Unusual speleothems, dolines, old land surfaces (Cambrian & Tertiary), underground drainage.

4.2.3.2: Tobeys Waterhole

A lateritic plain (the Kendall Surface of probable Pliocene-Pleistocene age, Grimes, 1985, p.5) has a ferricrete *duricrust* and *laterite DWP* beneath a sandy top soil. This is exposed around a retreating spring head at the source of a tributary of Nardoo Creek. The top of the ferricrete pavement is strongly undulating (photo KGS830303) which suggests subsidence above *piping* tunnels beneath it. This is an example of *laterite karst*.

National Heritage Significance

High: -

Mod: Laterite karst, piping effects.

4.2.3.3: Cobbold Creek

A fault block of Jurassic sandstone (mainly the Hampstead Sandstone with a capping of Loth Formation in places, Doutch & others, 1971) forms a plateau that has been strongly dissected to form extensive areas of *giant grikes* and local areas of *stone city*. There is a localised system of *underground drainage* through small *caves*. The deep but narrow gorge is an incised stream that has captured drainage on the plateau. The history of *stream capture* is complex with several capture points, some resulting in reversed flow and others in *dry valleys* (Withnall, 1976, 2002).

Grikefields are the most distinctive ruiniform landforms on the surface – partly because there is only one dominant joint direction (to the NE) so *stone cities* are only developed in local areas where there are sets of cross-joints. These include both giant grikes and smaller grikes (photos KG083694, 3825). Many of the isolated cross-joints form large *box valleys* and are on major lineaments, possibly faults. Some of the narrowest of the deep grikes are roofed locally (by chockstones, or a narrowing of the roof) to form small caves (photo KG083826Pb).

Karst-like *underground drainage* through conduits is evident from numerous seepages along the gorge walls, coming from small *tubelets*, bedding planes and some larger horizontal *tubes* (photos KG083548, 3509); and from a set of small stream *caves* found to the SE of the gorge. A well-formed wet-season stream channel (photo KG083728) runs from a basin-like *blind valley* westward through a set of two small caves (photo KG083634Pb & see map), eventually emerging from a pair of inaccessible holes in the cliff at the head of a short side branch of the main gorge (see section 4.1.1.4).

Tafoni, *cavernous weathering*, and *case-hardening* effects are common throughout the area. The larger examples form *rock shelters*, some of which penetrate right through the sandstone walls separating giant


Photo KG083657. Narrow section of **Cobbold Gorge**: boat for scale,

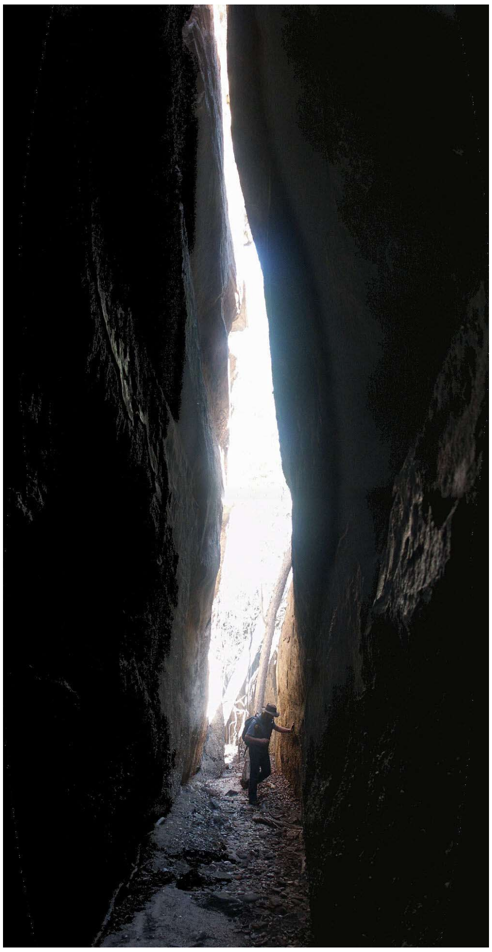


Photo KG083826Pb. Narrow grike at **Cobbold Creek**.

grikes (photos KG083819, 3821Pa). The area has some particularly good examples of thin case-hardened surfaces left outstanding by erosion of the softer material behind them (photos KG083820, 3849a).

Tessellations are particularly well-developed here. They are mainly polygonal with secondary etching and pitting (photo KG083777J). There are some kamenitza and runnels, but they are not well developed.

Significance: a spectacular and significant example of sandstone *ruiniform* terrain and smaller scale sculpturing, but specifically karst-like landforms are only a small part of the story. The giant *grikefields* are the most distinctive features if this area, but these are not as large and extensive as those at **Bunju**. The gorge is spectacular for its narrow and strongly sculptured form, and the commercial boat tour takes full advantage of this. But this is not a karst-like landform, although it does exhibit seepage from small (solution) *tubelets* and larger *tubes* along its walls. There is a good example of underground drainage where a (wet-season) stream runs through a group of small caves with an associated *blind valley* and *doline*. The area has particularly good examples of *case-hardening* and associated *cavernous weathering*. This area also has some particularly well-developed polygonal *tessellations*.


Photo KG083548, **Cobbold Gorge.** Seepages from small tubes within gorge.

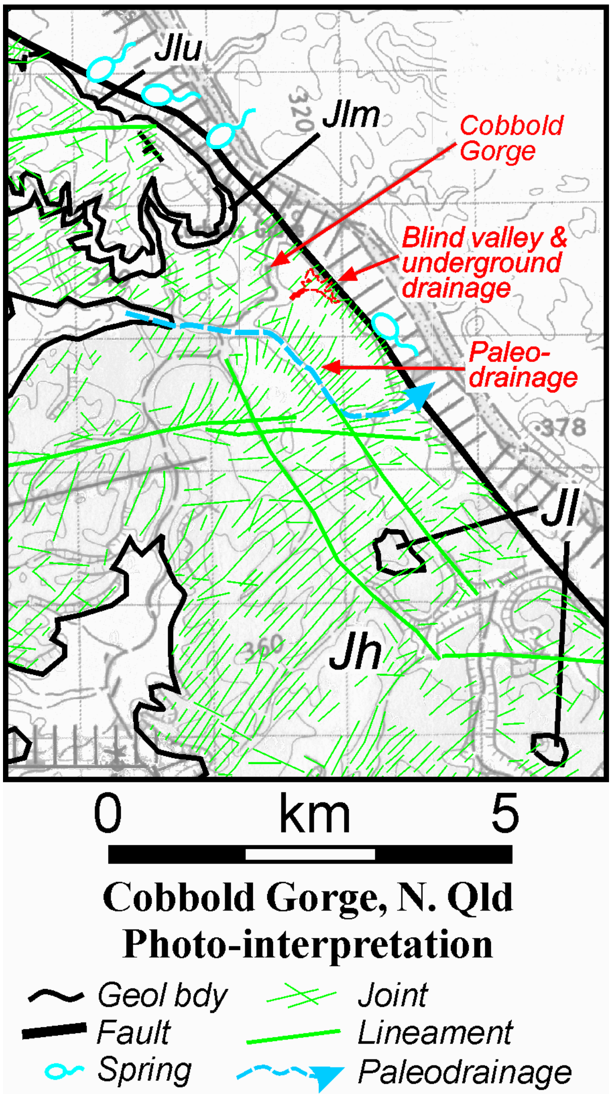


Figure 26: Part of a map of the **Cobbold Creek** area, showing the gorge and paleodrainage areas.

The *paleodrainage* and *stream capture* are not karst (though there is an unproven possibility that underground piracy may have contributed) but this adds extra geomorphological interest to the area.

National Heritage Significance

High: Giant grikes, stream capture, the gorge.

Mod-Good: Grikefields, tafoni, case–hardening, tessellations, caves, tubelets, underground drainage.

4.2.3.4: Kalkajaka (Black Mountain) and Cape Melville National Parks granite pseudokarsts

Our comments here are based on previous visits by one of us (APS), air-photo interpretation, the literature and discussions with Lana Little (QNPWS, Chillagoe) – see photos AS.BlackMtn014, AS.CapeMel002, KG083422J. Additional details are provided in Spate (2007a). We did not plan to visit Cape Melville during this fieldwork.

The geology of these two sites was described in general terms by de Keyser and Lucas (1968) and the granites in more detail by Donchak et al (1992) and Bultitude (1993) who recognised that the granites are different at each site. These are the I-type Trevethan Granite at Kalkajaka, and the Cape Melville Granite. However, the normal processes of granite weathering apply at each site, producing huge piles of core stones as topographic highs. It is possible that the strongly seasonal nature of the climate with high rainfall intensities promotes the removal of weathering fines.

De Keyser and Lucas (1968, p139-40) describe the hills as follows:

Some of the rugged convex granite hills ... south of Cooktown are covered by a loose jumble of large boulders of fresh granite. The best known example is the Black Trevethan Range, over 1000 feet [300 m] high ... The boulders range from 4 to 40 feet [12 m] across. There are a few patches of scrubby vegetation on the summits, but elsewhere there is no matrix between the boulders. The small subcircular depressions [subsidence dolines?], up to 100 feet [30 m] deep, on the summits are drained from below. Most of the boulders are equant to oblong, with some straight edges and rounded sides. Some boulders have been separated into several blocks by rectilinear joints.

In the Black Trevethan Range and in the smaller bouldery granite hills west of the Normanby River ... the hills pass abruptly into jungle-covered soil-clad slopes.

The most impressive example of bouldery outcrops is the Melville Range, a massive rugged inselberg, 12 miles [19 km]

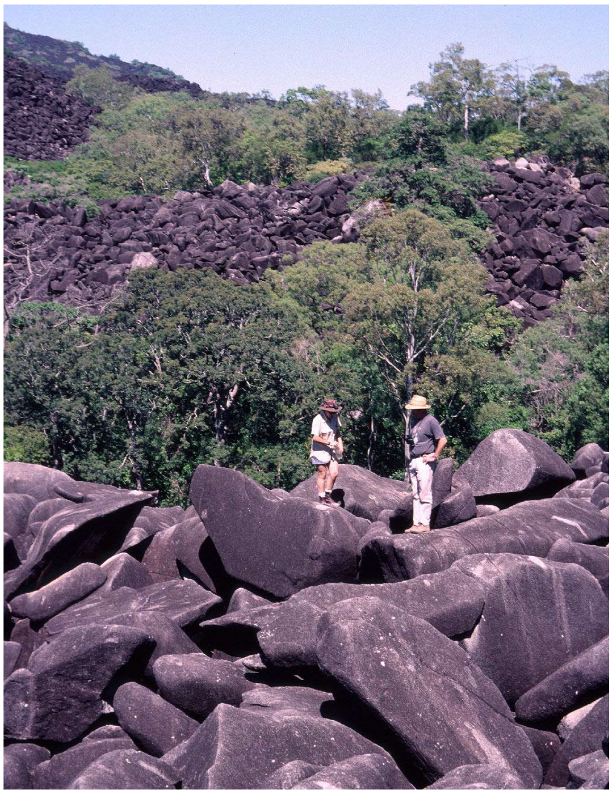


Photo AS.BlackMtn14. Granite boulders at Black Mtn.

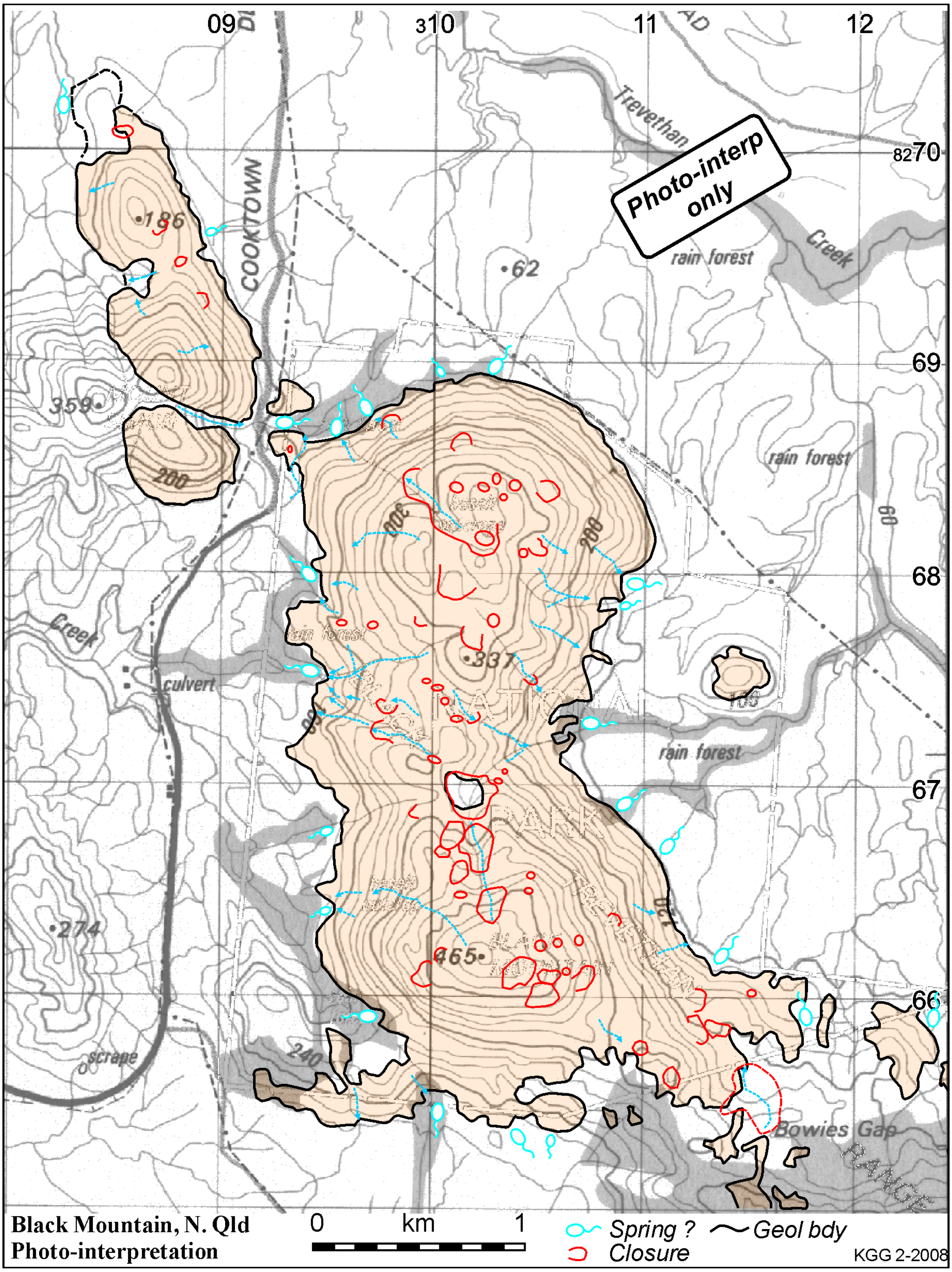


Figure 27: Map of **Black Mountain**. Pink area is bare granite.

long and 2000 feet [600 m] high, fronting the sea in the north ... The range is convex and steep-sided, with only occasional trees and a little lichen. In places the boulders are extremely large, and spire-like and blocky outcrops protrude locally from the jumble.

These bare bouldery hills resemble the 'metal hills' in the Chillagoe area ...

... the formation of the bouldery hills is probably due to a combination of steep slopes and change in climate. They are probably a type of residual deposit of core boulders and joint blocks derived from below. A deeply weathered profile may have developed on the early Tertiary landscape under humid conditions; a change to a drier and more seasonal climate may have killed the original lush vegetation and facilitated

the removal of soil by torrential downpours. In addition, the burning of grass in historic times may have exposed the slopes to increased erosion and soil stripping. Once the soil has been removed, re-establishment of the vegetation would be a slow process on the bare slopes under present climatic conditions.

The spaces between the core stones are said to penetrable for tens, if not hundreds, of metres – well into the dark zone – so count as *caves*. Lana Little (pers. comm.) states that the caves do not penetrate deeply into the mountain but rather are a ramifying network under a broken 'skin' of boulders on Kalkajaka. At Cape Melville the caves are larger because of the larger size of the boulders – but do not extend much deeper than three to four boulder diameters.

Our air-photo interpretation (Figure 27) confirms the presence of the closed depressions mentioned by De Keyser & Lucas (1968), some of which are occupied by 'jungle' patches. Similar depressions are not known from Cape Melville. The black colouration of Kalkajaka is probably due to cyanobacteria rather than lichens as is commonly stated.

There are many other examples of boulder pile hills in Far North Queensland including the **Metal Hills** at Chillagoe (photo KG083422J), on Torres Strait and other coastal islands. However, it would seem that the Kalkajaka (Black Mountain) and Cape Melville National Parks granite pseudokarsts are unusual and important geomorphic phenomena and are the most important of the boulder mountains in Far North Queensland.

National Heritage Significance:

High: Granite in-mountain *boulder caves*, subsidence(?) *dolines*

Mod-Good: Springs and underground drainage?

4.2.3.5: Chillagoe Metal Hills

The Metal Hills are piles of granite boulders, similar to Black Mountain, but at a smaller scale (both for the size of the hills and of the boulders). The rock is part of the Carboniferous Ruddygore granodiorite (Bultitude & others, 1998).

The *caves* (human-sized cavities between the boulders) are best developed where one or more, larger than usual, boulders provide a stable roof. The few inspected went down about 5 m into semi-darkness. They tend to have multiple entrances and daylight holes (photo KG083422J) and form a three-dimensional inter-granular mega-porosity. They end (for humans) in tight squeezes between boulders or at a *gruss* floor.

Coralloid *speleothems* (unidentified mineral, but presumably opal-A) form on the under-surfaces and sides of the boulders in the deeper (twilight) parts of the caves (Photo KG083432).

This was a fall-back site as we were unable to inspect **Black Mountain** (Kalkajaka), where the caves are reported to be much more extensive, and where surface dolines also occur.

Photo KG083422J, **Metal Hills, Chillagoe**. Looking out from a cave in granite boulders.

National Heritage Significance

High: none

Mod-Good: Granite boulder caves.

4.2.3.6: Ngarrabullgan (Mt Mulligan)

Ngarrabullgan (Mount Mulligan) is a remarkable sandstone massif about 100 km west of Cairns in northern Queensland. It rises abruptly from the surrounding landscape and displays many features of pseudokarst interest as well as possessing a diverse range of other natural and cultural values (David 1999). Mount Mulligan has long been recognised as a distinct landform in its own right. Geologically, it may well be the only major *obsequent* rift block mountain in Australia.

Despite its impressive size and unusual physical characteristics, there has been very little published on the geomorphology of Ngarrabullgan. Our work was confined to a fixed-wing flyover, results of previous visits, incomplete air-photo interpretation, and reports in the literature (see Spate, 1999a,b, 2007b).

Geological History

Ngarrabullgan is a remarkable landform rising abruptly several hundred metres above a basement of strongly folded, sedimentary, Devonian Hodgkinson Formation and somewhat less folded volcanics of the Carboniferous-Permian Featherbed Volcanic Group to the west. The mountain itself is made up of the Triassic Pepper Pot Sandstones and the underlying Permian Mount Mulligan Coal Measures (Amos & De Keyser 1964, Bultitude 1999).

The mountain is the product of faulting; but it is of somewhat unusual origins in that it is the result of a graben (a down-faulted rift valley) that sank as it was filled with fine to coarse sand and pebbly sediments. The resultant, highly resistant sedimentary rock mass

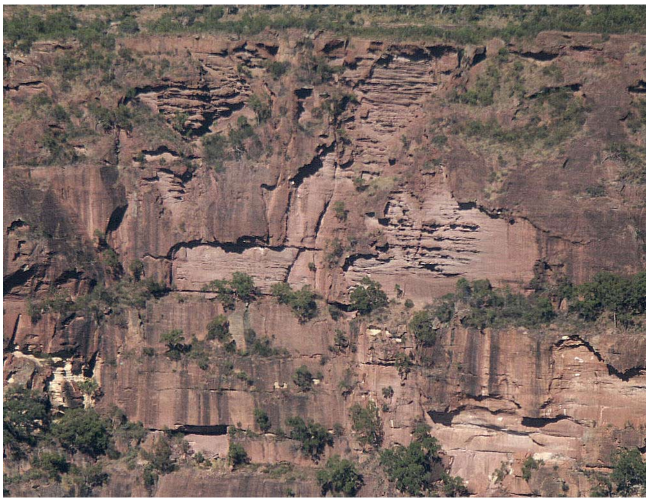


Photo KG083326, **Mt Mulligan**. Cavernous weathering on a cliff face.

Photo RW087958, Stone city blocks on the top of **Mt. Mulligan**.

withstood the erosion that removed both the Hodgkinson and Featherbed rocks surrounding the mountain. Such a mountain is termed 'obsequent'. The cliff faces are therefore not fault scarps but the edges of the hard sandstones after the surrounding sediments were eroded away.

The Pepper Pot Sandstone sequence has progressively finer-grained sandstones in the upper part of the sequence, with coarser conglomerates being more abundant lower in the section.

The 38 km or so of near-vertical cliffs are consistently several hundred metres in height and are broken by streamlines in only five or six places. The plateau top itself is therefore isolated above the surrounding hills and characterised by a low, rolling terrain dissected by gorges and steep-sided valleys. Apart from parts of Gorge Creek itself, the local relief reaches no more than 50-60 m; and yet slopes can be relatively long and shallow or extremely short and steep as they drop into local gorges.

Jointing of the sandstone at Ngarrabullgan produces *Ruiniform terrain* with local areas of *stone city* and squat *pinnacles* (Photo RW087975) as well as the cliffs, stream directions, *pagoda* pinnacles and the clint and grike terrains. However, spectacular pinnacles such as those commonly found at **Bunju** and the **Abner Range**, for example, are not found here. The joints are sometimes enlarged enough to form *stone city streets* and *avenues* many tens of metres across; most are wider than their depth, but others are only a few metres or less in width but many metres deep.

There is a full range of karst-like landforms developed in the Ngarrabullgan sandstones at all scales including *caves*, *bridges* and *arches*, *tubes* of various scales, very significant *case hardening* and *cavernous weathering*, *clint* and *grike* fields, extensive sandstone *pavements* – some displaying excellent *tessellations*, and solution *runnels* and *kamenitza* (Spate 1999a, b).

Many fine examples of *caves* are known from Ngarrabullgan, including broad caves several tens of metres long, 5-10 metres wide and up to 3 metres high. One karst stream cave has captured the water flowing down one *street* and delivered it to the next *street* downstream via a 5-6 metre waterfall (Spate 1999a, b). The archaeologically important Ngarrabullgan Cave (David 1999) is actually an overhang produced by the undercutting of a cliff, possibly by a former waterfall.

Significance: The sandstone landforms of Ngarrabullgan are of probable National significance, but further detailed study, inventory and review are required before this can be stated categorically.

National Heritage Significance

High: Giant grikes, the *obsequent* mountain itself.

Mod-Good: Stone cities, low towers, caves, cavernous weathering and tafoni, an enigmatic lake on the plateau.

4.2.3.7: Pelican Lakes

A group of four large (1-2 km across) but shallow lakes occur on an undulating lateritised plateau which straddles the "Great Dividing Range", overlying Cretaceous sandstone and mudstone, and Paleozoic granite (Withnall, & others, 1996; satellite image). They are much larger that the usual *laterite karst pans* seen on *deep weathered* surfaces (eg. on the Denna Plain near **White Mountains**, and Tabletop Swamp at **Litchfield**). Some similar large hollows/lakes occur in several places along the Great Divide between White Mountains and Lake Buchanan.

The lakes as a group might be solutional depressions formed as laterite karst, but there is only circumstantial evidence for this from the deep weathering profile occurring beneath the plateau surface.

There are small *lunettes*, indicating deflation of the dry lake bed at some time, but that might have postdated the formation of the initial hollows. The southwestern two lakes are upstream of a small volcano of late Tertiary

Satellite image of **Pelican Lakes**. Scarp of Great Divide to right (East) and small volcano (v) to SW.

or early Quaternary age (Withnall & others, 1996) and might be partly a result of damming of the valley by its small lava flow. However, that should not have affected the lakes further upstream.

The genesis and significance of these lakes, and others that form along the crest of the Great Dividing Range, is still uncertain. We can only say that they are intriguing! The earth tank in Lake Louisa showed good examples of *piping* pseudokarst in the excavated lake sediments, a clayey sand (photo KG083305).

National Heritage Significance

High: -

Mod-Good: intriguing features, but of uncertain genesis.

4.2.3.8: White Mountains (laterite karst including the Denna Plain pans)

The White Mountains National Park was created partly because of its *ruiniform* sandstone formations which include large grikefields and some less extensive stone cities as well as cavernous weathering etc (see Stephens, 1976). The sandstone is the Triassic Warang Sandstone (Vine & Paine, 1974). The *ruiniform* sandstone formations are best developed in the NW part of the park (Stephens, 1976). However, we visited only the SE part and concentrated on the *laterite karst* pinnacles in that area and also the laterite *pans* of the adjoining Denna Plain (Coventry, 1978; Coventry & others, 1985).

The laterite within the park is best developed on localised areas of massive orange-red poorly-sorted sandy mud with occasional pebbly bands (an old valley fill) which are being eroded at the edge of the plateau, which is a *deeply weathered* and lateritised *old landsurface*.

Photo KG083189, **White Mtns**. Hollow laterite pinnacle.

Photo KG083287, **White Mtns**. Cemented wall, along a joint, in laterite.

Satellite image of the **Denna Plain**, showing many laterite karst pans beside the Flinders Highway.

The *pinnacles* are mainly narrow cones, up to 5 m high and 2 m wide (photo KGS780512). At one site 50% of the pinnacles were hollow (photo KG083189), each cored by a roughly cylindrical vertical *pipe*. A few complex or composite pinnacles occurred. The pinnacles are erosional residuals, and can be seen to be emerging as slightly better indurated areas where the scarp is being eroded back. Their genesis is discussed in section 4.1.2 which draws an analogy with syngenetic karst pinnacles.

Low *polygonal walls* were moderately common. These patterns occur in many laterite areas (e.g. photo KGS841404) and we interpret them as cemented areas between broad, but closely-spaced, solution pipes. Some relatively straight *cemented walls* were also seen – several of these seemed to be following a sinuous vertical joint (photo KG083287).

The laterite has common irregular 3-D patterns of solution *tubelets* (0.5-1 cm wide) and some larger vuggy porosity (photo KG083273). Some secondary precipitates form *coralloid* structures, or wavy flowstone-like patterns (photo KG083276), on vertical or overhung, protected walls of cavities.

On the lateritic Denna Plain (an *old landsurface*), shallow *laterite karst pans* occur on both sides of the Flinders Highway, between Prairie and Torrens Creek (see Satellite image). Their genesis is discussed in 4.1.2. A discussion of the geomorphic history of this region is in Coventry (1978) and Coventry & others (1985).

National Heritage Significance

High: Laterite karst: pinnacles, pipes and pans

Mod-Good: Tubelets and cemented walls in laterite. Sandstone formations elsewhere in the National Park (not inspected)

4.2.3.9: Carnarvon Ranges Sandstone Belt

The Carnarvon Range sandstone belt in central Queensland includes the well known Carnarvon Gorge, and a line of other national parks or areas of interest on private land (Blacks Palace, Tambo Gorge, Salvator Rosa NP, Kaka Mundi NP, and Mount Moffatt NP to the west, and to the east Mooleyember Gorge (at the headwaters of Moolayember Creek), Robinson Gorge and other parts of the Expedition Range NP, Isla Gorge NP and Precipice NP (which includes the Nathan Gorge).

Willmott (2006, chapter 6) provides an illustrated summary of the geology and landscapes of the whole belt. Young and Wray (2000) and Wray (2009) have discussed the long-term landscape evolution of the region and its karst-like features. The ranges, gorges etc are formed mainly in the Jurassic Precipice Sandstone; a white, clayey but porous, quartzose sandstone that dips gently to the south. The sandstone is jointed, but the jointing is less obvious than at **Cobbold Creek** or in the Proterozoic quartzites of the NT, and generally the sandstone forms gorges, flat topped ridges and large towers, rather than *ruiniform* features such as stone cities and grikefields etc. However, local exceptions are fields of *pinnacles* at Salvator Rosa and Isla Gorge and many of the smaller side gorges are joint controlled and some could be regarded as *giant grikes*. Willmott (2006, p.96) has a photo of a *stone city* in the Boxvale Sandstone at Shepherds Peak just east of Robinson Gorge.

Here we will discuss only the two sites visited during the present study: **Salvator Rosa** and **Mount Moffatt**.

At both Salvator Rosa and Mount Moffatt there are many weathering *arches* and *rock shelters*, and some local fields of *pinnacles*. However, the most interesting karst-like features are the smaller *tubes*, and *tubelets*, and the *caves* that result, in part, from enlargement and coalescence of these. *Tubes* are particularly well-developed in this area (Wray, 2009). The strong flows from the *springs* at Salvator Rosa, and the point sources visible for some of these (e.g. Belinda Spring), suggest they are fed from karst-like *conduits* (Wray, 2009).

All the *tubes* are sub-horizontal and most are straight with roughly elliptical cross-sections (photos KG084329b, 4603, 624, 661). Tube size varies from <10 cm up to a metre or more across, and up to 10 m long Wray, 2009 & Figure 29), but the larger ones tend to be less regular in outline and grade to small *cave* sized *conduits* 10 m or more long (e.g. photos KG084393, 4396, 4643). Where the inner end could be seen, the tube narrowed down to an abrupt or hemispherical end (photos KG084562, 624) . This suggests piping headwards from an exit point at a cliff face, but the original weathering that aided and guided the piping may have been partly by solution (Wray, 2009).

Several tubes were in groups that crossed or intersected as small mazes, or coalesced to form human-

Photo KG084562, **Mt. Moffatt**. Twin tubes in the back of a small cave.

Photo KG084245, **Salvator Rosa**. Small pinnacle with tunnel through its base.

sized cavities (see Figure 15 and photos KG084333j, 4562).

Tubelets were best developed at Mount Moffatt but also occur at Salvator Rosa. They formed three-dimensional networks of small branching *tubelets*, about 1 cm in diameter with smooth cylindrical walls and thin cemented rims (photo KG084616). Probing with grass stems showed that some went at least 40 cm into the rock. These are convincing examples of solutional erosion.

Cavernous weathering, tafoni & pseudo-karren: This group ranges from large *rock shelters* through *alcoves* with smaller tafoni within them (photo KG084357) to normal *tafoni* and (locally) small patches of *honeycomb weathering* (photos KG084357, 4530) and vertically elongated *pseudo-karren*. Some tafoni hollows are quite deep and grade to the horizontal tubes discussed above. *Case-hardened* surfaces are common, including the inner cylindrical surfaces of many of the horizontal tubes. Joint surfaces and bedding planes can also be cemented/ case-hardened.

Photo KG084268a, **Salvator Rosa**. The Wall.

Rectangular *tessellations* were very well-developed on some cliffs and on *slick-rock* slopes, particularly at Cathedral Rock at Mount Moffatt (photo KG084542, 4556, 4572, 4638)

Photo KG084284, **Salvator Rosa**. The Spyglass (an arch) at the top of a large tower.

Caves: Small *rock shelters* formed by cavernous weathering are common. Some small but true *caves* occur on the sides of the cliffs but seldom penetrate more than 10 m. Many of these caves are large *tubes* (see above and photos KG084393, 4643) or result from the coalescence of several tubes (Wray, 2009; photos KG084333j, 4562). Some have small straight tubes in their walls that cross over or intersect to form small impenetrable mazes (see Figure 15). Specific caves are described in section 4.1.1.4 and below in the site descriptions of Salvator Rosa and Mount Moffatt.

4.2.3.9.1: Salvator Rosa

The most interesting karst-like features here are the horizontal *tubes* that are found throughout the area. Also of interest are The Wall and The Spyglass (which is cavernous weathering). There are a few clusters of *pinnacles* (Photos KG084223 to 247), but these are not exceptional, apart from the unusual large tunnels that drill right through the base of two of them (photos KG084228, 245).

The Wall is a *cemented wall* about 100m long and up to 6m high but only 2-3 m thick (photo KG084268a, KG084263P)). It has a 1-2 m wide cemented zone on each side of a central vertical joint, but on the southern side of the joint much of this has toppled and disintegrated leaving the flat joint surface exposed (KG084263P). There is also a narrow (1-3 cm) zone of case-hardening right on the joint surface.

The Spyglass itself is a large *cavernous weathering* hole, or *arch*, through the crest of the peak (photo KG084284-5, 4296). However, the peak as a whole has many sub-horizontal tubes and small caves associated with them (see Figure 15).

Caves: Small *rock shelters* formed by cavernous weathering are common. Some large tubes are wide enough to qualify as caves and are reported to extend at least 10 m into the rock (Wray, 2009). Some small but true caves occur on the side of Spyglass Peak (and probably elsewhere). One (SR-4) is shown in the sketch map (Figure 15) and comprises a rock-shelter with pillar and a network of small tubes. Some caves (or large tubes) are reported to have been used by the Aboriginals as bone depositories.

National Heritage Significance

High: Tubes, walls, conduit flow (hydrology)

Mod-Good: Towers, arches, case-hardening, tessellations; pinnacles, tafoni.

4.2.3.9.2: Mount Moffatt

The area has a variety of towers, cliffs, arches and other unusually weathered sandstone forms. The most interesting karst-like features are the horizontal *tubes*, some of which are large enough to count as *cave* tunnels (see KG084622 and photos in caves section, 4.1.1.4). Mount Moffatt also has several areas of small 3-D networks of *tubelets*. Some of the cliffs are breaking up into *capped pinnacles* and *pillars*. There are excellent examples of *tessellated* surfaces, especially the rectangular type (photos KG084542, 4556, 4572, 4638). *Tafoni* and *pseudo-karren* were common in *alcoves* (photo KG084357) and elsewhere. A road closure prevented us from visiting a particularly impressive set

Photo KG084425, **Mt. Moffatt**. Tubes and tunnels in base of Marlong Arch (cf other photo).

Photo KG084423P, **Mt. Moffatt**. Marlong Arch. See other photo for detail of base.

Photo KG084556, **Mt. Moffatt**, Looking up a tessellated surface. Pipe with cemented rim at bottom.

of *pseudo-karren* illustrated by Wilmott (2006, p.87) in the soft Hutton Sandstone at The Mansion.

The Chimneys are named for their capped *pinnacles* and half-pinnacles (i.e. still attached to the cliff at the back) eroding out of the side of the block (photo KG084494). These may be analogous to the *pillars* & *half-pillars* seen in the NT.

Arches: Marlong Arch is the most spectacular landform in the area, being a thin arch ~14 m long and ~7 m high , but not much more than a metre thick in the centre of the span (photo KG084392, 4423P).

A variety of small *caves* includes some of significance for both geomorphology and archaeology (see section 4.1.1.4 for details). The small caves are mostly found at the foot of the cliffs. Larger tubes are transitional to small "tunnel" caves. At Marlong Arch, there were several tubes and tunnels up to 1 m diameter that drilled part or all the way through the wall beside the arch (e.g. photo KG084393, 4423P). At and near Cathedral Rock there were several small but interesting *caves* described in section 4.1.1.4. There are also the archaeological caves at The Tombs (photo KG084464P) and Kenniffs Cave, described by Mulvaney & Joyce (1965), Robins & Walsh (1979) and QPWS (2005) and in section 4.1.1.4.

Significance: The significant karst-like features here are the 3-D networks of *tubelets* (quite convincing for solution) and the horizontal *tubes* and associated *small caves*, though the solutional or other origin of the latter needs discussion.

National Heritage Significance

High: Tubes.

Mod-Good: Tubelets, towers, arches, tafoni, case-hardening, tessellations, pillars, pseudo-karren: Aboriginal significance.

Photo KG084494, The Chimneys at **Mt. Moffatt.** Capped pinnacles.

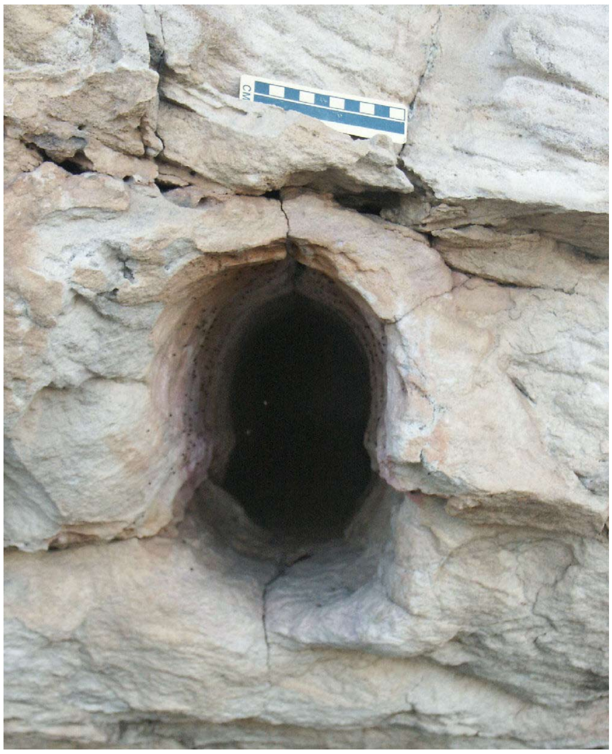


Photo KG084622, **Mt. Moffatt**. Horizontal tube in sandstone.

Capped pinnacles at Limmen West, NT. RW082834

4.3: Specific data

4.3.1: Photographic Record

The accompanying CD-ROM has a selection of photos of features and sites. These are referenced in the text by their file names, and there is an index (on page iv-vi) to those which are printed within the report.

While the Department has a non-exclusive right to use these photos, copyright is retained by the original photographers (and is indicated in the EXIF information embedded within the file). The initial two letters of the filename indicate the owner of copyright, as follows:

AS Andy Spate
IH Ian Houshold
KG Ken Grimes
RW Robert Wray

Other initial letter codes indicate external sources (including air photos and satellite imagery) that are not covered by the contract.

4.3.2: Microscopic Thin-Section and Scanning Electron Microscope analyses

A laboratory microscopic investigation into the relationships between landscape form and the degree and mode of weathering was conducted on small specimens of various sandstones. Analysis was performed at the University of Wollongong using optical thin-section and scanning electron microscopy (SEM).

Detailed discussion of individual samples is provided in Appendix 4. Those results are summarised here.

Bunju, Purnululu, Caranbirini, Limmen South and West, Kakadu, Yuiirienji, Abner Range and Litchfield.

These sandstones are all highly quartzose and no carbonate or other easily weatherable minerals were seen. Some of the sandstones display very intense chemical weathering at the microscopic scale. This was seen to be best developed within the sandstones from **Bunju** in east Arnhem Land, which display some of the best evidence for deep solution of quartz grains and overgrowths. However, similar evidence was seen from the other sites.

There is widespread good evidence for a large amount of fine, crystallographically controlled chemical corrosion or etching (especially at **Bunju** and **Kakadu**). This occurs where corroding solutions are relatively weak and the corrosion process is slow. Because of this deep weathering, the sand grains composing this rock and are now poorly cemented, very friable and very easily detached.

There is quite a high proportion of void within these rocks, and weathering of the rock has formed many fine gaps between grains. However, because the grains are still (at least partially) interlocking the rock maintains a medium to high compressive strength, as shown but the consistent moderate to high Schmidt Hammer readings (Appendix 6 & 4.3.4 Table 2). This allows the rock to stand in steep faces and form cliffs. However, when a tensional or shear force is applied (such as by running water), the lack of cement binding the rock together allows the grains to be easily detached and the rock is quite easily eroded.

However there is ample microscopic evidence that these sandstones were once quite strong. But because most were not deeply buried and strongly cemented, they retained some primary porosity with fine interconnected void between sand grains. This allowed the penetration of weathering solutions over time deep into the rock. Add to this the apparently long time these sandstones have been near the earth's surface, and we now have very deeply weathered sandstones.

These samples present excellent evidence for 'arenisation', and support theories of the poorly understood microscopic solution of quartz. More microscopic study needs to be done on these, and particularly the Bunju sandstones.

Whalemouth Cave

The Proterozoic sandstone at Whalemouth Cave is different. Young (1986, 1987, 1988) found that the older Proterozoic east Kimberley sandstones are much more highly cemented and display far less internal void than the younger Proterozoic and Paleozoic sandstones. This has reduced the amount of water penetrating the rocks and therefore the amount of weathering. The Whalemouth Cave sandstone displays well-developed secondary quartz overgrowths with only a small primary porosity. This has restricted the movement of water through the rock, and this rock is therefore only mildly weathered, and still mechanically very strong (shown by high to very high Schmidt Hammer readings, Table 2). There is some thin void opening between grains and overgrowths that are diagnostic evidence for some chemical dissolution, but to nowhere near the degree of the nearby Purnululu Paleozoic sandstones.

Lawn Hill

The Proterozoic Constance Sandstone from Lawn Hill Gorge is different to the sandstones described so far. It has a large amount of kaolinite clay matrix with relatively few grain-to-grain contacts. Some secondary quartz overgrowths are seen, but the rock is only poorly cemented and retains a very high primary porosity now filled with matrix-clays. Some grains and overgrowths also show surface corrosion features. Some of this clay could be weathering from other minerals in the sandstone such as feldspars.

Because they lack much cement to hold the grains together, the rocks are easily eroded in shear or tension.

None-the-less they form cliffs, caves and ruiniform relief.

Cobbold Creek

Samples from Cobbold Creek (Jurassic) are also strongly matrix clay supported quartz grains with a relatively low number of grain-to-grain contacts. Many grains display well-developed secondary quartz overgrowths, but these overgrowths are not well cemented together. Most grains and overgrowths show relatively little evidence for chemical dissolution.

Because of the clay matrix the rock has a moderate compressive strength as shown by Schmidt Hammer, allowing it to stand in small faces, but lacking cement to hold them together, grains are easily detached in shear or tension. The rock is therefore susceptible to erosion, particularly by flowing water. The strength of this rock also probably diminishes significantly when wet. Organic surface coatings (algae etc) are probably important in increasing surface resistance and protecting the rock from erosion.

The mechanical properties of this sandstone are important factors in the way the landscape has developed. There is some variability within the sandstone (the Schmidt Hammer readings are quite variable, Table 2), but it is mechanical breakdown and erosion that are the dominant processes here. Yet the ruiniform landforms are similar to the other sandstone areas where arenisation did occur.

There is little evidence for ‘solutional’ or ‘karstic’ weathering here.

Carnarvon

All samples studied from the Carnarvon Range area of central Queensland, one each from **Mount Moffatt**, Carnarvon Gorge and **Salvator Rosa**, are very poorly bonded or cemented together, with little quartz overgrowth development. There are few grain-to-grain contacts and quite large amounts of matrix clay and interconnected void throughout the rock (sometimes as much as 30-40% void). Matrix clays are kaolinite (presumably from weathering of some feldspars).

Many grains display some evidence for highly irregular surface features and embayments, but this is not extremely well developed.

Surface layers generally showed a lot of void and so the grains are easily detached. The rock has a low to medium mass-strength when measured by Schmidt Hammer. This means that there is a moderate compression strength allowing the formation of towers and cliffs. But the rock has a low shear and tensional strength with only a low resistance to erosion.

Castle Rock (Renner Springs)

This sample is overwhelmingly a matrix-supported sandstone with few remaining grain-to-grain contacts. The matrix is probably amorphous iron oxy-hydroxides. Quartz grains are relatively rare and those remaining have been highly altered. Grains are now highly irregular with widespread evidence for chemical dissolution.

There is a very large amount of closed (not interconnected) void within the sample, and most void-space appears to have resulted from the partial or complete dissolution of quartz grains. Most remaining grains show embayments and other corrosive features formed by the dissolution of the grains.

This sample is very significant in that it seems to provide very strong evidence for an iron-accelerated (almost total) dissolution of quartz. This is an area of academic interest around the world. We do not know the exact formative conditions at Castle Rock, but this site or specimens could warrant further study for what it might tell us about the effects of iron on quartz dissolution.

4.3.3: Water Chemistry

A simple program of water testing was conducted to ascertain the amount of silica being dissolved and transported from within the sandstones of the areas visited. A total of 34 water samples were tested, with determinations of dissolved silica and iron made in the field. The pH and electrical conductivity of these sampled waters were also recorded.

The measured pH of surface waters was well within the natural and expected pH range on rocks of this type, and concentrations of conducting salts were very low. However, the levels of dissolved silica were generally found to be significantly higher than expected, and about twice the expected range. Amounts of dissolved iron were generally low.

Ignoring values from streams draining mixed lithologies: Si ranged from 1.75 to 30 mg/L with a mean of 14; Fe ranged from <0.1 to 2.8 mg/L with a mean of 0.28; pH ranged form 4.1 to 7.3, mean 5.3; and EC ranged 5.7 to 176 μS/cm^2 with a mean of 48.

Photo KG080089, Measuring electrical conductivity in a seep at Widdallion Cave. The orange flocculated "mud" had an interesting chemistry (see Appendix 7 and section 4.1.5, on speleothems).

Detailed discussion of these results are found in Appendix 5.

The higher than expected levels of dissolved silica may be due to a number of factors: there are not a lot of other minerals in the sandstones that could be contributing dissolved silica, but breakdown of small amounts of kaolinite clays could be a contributing factor. The largest source of dissolved silica is probably the quartz grains and overgrowths of the rock itself. This is supported by the microscopic evidence that shows widespread attack of the quartz.

The exact mechanisms of this corrosion are still unknown. There may be some concentration effects of low dry-season water flows. Analysis of more comprehensive, year-round, data is therefore needed.

Schmidt hammering a case-hardened tube, a co-operative effort

4.3.4: Schmidt Hammer measurements

Table 2 is a summary of the Schmidt Hammer Results – details are in Appendix 6. The Schmidt Hammer measures the relative compressive strength of the sandstone. The higher the value the higher the compressive strength of the rock. Rocks with a low compressive strength have an R value less than about 25, medium strength is from about 25 to 40, and rocks with an R value above about 45 can be regarded as having a high compressive strength.

Location		**Adjusted R Values**							
Caranbirini		58	53	48	58	48	37		
Cape Crawford, Abner Range		46 (surface)			22 (beneath surface)				
		41	38	55	35	26			
Limmen South	Pinnacle area	36	37	38	41				
	Profile 4	27	31	40	29	30	30	28	28
		29	22	33	24	25	30	39	33
		42							
Limmen West	Case-hardened surface	45	50						
	Non case-hardened surface	31	32						
Yulirienjie Cave	Case-hardened surface	38	30	32					
	Non case-hardened surface	20							
Kakadu - Nourlangie	Unweathered sstn	47	34						
	Weathered sstn	20	21						
Litchfield	Natural sstn surface	49	57	50					
Bunju	Sstn from inside "blasted tower"	36	33						
	Weathered surface sstn	15	24	25					
Lawn Hill	Widdallion Cave	39							
Cobbold Creek	Various sites	40	50	16	27	22	37	29	
Whalemouth Cave	Lower entrance	52	39	60	31	33	47		
Carnarvon – Salvator Rosa	Precipice Sstn	31	25	25	19	17	16	17	15
Carnarvon – Mt Moffat, Cathedral Rock	Precipice Sstn	15	15	17	13	27	23		

Table 2: Schmidt Hammer measurements

4.3.5: Profiles through the stone cities.

Four profiles were measured by Houshold across the eastern *Pre* ridge at Limmen South and one was measured by Grimes (Figure 5). Schmidt Hammer values were also measured at the southernmost profile. The results for that profile are shown in Figure 28. Details are in Appendix 9.

The profiles all suggest concave profiles in the basins and (an admittedly variable) over-steepening of the profile as the sand plain is approached.

Profile 4 shows the relationship between rock hardness, the average 'summit' profile and the stream profile in relation to both. What can be seen is that the convex stream profile in the 'funnel' has migrated back into softer rocks, from a reasonably hard band not far from the sand plain. This hard band remains high on the 'surface' (as it is only exposed to local weathering) but the stream is now graded through it, its elevation not far above the plain. There is no evidence that the waterfall is currently perched on harder rock, or that the gorge walls in the funnel are related to harder lithology (apart from the very downstream gorge section, referred to above). This supports a 'geomorphic' rather than structural explanation for the form of these basins, more related to headward extension of drainage and recessional knickpoint retreat, rather than simple lithological/ structural control.

Obviously the Schmidt results reflect only surface hardness rather than average hardness of the unit. There may be case hardening or local weathering effects involved. However, the good relationship between changes in elevation of the 'surface' and hardness suggests the values are reasonable.

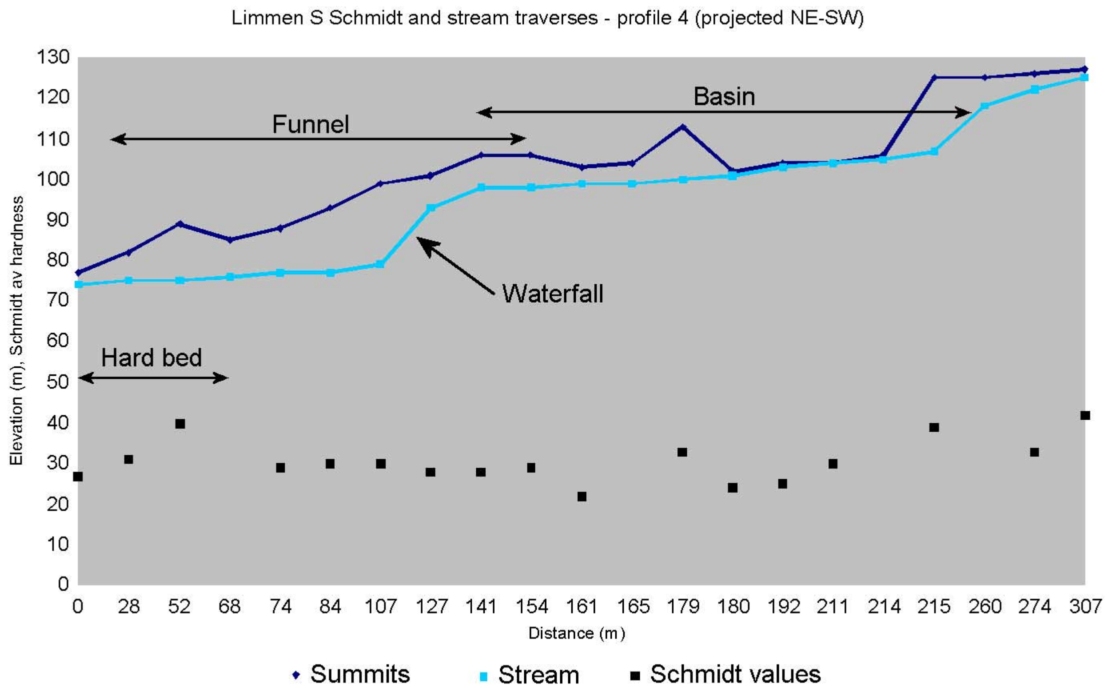


Figure 28: Profile 4 at Limmen South

4.3.6: Tube morphometrics

The tubes at Salvator Rosa and Mt. Moffatt show a broad range of sizes and elongations. Figure 29 plots the width and height of tubes observed at the two sites.

These were all approximately horizontal, but Wray (2009) reports inclined tubes in the area. Some are obviously located along (or just above) a bedding plane (e.g. photos KG084292-3, 4332-3 and the group in KG084209-10) but others are in the middle of a massive or cross-bedded bed (photo KG084200-1, 4235-6). Some have a plan direction aligned with an obvious joint, others have no obvious joint but most tend to be fairly straight (see Figure 15), although photo KG084297-8 shows a sinuous tube.

Photo KG084403-4 shows a group of "half-tubes" running below a bedding plane that has been partly cemented (case-hardened); photo KG084405-6 is another set beneath a more strongly cemented bed.

Tube size varied from <10 cm up to >1 m across, and up to at least 3 m long (the inner ends were not always visible), but Wray (2009) reports tubes up to 10 m long. The larger ones tend to be less regular in outline (eg KG084332-3). Where we see the ends they tend to be abrupt and rounded – suggesting a headward erosion of lose sand-grains by a "spring-sapping" process.

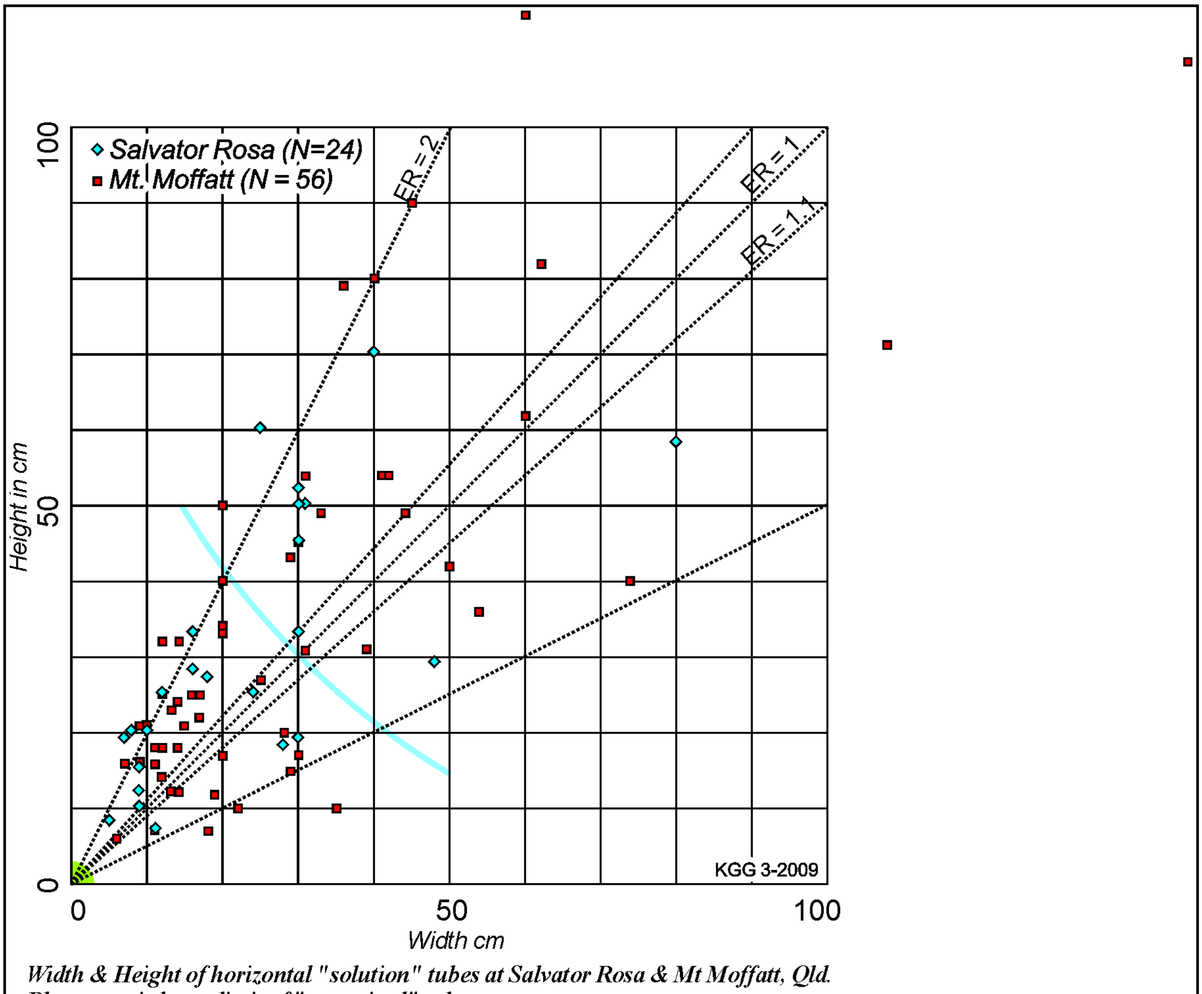
There was a tendency for the tubes to be more vertically elongate than horizontal (Table 3 lists elongation ratios), especially the ones with an obvious guiding joint, but about 15% were nearly circular (elongation ratio <1.1) and 20-30% were elongated horizontally (see Figure 29). Maximum vertical elongation ratio was 2.7, maximum horizontal was 3.5.

Some (about 20-30%) had cemented rims from 2 to 8 cm wide, but the width was variable even around a single tube.

The smaller 1-2 cm *tubelets* form three-dimensional branching patterns and represent a different phenomena.

Site	N	Vertical elongation	Circular (ER < 1.1)	Horizontal elongation
Salvator Rosa	24	67%	13%	20%
Mt. Moffatt	56	57%	14%	29%

Table 3: Elongation Ratios (ER) of tubes



Width & Height of horizontal "solution" tubes at Salvator Rosa & Mt Moffatt, Qld.
Blue curve is lower limit of "cave-sized" tubes,
Green area is size range of Tubelets (1-2 cm)

Figure 29: Tube dimensions at Salvator Rosa & Mt. Moffatt.

Pinnacles viewed from narrow canyon, Limmen West, NT. KG080918

Looking out from the Nourlangie maze cave to a giant grike, Kakadu, NT. IH08072008_71

5: Significance

The reconnaissance survey across northern Australia reported herein has revealed a wealth of sites of great geomorphic and geologic importance on sandstones, laterites and granites. The natural heritage significance of the sites ranges from World Heritage standard having 'outstanding universal values' to local significance. It is also likely that many sites will have important biological values, incorporating both surface and underground ecology.

All of the sites probably have cultural significance to their Traditional Owners. Any formal assessment of significance will need careful interaction with the Indigenous peoples. Many of the sites, particularly on sandstones, are already important for the 'grey nomad' tourism industry. Others, on Aboriginal lands in particular, have restricted access or can only be overflown.

The potential for an increased focus on quality geotourism is evident and operations such as **Cobbold Creek** are very important in offering good interpretation of the natural features. Such interpretation as currently exists elsewhere is variable in content in regard to its geological content.

For the sandstone landscapes, the following points can be made:

- Absolute age of the rock is not significant (ranging across the Proterozoic to Mesozoic Eras);
- All sites have been sitting close to the surface for extended periods. Ruiniform and karst-like landforms are therefore likely to exhibit a wide range of ages, from early Tertiary to late Quaternary, depending on landscape context and geomorphic history. Excellent preservation of many of the older landscape features contributes to the significance of many sites;
- Beds are always flat to gently dipping – ruiniform and karst-like landforms are not found on the steeply folded sections of **Limmen South**, nor the steep dipping ridges we flew over east of **Bunju**; and
- They are all currently in a tropical monsoon climate (semi-arid to humid) - but past climates would have differed and could have been more important given the long time scale involved. The mid-Queensland **Carnarvon** sites are only just tropical but show less of the ruiniform styles anyway.

The laterite features examined are not as spectacular as the sandstone landforms but are still scientifically significant. They are unlikely to become important tourism destinations although two sites are of probable national significance. The two boulder mountains of Queensland are already important sites for tourism.

Many of the sites visited during the course of this fieldwork are within national parks or similar reserves and thus their significance has some formal recognition although the reasons for reservation may well not have included recognition of their geomorphic values. Other sites are on Aboriginal lands with restricted access, or on privately managed lands (Table 4).

Two northern Australian sandstone sites, **Kakadu** and **Purnululu**, are already inscribed as World Heritage properties, with the sandstone karst values of the latter recognized as a major part of the justification for inscription. The sandstone karst landforms of Purnululu were, at the time (2002), regarded as unusual in northern Australia and worthy of World Heritage inscription.

Without degrading the World Heritage status of Purnululu, much more is now known about sandstone landscapes across northern Australia although knowledge of the processes producing the landforms requires much further study. We now know that the influence of karstic weathering on sandstones is not just localised to Purnululu, but is much more widespread in place and type than was previously known. For example, we can now recognise that much of the **Kakadu** World Heritage property should not just be recognised for its cultural and biological significance (the reasons for its World Heritage inscription), but should now *also* be recognised for the karst-like and ruiniform weathering of its sandstone.

Because of this, as discussed below, the diversity and scale of karst-like landforms in a number of the sandstone sites across northern Australia is such that a serial nomination for World Heritage status as an addition to Purnululu should seriously be considered.

Other sites are clearly of national (and potentially international) significance but not of 'outstanding universal value' and thus probably not suitable for World Heritage nomination individually (with the possible exception of **Bunju**). In these cases, expansion of recognition and protection of those areas already in national parks or other specifically managed areas should be considered. Many sites that are not presently protected in some form should be incorporated into suitable protected areas.

The values and significance of each of the sites visited have been discussed above in Sections 4.1 and 4.2. These are summarized in Table 4. Specific sites deemed by us as of International Significance include:

- Bunju in the restricted access lands of East Arnhem Land;
- The caves and surface features at **Nourlangie** in Kakadu National Park;
- **Whalemouth Cave** in the Osmond Range of Western Australia;
- **Widallion Cave** at **Lawn Hill**; Queensland,
- The **Abner Range** of the Northern Territory; and perhaps
- The various 'stone cities' within (and adjoining?) the 'proposed' **Limmen** National Park in the Northern Territory.

Table 4: Significance of Sites studied in this project.

Site		Status	Character	Significance
WA	Whalemouth Cave	P/A? *	Sstn: Large stream cave at edge of plateau	Add to Purnululu WH
	Osmond Range	NP/ WH?	Sstn: Plateau with karstic drainage features, ruiniform terrain, and possible caves	Add to Purnululu WH – contrasting sandstone landscape with karstic development.
	Purnululu	WH	Sstn: Ruiniform terrain, Pinnacles etc	Existing WH
Northern Territory	Keep River	NP	Sstn: Ruiniform terrain, large towers	State significance
	Gregory Karst	NP	Limestone karst: grikefields etc	National significance
	Litchfield	NP	Sstn: Small ruiniform area, also laterite karst	State significance
	Darwin area	mixed	Laterite karst features	Local significance
	Kakadu, Ubirr	WH	Sstn: Varied ruiniform features, karren, caves	Existing WH
	Kakadu, Nourlangie	WH	Sstn: Caves, ruiniform features.	Existing WH
	Kakadu misc	WH	Sstn: Sinkholes, arches and ruiniform features on the main plateau	Existing WH
	Mt Price	P?	Sstn: Small cave	Local significance
	Yulirienji Cave, Old St. Vidgeon	NP	Sstn: Cave & ruiniform features	National significance – needs active management now for its important cultural values
	Bunju (Boorlungu)	A	Sstn: Ruiniform features, caves, ... etc. (more study needed).	Potential serial WH with Purnululu
	Bath Range	A	Sstn: Large sinkholes scattered over a broad area	State significance – but unvisited and thus may have a higher level of significance
	Limmen S	NP	Sstn: Ruiniform terrain	Potential serial WH with Purnululu
	Limmen W	NP	Sstn: Ruiniform terrain	Potential serial WH with Purnululu
	Nhumby Nhumby	A	Sstn: Two large sinkholes in plain	State significance?
	Caranbirini	CP	Sstn: Ruiniform features	State significance
	Abner Range (Cape Crawford)	P, T	Sstn: Ruiniform features	Potential serial WH with Purnululu
	Sturt Plateau	P	Laterite sinkholes	State (?national) significance
	Castle Rock	P	Laterite mesa, pipes.	State (?national) significance
	Barry Caves	P	Laterite + sstn: caves	State significance

The **Nourlangie** landforms are already within the Kakadu World Heritage property and the interesting, but essentially unstudied, **Osmond Range** adjoining the Purnululu World Heritage property should be considered as an addition to Purnululu. The Osmond Range area is very difficult to access but the suite of sandstone ruiniform features and karst-like drainage, including the world-class **Whalemouth Cave**, provide important contrasting karst geomorphic systems to those at Purnululu. Knowledge of the karst systems of the Osmond Range is confined to Jennings (1983) and to the 'sinkholes' marked on the Bungle Bungle 1:50,000 topographic mapsheet (4563-2). That these latter features are actually closed, karst-like, depressions at the end of drainage lines was confirmed by our brief helicopter reconnaissance.

A possible serial nomination of an "Australian Tropical Sandstone Landscapes" World Heritage property taking in and extending the existing **Purnululu** World Heritage area, with the inclusion of **Bunju**, **Abner Range** and possibly parts of the **Limmen** National Park

Site		Status	Character	Significance
Queensland	Lawn Hill (Boodjamula)	NP	Sstn: Significant caves, underground drainage.	State (?national) significance. Widdallion Cave is of national significance.
	Tobeys Waterhole	P	Laterite karst	Local significance
	Cobbold Creek	P,T	Sstn: Ruiniform features, gorge, caves.	State (?national) significance
	Chillagoe Metal Hills	P?	Granite boulder caves	State significance
	Mt Mulligan	A	Sstn: Table mountain with ruiniform features	National significance
	Black Mountain and Cape Melville	A	Granite boulder caves, unusual closed depressions (?dolines) in boulder piles	National significance
	Pelican Lakes	P	Laterite: Closed depressions of uncertain origin	State significance
	White Mountains, Denna Plain.	NP+P	Laterite karst pinnacles & pans	State (?national) significance
	Salvator Rosa	NP	Sstn: Large towers, pinnacles, caves, springs	National significance
	Mt Moffatt	NP	Sstn: Large towers, caves.	National significance

Status: WH, World Heritage; NP, National Park; P, Private land; A, Aboriginal land; T, Tourist operation on private land.
* Note: Location of Whalemouth Cave is about 1 km outside the boundary of the Purnululu Conservation Reserve.

seems to us to be a supportable proposition as having outstanding universal value under World Heritage Criteria *vii* and *viii*. Consideration under Criteria *ix* and *x* is outside our area of expertise, but these areas may also satisfy these criteria. **Bunju** may well also have values that might meet one or more of the cultural Criteria *i* to *vi*.

There are also the not-to-be-underestimated political realities in dealing with overlapping National, State and Territory jurisdictions, with land owners/leaseholders at Cape Crawford (Abner Range), and with the restricted access at Bunju in Arnhem Land.

Specific Sites of National Significance include:

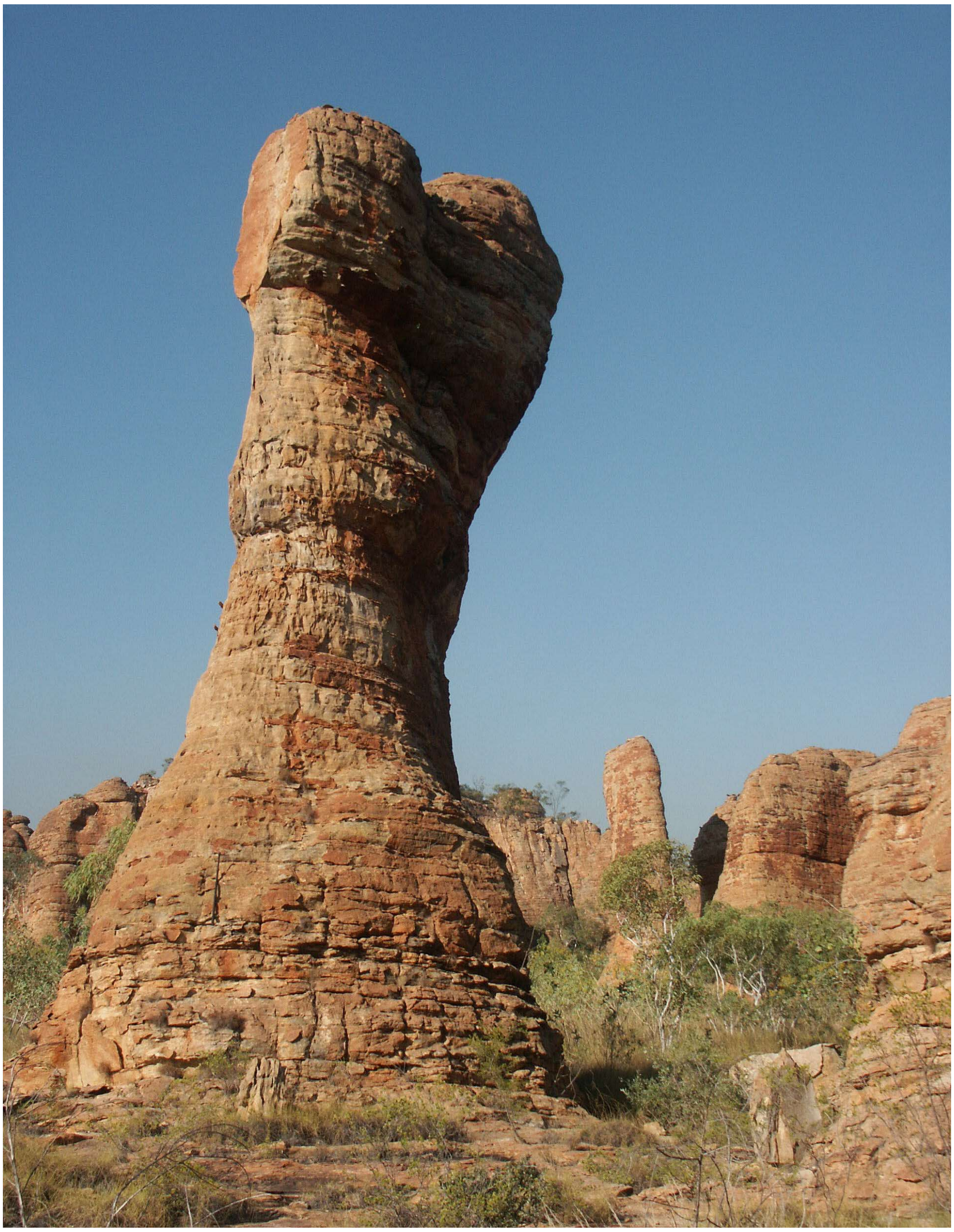
- The **Salvator Rosa** and **Mount Moffatt** sections of Carnarvon National Park in Queensland as well as other occurrences of the Precipice Sandstone
- **Yulirienji Cave**, south of Roper Bar, in the 'proposed' Limmen National Park. Management of the cultural artefacts in this cave is urgently needed.;
- **Ngarrabullgan (Mount Mulligan)** north of Dimbulah in Queensland;
- The boulder mountains in **Kalkajaka (Black Mountain)** and **Cape Melville** National Parks near Cooktown, Queensland; and possibly
- The **Sturt Plateau** dolines and **White Mountains** laterite parakarsts.

All other sites described in this report, with the exception of Mount Price, are of at least State Significance and should be offered suitable management or protection. **Cobbold Creek** in Queensland is currently being considered as a significant site of some type under Queensland legislation.

We have visited, studied and described various sites that include most of the known spectrum of ruiniform and karst-like landforms to be found in tropical, northern Australia. There are likely to be other areas with high significance not seen in this reconnaissance level survey. Based on this field research, this report makes the recommendations outlined above. However, the minimal scientific literature and the limited fieldwork opportunities do not necessarily provide enough detail for proceeding at this time with nominations to State heritage listings, the new National Heritage List – nor, obviously, to proceed at this time with a new World Heritage nomination. This is especially the case if **Bunju** in East Arnhem Land was to be included in any serial nomination.

However, this report does at least provide some uniformity of perspective across Queensland, the Northern Territory and Western Australia and across a variety of land tenures ranging from Commonwealth and State owned and reserved, through lands held by Indigenous people to freehold and leasehold lands held by miners and graziers.

But more detailed scientific data-collection and research is sorely required, both for improved heritage assessment, management and scientific knowledge. In reality, very difficult wet weason access to many of these sites would be highly desirable, if not essential, as would be expert consideration of biotic and cultural values as well as abiotic considerations. Some peer-review of this report would seem desirable to further set the scene for a way forward.



Pinnnacle at Abner Range. KG080530

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Appendixes

These appendixes are supplied in electronic form on a separate CD-ROM.

Authorship of the appendixes is: **AS**, Andy Spate; **KG**, Ken Grimes; **IH**, Ian Houshold; and **RW**, Robert Wray.

1: **Samples collected** (RW) - XLS file.
2: **Glossary of terms** used (KG, RW, AS, IH) - DOC file
3: **Photographs** (KG, RW, IH, AS) - multiple folders on CD-ROM
4: **Microscopic studies** (RW) - multiple DOC & JPG files
5: **Water analysies** (RW, IH, KG) - DOC & XLS files
6: **Schmidt hammer results** (RW, IH, KG,AS) DOC & XLS files
7: **Speleothems** (RW) DOC file
8: **Limmen Pinnacle morphometrics** (RW&AS) DOC file
9: **Profiles at Limmen** (IH, KG) - DOC & XLS files
10: **Tube metrics at Salvator Rosa & Mt. Moffatt** (KG) - DOC file
11: **Site list** (KG, AS, RW, IH) - DOC file
12: **Bath Range sinkholes data** (KG) - DOC file
13: **Relevant Publications** (various authors) PDF & DOC files on CD-ROM.

Cabbage-tree palms in a rock shelter at Keep River, NT. KG082373xj