Potential Geoheritage Values of Landscapes in the Australian Drylands

A report to the Commonwealth Department of Sustainability, Environment, Water, Population and Communities

2nd Edition, March 2016
(replaces 1st Edition, June 2011)

Gresley A. Wakelin-King, Susan Q. White

Wakelin Associates Pty. Ltd

Wakelin Associates Pty Ltd. ABN 11 002 971 262
PO Box 271, Clifton Hill Victoria, Australia 3068. Ph 03 9482 4584
www.wakelinassociates.com.au

DISCLAIMER

Information contained in this report is correct as far as possible within the scope of the project and at the time of writing. It can be used to inform management practice or project design criteria, but is not intended for specific engineering design.

This report may be cited as:

Wakelin-King, G.A. and White, S. 2016. Potential geoheritage values of landscapes in the Australian drylands (2nd Edn). A report by Wakelin Associates to the Australian Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Cover picture: A waterhole in the Neales River, Lake Eyre Basin.

Photo: Gresley Wakelin-King, 2010.

Figure Credits: unless otherwise noted, photos are by Gresley Wakelin-King and images are by Wakelin Associates.

Table of Contents

Acknowledgements

We would like to thank Pauline English, Cameron Grant, Paul Hesse, Ron Hacker, John Magee, Gerald Nanson, and Lisa Worrall for generously making available their time, experience, and photographs. We would also like to acknowledge the work of the Cooperative Research Centre for Landscape Environments and Mineral Exploration, whose long-term research focus on regolith geology has provided much new information, particularly for remote and difficult areas.

This second edition (2016) of our report has benefited greatly from the reviews of the papers (White and Wakelin-King 2014, Wakelin-King and White 2015) we published subsequent to the release of this report's 1st edition (2011); we thank the reviewers for their care and suggestions.

Figures

Tables

Abbreviations, Acronyms, and Glossary

Dept. SEWPaC - Australian Department of Sustainability, Environment, Water, Population and Communities;

DES – discontinuous ephemeral streams;

ESCoM -Earth Sciences Comparative Matrix (White & Wakelin-King 2014), the methodology used in this report for geoheritage assessment;

feature - in the context of this report, a landform or landscape element from one geomorphic theme which may contribute geoheritage value to sites or indicative areas from other geomorphic themes;

GAB - Great Artesian Basin;

GSA - Geological Society of Australia;

IBRA - Interim Biogeographic Regionalisation for Australia;

indicative area - in the context of this report, a very wide area for which the heritage values are being described and within which specific geoheritage sites may later be identified;

LEB - Lake Eyre Basin;

MI - moisture index;

Neogene - the geological time period including the Miocene and Pliocene epochs; approximately corresponding to late Tertiary in the previous timescale nomenclature;

NHL - National Heritage List;

outstanding - in the context of this report, 'to a very high degree', as in 'outstandingly significant, outstandingly important' (as opposed to outstanding in the sense of unusual, unique);

Palaeogene - the geological time period including the Palaeocene, Eocene and Oligocene epochs; approximately corresponding to early to mid-Tertiary in the previous timescale nomenclature;

site - in the context of this report, a reasonably specific geographic location for which the heritage values are being described.

Executive Summary

In this study, the landforms of Australia's desert country are assessed against National Heritage criteria. The landforms are grouped and discussed according to their dominant geomorphic theme:

- astroblemes (impact structures);
- sand deserts (derived from aeolian sediment transport) (sub-themes: basins; ridge-valley);
- karst (created by the dissolution of soluble rocks);
- arid coasts;
- tectonic landforms (sub-themes: flexure; faulting; diapirism);
- uplands;
- regolith (sub-themes: vertisol plains and slopes; saprolite; silcrete and gibber plains; other duricrusts);
- watercourses (sub-themes: sand-bed rivers; discontinuous ephemeral streams; anabranching rivers; mud-aggregate floodplains; freshwater basins; mound springs; banded vegetation sheetflow plains; floodouts; palaeodrainages; megaflood landforms; playa lakes and megalakes; post-European drainage incision).

Twenty eight sites or indicative areas were identified which have either met the NHL criteria thresholds, or have been judged in this study to have potential to do so (Table 1, Fig. 1). Site clusters occur in the Amadeus Basin and the Lake Eyre Basin. Site or area NHL value is variously assessed as clear, likely, or probable (pending further investigation). The identification of these places does not, in itself, constitute a nomination, it is a recommendation that they be considered. The study area is generally under-researched, and particular knowledge gaps are identified in the Davenport-Murchison Ranges and the Great Sandy and Great Victoria Desert dunefields.

Aridity, which is widely regarded as a defining characteristic of the Australian inland, is only the latest imprint of a long series of processes. It is now the most important condition modifying the landscape, but is not the reason that this landscape exists. The key drivers which have created the unique Australian desert landscapes are the length of time that the stable landscape has existed, the previous climates which have operated on that landscape, the development of aridity in geologically modern times, and the high degree to which these landscapes display features inherited from the past. These drivers are the context within which operate the agents that work upon the landscape: water, wind, gravity, plate tectonics, chemical reactions, and living things.

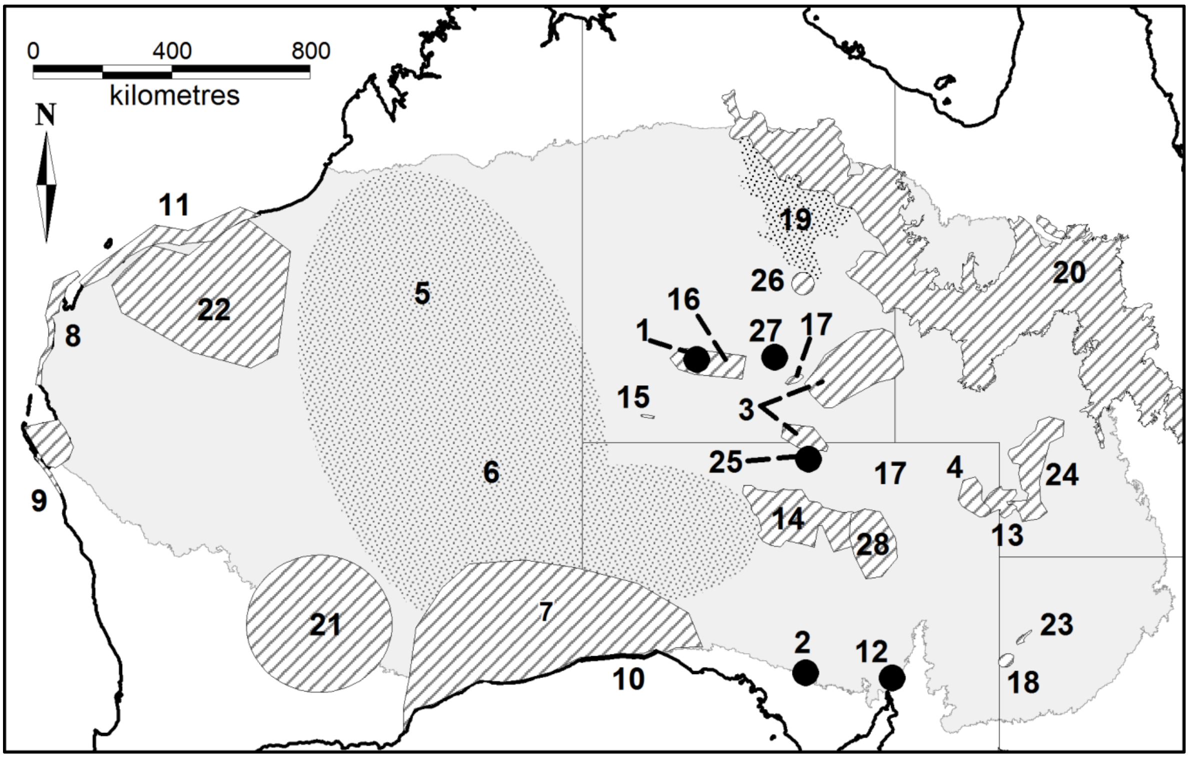
Table 1 Sites or areas of potential geomorphic heritage in drylands Australia

Sites/areas are grouped by dominant geomorphic theme. Status: D, defined in this study; E, existing NHL or WHL listing; I, indicative area; KG, knowledge gap. Value with respect to NHL criteria: C, clear; L, likely; P, probable (pending further information). See Fig. 1 for location map, and p. 28 (Table 6) for theme abbreviations.

Theme	Sub-theme	Site or Area no.	Site/Area	Status	NHL Value	Concurrent Themes	Links to other Sites
As		1	Gosse's Bluff	D	C		16
		2	Acraman Impact Structure	D	C	W (PL)	
Sa	B	3	Simpson Desert Floodouts	I	C	Te (Fl), Up, Rg (Si), W (SR, Fd, Pd)	17
	B	4	Cooper Distributaries (Strzelecki Desert)	D	C	Rg (Si), W (AR, FW, Pd, PL)	13, 28
	RV	5	Great Sandy dunefield	KG, I	?	Rg, W	
	RV	6	Great Victoria dunefield	KG, I	?	Rg, W	
Ka		7	Nullarbor Plain	I	C		10
		8	Exmouth Peninsula and Ningaloo Coast	E	C	AC	
AC		9	Shark Bay and the Zuytdorp Cliffs	E, D	C	Ka	
		10	Bunda Cliffs	D	C	Ka	7
		11	Pilbara coastline	I	L		22
Te	Fa	12	central Flinders Ranges and Wilkatana fan complex	D	P	Up	
	Fl	13	Innamincka Dome, Cooper Creek valley	D	C	Rg (Si), W (AR, FW)	24
	Fl	14	Neales River Catchment	D	C	Rg (Sp , Si, Gy), W (AR, FW, MS, Pd, Mf)	28
Up		15	Uluru – Kata Tjuta	E	C	Sa, Te (Fa), W (BV)	
		16	Amadeus Basin / MacDonnell Ranges	I, P	L	Te (Dp?), W (SR, BV, Fd)	1, 27
		17	Amadeus Basin / Rodinga Range	I	L	Te (Dp?), W (SR, Fd, Mf)	3
		18	Barrier Range / Mundi Mundi rangefront	D	P	Te (Fa), W (DES, BV, PEI)	23
		19	Davenport-Murchison Ranges	KG, I	?		
Rg	Vt	20	Black Soil Plains	I	L	Ka	24
	Sp	21	Eastern Goldfields Palaeodrainages	I	C	Rg (Sp, Si, Ca, Fc), W (Pd, PL)	
	Sp	22	Pilbara Channel Iron	I	C	Rg (Fc), W (Pd)	11
W	DES	23	Fowlers Creek	D	L	Te (Fa), Up, Rg (Vt), W (AR, MA, BV, Fd, PEI)	18
	AR	24	Cooper Creek (Windorah to Nappa Merrie)	I	C	W (MA, FW)	4, 13, 20, 28
	MS	25	Dalhousie Springs	E	C	Te (Fl)	
	Fd	26	Sandover-Bundey confluence floodout	D	P	W (SR)	
	Mf	27	Ross-Todd confluence	D	L	Up, W (SR, Fd)	16
	PL	28	Kati Thanda - Lake Eyre	D	C	Te (Fl), Rg (Si, Gy, Ca, Fc)	3, 4, 13, 14, 24

Fig. 1 Sites, areas, or indicative areas with potential to pass NHL criteria

Larger areas are striped; smaller sites are black dots; stippled areas are knowledge gaps. The study area is light grey. See Table 1 for site numbers.



1 Introduction

In early 2011, the Australian Department of Sustainability, Environment, Water, Population and Communities (Canberra) (Dept. SEWPaC) commissioned Wakelin Associates to investigate the potential geoheritage of Australian landscapes within a geographically-defined area (referred to as 'desert' in the commissioning document) where remoteness and scant population had discouraged previous assessment. The aim was to identify places that chronicle the development of Australia's landforms and which have potential to be of National Heritage List (NHL) value. The steps in this process were:

- to undertake a literature survey focusing on geomorphology of Australian drylands;
- to identify registered geoheritage sites;
- to analyse the results of the literature survey, with reference to the National Heritage criteria, to identify places that best tell the stories of the development of Australian deserts;
- to liaise with the research community for additional information or expert opinions as required;
- for places identified as potentially valuable geoheritage, to provide arguments as to the place's significance, physical description and relevant geological history;
- to identify any significant data gaps.

This report is the result of the investigation. The 1st Edition of this report was completed in June 2011, and was later released on the Dept. SEWPaC website. Subsequently, two peer-reviewed papers were written from this work (White and Wakelin-King, 2014; Wakelin-King and White, 2015). The publication process resulted in a greater clarity of methodology and site classification, and it was decided to revise the report, producing this 2nd Edition.

The project's scope was within a defined area and specific to landscapes and landforms. Other aspects of geoheritage, e.g. important rock outcrops, type sections, etc., are not considered here (unless the geological value is also related to the geomorphology, for example where a type section is exposed in a cliff face). Geological heritage is addressed through the Geological Society of Australia's (GSA) Geoheritage Standing Committee (www.gsa.org.au, follow links to *Heritage*), and committees at State divisions.

How to Use This Report

This report consists of three parts: introductory material, geoheritage places or features, and the bibliography. The introductory material includes NHL criteria, project methodology and the study area's geological context. The main section contains descriptions and provisional heritage assessments for places that are potentially the best examples of geomorphic heritage. However, they are not the only possible heritage sites in the study area; they are those which are currently sufficiently well-known to assess their significance. Later investigations may find other sites worthy of inclusion. The bibliography contains citations of material referred to in this report, and also citations for other material relevant to the locations discussed. The bibliography aims to include as many references relevant to the landform themes in the study area as possible, however it is not exhaustive. It is weighted towards recent references, those with process as well as morphological information, and/or peer-reviewed works.

The inclusion of locations in this report does not constitute formal nomination for heritage status. Nomination relies on interested individuals or groups to engage in the administrative process of putting a site forward. Information on the nomination procedures are available on the Australian Department of the Environment website http://www.environment.gov.au/heritage/places/nominating-heritage-place (accessed December 2014).

1.1 Boundary of the Study Area

The study area is very large (4.14 million km^2) and extends across five Australian states (Fig. 2). Its boundary was defined by the Dept. SEWPaC, and is based on the moisture index (MI: a ratio of moisture lost through evaporation, compared to moisture gained from rainfall; a value less than 1.0 indicates that evaporation exceeds rainfall). The defined boundary was a means of setting the study's scope: it was not the aim of this investigation to encompass all of Australia's 'desert'. Consequently some places that can be considered arid or semi-arid were not included: the Mallee, Hattah-Kulkyne, Willandra Lakes, the Bungle Bungles, the Kimberley. The latter three places were included in a recent report on world heritage desert landscapes (Goudie and Seely, 2011).

There have been various quantified definitions for Australia's 'desert', e.g. areas where MI<0.2 are arid, and the semi-arid zone is MI 0.2 - 0.4 (DKCRC 2006). However, the practical, common language recognition of 'desert' is essentially biological: a place where moisture deficit restricts the growth, distribution, and life strategies of plants and animals. The study area encompasses a wide range of bioregions (Fig. 3).

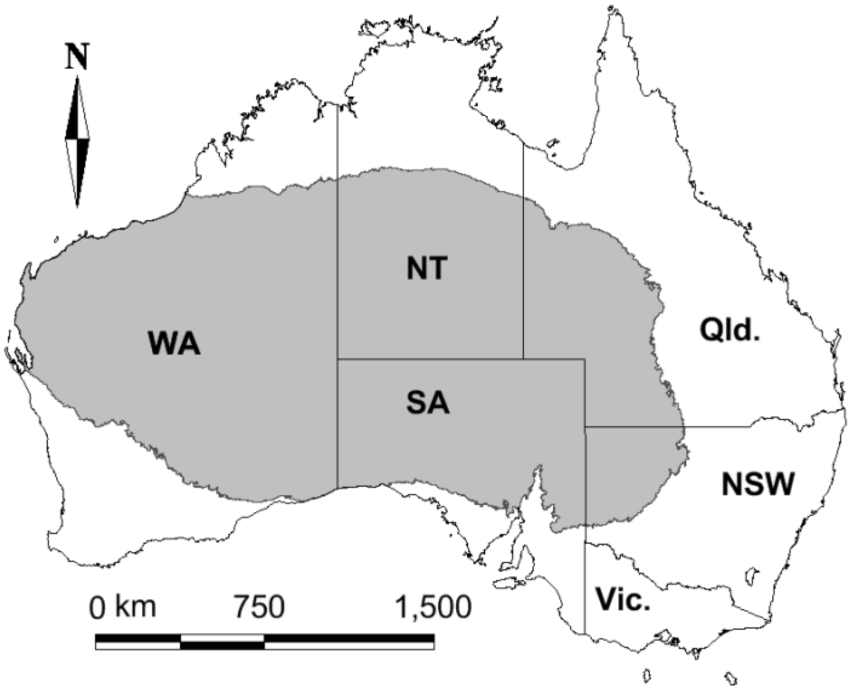


Fig. 2 The study area (grey)

Of these, some seem more biologically rich than might be expected for a desert, for example the Mitchell Grass Plains have deep black soils, occasional wetlands, and sometimes substantial vegetation. In others, ecology and landscapes suggest they are 'desert' but they do not fall within the study area. In particular, the Willandra Lakes, the Hattah-Kulkyne area and the northern Mallee have many desert-like features: red sand dunes, dry lake beds, thin soils, spinifex and sparse vegetation cover; but they are not covered in this report. Defining Australia's 'desert' is not straightforward (e.g. Trewin, 2006; CSIRO, 2008), and in this report the general term 'drylands' is used.

The moisture index is a purely climatological measure. Since the balance between rain and evaporation is a major ecological factor, it is a reasonable approximation of Australia's 'drylands'. However, vegetation does not suck water directly out of the air; it absorbs it through the interface of the soil. The soil's ability to retain rainfall and make it available to vegetation must be another important factor in whether an ecology is moisture-limited or not. If the soil surface is impermeable or sheds water rapidly, rain will be unavailable to the vegetation. Soils of limited field capacity – shallow, or too coarse to store water, or with underlying structure that transports water away – will only bring some of the available rainfall to vegetation. It is likely therefore that a more comprehensive assessment of the physical environment of moisture-limited ecosystems will include some considerations of soil's ability to retain rainfall. In that circumstance, areas like the Mallee, Willandra Lakes, and Hattah-Kulkyne would fall within the definition of an Australian 'drylands'.

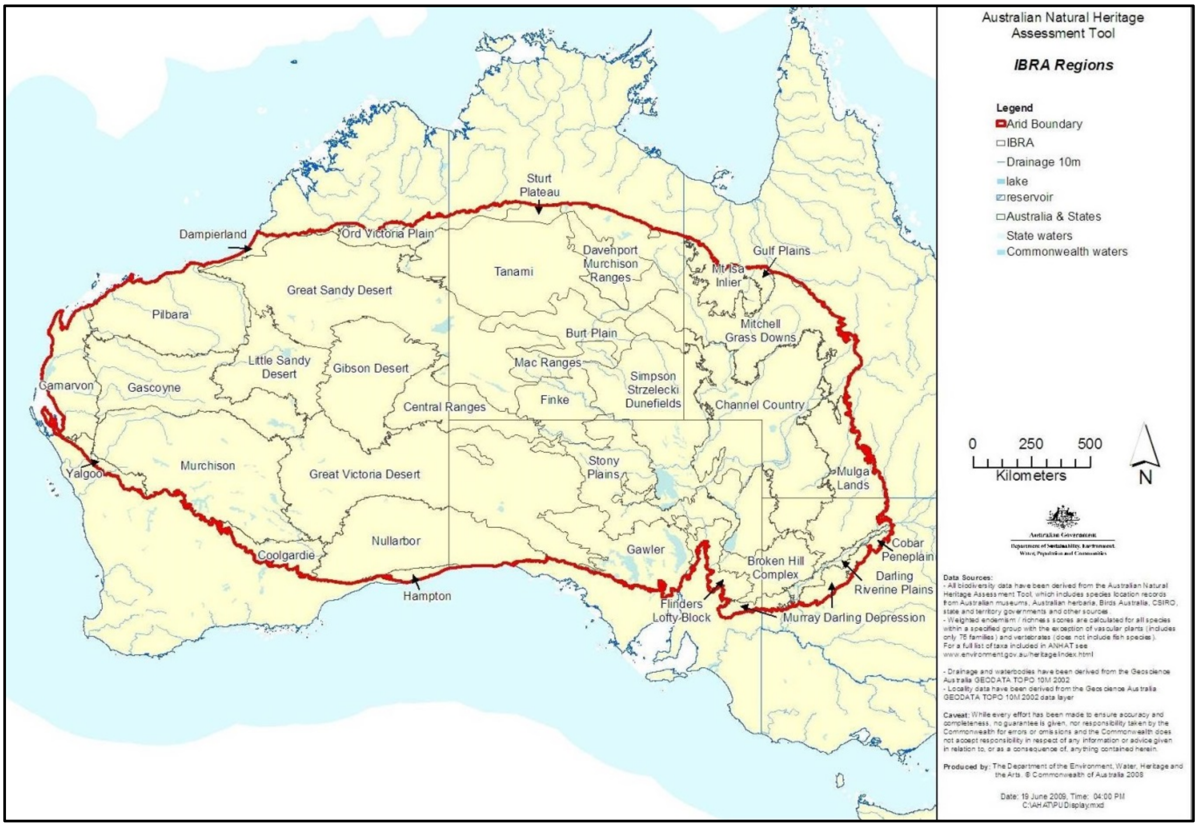


Fig. 3 The study area and its IBRA bioregions

1.2 National Heritage List: Criteria and Thresholds

The Australian Government administers the three highest levels of Australian heritage: World Heritage, the National Heritage List (NHL), the Commonwealth Heritage List. Heritage places are listed in the Australian Heritage Database, which is accessible via the Internet. This report is concerned with the NHL.

The NHL was established to list natural, historic and indigenous places that are of outstanding national heritage value to Australia. Such places must be of the highest level of importance to the Australian community; places which as a nation we want to keep or preserve with respect to those qualities for which significance is claimed. To be successfully listed, a place must have qualities or values which meet one or more of the defined heritage criteria (Table 2), and it must meet the criteria at a certain threshold of importance. The information presented in this section is drawn from information presented by the Australian Heritage Council (Australian Heritage Council 2009; Australian Government Department of the Environment - no date).

The defined NHL criteria are applied in this report with respect to how those criteria are relevant to geomorphology and landforms (Table 2). For example, criterion:

> **g** – "value to the nation because of the place's strong or special association with a particular community or cultural group for social, cultural or spiritual reasons (social)",

as it applies to geomorphology, is usually relevant to a site's importance to the scientific community because of its qualities as a geomorphological research or teaching site.

Two aspects of the NHL criteria should be noted with respect to their use in this report. Firstly, a site may be of great spiritual importance to a group, but unless that importance is specifically with reference to the site's geomorphology, it is not the subject of this report. Similarly, the criterion:

> **i** – "importance as part of Indigenous tradition (indigenous)"

is not considered in this report because it is outside the authors' expertise, and the authors cannot speak for Australian indigenous tradition. No disrespect is intended in the non-inclusion of such matters in this report. Secondly, the criterion:

> **e** – "importance in exhibiting particular aesthetic characteristics valued by a community or cultural group (aesthetic)",

requires clear handling. Beauty is not a direct function of a place's geomorphic or geological values; appreciation of beauty is related to culturally-created aesthetic concepts. This is particularly relevant to the Australian drylands: where the European explorers saw barren wasteland, Australians may see stark and uncompromising beauty; someone from the temperate zone might like forests, but someone used to 'big sky' might feel irksomely hemmed in by too many trees. Although aesthetics is one of the NHL criteria, it is only one of nine. A place may be beautiful without having geomorphically significant landscapes, and it may be significant without being at all visually attractive.

	The place has heritage value to the nation because of its:	
	NHL criteria	criteria as applied to Australian drylands geomorphology
a	importance in the course, or pattern, of Australia's natural or cultural history (*events and processes*);	importance in the processes of landscape formation or maintenance, or possession of geomorphic relics of significant earth events;
b	possession of uncommon, rare or endangered aspects of Australia's natural or cultural history (*rarity*);	possession of rare, unusual or endangered landforms or landscape processes;
c	potential to yield information that will contribute to an understanding of Australia's natural or cultural history (*research*);	potential to further understanding of Australia's development through geological time, or of Australia's characteristic landscape features;
d	importance in demonstrating the principal characteristics of: i) a class of Australia's natural or cultural places; or ii) a class of Australia's natural or cultural environments (*principal characteristics*);	importance in demonstrating the principal characteristics of a type of landform or geomorphic process;
e	importance in exhibiting particular aesthetic characteristics valued by a community or cultural group (*aesthetic*);	importance in exhibiting the aesthetic value of the landscape, especially in an Australian drylands context;
f	importance in demonstrating a high degree of creative or technical achievement at a particular period (*creative or technical*);	association of the geomorphic features with a particular human achievement;
g	strong or special association with a particular community or cultural group for social, cultural or spiritual reasons (*social*);	landforms or geomorphic processes which have strong or special associations with the scientific or educational community, or have been most intensively investigated, or have a particular cultural impact;
h	special association with the life or works of a person, or group of persons, of importance in Australia's natural or cultural history (*significant person*);	landforms or geomorphic processes which have special association with the works of a pioneering geologist, or a fundamental component of an artist's oeuvre;
i	importance as part of Indigenous tradition (*indigenous*).	(not within the scope of the authors of this study).

Table 2 The National Heritage Criteria as defined (left) and as used in this study (right)

To be successfully listed, a place must pass a *significance threshold* for any of the NHL criteria which are applied to it. The threshold expresses that the place has outstanding heritage value to the nation. The Australian Heritage Council suggests some questions that assist in determining whether or not a significance threshold has been reached:

- How important are the values? Would the loss of the place significantly impoverish our National Heritage?
- Is the place important to the Australian community as a whole?

- In comparison to other, similar types of places, is the place is 'more' or 'less' significant?
- A comparison can be related to scale of geographic area; in comparison to other, similar types of places, what is the extent of a place's significance (local, regional, national or international)?

The latter point is important in considering different levels of significance: some places may be significant at regional level for example, but not at state or national levels (Table 3). This concept is used by the Geoheritage Committee of the Geological Society of Australia (Victorian Division) (White et al., 2003).

An ambiguity of terminology should be noted here: the term "outstanding" has two meanings relevant to heritage, both used in previous heritage discussions. In NHL assessment, "outstanding" is used to indicate that a place is of such great significance that it passes the threshold of importance. Outstanding can also mean unusual (special, unique, individual, distinctive), and it has previously been used in this sense (e.g. White et al., 2003). In the present report, atypical features are described as unusual or special.

International	Sites which are rare in the world, or whose scale, or state of preservation or display, are comparable with international examples (e.g. global type examples, or reference sites widely known to the international geological community). Such sites should be listed at a national level, and included in international registers of scientific significance; they may be suitable for listing on the NHL or the WHL.
National	Sites that are rare in Australia, or are important nationally by virtue of their scale or state of preservation (e.g. sites widely used as reference sites by the Australian geological community). Such sites should be included in a national register of scientific significance; they may be listed at a national level, or may be suitable for listing on the NHL.
State	Sites that are important in defining the geology of a state (e.g. reference sites or type examples). Such sites may be listed at a national or state level.
Regional	Sites that are representative of or important to regions of about 60km radius.
Local	Sites whose features are representative of smaller areas in a region; usually related the scale of a Local Government Area, or an area with a radius of 20km.
Unknown	Sites for which there is insufficient data to allow a complete assessment to be made: under investigation, or subject to continual change (e.g. active quarry faces or sites undergoing development).
Destroyed	Sites which have been destroyed, but for which documentation keeps the details (e.g. quarries and mines); important for some fossil and mineral sites.

Table 3 Criteria used for geoheritage assessment by the Geological Society of Australia (Victoria)

1.3 Assessment Methodology

The Earth Sciences Comparative Matrix (ESCoM) methodology was developed for this study. In the 1st Edition of this report it was not well-articulated; what we present here has been reorganised for clarity, and was published as a peer-reviewed paper (White and Wakelin-King, 2014).

In determining whether a site is eligible for listing on the NHL, natural heritage poses challenges in the areas of visibility and subjectivity.

There are numerous known sites of potentially great significance which have not been assessed for defined heritage lists, but there are also an unknown number of currently undocumented sites. The 'visibility' of a site depends on its being seen, recorded, and communicated in enough detail that its significance can be assessed. Clearly, in remote and difficult parts of a sparsely-populated country, there will be places of heritage value which are not yet known. This report is presented on the basis of knowledge available to us (the literature, our own experience and that of the Australian geological and geomorphological community) but we are sure that more and better information will become available over time.

The values of heritage are diverse and subjective; it is hard to weigh one aspect against another in the absence of objective measurable criteria (Pralong, 2005) because heritage assessment applies culturally constructed values to physical objects. However, many studies of geodiversity identify the same characteristics as being valuable: intrinsic, aesthetic, cultural, economic, scientific, and educational (Gray, 2005). The most achievable approach to maximise objectivity is to spread assessment across numbers of people (by working partnerships, committee partnerships, canvassing the professional community, or accessing a wide range of reports and peer-reviewed professional literature). Objectivity is also maximised by using a structured approach to assess sites in a comparative manner against defined criteria, as described above for the NHL and Geological Society of Australia (Victoria), and as presented below with the ESCoM. Some subjectivity necessarily still remains, and it is important that geoheritage assessments be transparent and can be revisited if circumstances require it. A robust and repeatable process should be followed.

Overlap between geomorphological and geological values, or between geomorphological and other natural values (e.g. biological) was addressed while defining this study's scope. This report deals specifically with geomorphology, and does not consider other sorts of geological significance (unless the geological value is also related to the geomorphology, for example where a type section is exposed in a cliff face). However, the ESCoM methodology presented here can be used explicitly to assess multi-disciplinary approaches to significance.

Assessment of whether a place passes the threshold of significance with respect to its nominated criteria is by comparison to other, similar types of places. This is the key to establishing significance. The comparison must be meaningful: between like places or within an essentially homogenous class, and considering the site within its context and as a whole (Australian Heritage Council, 2009). However, the study area is enormous (4.14 million km^2). As the report's study area was defined by a climatic boundary (as opposed to a physiographic or land system boundary for example), it includes extreme diversity of landforms, and comparisons had to be made not only within types but also across types. On a continental scale, how can fair comparisons be drawn between the relative merits of (for example) an ancient astrobleme measuring tens of kilometres and a modern waterhole a fraction of that size? Scale was the particular challenge to this study's geoheritage assessments.

The Earth Sciences Comparative Matrix (ESCoM) was developed to address this issue. Potential sites were grouped by their most important geomorphic process (either of their formative events, or dominating in the present day): see Section 3, *Themes and Sites*. Sites within each group were compared, either to each other or to the generality of that kind of landscape; with respect to each of the NHL criteria; and with respect to contextual information: unusualness on Australian and international scales, complexity (multiplicity of geomorphic themes), integrity, and authenticity.

- Integrity in the natural environment is related to how viable and sustainable it is over the long term, or (if a site has sustained damage related to its heritage values) how restorable to a satisfactory level it is.
- Authenticity considers if a place's value is genuine and/or of undisputed origin. In a pragmatic sense and specifically with respect to geomorphology, authenticity relates to whether or not the geomorphic processes are well understood and described accurately; whether the value ascribed to the area truly represents what is there. A valuable heritage quality derived from a misunderstood, incomplete, or incorrect scientific investigation distorts the heritage value of the place as a whole.

ESCoM: The Earth Sciences Comparative Matrix

The ESCoM is a methodology for managing complex comparisons; Table 4 is an example. Briefly, the rows are criteria and context, and the columns are a series of features and places, listed under themes of their dominant geological process. For each place/feature, a separate assessment is made with respect to each criterion and comparison, and each cell within the matrix is assigned a numerical rank representing its heritage value. These elements are described in more detail below, and in White and Wakelin-King (2014).

The rows are the criteria under which each place is assessed and the comparative standards against which each place is judged. Rows 1–8 are the NHL criteria, as applied to geomorphology. Rows 9–12 contain comparative and context information.

		Theme Sub-theme	Astroblemes		Karst	Arid Coasts	Hydrology		
							anabranching rivers	mud-aggregate floodplain	fresh-water basins
		Place or feature	Acraman Impact Structure	Henbury Meteorite Craters	Nullarbor Plains	Bunda Cliffs	Cooper Creek (Windorah to Nappa Merrie Waterhole)	mud-aggregate floodplain	waterholes
NHL Criteria	1	a) Events and Processes	5	2	5	5	5	5	5
	2	b) Rarity	5	2	5	5	2	2	2
	3	c) Research	5	2	5	3	3	5	5
	4	d) Principle characteristics	5	5	5	5	5	5	5
	5	e) Aesthetics	4	1	4	5	3	2	4
	6	f) Creative or technical achievement	-	-	2	-	-	-	1
	7	g) Social (scientific, educational, cultural)	5	1	3	2	5	5	5
	8	h) Significant people	-	-	2	-	-	-	-
Comparative and Context	9	Unusual (world)	5	1	5	5	5	5	5
	10	Unusual (Australia)	5	3	5	5	3	4	4
	11	Includes other themes	-	-	-	-	mud-aggregate floodplain, waterholes	(anabranching, waterholes)	(anabranching, mud-aggregate floodplains)
	12	Threshold (summed rankings)	39	19	41	35	(31+33+36)*=**100**	(33)*	(36)*
	13	Integrity (key heritage values remain intact)	Y	C	Y	Y	Y	Y	Y
	14	Authenticity (heritage value is genuine, undisputed)	Y	Y	Y	Y	Y	Y	Y
	15	Places: cross-reference other sites; Features: occurs at which sites	-	-	Bunda Cliffs (arid coasts)	Nullarbor Plains (karst)	Barkley Tableland, Cooper Ck at Innamincka Dome, Lake Eyre	Cooper Creek; Fowlers Creek	Cooper Creek, Neales Catchment
	16	Already cited on heritage lists	-	-	-	-	-	-	-
	17	IBRA region	GAW	FIN	NUL	NUL	CHC; multiple	multiple	multiple

Table 4 The Earth Sciences Comparative Matrix as used in this study for comparative assessment

*In this instance, the matrix is set up for NHL criteria and used in numerical ranking of multiple sites. * Feature scores are added together to make the site score.

Rows 9 and 10 invite comparison between the place/feature in question and similar ones on a world or a national scale. Some features may be uncommon on a national scale but be well represented elsewhere in the world. Unexpectedly, some things may be less common on a world scale than they are in Australia: for example, vertic soils are widespread in Australia but are poorly represented in some of the world's other well-known deserts (Hubble, 1984). Row 11 indicates whether the place/feature in question includes values from more than one process theme. Taking this into account, row 12 sums the numeric scores, expressing the degree to which the place/feature meets the threshold of 'outstanding heritage value to the nation' (Australian Heritage Council, 2009). A place/feature that has met the value threshold across one or more criteria must then be considered in terms of its integrity and authenticity (which may affect its relative significance in comparison with others of a similar type) (rows 13–14). Rows 15+ provide relevant contextual information specific to the study. In the present work, the contextual information that we noted was the Interim Biogeographic Regionalisation for Australia (IBRA) region(s), cross-references to other sites, and whether the site was already heritage listed at some level. Some existing Australian NHL sites are listed for natural values but not for their geomorphological values; in such cases, their geomorphological values could (and probably should) be added to the listing.

The columns identify the geomorphic processes by which the sites/features are grouped. Process-based themes have the twin advantage of avoiding equifinality (grouping together two superficially similar but actually different landforms, such as gibber plain and the Nullarbor Plain) and encompassing very different looking landforms that arise from the same geomorphic processes (such as caves, and karst-derived very steep hills). Process-based themes also facilitated Dept. SEWPaC's project brief – to 'identify key places that best tell the stories of the development of Australian desert landforms'.

Numerical scoring is a useful way to manage a large project calling for multivariate comparisons across a wide range of landform scales and types. In ESCoM, individual cells invite assessment for the place/feature (column) and criterion (rows) under consideration. Significance is assigned according to the size of area across which it is notable (Table 3), and ranked numerically; a scale of one to five was found to be practical in this study. It is also possible to rank sites in a non-numeric fashion (e.g. presence (+) or absence (−) of significance), but this was not found to be as successful in identifying relative significance of sites.

The process is often reiterative, calling for initial familiarisation with site and/or literature, followed by one or several considerations of criteria and comparisons. The rank values are entered into the appropriate criterion cells and then summed in the 'Threshold' cell (row 12). Where a single place scores across several themes, the scores for the themes are added together. In this way, a place with a high level of geomorphic complexity has its values appropriately recognised. In the examples shown in Table 4, within the theme 'Astroblemes', the outstandingly important Acraman Impact Structure scores much more highly than the Henbury Meteorite Craters. Within the theme 'Watercourses', waterholes assessed as individuals would only rate moderately, because no particular one expresses the importance of the group as a whole. As a class however, their importance as one of Cooper Creek's fluvial features can be assessed more truly, and they contribute to the site's outstanding value.

Scoring allows assessors to keep track of their judgements, making it easier to revisit them, or compare judgements across very different themes. It allows the process to be robust and repeatable. However, numbers make good servants but bad masters, and it is important that the scoring process not give undue importance to the final score. Heritage values are qualitative not quantitative; the object of the matrix is not the numerical score. The scores are a qualitatively-assigned aid to making the final recommendation, rather than being the recommendation itself. By comparison, life scientists use the Australian Natural Heritage Assessment Tool (ANHAT) for biodiversity assessment: its outputs are unavoidably dependant on the availability of numerical input data (binary statements across standardised areas).

ESCoM as a Flexible Tool

ESCoM is designed to be flexible, and adaptable to the needs of various types of heritage assessment. Other criteria can be used instead of the NHL criteria, and other levels of significance considered. Contextual rows may be adapted for specific project requirements. Because ESCoM is qualitative rather than quantitative (does not depend on a minimum or standard area), it is easily scaled to smaller projects (White and Wakelin-King, 2014). Most importantly, any process-based grouping can be used to sort potential heritage sites. This study focuses on geomorphology, but the matrix could be easily adapted, for example, for geology; when assessing heritage values of igneous rocks, assessors might group heritage possibilities according into themes of magma chemistry (basic, intermediate, acid) or tectonic context (island arc, mid-ocean ridge, rift). The matrix may be adapted for cross-disciplinary studies – places that share heritage values across disciplines. Researchers might assess, for example, geomorphology criteria separately from biological criteria, then cross-reference the two in the context rows, summing the joint rankings across the two disciplines (Table 4, row 12). In this way, a geomorphically significant waterhole, which is also an ecological refuge, would score more highly than a waterhole of geomorphic or biological significance only. The ESCoM assessment process allows for cooperative, joint work across disciplines, ensuring that all relevant values, and any synergies and connections between values, are acknowledged in the assessment process.

In this edition of the report, site and feature descriptions include modified ESCoM tables (Tables 8-45), in which the cells are populated with the qualitative descriptions of values according to criteria.

	Place / Feature	Name
	Theme (sub-theme)	
NHL Criteria	Events and Processes	
	Rarity	
	Research	
	Principle characteristics of a class	
	Aesthetics	
	Creative or technical achievement	
	Social	
	Significant people	
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	
	Unusual (Australia)	
	Multiple geomorphic themes	
	Value with respect to significance threshold	Clear, Likely, or Probable (pending further investigation)
	Integrity	
	Authenticity	
	Cross-reference	If the table refers to a place, what other places is it linked to; if the table refers to a feature, at what places does it occur.
	Status	Is the place or feature – • a specific area defined in this study, • an indicative area (a large area with insufficient available information to specify a site but within which a candidate place is likely to be identifiable in the future), • an existing NHL or WHL listing, • part of other heritage sites, • a feature which contributes value to places listed under other geomorphic themes, • a knowledge gap (potential heritage value but currently insufficient information to make an assessment).

Table 5 An ESCoM table as used in this report for site/feature descriptions

2 Drivers of Australia’s Drylands Landscapes

The study area comprises most of Australia's drylands, and inhabitants would probably regard its landscapes as identifiably part of Australia's arid inland. During the course of this project, the diversity of landforms within the study area prompted us to question what it is that gives these landscapes their essential character? Aridity is a common factor, but cannot be the only determinant. Though some landscapes are dominated by desert landforms (e.g. Simpson Desert dunefields), in others the dominant feature is not particularly created by aridity (e.g. the strike ridges of the MacDonnell Ranges), or is not restricted to drylands (e.g. silcrete, the parent material of gibber plains).

Geomorphology – the study of landforms and of landscape evolution – encompasses anything that affects landscape. Its province is the surface of the earth: rocky outcrop, regolith (anything that isn't solid rock: sediment, soil, and weathered rock), and interactions between living things and the physical world. It is dominantly a geological and geographical discipline, calling upon an understanding of lithologies, geological history, spatial relationships etc., but includes elements from meteorology (present-day climate and climate change over geological time), biology, chemistry, and the physics of fluid dynamics. In the discipline's early days, geomorphologists frequently focused on the description, naming and classification of landforms. As coherent patterns began to emerge, focus shifted towards understanding the forces that create and maintain landforms, and by the late 1900s *process geomorphology* was the way in which landforms were increasingly understood.

The agents whose processes work upon the landscape are wind, water, gravity, tectonism, weathering and living things. They occur in drylands throughout the world. It is the relative rate and/or intensity and/or duration of each agent's effect that collectively makes a landscape's character. During compilation of the literature review for this study, we found that four threads (discussed below) were consistently expressed in the stories of Australian landscape evolution: continental stability, previous climates, the modern landscape's inheritance from previous conditions, and modern aridity. We perceive these to be the drivers of the Australian drylands’ character. Geomorphology’s normal agents act within the context of these drivers, on the range of lithologies exposed at surface, and the result is a complex and diverse assemblage of landforms.

Length of Time, Rate of Activity

Much of the Australian continent has experienced only subdued tectonic activity for a very long time. In other continents, rapid uplift pushes rocks up into mountains where they can be worn down by erosion and scraped off by glaciers; but in Australia’s inland, Himalayan-type peaks existed so long ago that they are now worn down to their roots. Parts of the landscape have been at or near the Earth's surface for as much as hundreds of millions of years. Glaciation during the Permian (before the age of the dinosaurs began ~248 million years ago) was the last time the study area's landscape was scraped back. Even so there are remnants of even older regolith (Anand, 2005). The landscape here is very, very old.

This landscape's evolution over such a long time means that processes which are slow to occur have the opportunity to develop fully. A process need not be intense if it can persist over geological lengths of time. Weathering (the chemical alteration of rocks into regolith) can proceed to very high degrees, and in Australia the weathering profile can extend hundreds of meters below the surface (Anand, 2005). Erosion and deposition of sediments, taking place increasingly slowly as high mountains and deep valleys wear down to little hills and hollows, can continue until a very low-relief landscape is created. Australia's wide expanses of low-gradient slopes are a significant influence on the evolution of weathering profiles and fluvial styles (Nanson & Huang, 1999; Anand, 2005).

It would be a mistake, however, to think that Australia is wholly without tectonic activity. The Australian continental plate has a very rapid rate of movement, with resultant continental-scale pressures that create the stress field which produces modern tectonic activity (Sandiford et al., 2009). Activity includes (but is not restricted to) rapid uplift in the Flinders Ranges (Quigley et al., 2006) and more subtle expressions of tectonism which include continental tilting and long-wavelength low-amplitude landscape undulation (Sandiford et al., 2009).

Previous Climates

Over geological time, Australia has experienced many different climates (Anand, 2005). After the Permian glaciation, the continent experienced a generally warm climate. During the Cretaceous (144-66 million years ago, the last period of the age of dinosaurs) much of inland Australia was covered by ocean (including the Eromanga Sea, laying down the sediments of the Great Artesian Basin) under a mostly warm and humid climate. The post-Cretaceous Palaeogene, Neogene and Quaternary periods have been a time of progressive climate change. Although global cooling began in the Palaeogene, Australia experienced warm and wet rainforest conditions at that time. Fluctuations of climate between warm/wet and cool/dry continued through the Cainozoic.

The warmth and greater availability of water during Australia's previous climates has had a profound effect on what we see today. The repeated cycles of deep weathering and their associated duricrusts have shaped much of Australia, from West Australia through to Charters Towers, from the Top End to Ceduna (Anand & de Broekert, 2005; Bourman, 2006). Intense wet-dry cycles in some weathering profiles produced the cracking clays characteristic of parts of inland Australia (Hubble, 1984). The greater volumes of water once carried by the rivers were expressed not only in river landforms, but also in megalakes covering vast areas (English et al., 2001; Cohen et al., 2011). Caves and other karst landforms developed during previous climatic regimes (Webb & James, 2006).

Inheritance

Australia's tectonic and climatic history has created a situation where events that took place in the geological past are directly relevant to modern landscapes. The absence of recent glaciation and the subdued tectonic regime has preserved landforms and sediments created long ago. Many of the strongest landscape elements are inherited from the past, or owe their origins to conditions that no longer exist. The present study did not find a review paper surveying inheritance as an influence on Australian landscape evolution, however literature on individual sites or areas commonly referred to some aspect of inherited feature.

Modern Aridity

Aridity, which is widely regarded as a defining characteristic of the Australian inland, is only the latest imprint of a long series of events. However, the development of aridity during the Cainozoic has had an extremely strong effect on some aspects of the inland Australian landscapes; in the present day, aridity is a powerful geomorphic agent.

The development of aridity in Australia is linked to cooling of the Earth. By the mid-Miocene, a permanent southern ice cap formed, moving the Earth towards the present glacial/interglacial climate cycle, and moving Australia towards its present aridity. During the Quaternary (the last ~2 million years), there have been at least 20 oscillations from glacial to interglacial (Anand, 2005). In inland Australia these cycles have mostly been expressed as alternations of wet and dry, or alternations of warm and cool. (This is an extremely brief summary, which does not do justice to the complexity of climate change over a continent this size.)

Aridification of the Australian climate was accompanied by changes in the nature and intensity of geomorphic processes, as (inter alia) river flows decreased and became more variable, vegetation communities changed their composition and locations, and rates of erosion increased. Specifically:

- Soil mantles were stripped to reveal the gibber plains of Australia's stony deserts (Fujioka et al., 2005).
- Fluvial flow regimes changed. Overall discharge decreased, so that many river systems are now ephemeral, and/or have changed their planform in response

to low discharge (e.g. reduced meander sizes, or anabranching planforms). Aridity is linked to a high degree of fluvial variability, and Australia's present-day flow variability is extreme on a world scale (Finlayson & McMahon, 1988). Many river landforms are shaped by very large but infrequent flow events.

- Decreased flows have led some river systems to dry up entirely, becoming chains of playa lakes. Megalakes that once existed have dried out, leaving playa lakes surrounded by old lake beds: wide, flat surfaces that contribute greatly to the low-relief landscapes.
- Sand was mobilised, creating the vast dune fields of the Simpson (Fujioka et al., 2009) and incidentally burying the rivers that once ran from the MacDonnell Ranges towards a larger Lake Eyre (Craddock et al., 2010). Other dune fields were also mobilised or altered.
- The relative scarcity of water focuses vegetation on landforms which are near water or which retain water. Since vegetation plays an active role in landform development and maintenance, this creates process feedback loops which are an important element in some landforms (such as floodouts, Wakelin-King & Webb, 2007a).
- The present conditions constrain ecosystems and limit soil development, producing the characteristic scanty vegetation and rocky surface which governs runoff generation and the creation of desert pavements (Dunkerley, 2011).

Though aridity is only one of the factors changing the face of the Australian landscape during the Cainozoic, and is not necessarily the most powerful, it is the most recent, and its effects are extremely widespread.

3 Themes and Sites

This section lists and describes the places identified during this study as having achieved, or having potential to achieve, National Heritage List status with respect to their geomorphology. The places are sorted into geomorphic themes: grouped by their most important geomorphic process (either during their formative events, or dominating in the present day). Some places are specific ***sites*.** Some are large areas of a particular landscape type, within which there was insufficient available information to specify a site. For these, an ***indicative area*** was suggested, within which a candidate place is likely to be identifiable in the future. Some geomorphic themes are represented by ***features*** which contribute value to sites or areas listed under a different dominant theme (cross-referenced in Tables 1, 6).

There are eight geomorphic themes: astroblemes; sand deserts; karst; arid coasts; tectonic; regolith; watercourses; and uplands (Table 6). The sand desert, tectonic, regolith and watercourses themes are themselves diverse, and are subdivided. For each geomorphic theme or sub-theme, a brief review is followed by descriptions of the sites, indicative areas, or features, and ESCoM tables indicating which theme(s) are present and which NHL criteria the place's attributes fall under.

Twenty eight sites or indicative areas are identified (Table 1, Fig. 1) in this study. There are differing degrees to which the places were obviously outstanding with respect to NHL criteria. Some are clearly outstanding and very well documented, and should be a high priority for heritage recognition (e.g. the Acraman Impact Structure which is outstanding in numerous criteria and is connected to a geological event of world significance). Others are less immediately clear, for example if there are several similar places with outstanding qualities but some are better-known than others, or if the place has outstanding qualities but is less well-documented. These have likely heritage value and should be a moderately high priority for heritage recognition. Other landforms may be widespread and important, but poorly-researched or part of a poorly-researched landform type, so that it is not clear where the best, rarest, or most important example might be. These have probable heritage value and would benefit from further research. In summary, in the descriptions below, places or features are ranked as follows:

- clear value;
- likely value;
- probable value (pending further information).

Table 6 Geomorphic themes and sub-themes, and the sites or areas in which they occur

See Table 1 for site or area numbers.

Theme	Sub-theme	Abbreviation	Sites / Areas
Astroblemes		As	1, 2
Sand Deserts	Basin setting	Sa – B	3, 4
	Ridge-valley setting	Sa – RV	5, 6, 15
Karst		Ka	7, 8, 9, 10, 20
Arid Coasts		AC	8, 9, 10, 11
Tectonic Landforms	Flexure	Te – Fl	3, 13, 14
	Faulting	Te – Fa	12, 15, 18, 23
	Diapirism	Te - Dp	16?, 17?
Uplands		Up	12, 15, 16, 17, 18, 19, 23, 27
Regolith	Vertisol plains and slopes	Vt	20, 23
	Saprolith	Rg - Sp	5, 6, 11, 14, 21, 22
	Silcretes and gibber plains	Rg - Si	3, 4, 5, 6, 13, 14, 21, 22
	Gypcrete	Rg - Gy	5, 6, 14, 21, 28
	Calcrete	Rg - Ca	5, 6, 21, 28
	Ferricrete	Rg - Fc	5, 6, 21, 22
Watercourses	Sand-bed rivers	W - SR	3, 16, 17, 26, 27
	Discontinuous ephemeral streams	W - DES	18, 23
	Anabranching rivers	W - AR	4, 13, 14, 23, 24
	Mud-aggregate floodplains	W – MA	23, 24
	Fresh water basins	W - FW	4, 13, 14, 24
	Mound springs	W - MS	14, 25
	Banded vegetation sheetflow plains	W - BV	5, 6, 15, 16, 18, 21, 23
	Floodouts	W - Fd	3, 16, 17, 23, 26, 27
	Palaeodrainages	W - Pd	3, 4, 5, 6, 14, 21, 22
	Megaflood landforms	W - Mf	14, 17, 27
	Playa lakes	W - PL	2, 4, 21, 28
	Post-European drainage incision	W - PEI	18, 23

3.1 Astroblemes

Astroblemes are formed by the impact of material from space. The difference between craters and impact structures is that craters show a clear form related to the original impact, but impact structures are those where geological processes (e.g. erosion, sedimentation, tectonics) have destroyed most of the original crater topography and possibly buried the feature.

Young craters generally have a distinctive morphology, and are often associated with preserved meteorite fragments and impact glass. Impact structures are generally older, are deeply eroded or buried and are not expected to preserve unaltered meteorite debris. They may be associated with projectile-derived geochemical anomalies in impact melts, breccias, injected melt veins or ejecta layers. The investigation of an anomalous circular feature either exposed at surface or revealed in the subsurface by geophysical means is the usual first step in finding an impact structure. Identification follows from recognition of other astrobleme attributes such as shock metamorphic effects in the target rocks and/or an associated extraterrestrial geochemical/isotopic signature.

All impact craters produce ejecta such as fragments of target rock, proximal impact glass, or a variety of distal tektites. Distal ejecta layers can provide a record of impacts otherwise lost (through erosion, burial or tectonism). If deposited in a datable or stratigraphically identifiable position, ejecta can be time lines correlating impacts with regional (and sometimes global) geological or palaeontological events (e.g. mass extinctions).

Australia's long subaerial exposure and relative tectonic stability has allowed preservation of very old impact structures, and in the drylands good exposures are favoured by thin soils and scanty vegetation. Consequently, the Australian continent has one of the best preserved impact crater records on Earth, rivalling that of North America and parts of northern Europe. The rate of new discoveries remains high, however many Australian impact structures remain poorly studied in comparison to those in other western countries. The Australian cratering record is anomalously biased towards old structures and includes the Earth's best record of Proterozoic impact sites.

Haines (2005) reviewed twenty six impact sites, including five small meteorite craters or crater fields associated with actual meteorite fragments, and twenty one variably eroded or buried impact structures. The Australian impact record also includes distal ejecta in the form of two tektite strewn fields (Australasian strewn field, 'high-soda' tektites), a single report of 12.1 – 4.6 Ma microtektites, ejecta from the ca 580 Ma Acraman impact structure, and a number of Archaean to Early Palaeoproterozoic impact spherule layers. Possible impact-related layers near the Eocene – Oligocene and the Permian – Triassic boundaries have been described in the literature. The global K – T boundary impact horizon has not been recognised onshore in Australia but is present in nearby deep-sea cores.

Astroblemes occurring within the study area and with significant surface expression are listed in Table 7. Other significant craters and astroblemes occur elsewhere, such as the Wolfe Creek crater (WA), and impact structures at Crawford (SA), Flaxman (SA), Foelsche (NT), Goat Paddock (WA), Goyder (NT), Lawn Hill (Qld), Liverpool (NT), Matt Wilson (NT), Piccaninny (WA), Spider (WA), Strangways (WA) and Yallalle (WA). There are a number of other potential sites, so more astroblemes and craters are likely to be recognised (Haines, 2005).

The potential sites described under the astroblemes geomorphic theme are Gosses Bluff (Northern Territory) and the Acraman Impact Structure (South Australia). Key astrobleme references are Williams and Wallace (2003), Haines (2005), and Williams and Gostin (2005). Other references containing relevant material are Twidale and Campbell (1993; pp. 302-309, 333-336), Clarke (1994a), Macdonald et al. (2003), de Broekert and Sandiford (2005) and Davey and Hill (2009).

Name	State	Diameter (km)	Age (years)	Comments
Acraman	SA	90	about 590 million	A highly significant astrobleme
Amelia Creek	NT	20	1660 – 600 million	Impact crater
Boxhole	NT	0.17	5,400 ± 1,500	Impact crater
Connolly Basin	WA	9	< 60 million	Astrobleme
Dalgaranga	WA	0.024	about 3000	Smallest known crater in Australia
Glikson	WA	~19	< 508 million	Buried structure, limited surface expression
Gosses Bluff	NT	22	142.5 ± 0.8 million	One of worlds' best known craters
Henbury Meteorite craters	NT	0.157	4200 ± 1900	One of world's best small crater fields
Kelly West	NT	10	> 550 million	Limited surface expression of structure
Mount Toondina	SA	4	< 110 million	Heavily eroded structure
Shoemaker (was Teague)	WA	30	Proterozoic	Named after the Shoemakers, who were instrumental in discoveries and extending knowledge of Australian impact features
Tookoonooka	Qld	55	128 ± 5 million	No surface expression
Veevers	WA	0.08	< 20,000	Impact crater
Woodleigh	WA	60–120	364 ± 8 million	No surface expression
Yarrabubba	WA	30	~2 billion	No surface expression

Table 7 Impact craters and astroblemes in the study area (after Haines 2005)

Gosses Bluff (Northern Territory)

Gosses Bluff, located ~250 km south east of Alice Springs, is a well-defined but eroded impact structure dating from the early Cretaceous. The target strata, flat-lying Palaeozoic sediments of the Amadeus Basin, are exposed as a dissected central uplift containing abundant shatter cones. It is one of the best studied of the larger impact craters in Australia (see Haines, 2005). Early interpretations of Gosses Bluff as a diapiric structure or a volcanic feature were disproved after drilling and seismic investigations revealed its subsurface internal structure. The present-day landforms is a circle radius ~6.7 km, but the original crater rim has been interpreted as ~24 km in diameter.

	Place	Gosses Bluff
	Theme	Astroblemes
NHL Criteria	Events and Processes	Well-preserved remnant of an impact structure, marking an event dating from the early Cretaceous. Differential erosion has removed the more intensely shattered rocks.
	Rarity	This is an unusually well-preserved and well-exposed deep core of a large impact structure.
	Research	One of the best studied of the larger impact craters in Australia, its three-dimensional structure has been investigated by drilling and seismic during petroleum exploration.
	Principle characteristics of a class	This is the deep core of an impact structure hosted by the flat-lying Palaeozoic sediments of the Amadeus Basin. It exposes significant features of the central uplift (shatter cones, planar deformation features in quartz, impact melt rocks and evidence of centripetal deformation). The slow pace of erosion has preserved the tilted strata in situ.
	Aesthetics	-
	Creative or technical achievement	-
	Social	Prominent landscape feature in low-relief plains.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	One of the world's best known impact structures.
	Unusual (Australia)	One of Australia's best known impact structures.
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference: links to other place	N
	Status	Specific area

Table 8 Gosses Bluff

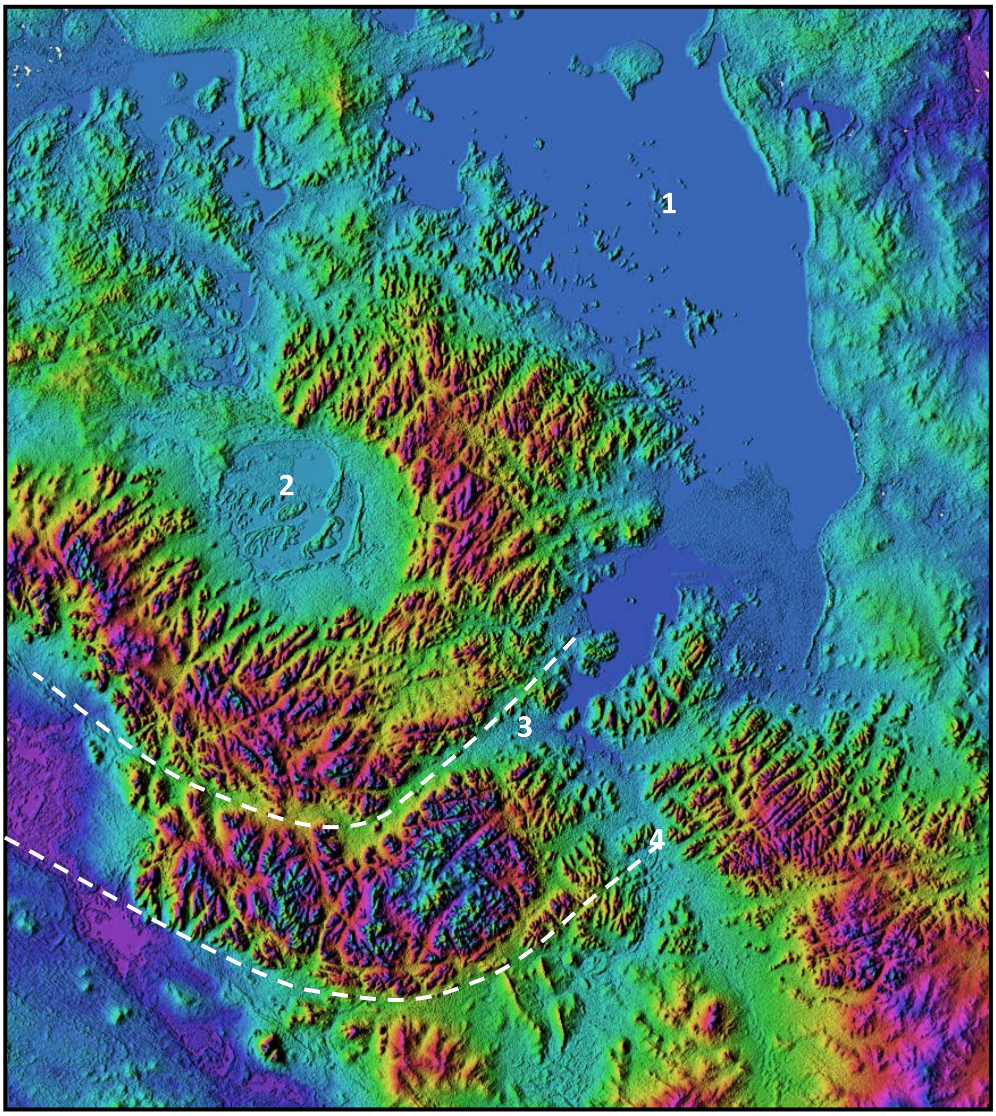


Fig. 4 Topography of the Acraman Impact Structure and Gawler Ranges region

DEM of the hills and valleys outline the target rocks' fracture pattern; the low-elevation areas of the lake and curved corridor valleys indicate impact effects. 1, Lake Gairdner; 2, Lake Acraman, at the centre of the Acraman Impact Structure; 3, the Yardea Corridor (white dashed line); 4, like the Yardea Corridor, this curved valley (white dashed line) lacks hills. Picture is ~150 km wide. Lowest elevation (lake level) is purple to deep blue, with rising elevation climbing through green-yellow-red-purple, to highest hilltops at dark blue to light blue. Image: Wakelin Associates, based on a Digital Elevation Model (DEM) created from SRTM data.

Acraman Impact Structure (South Australia)

The Acraman Impact Structure is located ~225 km west-southwest of Port Augusta. It is clearly visible on satellite image or Digital Elevation Model as a ~30 km diameter central depression surrounded by shatter zone extending out a further ~20 km (Fig. 4). The central depression includes a subcircular playa lake, Lake Acraman (a circle radius ~10 km). The central depression has little outcrop, whereas the hills that surround it are strongly-outcropping and display their fracture pattern clearly. The Meso-Proterozoic crystalline target rocks (dacitic lavas) contain shatter cones, planar deformation features in quartz and devitrified melt rock veins in the isolated outcrops of dacite. The structure is deeply eroded and the original crater floor and rim are not preserved. Ejecta from this impact (identified by ejecta lithology are found in

	Place	Acraman Impact Structure
	Theme	Astroblemes
NHL Criteria	Events and Processes	An impact structure occurring at ~580Ma in northern Gawler Ranges, which probably affected the course of evolution. Well documented distal ejecta layer are known as far away as the Flinders Ranges. The impact is linked to an important biological event (the radiation of the Ediacaran fauna). Differential erosion has removed the more intensely shattered rocks.
	Rarity	The only Australian known case of distal ejecta confidently linked to a well-established impact structure; the ejecta fix the time of the impact.
	Research	Well researched, dating well established, clear stratigraphic and structural relationships with local (Gawler Ranges) and distant (Flinders Ranges) rock units.
	Principle characteristics of a class	Classic impact structure characteristics including central and concentric fracture zones, shatter cones, end ejecta, with clear expression at landscape and mineralogical scales.
	Aesthetics	Clear expression of the shatter zones against the fracture set of the country rock is emphasised by surrounding plains; visible at a grand scale on remote images and digital elevation models.
	Creative or technical achievement	-
	Social	Outstandingly important scientific value.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	The ejecta and therefore the event is linked to the Adelaide Geosyncline (Flinders Ranges) and the Precambrian Ediacaran fossils.
	Unusual (Australia)	The ejecta and therefore the event is linked to the Adelaide Geosyncline (Flinders Ranges) and the Precambrian Ediacaran fossils.
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference: links to other places	Flinders Ranges
	Status	Specific area

Table 9 The Acraman Impact Structure

identifiable strata as far away as the Flinders Ranges to the east; the stratigraphic position of the ejecta allows the impact age to be established. This links the Acraman impact to a pronounced biotic radiation event in the Ediacaran fauna (Williams & Wallace, 2003; Haines, 2005; Williams & Gostin, 2005). That is, the impact is likely to have influenced the course of evolution.

3.2 Sand Deserts

Extensive sand deserts cover large areas of the arid and semi-arid zones and are a major landform in drylands Australia. They have complex relationships with topography, climate and substrate and have been the subject of protracted research efforts. This section's summary of sand deserts is derived from Hesse's 2010 continent-scale study and review, unless otherwise noted.

Hesse (2010) describes five main Australian sand seas. In eastern Australia, the Mallee, Strzelecki and Simpson overlie Quaternary sedimentary basins. In the western parts of the continent, the Great Victoria and Great Sandy dunefields are found in a non-basinal landscape of low-relief ridge and valley topography. (Other smaller dunefields occurring in the arid zone outside these areas are not discussed.) Not all Australian drylands contain dunefields: several large areas stand out as being dominantly free of dunes (e.g. Tanami, Nullarbor and Gibson). Longitudinal dunes, associated with low sand supply under moderately variable wind conditions (Wasson & Hyde 1983), are a common and dune form in Australia. Australia’s generally low sand supply and low storage in many landscapes (particularly in the west) has contributed to the characteristic dune morphologies: not only the longitudinal dunes, but also network and mound morphologies; and the absence of dune forms that require abundant sand, such as star dunes.

The potential sites described under the Sand Deserts geomorphic theme are the Simpson Desert Floodouts (Northern Territory and South Australia), the Cooper Creek distributaries in the Strzelecki Desert (South Australia), the Great Sandy Dunefield (Western Australia) and the Great Victoria Dunefield (Western Australia and South Australia).

Key sand desert references are Wasson and Hyde (1983), Hesse and Simpson (2006), Fitzsimmons (2007), Fujioka et al. (2009), Hesse (2010), Pain and et al. (2011). Other references containing relevant material include Wopfner and Twidale (1967), Jennings (1968), Brookfield (1970), Folk (1971), Mabbutt (1977) ,Van de Graaff et al. (1977), Gardner and Pye (1981), Wasson (1982), Beard (1982), Twidale and Campbell (1993), Clarke (1994a), Glassford and Semeniuk (1995), Croke (1997), Pell et al. (2000), Bullard and Livingston (2002), Fink (2006), Hollands et al. (2006), and Maroulis et al. (2007).

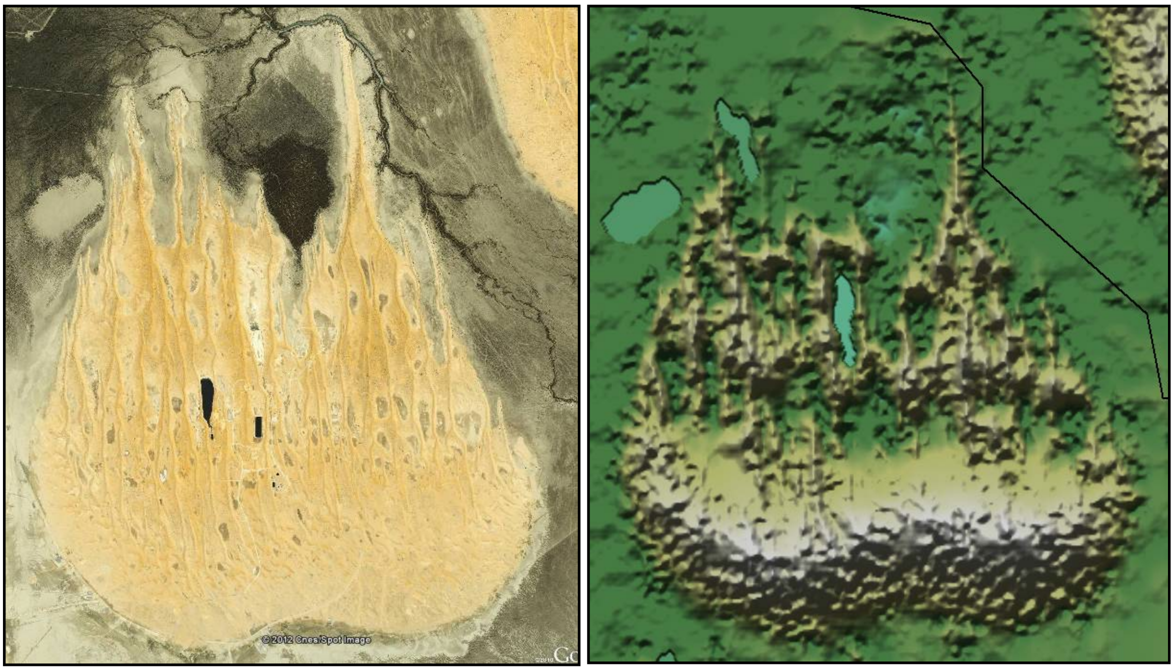


Fig. 5 The compound dune to the south of Embarka Swamp

Left, Google Earth image shows buff to pale orange dunes; black to dark grey alluvial flats. North to top, image is approximately 10 km N-S dimensions. Right, DEM (grey highest, dark green low, pale aqua lowest); the highest east-west trending crest is the source-bordering dune; north-south crests are longitudinal dunes; black line, approximate path of Cooper Creek DEM image Wakelin Associates from SRTM data.

Eastern vs. Western dunefields

The eastern dunefields occur in lowland basins, and their sand is derived from reworking of sand-rich Neogene coastal, shoreline and fluvial sediments eroded from lithologically diverse catchments. In the present report's study area, the Simpson and Strzelecki dunefields are separated by the low structural ridge of the Gason Dome (whose surface expression is known as Sturt’s Stony Desert). The Simpson and Strzelecki dunefields are underlain by Cainozoic sediments and sedimentary rocks of the Lake Eyre (geological) Basin, and are set within the topographic low that is the Lake Eyre (catchment) basin. A key difference between the two dunefields is with respect to the nature of fluvial-aeolian interaction, and its effects on dune morphology. In the Strzelecki Desert, the dunes are compound, composed of source-bordering dunes overprinted by relatively short longitudinal dunes (Fig. 5); their formation results from interaction between fluvial and aeolian processes over numerous iterations of the Cooper Creek drainage network (Callen & Bradford

1992,Fitzsimmons et al. 2007, Cohen et al. 2010, and see Wakelin-King 2013). In the Simpson Desert, previous fluvial networks are now concealed beneath the very long dunes (Craddock et al. 2010); debate on dune origin ranges between deflation from lake basins and reworking of the underlying weathered sediments (e.g. Pell et al. 2010, Hesse 2010), however spatial relationships between dunes and hills in the Rodinga Ranges area provide clear evidence of wind rifting and vertical accretion (Hollands et al. 2006) .

In the west the underlying geology, dominated by older cratonic crust, lacks Neogene basins. The Great Victoria and Great Sandy dunefields are extensive but discontinuous, and occur on landscapes of subtle ridge-and-valley topography. (In this respect they are different not only from the basinal dunefields of not only eastern Australia, but also most comparable dunefields of Africa or Asia; Hesse 2010.) Although the topography is often low enough that sand dunes can climb over and cover the ridges between valleys, it is clear from the dune's topographic dependence that the valleys are the source of the sediment. Aeolian processes have not only reworked valley and piedmont sediments, reshaping them into dunes, they have also blown sand over the ridges between (Hesse 2010).

Topography, Lithology, and Dune-free Deserts

Topography is one of the principal factors determining the distribution and character of the dunefields. Uplands and lowlands can define basins of sedimentary accumulation, such that uplands (e.g. Musgrave and MacDonnell Ranges) form boundaries of major dunefields (e.g. the Great Sandy and Great Victoria dunefields). Topography can also influence the erosiveness of runoff, and the acceleration or deceleration of wind. In a reversal of the topographic relationship described in the previous sentence there are low (100–200 m high) escarpments where the dunefields are topographically elevated (e.g. the escarpment marking the western boundary of the Lake Eyre catchment). Such escarpments mark a boundary between mostly dune-free landscapes with coherent fluvial drainage networks below, and landscapes above which are dominated by sand but lack well-connected drainage networks. These landforms suites arise from relationships between topography, runoff and dune formation. At a continental scale topography’s relationship to dunes is that the supply of erodible sand is based in areas of sedimentary accumulations; most dunefields occur in valleys, piedmonts, coastal plains or lowland basins.

Lithology is another key factor in dunefield formation. Some large low-relief areas of the Australian drylands are dune-free because of sediment starvation, either because of substrate or catchment lithology (e.g. Nullarbor Plain's limestone, the Georgina Basin's shale and mudstone, the Carpentaria Basin's clay soils and hardpans) or because of regolith development (e.g. dune-free areas associated with duricrusts in the Great Victoria and Great Sandy dunefields; and the Yilgarn in Western Australia).

In the western dunefields, sand appears to be largely reworked from shallow valley and piedmont accumulations. The Central Australian craton, parts of the Pilbara block and the Neoproterozoic–Mesozoic sediments of the Canning and Officer Basins seem to have yielded large volumes of sand for surrounding low-lying regions, whereas the Yilgarn appears not to have been a good source of sand. The eastern dunefields' sand is derived from reworking of sand-rich Neogene coastal, shoreline and fluvial sediments eroded from various sources. Nevertheless questions remain about sediment source and transport during formation of the large dunefields. Although there is evidence for downwind extension of longitudinal dunes (e.g. dunes extending from the Strzelecki to the Simpson dunefields over the Sturt's Stony Desert gibber plain), there are insufficient deflation basins and other sediment sources at the upwind margin of the dunefields to account for the present volume of dune sediments (Hesse 2010).

Most of Australia's dunefields today receive little or no new supplies of sand from fluvial sources; semi-annual and decadal weather-related cycles of sediment movement largely rework existing deposits (Hesse 2010).

Dune Formation and Australia's Changing Climate

Since the Miocene, the Australian continent has experienced increasing aridity. Superimposed on this general trend there have been climatic cycles (warmer/cooler, wetter/drier, and shifts in climate zones) related to the world's glacial cycles. As a consequence, the Australian continent has seen progressive landscape change, including the loss of fluvial drainage networks, the development of playa lakes, and the spread of aeolian landforms (including the evolution of the dunefields).

A Pleistocene age of the dunefields is now accepted; luminescence dates and cosmogenic nuclide burial ages on Strzelecki Desert and Simpson Desert dunes (Fitzsimmons 2007, Fujioka et al. 2009) have pushed back the age of earliest formation of at least some dunefields to the mid-Pleistocene (≥1 Ma). During the glacial stages of the Quaternary climatic cycles, there have been increases in aeolian sediment transport and expansion or shift in the arid zone. Dune formation during those times has left dunefields extending not only across Australia's present drylands, but also extending into places that are currently too humid for dune formation. Once formed, most dunes have experienced vegetation and occasional pedogenesis. Dune movements can be limited if there is insufficient sediment supply, and this can be the result of vegetation cover and/or and a consequence of increasing degrees of armouring of the desert surface (Hesse 2010).

The orientation of longitudinal dunes reflects the long-term resultant sand drift direction (roughly speaking, the direction in which wind blows aeolian sediments, taking into account the wind's varying strengths and directions over time) at the time of their formation. Most Australian longitudinal dunes have undergone little modification of orientation after their initial formation. The arid glacial stages, during which dunes were developed, were accompanied by changes in wind circulation patterns, which affected the orientation of the sand dunes. The anticlockwise whorl of longitudinal dune orientations and its general similarity to the winds of the sub-tropical high-pressure system has long been recognized, and it was previously thought that dune orientation indicated but little change between Pleistocene wind patterns and today's. However more detailed examination (Hesse 2010) demonstrates that continental dune orientation is more complex, with a double centre to the whorl, and that furthermore the differences in orientation between dunes and modern wind patterns are more variable than was previously recognised. In some regions there is close agreement, and in others there is divergence and even opposed wind and dune directions. There is no simple, continent-wide displacement of dune orientations, and therefore simple latitudinal shift of circulation patterns, as has been frequently postulated, is not an adequate explanation of the observed patterns.

Nomenclature and Definition of Dunefields

One problem in assessing the Australian sand deserts is that not all dunefields have common or widely used names (Hesse 2010). For example, the Great Victoria Desert dunefield extends from Western Australia into South Australia. The extension is not normally included in the Great Victoria Desert but has no acknowledged name even though it is large enough to constitute a sand sea in its own right. The most common alternative to established geographic names is the nomenclature established under the IBRA bioregions system; it is widely used in Australian conservation management. Unfortunately, the IBRA regions do not correspond to geomorphic boundaries, and use names which are different to the dunefield names (Hesse 2010). Subsequent to the publication of Hesse (2010), an updated physiographic region dataset (Pain et al. 2011) became available, parts of which address dunefield boundaries more explicitly.

Simpson Desert Dunefields and Floodouts

The Simpson Desert is a large dunefield located in the north and north-west sector of the Lake Eyre Basin (see Hesse 2010, his Fig. 1). It is the fourth largest Australian desert (176,500 km^2), extending ~600 km north-south and ~350 km east-west around a central point ~360 km southeast of Alice Springs. It contains the world's longest parallel sand dunes (some up to 200 kilometres in length). The dunes are asymmetric in cross-section (steeper eastern slopes), and vary in height from 3 metres in the west to around 30 metres on the eastern side. The largest and most famous dune, Nappanerica, (Big Red) is 40 metres in height. They are usually regularly spaced apart; dune height and interdune spacing are usually related. The dune sediments are dominated by quartzose sand varying in colour from pale buff near rivers and playas to deep red or red-brown elsewhere. The sand is predominantly rounded and sub angular siliceous grains, well sorted on the active crests but less so in the interdunes. Dune sediments may have a clay component especially in palaeosols, and the broad interdune corridors are often also more clay-rich than the dunes. Dune crests tend to be narrow, although this depends on the location within the dunefield and broad-crested dunes may reflect local runoff characteristics (Hesse 2010). The dunes are often well-vegetated which is held to be a factor in their lack of dune mobility, however drought and grazing can reduce vegetation and promote sediment mobility (Hesse 2010). The sand ridges have a trend of SSE-NNW. The Simpson Desert is separated from the Strzelecki Dunefield by Sturt's Stony Desert.

In the Simpson Desert's northern and north-west areas, the sand-bed rivers of central Australia flood out (the channel diminishes and disappears, and flow continues as unconfined sheetflow; see *3.8 Watercourses: Floodouts*). These are terminal floodouts: the river terminates within the dunefields (Fig. 6). These rivers benefit from arising in the Amadeus Basin ranges (see *3.6 Uplands*) whose location

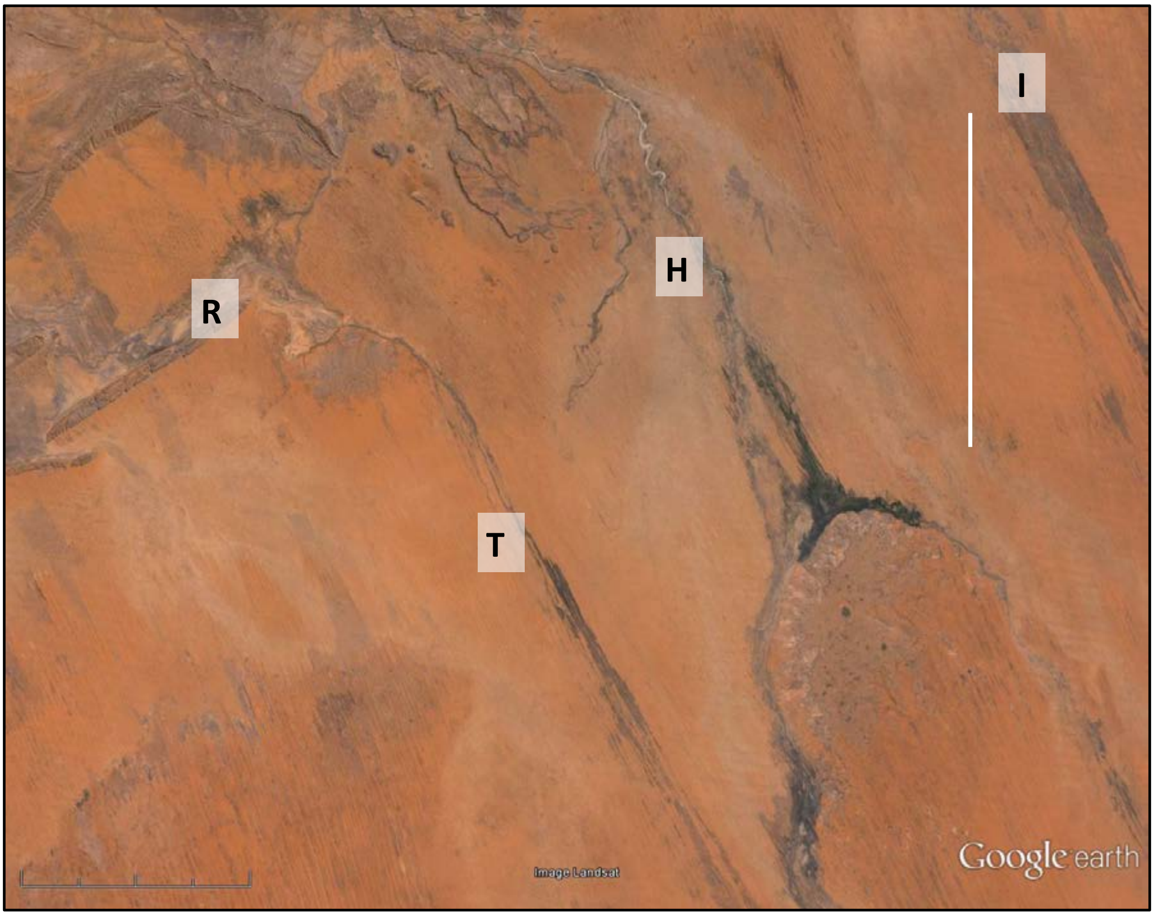


Fig. 6 Floodouts amongst the northwestern Simpson Desert dunefield

I, Illogwa Creek floodout; H, Hale River floodout; T, Todd River floodout; R, Rodinga Range; Google Earth image, north to top, white scale bar = 30 km.

occasionally receives substantial rainfall, and whose geological structure and tectonic history permits a well-integrated drainage network that delivers large volumes of water into the Simpson Desert. Consequently, the floodouts support biologically productive local ecosystems. Additionally, they represent the remnants of the previous drainage network which once drained into Lake Eyre (Craddock et al. 2010) but was subsumed by the development of the dunefield.

The Simpson Desert is itself an indicative area from which places can be found that exemplify the dunefield's heritage values. Within the Simpson Desert, a number of watercourses flood out: the Finke River, Todd River, and Hale River may be the most familiar names, but floodouts enter the dunefield all along its northern boundary. Together, the floodouts constitute an indicative area from which places can be found that exemplify their heritage values. It is possible that a place may be found that combines both dunefield and floodout heritage values. On the other hand, it is possible that the best development of longitudinal dunes is away from fluvial influence. Further investigation is required to determine where the best examples of dunefield floodouts and Simpson Desert dunes are

Table 10 The Simpson Desert dunefield, and the floodouts in its northwestern sector.

	Place	Floodouts and the Simpson Desert	
	Theme (subtheme)	Sand Deserts (basin setting)	Watercourses (floodouts)
NHL Criteria	Events and Processes	Dune formation from underlying fluvial/lacustrine sediments marks a dramatic landscape shift due to increasing continental aridity. The geometry of spacing, height and length are interrelated and the dunes show marked asymmetry with steeper eastern slopes, both reflecting aeolian processes. Sand colour, dunefield boundaries and dune disposition reflects sediment source and transport directions.	The floodouts are a physical demonstration of the late Cainozoic's reduced river discharges. The floodouts play an outstandingly important role in the area's natural history. In good rain years, water reaches the floodouts, recharging local groundwater and supporting local ecosystems. They host biologically rich ecosystems within the otherwise harsh Simpson Desert.
	Rarity	The world's longest parallel sand dunes.	The landform combination of large rivers flooding out into the interdune corridors of longitudinal dunes is unusual. There are a number of floodouts in the north western corner of the Simpson Desert, but none have their geomorphology heritage values recognised.
	Research	The Simpson Desert has already been important in studies in	There has been relatively little research into floodouts dominated by

		sedimentology, geomorphology and palaeoclimatology. Further investigation of dune type and distribution is likely to yield information on factors influencing dune formation, and the palaeogeography of the area. The variety of different crest types may indicate different kinds of longitudinal dune, or areas of the dune fields that have different histories of landscape evolution.	transmission loss; the Simpson Desert floodouts have the potential to provide good research sites. Floodout sediments, and their interaction with aeolian sediments, have outstanding potential to reveal information about Australia's climatic history in an area where the information is otherwise sparse.
	Principle characteristics of a class	The well-developed dunefield shows excellent examples of longitudinal dunes with a variety of crest types; it is shown in geomorphology reference works. The region includes extensive longitudinal and reticulate dune systems, plus associated landforms – gibber plains, outcrops of underlying Eromanga Basin rocks onlapped by the sand.	The north western corner of the Simpson Desert dunefield will contain places that express the principal characteristics of terminal interdune floodouts.
	Aesthetics	A spectacular Australian landscape.	The vegetated interdune corridors which receive the last floodwaters of central Australia's sand-bed rivers are extremely beautiful after a wet year.
	Creative or technical achievement	Pioneering geologist Reg Sprigg, who (with his wife Griselda and their two young children) made the first motorised crossings of the dunefield (north to south and west to east), the first of which was in 1962.	
	Social	It is the iconic sand desert of Australia.	
	Significant people	Pioneering geologist Reg Sprigg did some of the earliest work in this area's geology.	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y The longitudinal dunes are unusual on a world scale.	Y The floodouts are unusual on a world scale. (Although the concept of desert oases is known from the Middle East, those oases are geologically different.)
	Unusual (Australia)	Y	Y Of the Australian sandy deserts, only the Simpson and the Strzelecki receive flows from such substantial rivers. Only a few parts of the Simpson Desert benefit from the floodouts, so they are special even within the Simpson.
	Multiple geomorphic themes	Y: Sand Deserts (basin setting), and Watercourses (floodouts), as shown in this table; also • Watercourses (sand-bed rivers); • Regolith (silcrete) stony gibber uplands in the upslope dunefield margins;	

		• Uplands – small uplands within the dune fields (Andado, Allitra Tableland), which are important to local ecosystems • the Uplands are probably created by Tectonics (flexure) • Upland crests preserved by stony gibber (Regolith, silcrete).
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y - Old oil exploration tracks and/or seismic lines occur in places, and where still used as off-road tracks local erosion and dune crest lowering occurs, however their spatial scale is small in comparison to the size of the dunefield.
	Cross-reference to other places	Amadeus Basin/Rodinga Range; Lake Eyre
	Status	Indicative area

Cooper Creek distributaries and the northern Strzelecki Desert

The Strzelecki Desert is an extensive dunefield stretching from just east of the South Australia-New South Wales border to the gibber plains of Sturt's Stony Desert (Fig. 7, and see Hesse 2010, his Fig. 1). It extends ~530 km north-south and ~90 km east-west from a central point ~150 km south of Innamincka. Topographically, the Strzelecki Desert divides into the Benangerie Ridge (an elevated area covered in short longitudinal dunes and small deflation pans), and the Strzelecki Plain (a low-elevation area of longitudinal and compound dunes) (Fig. 7, and see Fig. 5). The Benangerie Ridge is to the east of Strzelecki Creek, and the Strzelecki Plain is to its west. The area is bounded to the north and west by elevated gibber plains of the Innamincka Dome and Sturts Stony Desert, and to the south by the Frome, Callabonna Blanche, Gregory playa lakes. The dunefields are strongly orange-red coloured on the Benangerie Ridge, but paler and more variable in colour in the Strzelecki Plain, reflecting differences in sand grain provenance. The Strzelecki Plain hosts the Cooper Creek Fan, a low-angle alluvial fan across which the various channels of Cooper Creek flow. The Cooper Creek Fan has evolved over many tens of thousands of years (at least), and reflects a long history of co-creation of fluvial and aeolian features. Landscape features of the Strzelecki Plain have been investigated by e.g. Callen and Bradford (1992), Gravestock et al. (1995), Fitzsimmons (2007), Cohen et al. (2010), and Wakelin-King (2013). In the Strzelecki Plain, Cooper Creek becomes distributary across the fan. One branch (Strzelecki Creek) flows south-south-west towards Lake Blanche. Two other major distributaries are Cooper Creek Main Branch, which eventually flows towards Lake Eyre, And Cooper Creek North West Branch, which feeds the Ramsar-listed wetlands in the Coongie Lakes area. Cooper Creek displays a complex fluvial geomorphology, including anabranches, waterholes, freshwater lakes, and swamps.

Fig. 7 Topography of the northwestern Strzelecki Plain

This digital elevation model image has high elevation pale grey, grading through green, down to low elevations dark blue. Black line is present-day Cooper Creek and its distributary Strzelecki Creek.
Red north arrow = ~50 km.
DEM by Wakelin Associates from SRTM data.

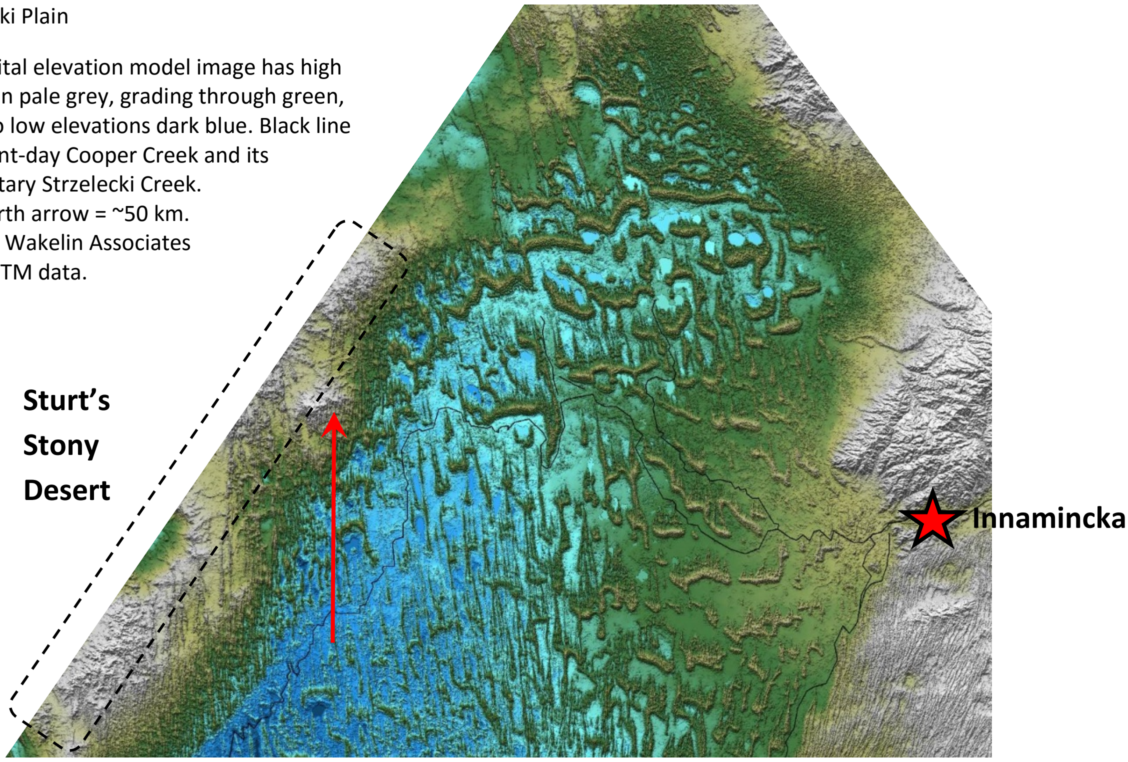
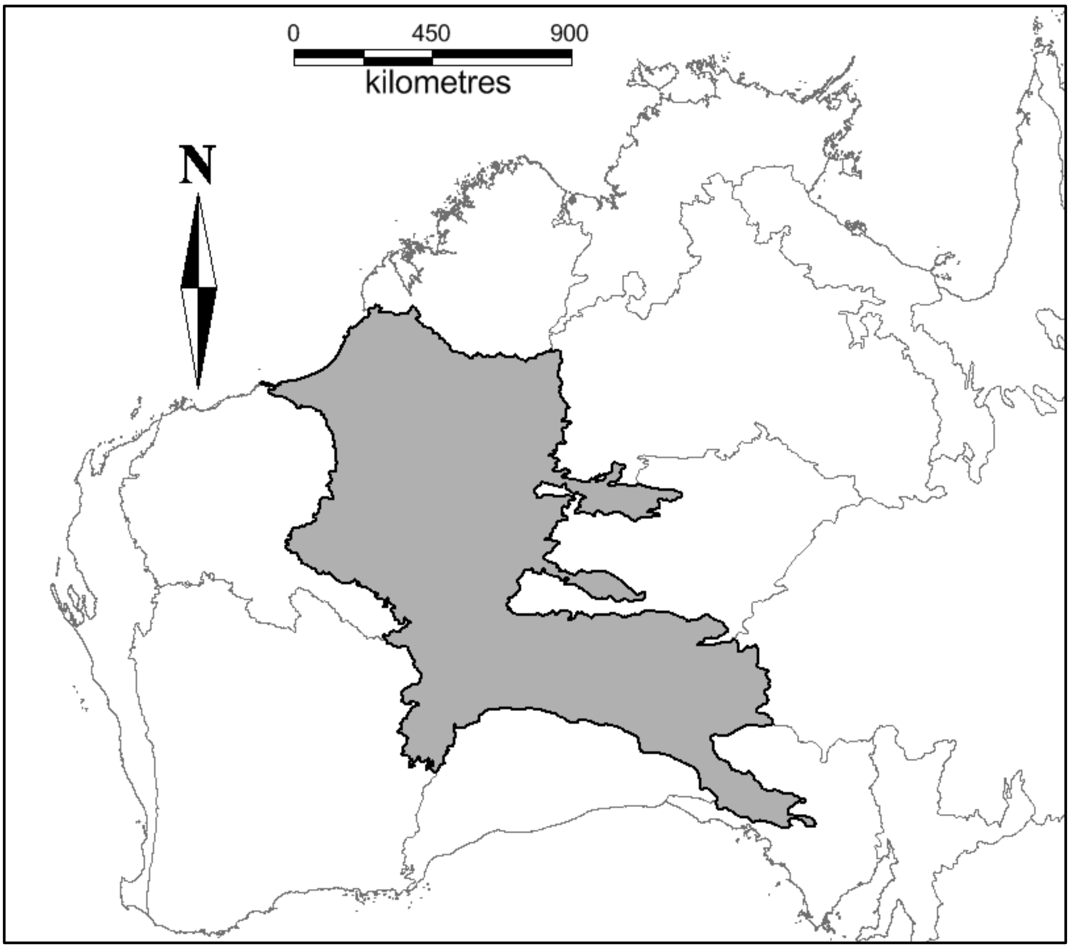


Table 11 Cooper Creek (NW Branch) in the Strzelecki Desert

	Place	Cooper Creek Northwest Branch in the Strzelecki Desert dunefield	
	Theme (subtheme)	Sand Deserts (basin setting)	Watercourses (freshwater basins)
NHL Criteria	Events and Processes	The Strzelecki compound dunes demonstrate complexly interlinked fluvial and aeolian processes taking place in a context of progressively increasing aridity overprinted by global glacial cycles. Sand colour, dunefield boundaries and dune disposition reflects sediment source (regolith versus exogenous alluvium) and transport directions.	Cooper Creek's biological richness in waterholes, lakes and swamps exist because Cooper Creek's drainage network extends into the subtropics, so the distal sections of the river are in a position to receive large volumes of water. The aquatic assets include refuge waterholes, and the lakes are Ramsar-listed wetlands.
	Rarity	This combination of landforms, is very unusual. The heritage values of its geomorphology have not been recognised.	Such permanent water in the driest part of Australia is extremely unusual, and only possible because of a particular combination of landforms. The combination of landforms linking dunes, lakes, and rivers, is very unusual.

	Research	Important in studies in geomorphology and palaeoclimatology, showing climate cycles (aridity with aeolian activity vs. fluvial activity). Unusually good access to study sites (because of petroleum industry infrastructure). Very well researched by several research groups.	The origin of the lakes and swamps is yet to be described in peer-reviewed literature. The drainage network is complex and flood peaks can be routed around in several different ways, an unusually complex hydrology.
	Principle characteristics of a class	Compound dune features and their relationship to sediment supply are well displayed, and linked to detailed research on the changing climates during sediment deposition.	The lakes and their relationships with the drainage network are excellent examples of an unusual landform suite.
	Aesthetics	-	The lakes have high aesthetic value.
	Creative or technical achievement	-	-
	Social	-	The waterholes and lakes and the ecosystems that they support are a tourist drawcard; they are socially and economically important.
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y – Compound dunes of this type are likely to be unusual on a world scale. The river's complex geomorphology (distributary channel network, waterholes, swamps, and lakes) and interaction with dune landforms is unusual on a world scale.	
	Unusual (Australia)	Y	
	Multiple geomorphic themes	Yes: Sand Deserts (basin setting), Watercourses (freshwater basins), as shown in this table; also Watercourses (anabranching rivers, palaeodrainages, and playa lakes).	
	Value with respect to significance threshold	Clear	
	Integrity	Mostly good, although there are prominent roads and some industrial landscapes, connected with the petroleum industry.	
	Authenticity	Y	
	Cross-reference to other places	In the upstream direction, this site links to *Innamincka Dome with Cooper Creek valley*; in a downstream direction, this site links to *Kati Thanda - Lake Eyre*.	
	Status	Indicative area	

Fig. 8 the Sandlands Province (after Pain et al. 2011)



Great Sandy and Great Victoria Dunefields: Knowledge Gaps

The Great Sandy Dunefield (Western Australia) and the Great Victoria Dunefield (Western Australia and South Australia), as defined in Hesse (2010, his Fig. 1) are not rigorously defined in terms of their geography. Locations encompassing these areas (or parts thereof) may also be known as or include the western Australian Desert Rangelands Natural Resource Management Board sub-region; the IBRA bioregions of the Great Sandy Desert, the Gibson Desert, the Little Sandy Desert and the Great Victoria Desert; and the Sandlands Physiographic Province of Pain et al. (2011) (Fig. 8).

The Great Sandy and Great Victoria dunefields are vast. The Great Victoria Desert is the biggest desert (as defined geographically) in Australia, being >700 kilometres wide with an area of 424,400 km^2 ; it extends from the Eastern Goldfields region (WA) to the Gawler Ranges (SA). The Great Sandy Desert is to the north east of Port Hedland. It is the second largest desert in Australia, and encompasses an area of 284,993 km^2. Because of their mineral resources, their geology is better moderately well known (for example the Telfer gold mine site is on the southwest edge of the Great Sandy Desert). The subsurface geology of the palaeovalleys has been the subject of investigation (e.g. Magee 2009). However, these areas are extremely remote and thinly populated, and there is little detailed information about their geomorphology. For that reason, they are presented here as knowledge gap areas.

Pain et al. (2011) describe the Sandlands Province as consisting of low plateaus, sand plains and dune fields, and the more detailed physiographic regions describe east-west longitudinal dunes, low tablelands and ridges, salt lakes and sandy or stony ferruginous plains. Both dunefields occur in a ridge-valley setting (Hesse 2010) and are characterised by various mostly longitudinal dunes. The descriptions of their surficial geology (stony, ferruginous) and the regolith studies that have been undertaken in the area (Anand and de Broekert 2005) indicate that deep weathering profiles are present. Various playa lakes occur in the area, including some that are likely to be palaeodrainages. Therefore, the geomorphic themes relevant to these areas are sand deserts (ridge-valley setting), regolith, and watercourses. Beyond that, there is insufficient information available to be able to assess their landforms against NHL criteria.

	Place	Great Sandy Dunefield
	Theme (subtheme)	Sand Deserts (ridge-valley setting)
NHL Criteria	Events and Processes	?
	Rarity	?
	Research	?
	Principle characteristics of a class	?
	Aesthetics	?
	Creative or technical achievement	The Canning Stock Route crosses part of the Great Sandy Desert; it would have been a significant feat to establish a stock route through this country.
	Social	?
	Significant people	?
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	?
	Unusual (Australia)	?
	Multiple geomorphic themes	?
	Value with respect to significance threshold	?
	Integrity	?
	Authenticity	?
	Cross-reference	?
	Status	Indicative area; knowledge gap.

Table 12 The Great Sandy Dunefield

Table 13 The Great Vistoria Dunefield

	Place	Great Victoria Dunefield
	Theme (subtheme)	Sand Deserts (ridge-valley setting)
NHL Criteria	Events and Processes	?
	Rarity	?
	Research	?
	Principle characteristics of a class	?
	Aesthetics	?
	Creative or technical achievement	
	Social	?
	Significant people	?
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	?
	Unusual (Australia)	?
	Multiple geomorphic themes	?
	Value with respect to significance threshold	?
	Integrity	?
	Authenticity	?
	Cross-reference	?
	Status	Indicative area; knowledge gap

3.3 Karst

In karst terrane, the topography is chiefly formed by the dissolving of soluble rock. It is characterised by disorganised surface drainage, and features such as sinkholes, sinking streams, closed depressions, subterranean drainage, and caves. Australian arid zone karst occurs in carbonates (limestone and dolomite). Elsewhere in the world, karst can also develop in even more soluble lithologies (gypsum and halite) under very precise conditions: sufficiently thick evaporite beds exposed at surface, preserved from total erasure by an arid climate, exposed to sufficient surface or subsurface water to form karst. Australia's surface geology and climate history precludes these conditions being met, and no evaporite karst is known in Australia.

(There is also pseudokarst, where similar hydrologic and morphologic features are formed by means other than bedrock dissolution, such as may occur in volcanic, permafrost or regolith contexts. It is not considered in this report.)

Karst features occur in many drylands around the world (Webb and White 2013); Australian drylands host extensive and important karst areas (the Nullarbor Plain and the Exmouth Peninsula), as well as an unknown amount of covered karst. Yet since karst requires water to dissolve carbonate rocks, it might be expected that in drylands, karst landscapes would be poorly developed. The low rainfall must inhibit karst processes, and the high evapotranspiration further reduces the effective precipitation. In fact, in every well-documented case, drylands karst developed either under a previous wetter climate or by hypogene processes.

Nevertheless, the karst landscapes in arid zones are not in a state of stasis; the karst features inherited from previous wetter climates are slowly modified by present-day processes. Calcite dissolution can occur when karst is flooded by rainfall undersaturated with respect to calcite; however the waters are usually in contact with the limestone for relatively short periods, so only limited solution occurs. Calcite dissolution can be aided by mixing corrosion (at the interface between water bodies of differing $CaCO_3$ saturations, thermodynamic conditions promote solution). One marked effect of aridity on karst is salt weathering, where salts (usually halite) crystallise within limestone pore spaces. Volumetric increases as crystal growth takes place wedges apart grains and fragments the rock. Limestones with substantial primary intergranular porosity are very susceptible to salt weathering. The rainfall regime (rain frequency and intensity) is also a strong influence on the importance or otherwise of salt weathering. Frequent low-intensity wetting and drying (e.g. showers of a few millimetres that evaporate almost as soon as they reach the ground, such as might occur in the Nullarbor Plain) allow salts to build up in the soil. It leaches through the upper layers of soil and limestone, precipitating salt crystals in the pore spaces of the cave walls beneath, and leading to various forms of salt weathering. In contrast, high intensity rainfall events flush salt through the soil before it builds up to high levels, so drylands areas like Cape Range in Australia, where a major proportion of the rainfall falls during cyclones, show little if any salt weathering.

Carbonate rocks in the drylands are frequently protected from both mechanical weathering and dissolution by a surface layer of calcrete, precipitated from groundwater and soil water due to the high levels of evaporation that characterise hot drylands. Other processes of mechanical weathering that are typically ascribed to drylands, particularly wind abrasion and daily heating and cooling of rocks, affect only the surface karren features, and so seem to have little impact on arid carbonate karst.

Where karst terranes are overlain by later deposits, it is known as covered karst. Although access to and visibility of the karst can be poor, value lies in the juxtaposition of karst and later deposits which will contribute to better understanding of an area's landscape evolution. In Australia, covered karst is known from the Barkley Tableland (Grimes 1988, Shannon 2010), where it is overlain by black vertic soils (see *3.7 Regolith: Vertisol Plains and Slopes*).

Australian drylands karst is located in harsh and remote locations, limiting access to researchers. The exploration and documentation of the Australian drylands karst regions have been done by mostly volunteer speleologists (Fig. 9) with minimal institutional or government support. Nevertheless Cape Range, the Nullarbor Plain and other karst areas have been and continue to be extensively explored and studied,

Fig. 9 Speleologists at work on the Nullarbor Plain. Photo: Nicholas White.

addressing the still significant knowledge gaps. Exploration is increasingly effective assisted by technological developments in navigation, digital mapping (GIS) and new dating techniques. Amateur specialist speleologists work in partnership with academic researchers to reveal the tectonic and climatic history of the karst areas, and the evolution of both landforms and biota associated with the cave systems.

Professor Joe Jennings was a prominent early researcher in Australian karst (Jennings 1967, Jennings 1971, Jennings 1985). Aside from material cited above, other references relevant to Australian arid karst include Lowry (1967), Lowry and Jennings (1974), Bowler (1982a), Davey (1986) , James (1989), Davey et al. (1992) , Allen (1993), Twidale and Campbell (1993), Drysdale and Gale (1997), Gale et al. (1997), Gillieson (1997), Doerr and Davies (2007), Hou et al. (2008), and Humphreys et al. (2009).

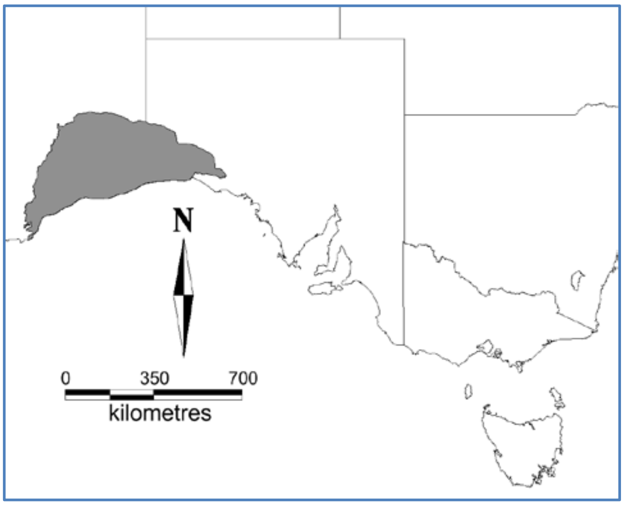
The Nullarbor Plain

The Nullarbor Plain (225,600 km^2; more than 3 times the area of Tasmania) (Fig. 10) is the largest karst area in Australia and one of the largest single karst areas in the world. It is a relatively flat, mostly treeless limestone plain (Fig. 9), extending ~790 km east-west, and ~340 km north-south. It is recognised in the IBRA bioregionalisation scheme as the Nullarbor IBRA region; its physiographic regions (as per Pain et al. 2011) are the Carlisle Plain the north, the Bunda Plateau (the largest and most well-known), and to its south the smaller and lower-elevation Roe and Israelite Plains. The Bunda Plateau is bounded along its southern edge by a long line of cliffs and escarpments: the Bunda (or Nullarbor) Cliffs, the Hampton Bluffs, the Baxter Cliffs, and the Wylie Escarpment (see *3.4 Arid Coasts*).

The Nullarbor's solutional karst features consist of about 100 larger caves, > 150 collapse dolines and over 4000 smaller features (generally blowholes and small shallow caves). Some 20 larger caves reach the water table and have extensive flooded passages which have been explored by cave diving teams. The features occur in bands parallel to but some distance from the coastline (Burnett et al. 2013) The features are substantial and extensive, yet in comparison to the size of the Nullarbor itself they are relatively small. The lack of more and better-developed surface and underground karst in the Nullarbor are not due to aridity: the climate was warm and wet in the past, when the Nullarbor's extensive horizontal phreatic system formed (Lipar and Firk 2015, Sniderman et al. 2016). Rather, they are the result of lithological and topographic characteristics (a highly porous calcarenite with limited jointing and few inception horizons, uplifted and flat) that discouraged concentration of runoff, and so inhibited karst development even under favourable climatic conditions.

The rocks forming the Nullarbor Plain are layers of Palaeogene limestones deposited as seafloor sediments; they are bioclastic calcarenites (sand-sized grains composed of

Fig. 10 The Nullarbor Plain



shell and other biological carbonates) with high primary porosity. The caves formed during the wetter climates that predate the present aridity (Webb and James 2006). Many began as flank-margin caves along the coastline of the time, in which mixing corrosion took place along an interface between saline groundwater and fresh meteoric water (Burnett et al. 2013). A series of major conduits developed during warm seasonally wet conditions of the Oligocene; they drained after the Nullarbor karst was uplifted in the late Miocene, and collapsed to form large passages and dome chambers that retain the general cave orientation. During the warm wet period of the late Pliocene (~5-3 Ma ago) shallow caves containing calcite speleothems developed. As the climate reached its present level of aridity ~1 million years ago, evaporite speleothems have formed (Webb and James 2006).

Since the uplift of the Nullarbor Plain, surface weathering rates have been exceptionally low (2 to 5 mm/kyr), inhibited by the indurated surface calcrete layer and the dry climate. Little surface solution sculpture, relatively few caves and no solution dolines formed over this time, and the Nullarbor karst largely retained its flat depositional surface.

The proximity of the ocean contributes salts into the system, which are important in past and present development of the karst features. Occasional high-intensity rain events result in a substantial, short-lived input of freshwater into the caves. This forms a surface layer up to two meters thick on top of the heavier saline water of cave lakes; mixing corrosion occurs at the interface (halocline) between the two water bodies and dissolves notches in the cave walls. Salt weathering is also of major importance on the Nullarbor Plain, because of the limestone's high primary porosity. Halite and gypsum crystallization within the pore spaces detaches particles from the cave walls and deposits these as sand on the cave floor. This process of crystal wedging is at least partially responsible for the extensive collapse that is a feature of most Nullarbor caves, and assisted in the development of the collapse dolines (Webb and James 2006), and forms tafoni on many cave walls as large irregular scallops (Lowry and Jennings 1974). Some caves contain formations composed of gypsum and

	Place	Nullarbor Plains
	Theme	Karst
NHL Criteria	Events and Processes	The distribution of karst features was determined by processes taking place on palaeoshorelines (flank margin caves), and so marks both climatic and tectonic history of Australia's southern margin. The types and quantity of karst features and relatively poorly developed surface features are the result of a particular set of circumstances, unusual in karst terranes. Salt weathering (crystal wedging, halocline corrasion) has been and is now an important process component.
	Rarity	The extent of the karst area and the evaporite speleothems are all rare. The low relief and distinctive vegetation are very unusual. The area's geomorphic value is not currently recognised in official schemes.
	Research	The Nullarbor's cave deposits contain important megafauna remains. The cave distribution is relevant to research in eustatic sea level change and continental evolution. Speleothem development is linked to climatic conditions; dating speleothems creates an important climatic record for the continent's southern margin.
	Principle characteristics of a class	The Nullarbor demonstrates karst modified by increasing aridity, and flank-margin caves developing into large conduits. The evaporite speleothems demonstrate the characteristics of a feature unusual in both its material (evaporite minerals) and its formative process (extrusion from the base). The caves, decoration, and dolines demonstrate salt weathering characteristics.
	Aesthetics	This is a stark and iconic Australian landscape.
	Creative or technical achievement	
	Social	The speleological community have undertaken collective self-organised and largely unrecompensed exploration and documentation by groups of individuals. Cave mapping and research has spanned the professional-amateur boundary, in which speleologists liaise with the academic research community.
	Significant people	
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y – One of the largest single karst areas in the world, the largest arid karst, the largest Tertiary-age carbonate platform.
	Unusual (Australia)	Y
	Multiple geomorphic or other themes	Also significant values in palaeontology, and biology (troglobitic fauna).
	Value with respect to significance threshold	Clear
	Integrity	Some pressures along the main highway, but unaltered in most places.
	Authenticity	Y
	Cross-reference: links to other place	Bunda Cliffs and the associated line of cliffs and palaeo-coastlines
	Status	Indicative area

Table 14 The Nullarbor Plain

halite, as stalactites, columns, crusts, curving crystal clusters and hair-like helictites. Some speleothems are composed of dark brown to black calcite, which are at present being overgrown and broken down into shards by salt crystallising in cracks.

The Exmouth Peninsula and Ningaloo Coast

The Exmouth Peninsula (including *inter alia* the Cape Range National Park, the Muiron Islands and the Ningaloo Coast) is a peninsula extending ~360 km along the western coast of Western Australia; the town of Exmouth is close to its northern edge. It is currently on the National and World Heritage Lists.

The carbonate rocks of Cape Range have experienced orogenic uplift and warping from the Neogene into the present. As a result of the elevated topography, the karst systems extend over a large vertical range (at least 300 metres) (Fig. 11): unusual in Australia's relatively flat continent. There is a high concentration of karst features, which are associated with troglodytic (subterranean) ecosystems of global importance. Karst processes at work here include active karst solution as a result of seawater incursion (rare in Australia, but globally a significant process), and erosion by sands and gravels washed into the caves.

The Ningaloo Coast is characterised by a number of biologically and structurally interconnected terrestrial, coastal and marine landforms, including wave-cut terraces, limestone plains, Pleistocene reef sediments, and the modern reef: a discontinuous barrier extending ~260 kilometres along the coast. The reef encloses a lagoon of variable width. The coral reef history of the last 26 million years can be seen in the terraces and fossil reefs which fringe the Peninsula, and the submerged fossil reef terraces which form the substrate of the modern reef. Spatial relationships (such as the juxtaposition of the modern Ningaloo Reef, and the late Pleistocene Tantabiddi terrace) contribute to the understanding of the mechanisms which led to the modern landscape character (Wyrwoll 1993). The landforms and their associated marine, terrestrial and subterranean ecosystems demonstrate a geological, hydrological and ecological unity which links the region's present ecosystem functions with its evolutionary history as a time-series of coral reefs and an evolving karst system.

Aridity in the hinterland promotes low river output and therefor clear water for coral reef development.

Much of the area is relatively undisturbed. Low visitation and limited development coupled with its isolation from large population centres contributes to the area's naturalness, the uninterrupted views of seascapes and the remote landscapes of the range and coastal plain.

Fig. 11 Rugged topography at Cape Range. Photo: Dragi Markovic

Table 15 The Exmouth Peninsula

	Place	Exmouth Peninsula (Cape Range, Ningaloo Coast and Karst)	
	Themes	Karst	Arid Coast
NHL Criteria	Events and Processes	The coast and karst features demonstrate a geological, hydrological and ecological unity which links the region's present ecosystem functions to its evolutionary history as a time-series of coral reefs and an evolving karst system.	
		Most of the geological and geomorphological features reflect a history of Neogene to present day uplift and warping .	
		The karst systems extend over a large vertical range, reflecting the uplift history.	Uplifted wave-cut terraces and fossil reefs , and submerged fossil reef terraces under the modern reef, reflect tectonic history.
	Rarity	The largest vertical range of karst in Australia. Active karst solution as a result of seawater incursion, and Cainozoic orogenic karst, are both rare in Australia.	Unusual juxtaposition of coastal and karst landforms on a passive continental margin.

	Research	Unusual trogloditic fauna associated with the karst. Spatial distribution of caves is likely to reflect aspects of landscape evolution.	Spatial relationships of ancient and modern coastal features contribute to the understanding of the landscape evolution of the west coast of Australia. Studies of ancient reef systems show that coral reefs have a level of resilience to extreme climatic events, but the effect on and hardiness of modern reefs is unknown. Studies of modern reefs over relatively recent geological time give better understanding of modern reef resilience.
	Principle characteristics of a class	A high concentration of karst features and associated subterranean ecosystems. Vivid Illustration the intimate ties between ecology and geology. One of the best Australian examples of seawater as an agent of karst solution.	The modern Ningaloo Reef is a discontinuous barrier extending ~260 kilometres along the coast, enclosing a lagoon of variable width. Coastal landforms include wave-cut terraces, Pleistocene reef sediments.
	Aesthetics	Recognised for its aesthetic values on its NHL listing.	
	Creative or technical achievement	-	
	Social	-	
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y	
	Unusual (Australia)	Y	
	Multiple geomorphic or other themes	Y: Karst and Arid Coasts, as shown in this table; also significant values in Biology (stygofauna).	
	Value with respect to significance threshold	Clear	
	Integrity		
	Authenticity		
	Cross-reference to other places		
	Status	Existing NHL and WHL; the Ningaloo Coast (including the Cape Range National park) is currently recognised on WHL for karst and biological values, and its other geomorphic values could be added to its listing.	

Covered Karst of the Barkley Plains

The Barkly Tableland's black soil plains are underlain by a thick limestone hosting a covered karst area (Grimes 1988) which extends from the arid /semi arid area into the monsoonal tropics of northern Australia. Only one main cave area is known, at Camooweal. The main cave development probably dates from wetter climates and higher water tables, with further development due to increasing aridity, low relief and the thick vertisol soils which appear to have restricted infiltration (Grimes, 1988).

The Barkly Tableland's well developed drainage system shows little expression of the solutional features in the underlying limestone; only isolated collapse dolines indicate karstification below. Access is difficult, and exploration and documentation are at an early stage.

The processes and relative timing of karst development and soil formation in this area is not currently known. There are likely to be spatial relationships between the drainage on the blacksoil plains and the underlying karst features; the vertisol's particular infiltration characteristics (see *3.7 Regolith: Vertisol Plains and Slopes*) may produce an unusual suite of karst features. One documented location is Alex 09 Cave, ~6 km from Alexandria Station, Northern Territory (Shannon 2010). (Cave data is held by the Victorian Speleological Association, www.vicspeleo.org.au, access to the cave is restricted and by permission of the landholders.) Here, a recently-collapsed doline cuts through the soil profile and leads into a cave in the underlying limestone. An exposure through the soil-rock interface may yield information about their potential causal relationships, and the relationship with the covered karst (Table 28).

3.4 Arid Coasts

The Australian drylands has an extensive coastal margin, as the arid zone extends right to parts of the continent's western and southern coastline. Coasts are not intrinsically arid landforms, however the hinterland's capacity to deliver sediment and freshwater to coastal and nearshore areas clearly influences coastal geomorphology, and this is significantly influenced by climate. An arid, flat hinterland has low-power streams with little output of freshwater or clastic sediments. The results are clear water (promoting coral reef development) and white sand, slow downwearing of coastal land surfaces (allowing uplift to produce cliffs), the dominance of evaporation rather than freshwater input in estuaries and lagoons (promoting stromatolite development in hypersaline pools), and a stronger influence of marine and coastal processes where rivers enter the sea (for example, in deltas).

The arid coastal areas in Australia fall into two major types: rocky, often cliffed coastlines, and sandy or beach coasts, sometimes with lagoons. Unlike the siliceous eastern coastline (where most of the Australian population lives), the arid coasts are dominantly calcareous or (in the case of the Pilbara coast) mixed siliciclastic and calcareous. The most common lithology exposed along the carbonate coasts is calcarenites (limestones composed of sand-sized carbonate grains), with the important difference that some (e.g. those forming the Zuytdorp Cliffs) are aeolian calcarenites (deposited in onshore dunes), whereas others (e.g. those forming the Nullarbor coastline) were deposited under shallow marine conditions. The different physical characteristics of the sediments resulting from these different depositional environments leads to different styles of cliff face.

The heritage values of Australia's rocky coasts (including arid coastal sites) was discussed in the Expert Workshop on Rocky Coasts convened by the Department of the Environment, Water, Heritage and the Arts in July 2009 and chaired by Peter Valentine from the Australian Heritage Council (Dickson 2009, Rosengren 2009). Coastal geoheritage in Western Australia was addressed in Brox and Semeniuk (2010). References containing relevant arid coast material include Lowry and Jennings (1974), Johnson (1982), Humphreys (1993), Wyrwoll et al. (1993), Semeniuk (1993; 1996), and Webb and James (2006).

Shark Bay and the Zuytdorp Cliffs (Western Australia)

Shark Bay (Western Australia) is located on the most western point of mainland Australia, in the transition zone between three major climatic regions and between two major botanical provinces. It is wide and shallow (10,000 km^2, with an average depth of 10 metres) and is divided by shallow banks. It has many peninsulas and islands, and a coastline over 1,500 km long. It is known for rich marine, shallow-marine and terrestrial ecosystems, including huge seagrass banks and the world-famous stromatolites (which represent one of the oldest forms of life on Earth). The Hamelin Pool contains the most diverse and abundant examples of stromatolite forms of the in the world.

In Shark Bay's hot, dry climate, evaporation greatly exceeds precipitation. The bay's salinity increases, while seagrass banks restrict tidal flushing through the bay. As a result, the shallow bays are hypersaline. At Hamelin Pool in the south of the bay, bacteria continue to build stromatolites that are over 3000 years old. Shark Bay's geomorphology is a direct contributor to the biological values for which it holds a World Heritage listing, and its geomorphological values could well be added to the

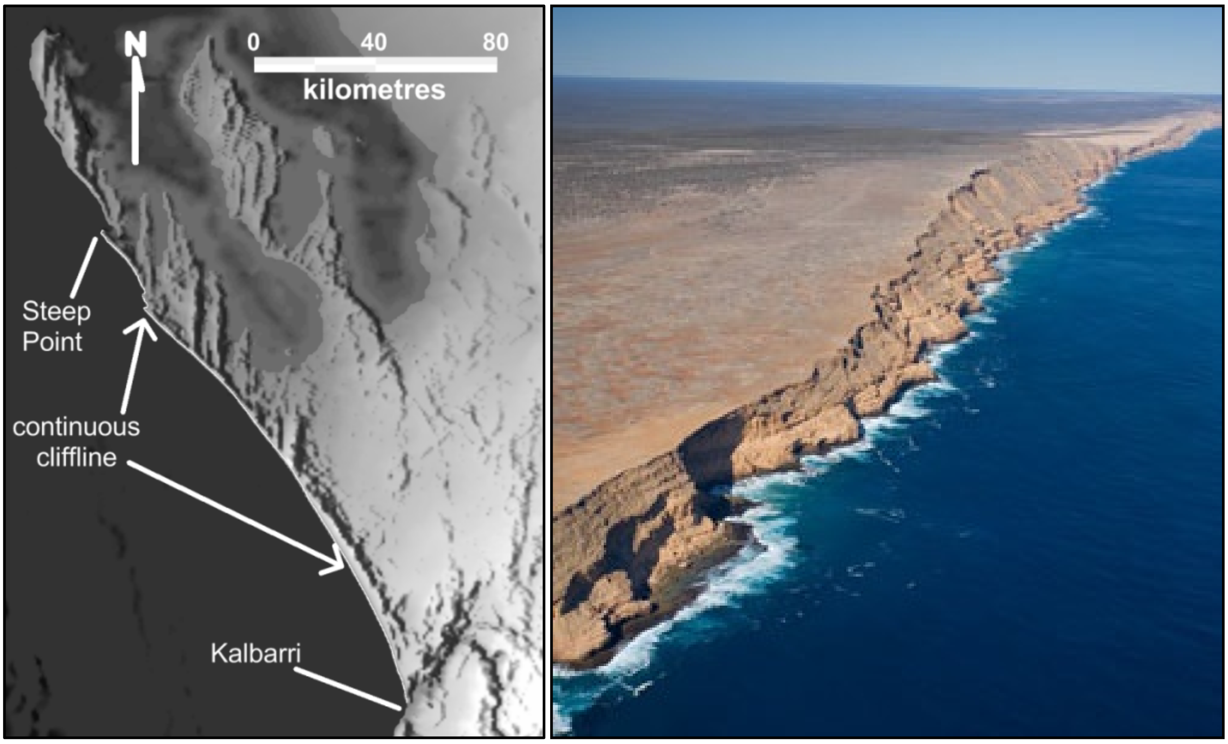


Fig. 12 The Zuytdorp Cliffs. Left, digital elevation model; right, photo: Nick Rains

qualities in its National heritage and world heritage listings. Coastal landforms in this area are documented in Eliot et al (2012).

The Zuytdorp Cliffs extend for 206 km along the Western Australian coast between Steep Point (Shark Bay) and the township of Kalbarri. These rugged and spectacular cliffs include a continuous cliff section 118 km long (Fig. 12) (Wakelin-King *in prep.*); they are a remote and little visited section of coastline. The lithology forming the cliffs is an uplifted Pleistocene (Hearty and O'Leary 2008) aeolian calcarenite with preserved dune features such as crossbedding, palaeosols and visible dune morphologies (ridges); this promotes a more topologically complex cliff face (in comparison to the Bunda and Baxter cliffs). The cliffs are forming under conditions that are wave dominated and also influenced by Western Australia's macrotidal to mesotidal conditions. They are of irregular height (mostly in the range ~80-180 m AHD); the maximum elevation near Womerangee Hill is ~280 m AHD (Wakelin-King *in prep.*).

Cliffed coasts in dune calcarenites are not rare in Australia but the Zuytdorp Cliffs are the most spectacular. Unlike Australia's other coastal calcarenite cliffs, the Zuytdorp Cliffs are not connected to hinterland karst.

Table 16 Shark Bay and the Zuytdorp Cliffs

	Place	Shark Bay and Zuytdorp Cliffs
	Theme	Arid Coast
NHL Criteria	Events and Processes	The exceptional biota are dependent on the geomorphic setting. Coastal landforms and location with respect to climate zones promote the sheltered and hypersaline qualities of the pools hosting stromatolite ecosystems. Cliff morphology relates to a tidal range and wave regime; cliff height relates primarily to uplift but there is a depositional surface component also. A lack of surface drainage from the hinterland is likely to assist in preserving the cliff edge.
	Rarity	Hamelin Pool's range of stromatolite forms is comparable to fossils in ancient rocks. A very long stretch of continual coastal cliff (118 km).
	Research	Research has focussed on the stromatolites; a better understanding of the landscape evolution of this coastline is desirable. The cliffs expose Pleistocene stratigraphy, and its relationship to the dominantly Holocene aeolianites elsewhere on the WA coast will improve understanding of landscape evolution. The absence of karst in the aeolianite hinterland will be related to some aspect in which this landscapes evolution differs from the development of Australia's other aeolianite coasts.
	Principle characteristics of a class	-
	Aesthetics	Visually spectacular rugged coastline.
	Creative or technical achievement	-
	Social	-
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	Y
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference	-
	Status	Shark Bay is an existing NHL and WHL listing but the geomorphological values should be strengthened. The Shark Bay listed area currently includes a only small part of the Zuytdorp Cliffs, however the Cliffs as an entity could be added to the existing listing, for their geomorphic values.

Bunda Cliffs (South Australia)

The Nullarbor Plain's southern boundary is an 824 km long continuous scarp of coastline and palaeocoastline (James et al. 2006), comprising (east to west, Fig. 13):

- The Bunda Cliffs (sometimes referred to as the Nullarbor Cliffs), 209 km long from Head of the Bight in the east to Eucla in the west. The cliff line is continuous along a length of 181 km. Cliff elevations range from ~96 m AHD in the west to ~38-40 m AHD in the east. The cliffs face into the ocean.
- The Hampton Bluffs, a 295 km long palaeocoastline to the north of the Roe Plain, elevations ~80-100 m above sea level and ~60-80 m above Roe Plain.
- The Baxter Cliffs, a cliffed coastline 163 km long, greatest elevation ~95 m AHD in the west but mostly ~60-75 m AHD.
- The Wylie Escarpment, a 155 km long and ~80-140 m AHD in elevation palaeocoastline to the north of the Israelite Plain.

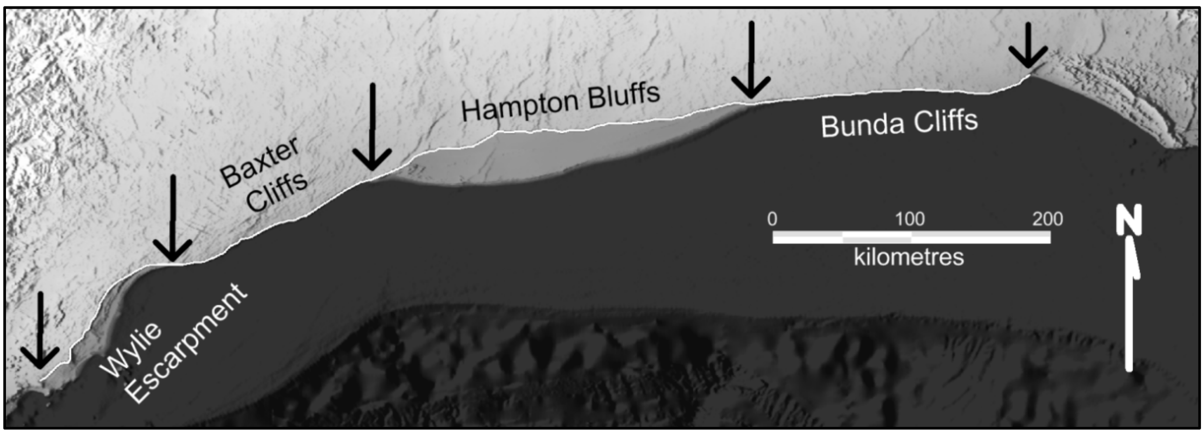
The length of these cliffs and scarps are taken from Wakelin-King (submitted; 2015), and are more accurate than those reported in White and Wakelin-King (2014).

The Bunda Cliffs, and particularly the spectacular continuous coastline, have strong aesthetic appeal and are one of the tourist sights of the Great Australian Bight (Fig. 14). The hostile coastline and stormy ocean are known in Australian history for their risk to shipping. The distribution of towns along the Great Australian Bight coastline demonstrate that the cliffs shaped exploration and settlement patterns during Australia's early European history.

Only limited research has been undertaken on the Bunda cliffs. They expose the geological units of the Nullarbor karst: the upper reddish brown Nullarbor and Abrakurrie limestones and the lower white Wilson Bluff limestone (Fig. 12), including

Fig. 13 The long scarp along the southern boundary of the Nullarbor Plain

Arrows indicate boundaries between the scarp sections.



the geologically significant type-section for the Wilson Bluff Limestone. The Bunda and Baxter cliffs along the Great Australian Bight, and their continuity with the Hampton Bluffs and the Wylie Escarpment, mark uplift processes at continental and at basinal scales (e.g. James et al. 2006, Sandiford 2007).

Two classes of geomorphic processes maintain the coastal cliffs. Oceanic processes are represented by cliff recession, as soft limestone facing into the immense Southern Ocean fetch is undercut by strong swell and storm waves. Landscape processes related to aridity are that in the hinterland, aridity restricts fluvial and hillslope erosion, so the surface experiences minimal subaerial downwearing. This allows the uplift surface to meet the coastline with unmodified elevation. Cliff recession isn't a rare process, but the combination of uplift, absence of subaerial downwearing of the hinterland, the relatively soft nature of the limestone, and the exposure to strong southerly swell and storm waves across the very long fetch of the Southern Ocean result in an excellent example of marine processes driving rapid cliff recession.

The Bunda Cliffs are significant in their own right, however they are an integral part of the Nullarbor Plain's very long southern scarp and it is likely that their significance could be folded into the general consideration of significance of the Nullarbor Plain and its attendant coastal components.

Fig. 14 The Bunda Cliffs. Photo: G Richardson.

Table 17 The Bunda Cliffs.

	Place	Bunda Cliffs
	Theme	Arid Coast
NHL Criteria	Events and Processes	The cliff marks uplift along the continent's southern boundary, relating to whole-continent rotation and to differential uplift from Cainozoic post-rift landscape development. Despite the soft lithotype, cliff edges are sharp and the cliff face is vertical; lack of surface drainage in karst hinterland preserves land's edge during uplift.
	Rarity	The 209 km long cliffed coastline in is one of the two longest arid coast cliff lines in Australia, and includes the longest continuous cliff line (181 km). This may be the longest continuous coastal cliff line in mainland Australia.
	Research	The datable interactions between deposition, sea level change, and uplift have provided valuable information on landscape evolution, and have the potential to repay further investigation.
	Principle characteristics of a class	An outstanding example of a wave-and storm-dominated coastline.
	Aesthetics	A visually spectacular rugged coastline.
	Creative or technical achievement	-
	Social	The hostile coastline and stormy ocean shaped exploration and settlement patterns in this area.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	Y
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Clear
	Integrity	Unaltered by human activity.
	Authenticity	Yes
	Cross-reference: links to other place	Nullarbor Plain
	Status	Indicative area; potentially, a component of the Nullarbor Plain heritage area.

Pilbara Coastline,(Western Australia): Ashburton River delta to De Grey River delta

The 530 km of Pilbara coastline (WA) between the Ashburton River and De Grey River deltas is a complex siliciclastic and carbonate sediment coastline formed during the Quaternary in the most arid part of the continent. Mixed coastal and terrigenous influences acted in a context of ancestral landforms. The area's stratigraphy and geomorphology indicate aridity strongly influenced the nature of the sedimentation, landform evolution, pedogenesis and diagenetic alteration of this coastal zone throughout its Quaternary geological period.

This arid coast is characterised by a range of features such as construction of arid zone deltas, delta destruction and sediment redistribution during times of sediment depletion, cyclone-induced erosion and sedimentation, mangroves and their associated sedimentary deposits, evolution of coastal groundwater hypersalinity, formation of salt flats, and precipitation and cementation to form beachrocks, high-tidal crusts and gypsum precipitates (Semeniuk 1996).

This is one of the few Australian arid siliciclastic coasts; its small carbonate component is unusual and arises from its climatic and geomorphic setting. Influenced by the warm waters of the Northwest Shelf, oolites formed and were deposited in Pleistocene and Holocene oolitic aeolian limestones. This lithology is very unusual for Australia: although the southern coastal margin from just north of Perth to Wilson's Promontory is dominated by discontinuous strandline calcarenite dunes, these are bioclastic rather than oolitic.

Table 18 The Pilbara Coast

	Place	Pilbara Coast
	Theme	Arid Coast
NHL Criteria	Events and Processes	The landforms are an integrated record of Holocene north-western shelf and arid hinterland sedimentation, landform development, and post-depositional alteration (pedogenesis and diagenesis).
	Rarity	The Pilbara coast is unusual in that it is siliciclastic (at the rest of the Australian arid coast is dominated by carbonates).
	Research	This complex terrigenous and carbonate coast has the potential to contribute information on the landscape evolution on the western side of the continent. Some documentation has taken place, but the area is complex and under-researched.
	Principle characteristics of a class	Further research is likely to demonstrate characteristics of arid-influenced deltas, mangroves, and evaporite (sabkha) landforms.
	Aesthetics	-
	Creative or technical achievement	-
	Social	-
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	-
	Unusual (Australia)	Y
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Likely
	Integrity	Y
	Authenticity	Y
	Cross-reference: links to other place	Pilbara Channel Iron
	Status	Indicative area

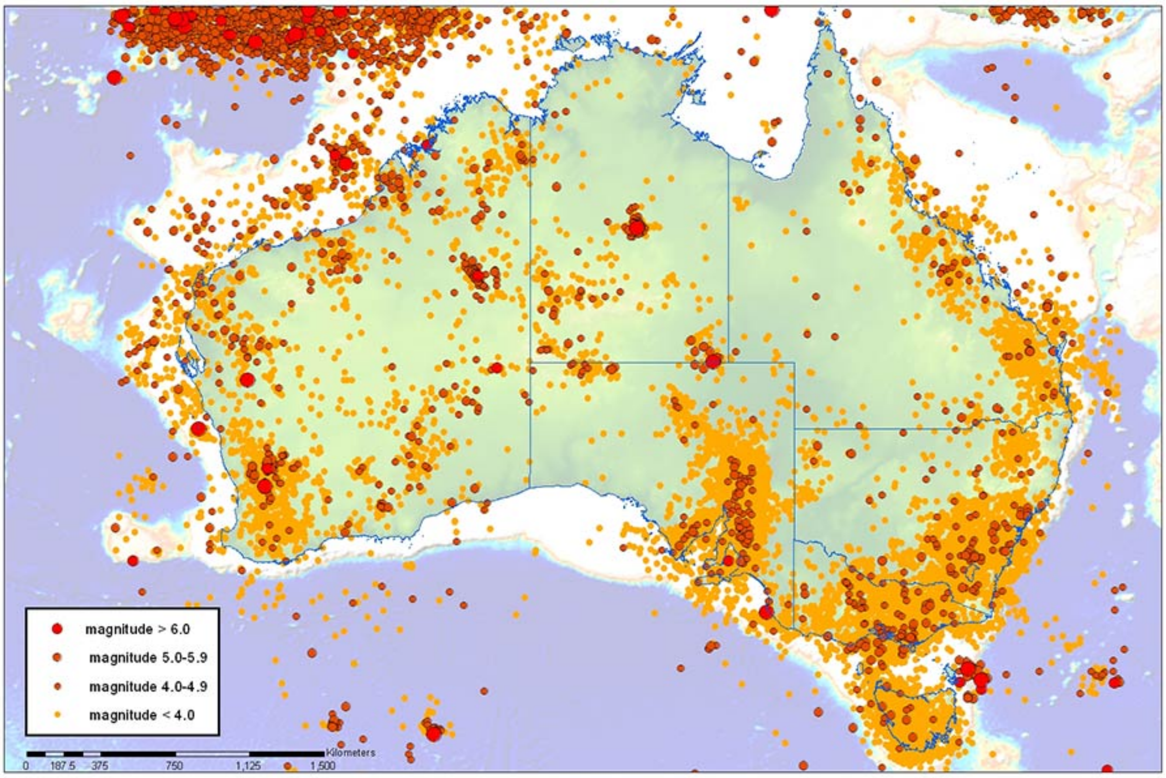
3.5 Tectonics

Tectonism is that behaviour of the Earth in which rocks bend, break, or move in response to the forces of plate tectonics. Worldwide, amongst the most visible tectonic processes are faulting, (such as the large earthquakes which devastated New Zealand and Japan in 2011) and uplift (such as that which raises mountains). Tectonic landscapes are those in which the effects of tectonism are expressed at the Earth's surface. Amongst the most well-known overseas tectonic landscapes are the trace of the San Andreas Fault and the Himalayan mountains.

It is a common misconception that Australia has no tectonic activity. It is true that the Australian continent has been relatively stable over geological time, however it is not tectonically inactive. Earthquakes have been recorded from locations all across Australia (Fig. 15), including several clusters of activity within the study area. The Australian plate's rapid rate of movement produces continental scale pressures, and the resultant tectonic activity affects modern landforms (e.g. Hill et al. 2003; Sandiford et al. 2009). Tectonic activities (whether ancient or geologically recent) which have expression in the geomorphology of the study area include uplift along faults, salt-influenced folding and uplift in a sedimentary basin, and two kinds of flexure: gentle folding of sedimentary basin rocks, and undulation of the Australian plate.

Fig. 15 Australian earthquakes, located, records to 2011

Map produced by Geoscience Australia and reproduced here under Creative Commons License.



References containing material relevant to tectonic landscapes in the study area include Alley (1998), Davey and Hill (2009), Gibson (1997), Hudec and Jackson (2007), Lindsay (1987), Marshall and Dyson (2007), Marshall and Wiltshire (2007), Quigley et al. (2006; 2007a; 2007b; 2010), Sandiford (2007; 2010), Waclawik et al. (2008), Wakelin-King (2011).

Fault Tectonics: the Flinders Ranges

Faulting is the movement of one body of rock with respect to another, along an approximately semi-planar surface. In Australia, fault movement is dominantly roughly vertical (uplift, subsidence), in response to the plate's current compressive stress regime. Uplift of fault-bounded blocks is one factor in the creation of some Australian ranges and uplands. Faulting and fault lines contribute aesthetic values to, and are important in the natural history of, fault-bounded uplands such as Uluṟu, Kata Tjuṯa or the Barrier Range, and have been one of the geological influences on the Amadeus Basin ranges.

The Flinders Ranges (South Australia) are formed in strongly folded Neoproterozoic to Cambrian rocks which display distinctive lithologically controlled strike-ridge topography (Fig. 16). The Ranges host a concentration of present-day seismicity (Fig. 15), and uplift along faults is a dominant factor in the area's landscape evolution. The amount and rate of uplift is unusual in comparison with the rest of Australia, and is expressed in a youthful topography of gorges, steep hillsides, scree and talus slopes, and coalesced alluvial fans along the rangefront. Although many of these features are found throughout the Flinders Ranges, the area near the Wilkatana Fan Complex (~12 km northwest from Quorn in the central Flinders Ranges) is chosen here for recognition because the geology and geomorphology has been documented in peer-reviewed research (e.g. Quigley et al. 2006; 2007a; 2010).

In the Quorn to Wilkatana Fan Complex area, the Flinders Ranges form part of a N-S trending upland system of prominent quartzite and sandstone hogback ridges with narrow intervening valleys. In the more easterly sequences, ridges are separated by broader valleys incised into dolomites and shales. Up to 600m of relative relief is present between the valley floors and ridgetops. The prominent western rangefront is notably steep and linear fault scarps. The fluvial valleys show a general pattern of broader, gently-curved cross-valley profile steeply incised by narrow v-shaped inset valleys. This pattern indicates a long period in which valley profiles adjusted to give continuity of slope from ridge to valley floor, followed by uplift and fluvial rejuvenation during which streams incised into the valley floor. (The literature speaks of U-shaped valleys incised by narrow V-shaped valleys, however the term 'U-shaped valley' has a meaning in glacial geomorphology, and is avoided here.) Hillslopes demonstrating mass-wasting processes (landslide scars scree slopes and talus breccias) also indicate recent uplift. Much of the uplift is post-Miocene and some is very recent: a particularly noteworthy outcrop shows Precambrian basement thrust over unconsolidated Cainozoic gravels.

Neogene and Quaternary coarse sediment alluvial fans flank both the steep and lower-angle slopes, particularly along the western range front. The Wilkatana Fan Complex may be amongst the largest and best developed alluvial fans associated with fault scarps in arid Australia. The fans preserve the sedimentary record of sediments coming off the Flinders Ranges: this is an integration of uplift-driven and climate-driven sediment transport events. The fans themselves are incised by modern and palaeo-channels which are partially filled by later sediments: a further integrated record of a complex landscape evolution.

Fig. 16 Incised fans in the Flinders Ranges. Photo: John Baker

	Place	Central Flinders Ranges and Wilkatana Fan Complex	
	Theme (subtheme)	Tectonic (Faulting)	Uplands
NHL Criteria	Events and Processes	Fault lines and tectonic landforms indicate continental-scale east-west compression. Complex cross-valley profiles shows recent uplift and fluvial rejuvenation. Landslide scars, scree slopes and talus breccias indicate uplift which is sufficiently recent that gravity-driven mass-wasting is an important hillslope process. A well-exposed reverse fault showing Precambrian rocks thrust over Cainozoic sediments. The combination of ranges and alluvial fans is an integrated record of active tectonics, sediment transport and rangefront deposition.	Rocky hillslopes shed water and deliver sediment to the surrounding plains, forming alluvial fans. Erosion-resistant quartzite is prominent through differential erosion.
	Rarity	Unusual and well-exposed reverse faults in which ancient (Precambrian) rocks are thrust over unconsolidated Cainozoic gravels. An unusual degree of vertical tectonism in comparison with the rest of Australia. In the Australian context, an unusually clear and linear fault scarp, and unusually well developed alluvial fans.	
	Research	The area reveals an unusual tectonic history, and are well-exposed integration of sedimentary record and landforms development which clarifies the differences between climatic and tectonic influences. The area contributes to understanding Australia's present-day stress field.	
	Principle characteristics of a class	Demonstrates characteristics of a young landscape (landslides, talus and scree, gorges).	Incised alluvial fans.
	Aesthetics	Visually spectacular fault line rangefront.	Hills, gorges, confined rivers have strong aesthetic appeal and are a marketed part of the tourist experience.
	Creative or technical achievement	-	
	Social		Part of an early debate on mechanisms of landscape evolution (scarp retreat vs. ground surface lowering).

	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	N
	Unusual (Australia)	Y
	Multiple geomorphic themes	Y, Tectonic (faulting), and Uplands as shown in this table; more broadly, the Flinders Ranges are also known for the Precambrian Ediacaran fossil fauna, and for hosting the ejecta of the Acraman Impact Structure.
	Value with respect to significance threshold	Likely
	Integrity	Despite historical overgrazing and problems with feral rabbits and pest plants, the geomorphological values are retained.
	Authenticity	Y
	Cross-reference	
	Status	Specific area

Table 19 The central Flinders Rangers and Wilkatana Fans

Salt Tectonics: Amadeus Basin

Under certain conditions of geology, thick layers of rock salt (halite) and other evaporite minerals can accumulate in sedimentary basins. The properties of these minerals are such that they undergo plastic deformation under certain conditions of tectonic stress. That is, they can be squeezed into new shapes and places. The Amadeus Basin geological province (central Australia) contains geological units (e.g. the Bitter Springs Formation) which include evaporite minerals. Amadeus Basin evaporites have long been known to have played a central role in the development of the basin (e.g. Lindsay 1987, Marshall & Dyson 2007), and salt cores are known from many of the Amadeus Basin's major anticlines, which have experienced episodic growth (Warren and Shaw 1995).

While the effects of evaporites on Amadeus Basin geology are known, their effects on the geomorphology of central Australia have received less attention. However, one of the characteristic structural types resulting from evaporite diapir movement is the salt anticline: uplift driven by salt diapirism is expressed as a doubly plunging anticline, very narrow but long (Hudec & Jackson 2007). This is generally a very apt description of the strike-ridge topography of some Amadeus Basin uplands. Particularly clear examples of this structural style are found in the Rodinga Range area (including the nearby Steele Gap). In the MacDonnell Ranges (the Amadeus Basin uplands closest to Alice Springs), there are not only long narrow folds but also nappe structures. (That is, the rocks there owe their disposition to faulting as well as possible diapiric uplift.) While this association between salt geology and central Australian geomorphology is as yet untested, it is a persuasive explanation for some of the differences between the central Australian ranges and other uplands such as the fault-bounded Barrier Range.

The Amadeus Basin's surface expression of deep crustal events is a value in the 'events and processes' NHL criterion. Two Amadeus Basin sites are discussed in the Uplands section of this report.

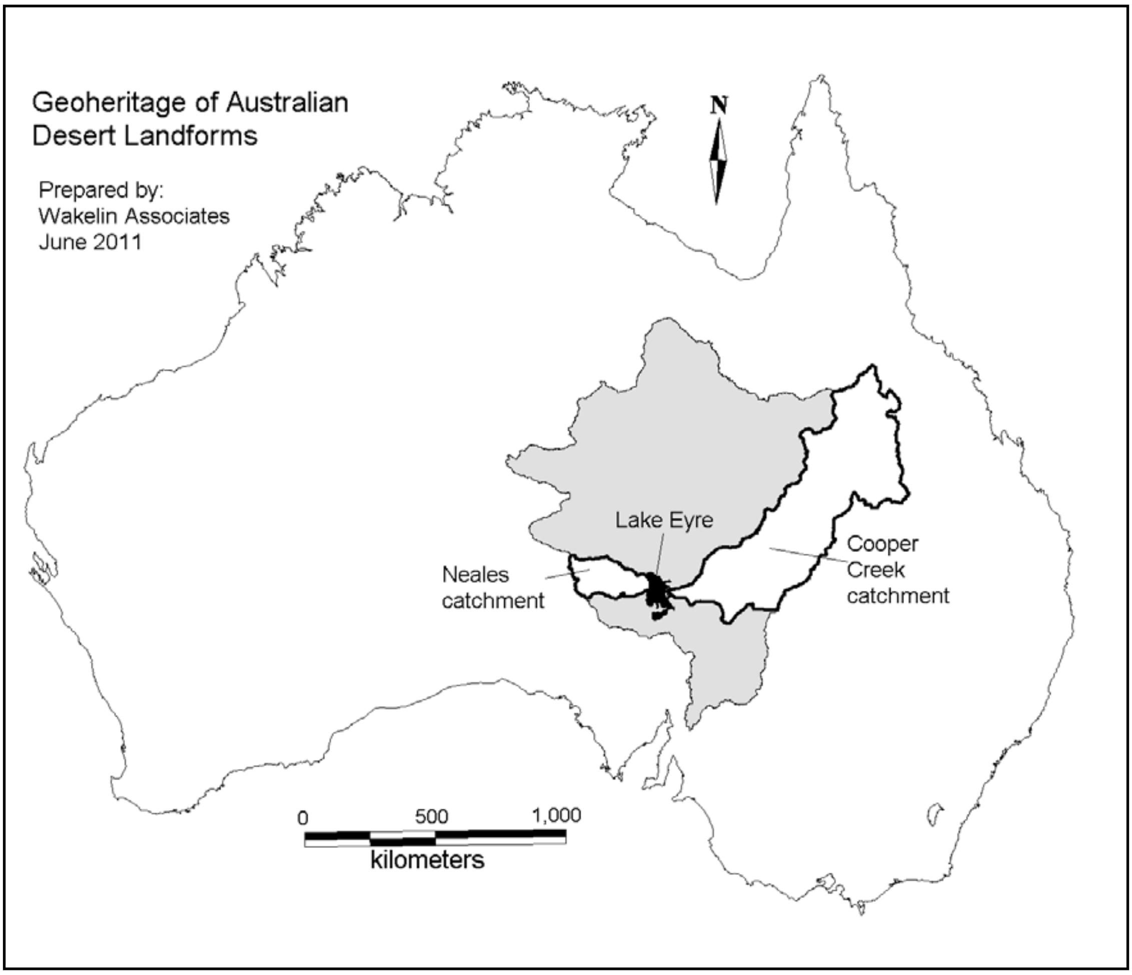


Fig. 17 The Cooper Creek and Neales River Catchments, in the Lake Eyre Basin

Flexure: Cooper Creek at the Innamincka Dome

Tectonic forces can bend and fold rocks in a variety of ways. Within the landscapes of the study area there are two types of broad open bends (dome-basin folding, and surface undulation), in this report grouped under the sub-theme flexure.

Low-amplitude folding of sedimentary rocks into broad domes and basins (anticlines and synclines) can occur during the development of large sedimentary basins. One of Australia's largest sedimentary basins is the Eromanga Basin (part of the Great Artesian Basin). Eromanga Basin rocks are exposed across wide areas of western Queensland, north-eastern South Australia, and parts of New South Wales and the

Northern Territory. Much of the surface exposure of Eromanga Basin rocks is within the catchments Lake Eyre Basin rivers such as Cooper Creek (Fig. 17).

Since its deposition during the Mesozoic, the Eromanga Basin has been gently folded into broad low-amplitude domes and basins. Usually such folding occurs below the ground's surface. In parts of the Lake Eyre Basin, however, dome crests are unusually well expressed at the surface, in part because their uplift is recent (having continued through the Cainozoic) and synsedimentary (Moussavi- Harami and Alexander 1998; Nanson et al. 2008). The other reason for the good expression of dome crests is the long exposure of these rocks to previous climates which has led to overprinting by weathering profiles including a substantial silcrete component. The silcrete forms a dense erosion-resistant gibber plain, which preserves the dome crests from erosion; planar silcrete outcrops preserve table-top hills (Fig.18). The basins are also well expressed at the surface, as broad shallow valleys which host the rivers of the Channel Country.

One of these anticlines is the Innamincka Dome, a broad physiographic high raised above the surrounding sand plains. It is approximately circular, ~90 km in diameter, with the township of Innamincka near the southwest (downstream) edge, and the Nappa Merrie waterhole at the upstream edge. The Innamincka Dome's gibber plain is a fine example of the type, including some excellent desert pavements. It is an iconic landscape, a significant component in local identity and tourist attraction. The stony uplands are bisected by the irregular valley of Cooper Creek, one of Australia's largest and most important inland rivers.

The primary geomorphic significance here is the spatial and temporal relationship between uplift and river processes, which is a critical determinant of fluvial style and therefore the rich ecosystems of Cooper Creek. The drainage network is antecedent to the dome's uplift, and fluvial downcutting is keeping pace with the uplift such that the river continues to flow through the dome. The Innamincka Dome defines Cooper

Fig. 18 Table-top hills in the Innamincka Dome

Creek's fluvial base level for hundreds of kilometres upstream, determining a low gradient and therefore promoting the anabranching fluvial style (e.g. Nanson and Huang 1999). The narrowing of Cooper Creek's broad floodplain at Innamincka Dome constrains the river to a single-thread channel, increasing stream power and removing the necessity for the river to anabranch. During flood conditions, large and deep waterholes are created, which are ecosystem refugia (Schmarr et al. 2012, Wakelin-King 2013).

The underlying geology and geological history of the Innamincka Dome is well-documented because this is one of Australia's first and best-developed hydrocarbon provinces. The area is associated with the work of Reg Sprigg (geologist) and the beginning of the Australian hydrocarbon exploration industry. The north-east of South Australia is also a focus of land management research (including ecology and geomorphology) by the South Australian Arid Lands Natural Resource Management Board (e.g. Schmarr et al. 2012, Wakelin-King 2013).

The several large waterholes in these reaches of Cooper Creek were undoubtedly highly significant in pre-European times because of the permanence of their resources in this otherwise very arid setting. They were significant during early post-European exploration: the Burke and Wills expedition ended here, with the Dig Tree at the eastern end of the Innamincka valley and Wills' grave at the western end. The combination of beautiful waterholes and historical interest has made Cooper Creek in the Innamincka valley a growing tourist location.

Cooper Creek and the Innamincka Dome occur downvalley from Cooper Creek (Windorah to Nappa Merrie), and upvalley from the Cooper Distributaries (Strzelecki Desert).

Table 20 Innamincka Dome and the Cooper Creek Valley

	Place	Innamincka Dome with Cooper Creek valley	
	Theme (subtheme)	Tectonic (Flexure)	Watercourses (Freshwater basins)
NHL Criteria	Events and Processes	Ongoing tectonism (folding) is expressed at the surface as stony desert uplands and wide river valleys. Bisection of the uplifting dome by the river valley indicates relative rates of uplift versus fluvial downcutting creates local base level which governs fluvial style for hundreds of kilometres upstream constrain the river between valley walls, increases stream power, produces refuge waterholes demonstrates that tectonics can have a critical effect on ecosystems.	Large refuge waterholes which play a key role in aquatic ecosystems are directly based on the geomorphology (because the waterhole size and position in the drainage network directly determines its permanence, and thus refuge value).

	Rarity	Very unusual to have uplift and downcutting so finely balanced.	The waterholes are the largest and deepest in the Cooper Creek catchment.
	Research	-	
	Principle characteristics of a class	Demonstrates the effect of tectonics on river planform (via the effects of base level on gradient, and valley constriction on flow depth and stream power).	-
	Aesthetics	The stony uplands are an iconic landscape, and one which is strongly identified in the tourist experience.	The aesthetic appeal of the river and its waterholes is a tourist drawcard.
	Creative or technical achievement	-	-
	Social	The area is very well-researched: the underlying geology and geological history is well-documented.	The river and its waterholes are culturally important: the Burke and Wills expedition ended here, with the Dig Tree at the eastern end of the valley and Wills' grave at the western end.
		The north-east of South Australia is an increasingly important tourist destination and focus for "wild camping".	
	Significant people	Pioneering geologist Reg Sprigg, and the beginning of the Australian onshore hydrocarbon exploration industry.	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y	
	Unusual (Australia)	Y	
	Multiple geomorphic or other themes	Y: Tectonic (flexure) and Watercourses (freshwater basins), as shown in this table. Also Regolith (silcrete): preserves the uplifted hill crests; constrains valley width, therefore strongly influencing fluvial style and ecosystems across an extremely wide area; silcrete-capped mesas and gibber plains are an iconic Australian landscape. The western catchment edge has excellent exposures demonstrating the relationships between silcrete, saprolite, and relict land surfaces. Ecological: important (refuge) aquatic ecosystems.	
	Value with respect to significance threshold	Clear	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	Cooper Creek (Windorah to Nappa Merrie); Cooper Creek NW Branch (Strzelecki Desert) Lake Eyre/Kati Thanda	
	Status	Specific area	

Flexure: Kati Thanda - Lake Eyre, and the Neales River Catchment

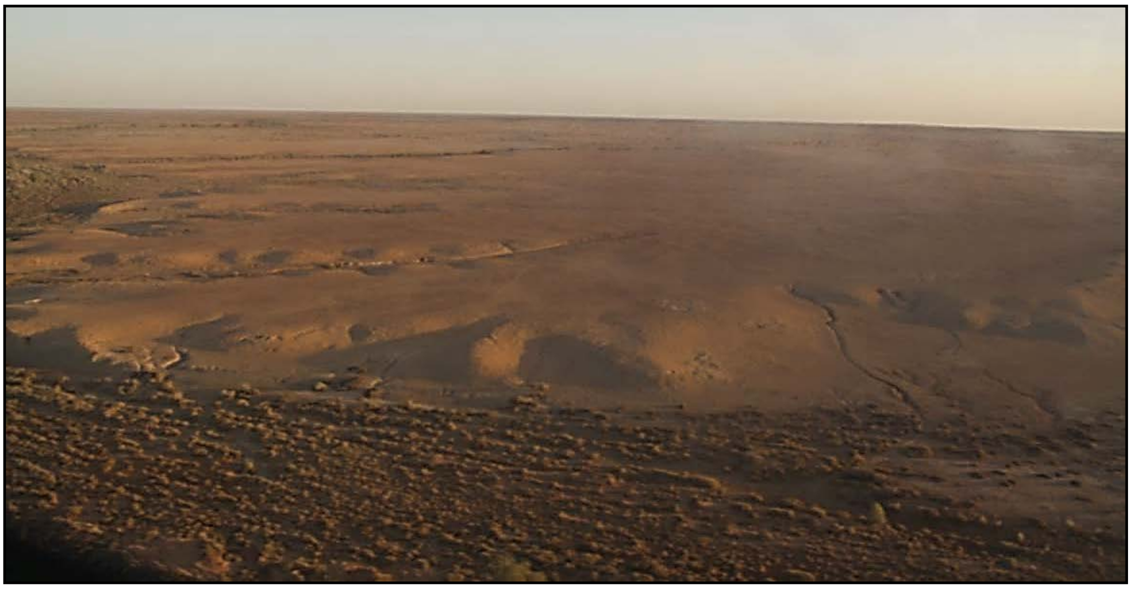
Tectonic forces can also bend whole continents. The Lake Eyre Basin is a continent-scale intracratonic sag that overlies rocks of the Eromanga Basin (themselves deposited in a continent-scale intracratonic sag). The Lake Eyre Basin is asymmetric (Fig. 17) and its depocentre Kati Thanda - Lake Eyre (- 15 m AHD at its deepest point in Lake Eyre south) is relatively close to the southern catchment boundary. Subsidence of the Lake Eyre Basin dating from early Miocene, and migration of the basin depocentre from north to south, is likely to result from deep-crustal processes related to the Australian plate's overriding a subducted slab of New Guinea crustal material (Schellart and Spakman 2015).

On a smaller scale, factors resulting from the Australian plate's movement towards Indonesia have caused the land surfaces in north-eastern South Australia to undulate, with upwards doming and downward subsidence on a scale of hundreds of meters vertically, extended over hundreds of kilometres of landscape (Sandiford et al. 2009, Quigley et al. 2010). This movement has taken place since the Miocene, making it geologically very recent. Notable examples of landscape inversion have resulted, such as palaeolake Billa Kalina, once a depocentre, now the drainage divide between Lakes Eyre and Torrens, and the Mirackina Conglomerate, once a river bed, now a line of table-topped hills (Barnes and Pitt 1976, Callen and Cowley 1998). The result of this undulation, in combination with widespread deep weathering and the emplacement of several layers of erosion-resistant silcrete, is a landscape of several flat layers stacked one on another.

The Neales River catchment (South Australia) extends ~350 km from Marla on the Stuart Highway to Lake Eyre. Oodnadatta township is close to its northern boundary. Parts of the western portion of the catchment have been uplifted, while Lake Eyre South has developed as the regional low point. The catchment has two main tributaries: the Neales River in the north west, and in the south west Lora and Arckaringa Creeks combine to Peake Creek, which joins the Neales River as it approaches its lower reaches.

Surface lithologies are dominated either by erosion-resistant gibber or by soft saprolite, both part of weathering profiles created during previous climates and exposed by the development of modern aridity (e.g. Alley 1998, Fujioka et al. 2005). The result is an iconic landscape of mesas, scarps of often brightly-coloured saprolite, and wide gibber plain uplands (Fig. 19). The distribution of gibber strongly influences the disposition of the drainage network in the different tributary branches (Neales versus Arckaringa) (Wakelin-King 2011, 2015). Tributaries set within the gibber plains tend to be of higher elevation, lower gradient, and carry little bedload. They erode over a wide area with slow downwearing. Tributaries developing in the absence of gibber tend to be of lower elevation, steep gradients, and carry large quantities of

Fig. 19 Gibber plain uplands (bare) and the Neales River (trees)



coarse bedload. They erode over a narrow area with rapid downcutting and headwards extension.

There are two important consequences of these differences in fluvial style. Firstly, the conditions exist for stream piracy by headwards extension. Where high and low land surfaces are juxtaposed, stream capture takes place; the largest example is the spectacular Oodnadatta "S", a reversed-S drainage pathway (Wakelin-King 2011). Many smaller examples of this can be found in the Neales catchment, whereas it is not often described from other parts of the study area. Secondly, in the low-bedload tributary, conditions support the formation and maintenance of narrow deep waterholes which are ecological refugia, whereas the high-bedload tributary has few waterholes and no refugia (Wakelin-King 2015a). The waterholes are critical ecosystems in this harsh landscape.

Small fault-bounded uplift ranges (the Peake Denison Ranges) strike through the catchment ~100 km from its eastern edge, constraining the Neales and Peake rivers into narrow floodplains as they passed through the rocky outcrop. Elsewhere, the rivers occupy wide floodplains. The rivers have complex fluvial styles, alternating between anabranching (with major waterholes) and anastomosing. Major floodouts occur at some tributary outlets. Other fluvial landform types include palaeodrainages, megaflood deposits and mound springs. There is potential for increased understanding of fluvial process in examining waterhole characteristics, and comparisons between anabranching to anastomosing reaches. Palaeoclimates and landscape development will be better understood through examination of the palaeodrainages, megaflood deposits, and drainage network.

The waterholes and mound springs placed small but reliable water resources in pathways across the continent's most arid places. These were undoubtedly important in pre-European times, and have since been used by succeeding waves of technology in settling the inland (explorers, cameleers, the Ghan railway). Algebuckina and Hookey's Waterholes are amongst the most significant. The Algebuckina railway bridge and the string of sidings and fettler's cottages along the old railway are noted parts of Australia's cultural history.

	Place	Neales River Catchment	
	Theme (subtheme)	Tectonic (Flexure)	Regolith (saprolite, silcretes and gibber, gypcrete)
NHL Criteria	Events and Processes	The interaction between uplift and gibber plains has 1. governed the evolution of the drainage network; 2. differentiated tributaries into high-bedload and low-bedload 3. consequently the tributary ecosystems have different access to refuge waterholes.	Catchment edges demonstrate landscape evolution as soils from old land surface are stripped away and drainage develops over the exposed weathering profile. In uplifted areas, distribution of the erosion-resistant gibber and silcrete surfaces has governed the evolution of the drainage network.
	Rarity	In the context of the study area, stream piracy is unusually common here, and the Oodnadatta 'S' is unusually large example of stream piracy by headwards erosion.	
	Research	Great potential for better understanding of evolution of the Western Craton.	
	Principle characteristics of a class	Stream piracy: beheading, stranded valleys, sharp changes of drainage direction, flow reversal.	Catchment edges expose profiles through remnant soils and complete siliceous weathering profiles.
	Aesthetics	A stark and iconic landscape.	
	Creative or technical achievement		
	Social	Water resources across the arid zone used by succeeding waves of settlers.	
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y: drainage development by crustal flexure	
	Unusual (Australia)	Y	
	Multiple geomorphic or other themes	Y: Tectonic (flexure), and Regolith (various), as shown in this table; also Watercourses (anabranching, floodouts, mound springs, palaeodrainage, megaflood deposits, and freshwater basins). Ecology: The landforms create the refuge waterholes, which are important to the ecosystems and which also possess strong aesthetic value.	
	Value with respect to significance threshold	Clear	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	Kati Thanda - Lake Eyre	
	Status	Indicative area	

Table 21 The Neales Catchment

3.6 Uplands

Uplands are prominent features in Australia's low relief drylands. Some are isolated monoliths, like Uluṟu and Kata Tjuṯa, some are ranges that cover considerable areas, like the western MacDonnell Ranges. Many are surprisingly rugged in the topography along their upper parts, whereas others have the semi-planar concordant tops that are relics of previous land surfaces. Typically the uplands rise abruptly from the surrounding country, making them conspicuous; they are usually a cultural or aesthetic focus. Their rocky hill slopes shed water onto the thirsty plains, so they are a strong influence on local fluvial geomorphology and therefore ecology.

Although tectonic activity has produced some uplift in uplands such as central Australia's MacDonnell Ranges or the Barrier Ranges (New South Wales), Australia's general lack of long-term *rapid* uplift means that most of the study area's uplands are not dominantly tectonic in origin. Rather, the uplands theme integrates a number of factors: a bit of uplift, which only slightly exceeds rates of erosion; the physical properties of the lithologies, which have been strongly mediated by weathering; differential erosion, acting over geological time on the various lithologies.

In particular, the uplands are the class of landform which most demonstrate the effects of differential weathering over very long periods of time. Lithologies such as quartzite are less likely to be broken down by weathering and so form strongly outcropping hills, whereas shales can weather to soft erodible clays and form valleys. Consequently standard geological references (such as geological maps and their explanatory notes) are more useful in understanding uplands geomorphology than they are in other geomorphic themes. Climatic variations also play a role: at some point during the landscape evolution of the uplands, the climate must have been sufficiently wet to transport the products of weathering away from the hillslopes.

A varied terminology exists for some of these landforms. An **inselberg** is an isolated rock, hill, or ridge that rises abruptly from flat or gently sloping surrounding plains. **Monoliths** are single rock masses, and can be **bornhardts**, **knolls**, or **castle koppies**. Bornhardts are large dome-shaped, steep-sided, bald rock outcroppings ≥30 m high and 100s m in diameter. They are commonly granitic but can be composed any massive lithology. Bornhardts are seen at their best in arid and semi-arid regions, but occur over a wide range of climates, mainly in multicyclic landscapes. They are residual landforms resulting from differential erosion. Their steep flanks are steepened by scarp foot weathering, undermining and collapse, and sheet structures often occur. Uluṟu is Australia's 2nd-largest monolith (Mt Augustus, in Western Australia, is larger; Sweet et al. 2012). Knolls are block-strewn nubbins, and castle koppies are small angular rock clusters. This type of less spectacular monolith (e.g. Devil's Marbles, NT) result from similar but less intense or less prolonged weathering processes than forms bornhardts.

Uplands have been significant in the sometimes controversial development of ideas regarding the landscape evolution of Australia's pediments, gibber, plains and scarps. This discussion was part of a wider discussion on planation and cycles of landscape development, centring around how a land surface is worn down. End-member arguments took place as to whether it was back-wearing (slope retreat) or down-wearing (slope decline) that decreases the amount of relief as landscapes move from "young" to "old", creating pediments which then coalesce to form pediplains. Some of the references relevant to this discussion include Woolnough (1927), Twidale (1967), Dury (1970), Mabbutt (1978), and Bourne and Twidale (1998). However, the question is now seen as irrelevant, as it is recognised that dissimilar geomorphic processes may converge to produce similar landforms (equifinality). In many landscapes it appears that scarp retreat, if present, is less important than surface lowering however landscapes are complex and no one process is sufficient to explain all low-angle surfaces. The original debate is present in the older literature, and it is necessary to be aware of it if the same sterile discussions are not to be reactivated.

Other references containing material relevant to uplands in the study area include Mabbutt (1967), Twidale (1980), Bagas (1988), Wakelin-King (1989), Goudie et al. (1990), Twidale and Campbell (1993), Bierman and Caffee (2002), Goudie (2002), Gibson (2005) , and Bourman et al. (2009).

Uluṟu - Kata Tjuṯa (Ayres Rock and the Olgas)

Uluṟu and Kata Tjuṯa lie within Uluṟu-Kata Tjuṯa National Park near the town of Yulara in the Northern Territory. They are listed with the NHL and WHL. Uluṟu (previously known as Ayres Rock) is a one of the world's largest monoliths, a rounded, red metasandstone bornhardt, 9.4 km in base circumference. It is an inselberg; its smoothly sloping sides rise steeply from the surrounding plain to a ridged but relatively flat top ~340 m in elevation (Fig. 20). Kata Tjuṯa (previously known as The Olgas) are a group of 36 steep-sided domes located ~32 km west of Uluṟu, covering an area of 3,500 hectares. The domes of Kata Tjuta tend to have hemispherical summits, near vertical sides, steep-sided intervening valleys. Mount Olga, the highest feature, rising to an elevation of 500 m. Uluṟu and Kata Tjuṯa are surrounded by small scree slopes, and gently sloping sheetwash aprons. A dunefield surrounds these alluvial outwash plains, and there are areas of banded vegetation in some of the valleys and interdunes. Surface water is largely restricted to seasonal pools fed by short shallow water courses from the rocky uplands. Defined water-courses do not exist in the dune formations, although swales are moister and ponding may occasionally occur.

The geology, geomorphology and landscape evolution of Uluṟu and Kata Tjuṯa are described in (*inter alia*) Forman (1965), Wells et al. (1970), English (1998), Young et al. (2002), and Sweet et al. (2012). Uluṟu and Kata Tjuṯa display geological history of the Amadeus Basin in their steeply dipping sandstones (Uluṟu) or a relatively flat-lying conglomerates (Kata Tjuṯa). The sediments forming these rocks were deposited near mountains. After burial and lithification the rock layers were folded and faulted, then uplifted. A long period of differential erosion followed, leaving the domes of Uluṟu and Kata Tjuṯa exposed. Weathering is most effective where water can promote chemical changes in the minerals, and therefore precedes most rapidly in joints and fissures. In Uluṟu, the absence of joints promotes its monolithic structure. In Kata Tjuṯa, widely-spaced joints determine the spacing of the valleys, and therefore the location and size of the domes. During weathering, Uluṟu and Kata Tjuṯa developed surface features such as honeycomb weathering, onion-skin weathering (peeling sheet erosion), deep parallel fissures, and caves, inlets and overhangs.

Fig. 20 Uluṟu and Kata Tjuṯa. Photo: Esther Beaton. Credit: Director of National Parks

	Place	Uluṟu-Kata Tjuṯa	
	Theme (subtheme)	Uplands	Tectonic (Faulting)
NHL Criteria	Events and Processes	Lithology, grain size, and bedding orientation track the orogenic record of this part of the Amadeus Basin. Surface features track the weathering history of the landscape. Rocky hillslopes shed water onto the plains, strongly influencing local ecology.	Faulting around some outside edges of these inselbergs, and fracturing within them (Kata Tjuṯa) or the absence of fracturing within them (Uluṟu) determines their existence.
NHL Criteria	Rarity	-	
NHL Criteria	Research	The area's geology and geomorphology is well-researched, however several aspects of the landscape history are still unclear. The subsurface distribution of palaeovalley deposits contribute substantially to understanding Cainozoic landscape evolution in the area.	
NHL Criteria	Principle characteristics of a class	One of Australia's most impressive and accessible inselbergs.	
NHL Criteria	Aesthetics	The steep sides of the inselbergs rise dramatically from the surrounding flat plains, contributing substantially to the area's aesthetic appeal.	Faulted upland edges and distribution of fracture lines within the uplands contribute substantially to the area's aesthetic appeal, by governing the size and prominence of the rounded hills.
NHL Criteria	Creative or technical achievement	-	
NHL Criteria	Social	The striking geomorphology of Uluṟu-Kata Tjuṯa is a significant component of the tourist industry of the area.	
NHL Criteria	Significant people	-	
NHL Criteria	Indigenous	(Significant, and part of the valleys for which the area is listed on the world heritage list, however not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	N (However Uluṟu and Kata Tjuṯa are well-known on a world scale).	
Comparative and Context	Unusual (Australia)	Y Uluṟu is Australia's 2nd-largest and best-known inselberg.	
Comparative and Context	Multiple geomorphic themes	Y, uplands, tectonics (faulting) as shown on this table; also Sand Deserts, and Watercourses (banded vegetation) in the dune fields.	
Comparative and Context	Value with respect to significance threshold	Clear	
Comparative and Context	Integrity	Y	
Comparative and Context	Authenticity	Y	
Comparative and Context	Cross-reference	Amadeus Basin (MacDonnell Ranges), Amadeus Basin (Rodinga Range)	
Comparative and Context	Status	Existing NHL and WHL listing; its geology and geomorphology are listed amongst its values.	

Table 22 Uluṟu-Kata Tjuṯa

Amadeus Basin – MacDonnell Ranges (Northern Territory)

The MacDonnell Ranges are a 644 km long series of ranges extending east and west from Alice Springs in the Northern Territory. They are characterised by parallel strike-ridges and -valleys, in which quartz-rich lithologies and to a lesser extent carbonate rocks crop out strongly, often as steep rocky hills and ridges, whereas pelitic lithologies form valleys. Many hilltops and ridge crests show a concordant bevelled surface and wind gaps. Rivers cut through the ridges at points of relative weakness (fractures, faults, or dykes), forming a series of gaps and gorges (e.g. Simpson's Gap, Stanley Chasm, Ormiston Gorge and Glen Helen Gorge). The rocky surfaces of the upper hillslopes readily shed water, supporting ecosystems in the rivers and plains, and weathering has produced rich colours in the rocks, especially the striking red quartzite of the gorges and chasms. The beauties of the ecosystems and the landscapes are fundamental to the tourist experience (a substantial part of the local economy) and are expressed in important cultural works such as the oeuvre of artist Albert Namatjira.

The geomorphology of the MacDonnell Ranges results from its geology, and the modifications produced on different lithologies by weathering over timescales that are long even by geological standards. Sedimentary rocks of the Amadeus Basin dominate, with contributions from the underlying metamorphic rocks of the Arunta Block. A wide range of rock types is present. Folding and faulting during orogenic events has produced steep to near-vertical dips in many of the rock layers; fracturing and dolerite dyke emplacement also occurred. At some time in the geological past, the ground surface was of very low relief. A planation surface developed across the outcrop (Fig. 21), and drainage networks developed such that the major drainage directions cross-cut the east-west trend of the geology. Later, during relative uplift of the ranges, weathering and erosion acted differentially on the various lithologies: erosion-resistant quartz-rich lithologies stand up as hills and uplands, and shales erode down to form valleys. On remote imagery such as Google Earth the ridges and valleys clearly display the geological structures.

In the present day, steep cliffed scarps, dip-slopes and talus and scree slopes characterise the hillsides, and the near-vertical geological boundaries allow excellent clear expression of the large-scale geological structures. The high degree of connectivity between runoff-shedding hillslopes and large, well-connected drainage networks allows floodwaters to travel far beyond the uplands catchments, in some cases as far as the Simpson Desert. The runoff-shedding hillslopes also support rich ecosystems in rivers and plains in and around the Ranges.

In central Australia, many of the east-west trending ranges formed by outcrop of the Amadeus Basin have similar geomorphology to that described here for the MacDonnell Ranges. In this report, the MacDonnell Ranges are singled out for recognition of their geomorphology values because large areas are already preserved in parks or reserves, and because the western MacDonnell Ranges have already been proposed for the National Heritage List. However, the parks and reserves exist partly because the MacDonnell Ranges are accessible via the township of Alice Springs. Alice Springs exists because it was an important watering point on the north-south Overland Telegraph, and it became a significant population, administrative and economic centre because of its geomorphic resources (water, natural ecosystems, beauty, and amenity). Thus, it is likely that the geomorphology has an unrecognised influence on these human-created geographies of township and reserves.

The geology and/or geomorphology of the central Australian ranges is described in (*inter alia*) Mabbutt (1967), Bagas (1989), Derriman (1989), Wakelin-King (1989), Thompson (1995), and any of the 1:250,000 scale geological maps produced by Geoscience Australia (previously known as the Bureau of Mineral Resources), Canberra, or the Northern Territory Geological Survey, Darwin.

Table 23 Amadeus Basin / MacDonnell Ranges

	Place	Amadeus Basin / MacDonnell Ranges	
	Theme (subtheme)	Uplands	Tectonic (folding, faulting)
NHL Criteria	Events and Processes	Rocky hillslopes shed water onto the plains, and coarse quartzose sediments into fluvial transport. Hillslope type and connectivity with floodplains governs local fluvial styles and ecosystems. The spatial relationship of drainage to hills allows efficient collection and transfer of water downvalley, creating an integrated drainage network capable of high-volume flows that extend as far as the Simpson Desert. Thus, the Central Australian uplands are key to fluvial systems of the whole north-western Lake Eyre Basin, influencing ecosystems over a very wide area. Landscape inheritance is demonstrated in the ridge-top planation surface. The strongly expressed differential erosion integrates geological time and weathering regimes of previous climates.	Long narrow folds and nappe-transported fault blocks are exposed as strike-ridge topography. They express ancient deep-crustal events.

	Rarity	-	
	Research		Well researched; part of the Central Australian Superbasin, contributes to an understanding of very long-term continental evolution. Potential for further understanding of salt tectonics in the area.
	Principle characteristics of a class	Drylands differential weathering	
	Aesthetics	Ridge-valley topography is of high aesthetic value, widely recognised in tourist promotions and with strong contemporary cultural expression e.g. painting, photography.	The clear expression of graceful fold structures and dramatic fault juxtapositions is valued within the scientific and field-naturalist communities.
	Creative or technical achievement	The geomorphology of the ranges and rivers are primary subjects in the oeuvre of artist Albert Namatjira.	
	Social	-	
	Significant people	Albert Namatjira.	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	N	
	Unusual (Australia)	N/Y: There are a number of uplands and ranges associated with the wide area of central Australian Amadeus Basin outcrop, however the central Australian ranges are unusual with respect to much of the rest of arid Australia.	
	Multiple geomorphic themes	Y, uplands, tectonics (folding and faulting) as shown on this table; also see 3.8 Watercourses (sand-bed rivers)	
	Value with respect to significance threshold	Likely	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	Rodinga Range	
	Status	Indicative area; the Western MacDonnell Ranges are currently proposed for NHL, geoheritage values should be added to the other values listed in the proposal.	

Fig. 21 Bevelled upper surface of a quartzite ridge in the MacDonnell Ranges. Photo: Michael Jenson

Amadeus Basin – Rodinga Range (Northern Territory)

The Rodinga Ranges are located in the southeastern part of the Amadeus Basin, at the northwestern margin of the Simpson Desert dunefields. Several anticlinal ranges (e.g. the Arookara Range, Figs. 22, 23) and synclinal plains (e.g. Camel Flats) have a NW-SE trending orientation; they cut across the general fall of the land (SSE towards Kati Thanda – Lake Eyre). That being the case, they are also oriented across the drainage networks of Central Australian sand-bed rivers on their way to floodouts in the Simpson Desert Dunefields. The present-day course of the Todd River diverts around the ranges (Fig XX2), as do its palaeodrainage traces (Hollands et al. 2006). The ranges are also arrayed across the NNW trend of the longitudinal dune crests.

The processes and heritage values described above for the MacDonnell Ranges (layered lithologies, folded, and revealed at the surface by differential weathering; bevelled ridgetops; rocky uplands shedding water) apply here also. Additionally, the particular structural style of the Rodinga Ranges may be a good example of folding influenced by diapirism (see *3.5 Tectonics*). However, this remains to be tested by research.

The Rodinga Ranges bring together a number of geomorphic themes. As well as being tectonically-influenced uplands, the location hosts the sand-bed Todd River, its reaches diminishing as it extends towards its floodout, and the Todd's palaeodrainage traces. The area also hosts Simpson Desert longitudinal dunes, in spatial relationships that indicate local corrasion and vertical accretion (rather than downwind sand transport) is the dunefield's primary method of formation (Hollands et al. 2006).

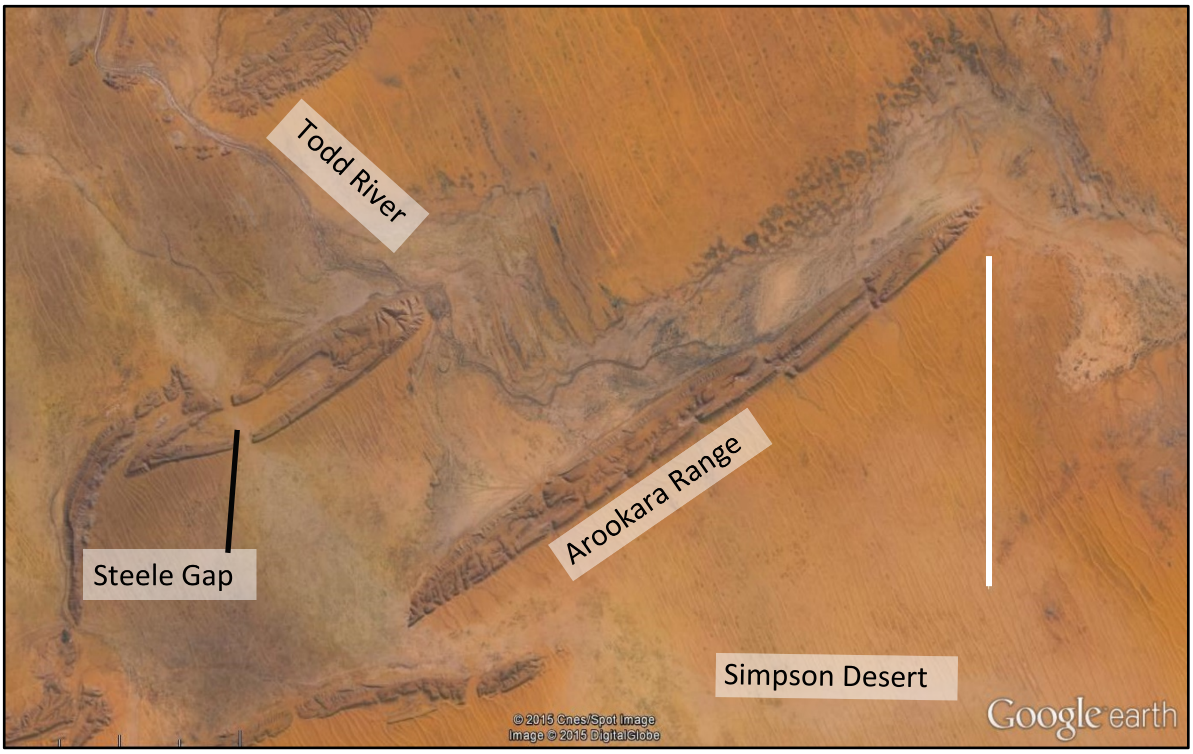


Fig. 22 Part of the Rodinga Ranges

The present course of the Todd River, and Steele Gap through which flowed a branch of the palaeoriver. Google Earth image; white scale bar = 10 km.

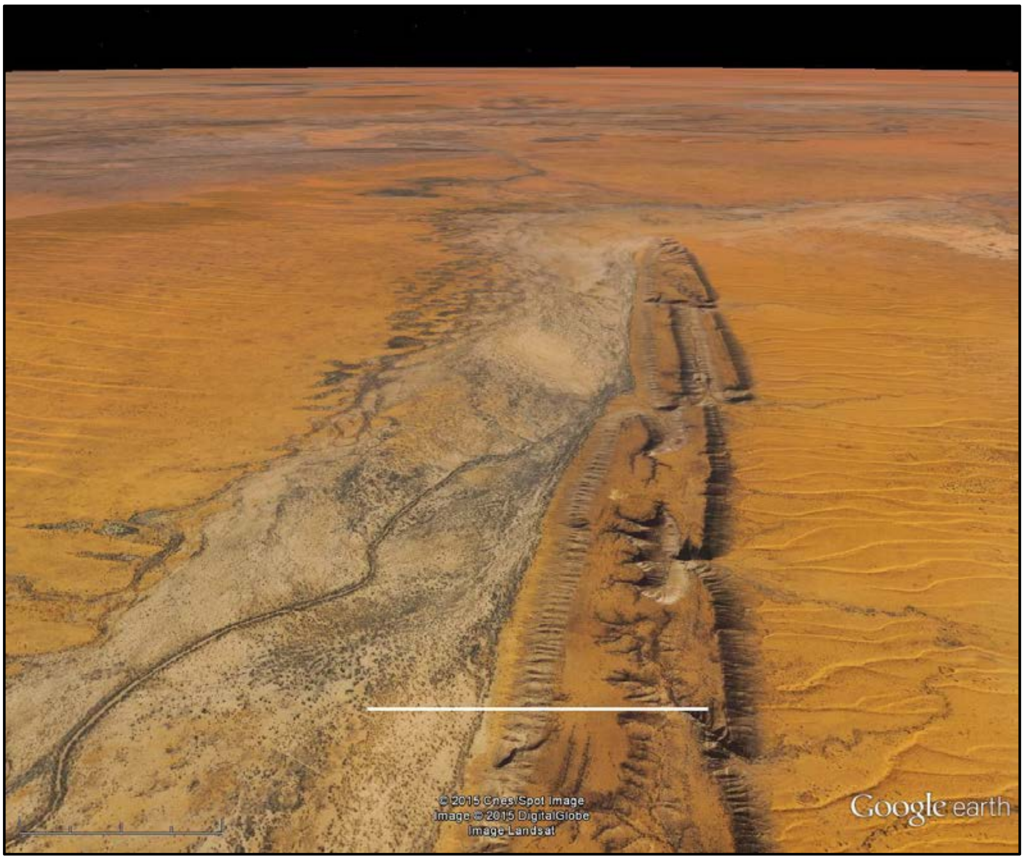
Table 24 Amadeus Basin / Rodinga Ranges

	Place	Amadeus Basin / Rodinga Range	
	Theme (subtheme)	Uplands	Tectonic (Diapirism)
NHL Criteria	Events and Processes	The spatial relationship in which hills are barriers to the drainage's downvalley gradient also to the dune-creating northern winds expresses the processes and relative timing of uplift, drainage development, and dune creation. Because of the ridge:drainage orientation, megaflood deposits are spatially separated from present day fluvial landforms, and so are well	Surface exposure of probably diapir-influenced geological structures, expressing ancient deep-crustal events.

		preserved. The ridge:drainage orientation creates places where flow can collect, enriching local ecosystems. Landscape inheritance is demonstrated in the ridge-top planation surface. The strongly expressed differential erosion integrates geological time and weathering regimes of previous climates.	
	Rarity	This is an unusual grouping of different geomorphic elements	
	Research	The juxtaposition of the uplands, the drainage network and the desert dunefields has the potential to present an integrated picture of the north western Lake Eyre Basin's landscape evolution under conditions of progressive climate change.	There is a probable but currently unresearched link to diapiric uplift; there is potential to contribute to understanding the Amadeus Basin's structural style.
	Principle characteristics of a class	Differential erosion; uplifted land surface (range-top bevelled surface).	Particularly good examples of long narrow doubly plunging anticlines (a characteristic linked to diapiric uplift), with minimal complications from other structural elements.
	Aesthetics	-	
	Creative or technical achievement	-	
	Social	-	
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y	
	Unusual (Australia)	N/Y: There are a number of uplands and ranges associated with the wide area of central Australian Amadeus Basin outcrop, however the Rodinga Ranges are unusual with respect their structure, and their interrelated landform suites (multiple geomorphic themes).	
	Multiple geomorphic themes	Y: uplands and tectonics as shown on this table; also watercourses (sand bed rivers, megaflood, terminal floodouts), and sandy deserts (Simpson Desert dunefields), including research into dunefield origins.	
	Value with respect to significance threshold	Likely	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	Amadeus Basin/MacDonnell Ranges; Ross-Todd confluence.	
	Status	Specific area defined in this study	

Fig. 23 Oblique view of the Rodinga Ranges area

Looking northeast along the Arookara Range, and downstream along the Todd River. Google Earth image; white scale bar = 2 km.



Barrier Ranges / Mundi Mundi Scarp

The Barrier Ranges are a low set of hills, which are fault bounded on their western, south-eastern and north-eastern margins. The western margin (Mundi Mundi Scarp) is a linear fault scarp fringed by colluvium and low angle alluvial fans (Umberumberka, Mundi Mundi, and Eldee Fans) which are fed by small streams such as the Umberumberka Creek. The township of Broken Hill and the research facility Fowlers Gap Research Station are in the Barrier Ranges. The area has been important in early Australian history, having carried important explorers, prominent pastoral empires, and a resources boom. These historical events are relevant to the local geomorphology, as the geomorphology created the conditions (rangefront floodouts; see *3.8 Watercourses*) that guided the explorers and subsequent pastoralists, and in turn the human activity had a marked effect on the waterways (Post-European Incision; *see 3.8 Watercourses*).

Cainozoic uplift along a series of faults has produced upland surfaces of various degrees of relief, with associated low angle alluvial fans. The hills and scarps are the latest expressions of a very long history of vertical tectonic movement in the Barrier

Range, and which is connected to the tectonics of the Flinders Ranges (Gibson 1997, 1999, 2000, 2005a, 2005b; Neef et al. 1995, Mills and David 2004, Quigley et al. 2006), and which has expression in present-day regolith and landforms (Hill 2005; Hill et al. 2003, 2005).

The geomorphology of the Barrier Ranges uplands is a key factor in shaping fluvial systems (and therefore ecosystems) in the hills and the adjoining plains. Rocky hills shed water however many hillslopes between hilltop and channel are low-runoff because of their thick regolith and water-retaining banded vegetation landforms (see *3.8 Watercourses*, p. 131). Additionally, the spatial relationships of hill crests to drainage networks do not encourage efficient collection and transfer of water downvalley. Consequently, fluvial networks are dominated by short discontinuous ephemeral streams and floodouts, and ecosystems are dependant on relatively local rainfall (as opposed to the highly connected watercourses of Central Australia's sand-bed rivers, see *3.6 Uplands: Amadeus Basin-MacDonnell Ranges*).

Low-angle rangefront fans are a relatively common Australian landscape component, however in some respects they are not well-documented. The geological literature has instead a preponderance of research on alluvial fans such as are found in the Basin-and-Range country (USA); these are considerably more steep and gravelly, result from different processes and produce different sedimentary deposits than the lower-gradient and more fine-grained Australian low-angle alluvial fan. It is possible that this type of landform is more typical of Australia, and occurs less in other parts of the world. Research into the Barrier Range rangefront fans have potential to contribute information to this under-explored facet of Australian landforms. The Umberumberka Fan has been the subject of an influential study on post-European erosion rates (Wasson 1979; Wasson and Galloway 1986).

	Place	Barrier Ranges / Mundi Mundi rangefront	
	Theme (subtheme)	Uplands	Tectonic (Faulting)
NHL Criteria	Events and Processes	The spatial relationship of drainage to regolith-covered hills makes for inefficient collection and transfer of water downvalley. The drainage network is poorly integrated and features discontinuous ephemeral streams and floodouts. Thus, the western NSW uplands supports fairly sparse ecosystems which are dependant on relatively local rainfall.	Uplift along fault lines here is linked to uplift in the Flinders Ranges, and this expresses continental scale subsurface relationships. The distribution of ranges and plains, and the fault scarps or retreated fault scarps between them, are the latest expressions of a very long history of vertical tectonic movement.
	Rarity		

	Research	The Umberumberka Fan has been the subject of an important study of erosion rates. The rangefronts are suitable study sites for low-angle alluvial fans, a poorly understood but common Australian landform. Some creeks and sediment packages show expression of subtle but relatively recent tectonic activity. There is potential for a better understanding of Australia's low-intensity but ongoing tectonic evolution.	Spatial relationships between faults, uplands, sedimentary rock, and metamorphic rock have the potential to contribute significantly to understanding evolution of the Australian plate. Better recognition of subtle fluvial responses to seismic creep will contribute to understanding Cainozoic tectonic evolution of the area. The Barrier Range would be an appropriate place to document low-angle alluvial fans.
	Principle characteristics of a class		Different magnitudes of Cainozoic uplift along a series of faults has produced upland surfaces of various degrees of relief, with associated low angle alluvial fans.
	Aesthetics		Visually striking fault line rangefront at Mundi Mundi.
	Creative or technical achievement		
	Social	Western New South Wales hosts a number of uplands; of these, the Barrier Ranges are the best researched.	
	Significant people		
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y?	
	Unusual (Australia)	N?	
	Multiple geomorphic themes	Yes: Uplands and Tectonic (faulting), as shown in this table. Also Watercourses (discontinuous ephemeral streams, post-European channel incision, banded vegetation, floodouts).	
	Value with respect to significance threshold	Probable	
	Integrity	The area has been subjected to heavy grazing, and some discontinuous ephemeral streams systems have been heavily affected by post-European drainage incision. The fan and scarp landforms are not compromised.	
	Authenticity	Y	
	Cross-reference	Fowlers Creek; Flinders Ranges	
	Status	Indicative area	

Table 25 The Barrier Ranges and Mundi Mundi Rangefront

	Place	Davenport-Murchison Ranges
	Theme (subtheme)	Uplands
NHL Criteria	Events and Processes	?
	Rarity	?
	Research	?
	Principle characteristics of a class	?
	Aesthetics	?
	Creative or technical achievement	
	Social	?
	Significant people	?
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	?
	Unusual (Australia)	?
	Multiple geomorphic themes	?
	Value with respect to significance threshold	?
	Integrity	?
	Authenticity	?
	Cross-reference	?
	Status	Indicative area; knowledge gap.

Table 26 The Davenport-Murchison Ranges

Davenport –Murchison Ranges

The geology of the Davenport-Murchison Ranges in the Northern Territory is reasonably well-documented but their landscapes are only described briefly. It is evident from the geological reports (e.g. Smith et al 1961, Blake et al. 1987, Stidolph et al. 1988) that the ranges have strike-ridge topography that displays the geological structures (large-scale folding in the sedimentary rocks), concordant summit surfaces and bevels indicating a previous land surface, a second palaeosurface at a lower elevation, and that they are uplands controlling the regional fluvial character. Therefore, the area may be host to landforms of value within the themes of uplands and tectonics (similar to the types of values expressed by the Amadeus Basin ranges). The plains around the ranges include the Sandover-Bundey confluence floodout (see *3.8 Watercourses*). However, there were insufficient resources available to assess the geomorphology's heritage values, and the Davenport-Murchison Ranges are here presented as a knowledge gap.

3.7 Regolith

Regolith is material that sits above solid bedrock and includes soils, unconsolidated or partly consolidated sediments, and rocks whose physical structure and/or mineralogy has been altered by weathering. Regolith is created by chemical reactions driven by organic (e.g. tree roots, soil microbes) and inorganic (e.g. climate, groundwater) factors. The history of Australia's regolith is one of long subaerial exposure and intense weathering by previous climates (Anand 2005, Pillans 2005, 2007); the results of those processes have been inherited by the present-day landscape, and exposed by present-day aridity.

The landscape evolution of almost the entire study area is affected to some degree by the history of its regolith. Because of its complexity and ubiquity in the study area, the regolith theme has been divided into sub-themes in which we consider soil (the more biological regolith) separately from the more inorganic weathering profiles:

- soil (specifically, vertic soils)
- weathering profiles
- saprolith
- silcrete and gibber
- gypcrete
- calcrete
- ferricrete.

Vertisol Plains and Slopes

It is not the purpose of this report to document soils across the study area. We discuss here a particular type of soil which is characteristic of parts of the study area and which plays an important role in the landforms and the ecosystems hosted by the landforms.

Vertisols, or cracking-clay soils, are a type of soil exhibiting great capacity to expand when wet and contract when dry. Many have mineralogy which includes swelling clays (smectite, montmorillinite, etc.). Vertisols embody all four drivers of arid Australia landforms: they are associated with old weathering profiles in previous climates, and are related to present aridity. Vertisol formation derives from high clay content and an alternate wet-dry soil water regime; red-clay vertisols (e.g. western New South Wales) are created by long weathering, short-period wetting, and severe drying under high temperatures, and black earth vertisols (e.g. the Barkly Tablelands) are created with moderately abundant rainfall, alkaline parent material, and grass-dominant plant communities (Hubble 1984).

Australia has 48,000,000 ha of vertic soils; we are one of the three world regions with large amounts of this type of soil (Hubble 1984). In comparison with the rest of the world's drylands, India is the only other country rich in vertisols; sub-Saharan Africa and Latin America have some (Hubble 1984). The places from which popular culture derives its images of deserts, and where so much drylands research has taken place (e.g. the Middle East and the USA) have very little.

The presence of so much clayey soil has important consequences for the appearance and function of Australian drylands. In general terms, any clay will have important moisture-retaining and nutrient-containing properties that are not present in sands and gravels, and so will determine ecosystem type and distribution. In terms of fluvial form and behaviour, clays are cohesive and hard to erode, yet light and easy to transport, so a river flowing through a clay-rich environment will be unlike a river flowing through sands and gravels.

In addition, this particular kind of clay soil has a special properties related to the shrink-swell nature of the clays. Vertic soils exhibit very deep cracking when they are dry, so rainfall can penetrate deeply. They absorb and retain a lot of moisture. In consequence, vertic soils are very biologically rich and are known as productive agricultural and pastoral land. These qualities provide some of the stories that enrich Australian culture: the black-soil plains, so hard when they are dry, so boggy when they are wet, so rich and green after rain; then mice breed in the cracks, so there is a mouse plague, then snakes after the mice; but it's good cattle country. The swelling properties of vertic soils also contribute to the soil phenomenon known as gilgai, in which the shrink-swell behaviour promotes circulation within the soil profile. The circulation can bring stones to the surface, creates microtopography, and is associated with banded vegetation (see *3.8 Watercourses*, p. 131), including the stony gilgai which is a distinctive feature of some Australian landscapes (e.g. the Barrier Range, Dunkerley and Brown 1999a). The other unusual and significant property of vertic soils is that they can be self-mulching: when dry, they fragment into silt- and sand-sized pellets which are robust enough for fluvial transport (Maroulis and Nanson 1996). Fluvial transport of mud aggregates (c.f. clay flocs, which are different) is extremely unusual on a world scale, and they are a key feature of Cooper Creek (Fagan and Nanson 2004) and other Channel Country rivers.

Much of the literature on Australian vertic soils is concerned with agricultural areas, and does not fall within the scope of this study. Literature mentioning aspects of Australian vertic soils includes Ollier (1966), Hallsworth and Beckman (1969), Upton (1983), Nanson et al. (1986), Rust and Nanson (1986), Goudie et al. (1990), Ludwig et al. (1999), Dunkerley and Brown (1999a, 2002), Wakelin-King (1999), Berg and Dunkerley (2004), Edgoose (2005), Wakelin-King and Webb (2007a, 2007b), Cattle et al. (2009).

Table 27 presents geoheritage values for vertic soils as a feature, and the next section of this report (Table 28) presents information for the Black Soil Plains.

	Feature	Red vertic soils and black vertic soils
	Theme (subtheme)	Regolith (Vertisol plains and slopes)
NHL Criteria	Events and Processes	Where they occur as the major component of stony gilgai, or as a major or partial component of soils beneath banded vegetation, or as a major or partial component of plains and floodplains, vertic soils with shrink-swell characteristics are important in the pattern of that landform's geomorphic processes.
	Rarity	-
	Research	Although widespread in Australia's drylands, the contribution of vertic soils to characteristic landscapes is poorly recognised outside the soil science community.
	Principle characteristics of a class	Stony gilgai with red vertic soils are characteristic of parts of drylands Australia, for example western New South Wales.
	Aesthetics	-
	Creative or technical achievement	-
	Social	-
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y: banded vegetation and stony gilgai with associated banded vegetation are most concentrated in certain parts of the world, including Africa and Australia.
	Unusual (Australia)	N
	Multiple geomorphic themes	in some places, vertic soils are an integral part of banded vegetation landforms
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: the feature occurs at these sites.	Barrier Range; Fowlers Creek; Cooper Creek (Windorah to Nappa Merrie)
	Status	Contributes value to places listed under other geomorphic themes

Table 27 Vertisols

Vertisols: Black Soil Plains (Northern Territory, Queensland)

The Black Soil Plains are a prominent landscape of wide mostly flat plains of dark grey to black cracking clay soils, extending ~800 km across the Northern Territory and western Queensland, including the Barkly Tableland; it extends from the townships of Elliott (~250 km north of Tennant Creek in the Northern Territory) to Boulia (~300 km south of Mount Isa in Queensland). The Black Soil Plains area is not defined within this report, but the black-soil country is characterised by Mitchell Grass, and the boundary of the Mitchell Grass Plains IBRA bioregion (Fig. 24) is used here as a proxy for the Black Soil Plains. The Black Soil Plains overlie Georgina Basin limestones in the Northern Territory (including the covered karst of the Camooweal area, see *3.3 Karst*) and arkosic sandstones of the Rolling Downs Group in western Queensland (Vanderstaay 2000; Edgoose 2005).

The moisture-holding properties of the Black Soil Plains allow them to be highly biologically productive, making them important as the basis for the Mitchell Grass IBRA region's ecosystems, and economically important to the area's pastoral industry. The upper reaches of the Channel Country rivers (Cooper Creek, Diamantina River,

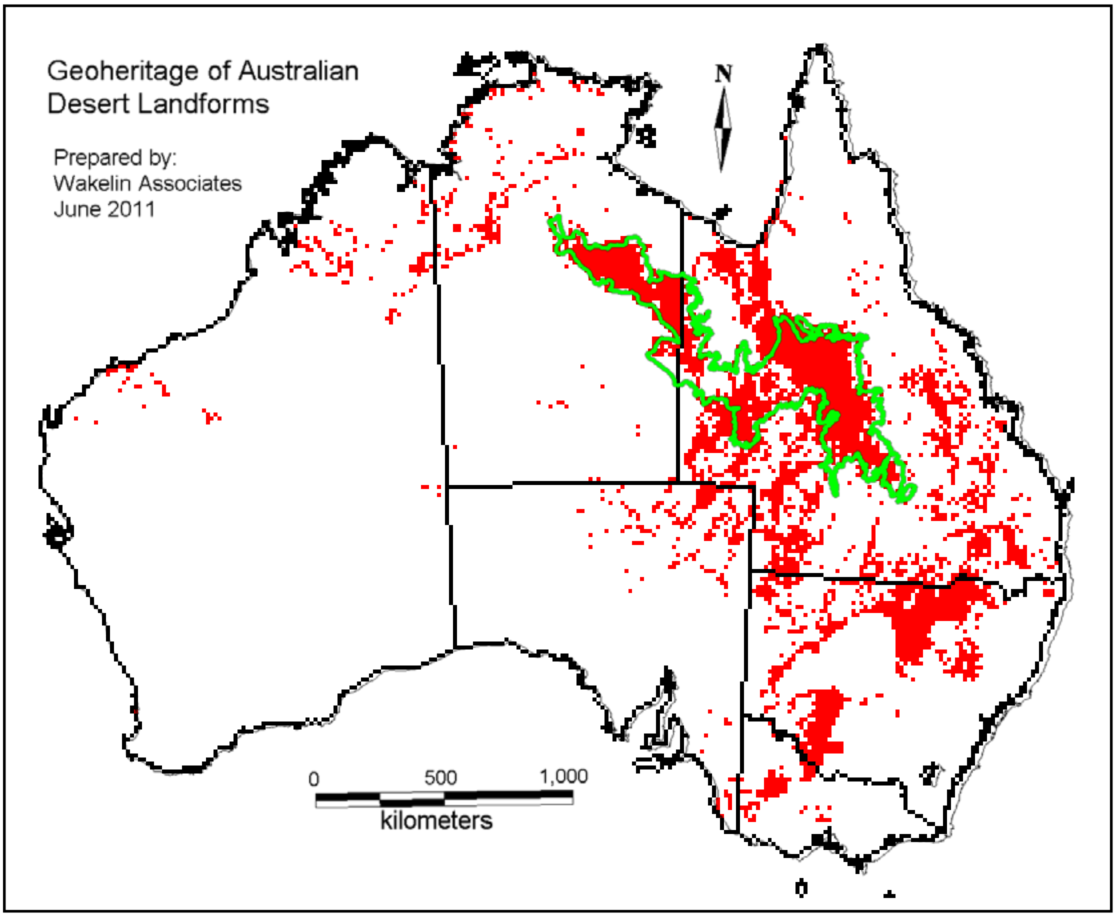


Fig. 24 Vertic soils and the the MGD bioregion

The Mitchell Grass Downs IBRA region (green outline) is dominated by vertisols (red dots, from a CSIRO online soil map).

Georgina River) extend into plains; these reaches are non-depositional and their geomorphology indicates that the hillslopes are delivering vertisol sediments into fluvial transport (Wakelin-King, unpublished data). This suggests the influence of the Black Soil Plains extends beyond their immediate boundaries: as a source of floodplain muds to the lower reaches of the Channel Country, they supply moisture-retaining soils to dry areas where moisture retention is a key ecosystem service (Wakelin-King, unpublished data).

The Black Soil Plains have developed across wide expanses of two different lithologies (Georgina Basin limestone, and Eromanga Basin arkosic sandstone), indicating an as-yet uninvestigated aspect to this area's landscape evolution.

Table 28 The Black Soil Plains

	Place	Black Soil Plains (NT, Qld)	
	Theme (subtheme)	Regolith (Vertisol plains and slopes)	Karst
NHL Criteria	Events and Processes	Development of this soil's mineralogy is likely to be related to Cainozoic climatic conditions and evolution of grassland communities. This area is important as a likely source of Cooper Creek's floodplain sediments, which are themselves noteworthy on a world scale. The black soil plains are critical to the area's ecosystems, as their deep cracking and moisture retention underpin great biological productivity in an arid setting.	The Barkly Tableland covered karst demonstrates previous drainage and groundwater conditions, unrelated to the overlying vertic soils.
	Rarity	Unusual in their extent.	
	Research	This extensive vertisol has developed over two differing lithologies; this indicates some aspect of local landscape evolution which is not yet understood. The link between the black soil plains and the Channel Country rivers is likely to be strong but is currently uninvestigated.	Spatial relationships between karst and vertisols may clarify probable causal links between the limestone hosting the karst and the overlying vertic soils. The extent, type and quality of the covered karst is currently not well documented.
	Principle characteristics of a class	This area will contain places that express the principal characteristics of this landform. It is likely that two locations may be required, demonstrating characteristics of the black soil above each of the parent	This area is likely to demonstrate process relationships between restricted infiltration through the vertic soil layer, and current karst behaviour.

		materials.	
	Aesthetics	-	
	Creative or technical achievement	-	
	Social	-	
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y: Australia is one of three world regions with large amounts of vertic soil.	N
	Unusual (Australia)	Y: Unusual in their extent	Y
	Multiple geomorphic themes	Y: Vertisols and karst as shown in this table.	
	Value with respect to significance threshold	Likely	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	Cooper Creek (Windorah to Nappa Merrie)	
	Status	Indicative area	

Weathering Profiles

Created under present and previous climates and preserved by continental stability, weathering profiles are the result of chemical reactions between groundwater/ rainwater and the sediments or rocks through which it flows. The reactions can transform or leach minerals and transport and precipitate solutes. Weathering profiles are everywhere from the tropics to Bass Strait but are well-developed in the study area and probably best developed in e.g. the Pilbara, Gascoyne, Murchison and Gibson Desert areas). Australia's weathering profiles are often polygenetic and complex (Anand 2005; Pillans; 2005; Anand and de Broekert 2005; Magee 2009), and may be ≤200 m deep.

Good exposures may be found in areas of uplift (see *3.5 Tectonics: Flexure, Neales Catchment*), but for most of the study area, the deep weathering profiles are concealed below low-relief land surfaces, and are expressed at the surface as ironstone pebbles ("buckshot gravel"), ferruginous gravels, and siliceous gravels and cobbles. Regolith geology is intimately connected to Australia's mining prosperity and some of the best exposures of weathering profiles are brought about by mining activities, from the dugouts of the opal country to the Super Pit in Kalgoorlie.

Even the simplest description of regolith geology is beyond the scope of this report. The complexity of weathering profiles is influenced not only by parent rock and groundwater chemistry but also by the repetition of weathering episodes taking place during drainage development and sediment transport: regolith contains both transported and in situ material. The work of CRC-LEME (the Cooperative Research Centre for Landscape Evolution and Mineral Exploration) during the period 1995-2008 was extremely important in developing and renewing Australian regolith science. They developed methodologies for regolith mapping in Australian terranes, age-dated many locations so that Australian landscape evolution was rigorously placed in time, and systematically documented representative locations across the country, including many remote and difficult locations. Their work is summarised in Anand and & de Broekert (2005), and Magee (2009) extensively reviews palaeodrainage weathering profiles. The regolith expression of numerous Australian ore systems is detailed in Butt et al. (2005)

Fig. 25 Dark ferruginous duricrust and soft pale saprolite in the Painted Desert, SA

Weathering profiles can contain both softer and harder components (saprolite and duricrusts, respectively), and these are considered separately in this report because of their different actions in the landscape. Saprolite's colours are a characteristic part of the Australian drylands. The bright bleached white, ochreous yellows, oranges, and tan browns, and the iron reds, from rich red-brown to a dark red that is almost black, are expressed in many location names: White Cliffs (NSW), Rainbow Valley (Northern Territory), Painted Desert (South Australia). In the saprolite, pre-existing sediments or rocks are leached and/or overprinted; where the rock's physical strength is reduced this a strong influence on landscape evolution. In an area of uplift, exposed soft saprolite is rapidly eroded, leading to vegetation-poor high-runoff rill surfaces which are steep and soft (Fig. 25).

	Feature	Saprolite
	Theme (subtheme)	Regolith (saprolite)
NHL Criteria	Events and Processes	Leaching, remobilisation and redeposition of the host rock's components is an integrated record of the area's palaeoclimates and groundwater chemistry. Leaching has a strong influence on nutrient availability to local ecosystems.
	Rarity	N
	Research	Weathering profiles are difficult to research but have potential to reveal landscape evolution across wide areas of the continent.
	Principle characteristics of a class	This area will contain places that express the principal characteristics of this landform.
	Aesthetics	-
	Creative or technical achievement	The work of CRC-LEME developed Australian regolith science.
	Social	-
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y: Australia has unusually complex and ancient weathering profiles.
	Unusual (Australia)	N
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Likely
	Integrity	Y
	Authenticity	Y
	Cross-reference (feature occurs at which sites)	Eastern Goldfields Palaeodrainages, Pilbara Channel Iron; also Great Sandy Dunefield, Great Victoria Dunefield, Pilbara Coastline, Neales River Catchment
	Status	Contributes value to places listed under other geomorphic themes

Table 29 Saprolite

Duricrusts are hard or semi-hard mineral precipitates which impregnate or replace the host rock. Arising from high concentrations of dissolved minerals and specific conditions of groundwater chemistry, they are usually associated with well-developed weathering profiles or evaporative concentration around groundwater discharge zones (e.g. playa lakes). The most common duricrusts are silcrete (mostly silica), ferricrete or other iron-rich rock (dominated by iron oxides), calcrete (mostly calcium carbonate, calcite), and gypcrete (mostly calcium sulphate, gypsum). Duricrusts can be vadose (deposited in the unsaturated capillary zone), also known as pedogenic (part of soil-forming processes), in which case their deposits are often irregular or nodular, or they can be phreatic (deposited as part of the saturated groundwater profile), in which case their deposits may be more dense and uniform. Different minerals create different types of duricrust; the chemical stability and physical strength of the duricrust determine its effect on the landscape. In areas of uplift, soft saprolites which are capped by silcrete or iron-rich duricrusts are protected from erosion and are expressed as mesas, upland plains and domes.

During the 1900s, scientific discussion of duricrusts was influenced by the idea that a single weathering episode was responsible for all duricrusts of a particular type, so that (for example) silcrete outcrops could be correlated across wide landscapes, and be used as a reliable stratigraphic marker. To some extent this was tied into a parallel debate about planation and landscape evolution (e.g. Woolnough 1927). More recent research has discarded this idea in favour of a more realistic view that groundwater deposits do not follow the laws of superposition, and that Australia's long subaerial exposure has resulted in complex patterns of polygenetic regolith (e.g. Anand 2005, Pillans 2005).

As well as the references cited elsewhere in this section, literature relevant to weathering profiles includes Mabbutt (1967), Wopfner and Twidale (1967), Dury (1970), Carlisle et al. (1978), Hutton et al. (1978), Wopfner (1978), Arakel and McConchie (1982), Langford-Smith (1983), Milnes and Twidale (1983), Bourman and Milnes (1985), Arakel (1986), Arakel et al. (1989), Clarke (1994c), Firman (1994), Glassford and Semeniuk (1995), Brown and Dunkerley (1996), McTainsh and Lynch (1996), Chen (1997), Watson and Nash (1997), Alley (1998), Twidale and Bourne (1998), Webb and Golding (1998), Gibson (1998, 1999), Harper and Gilkes (2004), Anand et al. (2005), de Broekert (2005), English (2005), Hill (2005), Hill et al. (2005), Hou et al. (2005), Johnson and McQueen (2005), Whitford (2005), Bourman (2006), Fink (2006), Al-Farraj (2008), Heimsath et al. (2008), Humphreys et al. (2009).

Saprolite: Eastern Goldfields Palaeodrainages

In the Yilgarn craton (Western Australia), wide alluvial valleys were incised into a very low-relief weathered landscape during the Palaeogene. Channel sands and other sediments almost entirely filled the valleys, over a long period of time and in a context of repeated weathering episodes (Clarke 1994a, Clarke 1994b, Johnson et al. 2005, Magee 2009). In the present day, the palaeodrainages occur as broad low areas marked by strings of playa lakes (Van de Graaff 1977) and by complex weathering profiles containing saprolite, ferricrete, silcrete, and calcrete (Fig. 26). The geological context of this region makes it highly prospective for a number of minerals and mining is a dominant part of the local economy. In addition, the palaeodrainages are potential sources of groundwater (Magee 2009).

These weathered palaeodrainages are extremely unusual on a world scale. They have outstanding importance to the natural history wherever they occur, as they are the fundamental structure upon which the modern land surface and ecosystems are built. They also mark the subtle tectonic development of the Australian continent: the geography of their drainage networks indicates slope directions that no longer exist

Fig. 26 Lateritic weathering profile exposed in a mine pit, Eastern Goldfields region

Photo: Pauline English, Geoscience Australia.

(Van de Graaff 1977). This very important landform assemblage should be represented on a national register, but with the present information it is not possible to say which parts of which palaeodrainage are likely to best represent this type of feature. The Eastern Goldfields is a very broad area; a circle radius 200 km around the township of Kalgoorlie would include many palaeodrainages, such as Lakes Lefroy and Cowan which are among those with the best publicly-available information.

The economic importance of regolith-hosted resources was a factor giving impetus to the development of regolith science in Australia, especially the ground-breaking work of the CRC-LEME (Cooperative Research Centre for Landscape Evolution and Mineral Exploration) during the period 1995-2008. They systematically documented representative locations across the country, including many remote and difficult locations. They identified one of the key questions in interpreting regolith: whether the profile under examination is *in situ*, or contains elements that have been transported before weathering. Regolith research in the area has permitted good understanding of Australian landscape evolution and changing climates; but this is only a fraction of the potential information that they contain.

Table 30 The Eastern Goldfields Palaeodrainages

	Place	Eastern Goldfields Palaeodrainages	
	Theme (subtheme)	Regolith (saprolite, ferricrete, silcrete, calcrete)	Watercourses (palaeodrainages and playa lakes)
	Events and Processes	The sedimentary successions and their complex overprinted weathering profiles mark the continent's stability and its successive climates.	Broad low-relief areas, originally valleys but now almost entirely filled by sediments, are marked by strings of playa lakes. The transition from drainage network to string of playa lakes marks the continent's increasing aridity. The palaeovalleys are the fundamental structure upon which the modern land surface and ecosystems are built.
	Rarity	These landscapes are widespread in the western part of Australia, however their geomorphic heritage is not recognised.	
	Research	Has already contributed to understanding Australia's landscape evolution, and there is potential for further information with more research.	The palaeodrainages mark drainage networks whose downvalley decrease in elevation has been altered (and in some cases reversed) by uplift: they contribute to understanding Australia's tectonic history.
NHL Criteria	Principle characteristics of a class	There are likely to be sites where characteristic features of, and genetic relationships between regolith and landforms are demonstrated.	There are likely to be sites where the characteristics of palaeodrainages and playa lakes are well demonstrated.

	Aesthetics	Iconic drylands Australian landscapes, characteristic of the Yilgarn Craton; especially striking when viewed from remote imagery e.g. Google Earth.
	Creative or technical achievement	The development of regolith science in Australia.
	Social	Rich in mineral resources, with long-term and continuing importance to the history, economy and society of Western Australia. Well-studied (considering its remote and difficult location) by (*inter alia*) the CRC-LEME. Associated with the development of regolith science.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	N
	Multiple geomorphic themes	Y
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference	Great Sandy and Great Victoria dunefields
	Status	Indicative area.

Saprolite: Pilbara Channel Iron

The Pilbara Channel Iron (also known as the Robe Pisolite) are linear outcrops and ridge lines in which the hillcrests are hard iron-rich regolith. There are many occurring across a very wide area (400 km radius) near Robe River, Western Australia, but they are otherwise rare: the only other known occurrences are in Kazakhstan (Ramanaidou et al. 2003). These landforms were created by the topographic inversion of transported regolith deposited in palaeovalleys (Ramanaidou et al. 2003, Killick et al. 2005). Ferruginous regolith has been eroded from its source area, transported and accumulated as pisolitic iron oxides within an alluvial valley. During subsequent landscape evolution, the softer saprolite around the ironstones has weathered and been eroded away, leaving what was once the valley bottom (that is, the pisolitic channel sediments) now the highest points in their landscapes. In this report, the Pilbara Channel Iron is listed under the saprolite sub-theme however it would be more accurate to regard both saprolite and iron-rich duricrust sub-themes as being equally important in this landform's formation.

The Pilbara Channel Iron are valuable resources, and some are currently being mined. The economic importance of regolith-hosted resources was a factor giving impetus to the development of regolith science in Australia, and the ground-breaking work of the CRC-LEME (Cooperative Research Centre for Landscape Evolution and Mineral Exploration) during the period 1995-2008.

	Place	Pilbara Channel Iron (Robe Pisolite)	
	Theme (subtheme)	Regolith (saprolite, ferricrete)	Watercourses (palaeodrainages)
NHL Criteria	Events and Processes	Ferruginous regolith has been eroded from its source area, transported and deposited in river valleys. Differential erosion has lowered the surrounding hillsides, and the ferruginous fluvial sediments are now the highest points on the landscape.	These palaeodrainages are now hills through topographically inversion; they mark drainage networks that no longer exist.
	Rarity	These landscapes are unusual on a world scale, however their geomorphic heritage is not recognised.	
	Research	The age of the regolith and the surrounding land surfaces is likely to provide information on the tectonic history of this part of the continent. Investigation into the genesis and transport of the ferruginous material will provide information on landscape evolution, groundwater chemistry, and climate change.	The relative uplift that has created the topographic inversion, and the spatial relationships between the palaeodrainage and the present-day drainage provides information on the tectonic history of this part of the continent.
	Principle characteristics of a class	There are likely to be sites where characteristic features of pisolitic alluvial iron ore are demonstrated.	
	Aesthetics	Characteristic of Western Australia's Pilbara; iconic drylands Australian landscapes.	
	Creative or technical achievement	-	
	Social	Important to the history, economy and society of Western Australia. The economic value of the resource has promoted investigation of the landform's characteristics, and been a factor in promoting CRC-LEME's development of regolith science in Australia.	
	Significant people		
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Yes: the only other known occurrence in the world is in Kazakhstan.	
	Unusual (Australia)	Y	
	Multiple geomorphic themes	Yes: Regolith and Watercourses as shown in this table.	
	Value with respect to significance threshold	Clear	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	possibly the Great Sandy Desert dunefield	
	Status	Indicative area	

Table 31 Pilbara Channel Iron

Duricrusts: Silcretes and Gibber

Silcrete is an extremely hard and durable rock composed mostly of silica. It occurs in a wide variety of colours and grainsizes (e.g. billy, pudding stone, terrazzo, pebbly, candle-wax, chalcedonic) and manifests as semi-planar outcrop of lumpy boulder piles (Fig. 27) or wide plains of rounded rocks (gibber plains, stony desert) which are sometimes densely packed into a desert pavement. Because of the conditions required for silica's precipitation, silcretes tend to have wide areal extent. Its mineralogy, grain size and outcrop habit depend on the conditions of host rock porosity and chemistry, groundwater chemistry, and climate at the time of its deposition, and so it will mark one or more stages in its landscape's evolution. Its variable and confusing field expression, and relationship to important discussions on planation, has prompted considerable research (e.g. Thiry et al. 2006).

Silcrete's widespread occurrence and extremely durable nature makes it the duricrust with the strongest visible expression in the Australian landscape; it is probably the single lithology with the widest geomorphic influence across the continent. Soft rocks capped by hard silcrete are protected from erosion, allowing preservation of uplifted old land surfaces. Where silcrete or gibber layers are discontinuous or partially removed, post-uplift erosion will remove the soft saprolite where it is not protected by silcrete. The resultant landscape of distinctive flat-top hills (mesas, breakaways, or jump-ups) and often brightly-coloured sarolite scarps are iconic (e.g. in the

Fig. 27 Silcrete in the Neales Catchment. Photo: Chris Bell

Innamincka area, Fig. 18). Its distribution is also a very important influence on shaping present-day drainage networks, therefore influencing ecosystems over a very wide area, for example:

- at Innamincka Dome and the Cooper Creek valley site, silcrete is a key component of the processes which constrain Cooper Creek's fluvial style (Wakelin-King 2013);
- in the Neales River catchment, the distribution of gibber plain has juxtaposed two very different types of river are within a single catchment, with concomitant effects on catchment-wide ecosystems (Wakelin-King 2011).

Silcrete is hard with a conchoidal fracture; fine-grained silcretes break to razor-sharp edges. It was an important source material for Aboriginal stone cutting tools, and it is likely that good silcrete was traded widely. Silcrete tools were important not only in ordinary life, but also as significant ceremonial items. Silcrete distribution would have had strong cultural importance in pre- European Australia (e.g. Doelman et al. 2001).

Investigations of Australian silcretes unravelled clues to its conditions of formation from its exceptionally variable and confusing field expression (e.g. Langford-Smith 1978a, 1978b), but silcrete's relationships to the broader questions of planation surfaces was more fully developed in later works (e.g. Hill et al. 2003, Anand 2005, Gibson 2005a, Gibson 2005b, Thiry et al. 2006). Silcrete, or silica-rich duricrust, can be coeval with calcretes in some settings, and with iron-rich duricrusts or ferricretes in others (Arakel 1991, Anand 2005). The western edges of the Neales Catchment have some particularly fine locations where the complete profile from solid silcrete top to porous saprolite base can be related to the relict land surfaces overlaying them (Wakelin-King, unpublished research).

Table 32 Silcrete

	Feature	Silcrete
	Theme (subtheme)	Regolith (silcretes and gibber plains)
NHL Criteria	Events and Processes	Silcrete has an extremely wide influence on landscapes: • preserving relict land surfaces and underlying soft saprolite, so producing characteristic terrains, • by governing an area’s runoff qualities and gradient, directs development of the drainage network (therefore influencing ecosystems over a very wide area). Elevation and dip on silcrete layers preserve records of uplift and tilting of the land surface. The wide variety of different silcretes and the specific conditions required for their precipitation within the regolith represent one or more stages in the local landscape evolution (including climate, sediments, and groundwater chemistry).

	Rarity	Silcrete is widespread but its heritage values have not been identified at any particular location.
	Research	Analysis of silcrete formation can contribute to understanding an area's Cainozoic groundwater and climate evolution. Understanding silcrete's spatial attributes allows reconstruction of post-depositional tectonism.
	Principle characteristics of a class	The study area will contain places that express the principal characteristics of silcrete landforms. It is likely that several sites would be desirable, representing the different expressions of silcrete in the landscape. It would also be desirable to have representation of silcrete in the context of its weathering profile and old land surface, such as the western edge of the Neales Catchment, which shows the gradual replacement of host rock with silcrete, and the progressive stripping of the old land surface.
	Aesthetics	The gibber plains and breakaway country are iconic landscapes of inland Australia.
	Creative or technical achievement	Silcrete cutting tools were a key technological advance, and were in use in Aboriginal society until relatively modern times.
	Social	Silcrete horizons and associated old land surfaces were an important part of 20th-century discussions on planation and landscape evolution.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	N
	Unusual (Australia)	N
	Multiple geomorphic themes	-
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: the feature occurs at these sites.	Silcretes contribute to heritage values for Innamincka Dome-Cooper Creek valley and the Neales River catchment. They occur at, and are likely to contribute value to, the Simpson Desert floodouts, the Eastern Goldfields Palaeodrainages, the Pilbara Channel Iron, and Kati Thanda-Lake Eyre. They probably occur at and contribute value to the Great Sandy and Great Victoria dunefields. In general, silcretes or gibber plains may be associated with other weathering profile components in relict land surfaces and palaeodrainages.
	Status	In many places, silcretes are not in themselves sufficiently prominent landscape elements to rate as natural heritage landscapes. However, they are important components in, and may contribute substantially to the heritage values of, landscapes dominated by other geomorphic themes.

Other Duricrusts and Regolith Precipitates: Gypsum, Calcite, Iron Oxides

Gypsum is a precipitate from water rich in calcium and sulphate. Liberated during widespread weathering (Thiry et al. 2006) it occurs in soils and weathering profiles. In playa lakes (e.g. Lake Amadeus, Kati Thanda-Lake Eyre, and playa lakes in the Eastern Goldfields region) gypsum is precipitated during evaporative groundwater evolution, sometimes in a situation of co-evolution with other duricrusts (Arakel 1991, Chen et al. 1991, Thiry et al. 2006. and e.g. Jacobson et al. 1988, English 2001). It occurs commonly in the study area. It can occur in a wide variety of crystal types, according to the degree of saturation and the and the groundwater's chemistry and concentration, so can indicate groundwater or palaeolake conditions at the time of its crystallisation. Gypsum's expression in the landscape depends on its crystal size and distribution; it is a brittle mineral of low hardness and is moderately soluble in rainwater, so it does not form strong outcrops. Weathering profile gypsum can form large glassy sheets of selenite and satin spar. Fine-grained gypsum (<2 mm) or gypsum earths (kopi) in soil or regolith is soft, fluffy and easily eroded. Centimetre-scale swallowtail or desert-rose crystals are less easily eroded, and can form e.g. low benches, especially if densely interlocked. Under the right circumstances of groundwater and climate, fine-grained gypsum around playa lake margins can be partially re-cemented into a harder crust of gypcrete.

Calcrete precipitates from water rich in calcium and carbonate ions, and is predominantly calcite. It is a component of many weathering profiles, and is associated with playa lake and palaeodrainage margins and surrounding countryside. It precipitates during the early stages of groundwater evolution, sometimes in a situation of co-evolution with other duricrusts (Arakel 1991, Chen et al. 2002, Magee 2009). It can occur in a wide variety of types, from lightly calcareous earths to nodular and laminated calcretes (in vadose or pedogenic calcrete), and phreatic or valley calcretes which can be very fine-grained and dense and extend widely along palaeodrainages.

Calcite is a tough and fairly hard mineral which is somewhat soluble in rainwater. In arid climates thick calcrete profiles can be resistant to erosion, protecting softer sediments beneath them, and can develop karst features such as surface laminations, piping and subsidence dolines. Calcretes may be most visible in the landscape as flat-topped land surfaces with steep scarps facing towards the playa lake margins, in which blocky or rubbly outcrop is exposed. Some palaeodrainage calcretes are aquifers important to local ecosystems or pastoral industry, such as those of the Karinga Creek palaeodrainage (Northern Territory) (Edgoose et al. 1993). Calcretes are important in the Lake Amadeus and Lake Lewis areas, as well as other playa lakes.

Calcretes, and gypcrete and other forms of gypsum are not, by themselves, sufficiently prominent landscape elements to rate as natural heritage landscapes. However they are very important part of Australian playa lakes, and the qualities of gypsum or calcrete landforms should be considered in any playa lake's geoheritage assessment.

The mobility of iron oxides through weathering profiles and varieties in which they can be precipitated leads to a great range of deposit types, from soft orange ochres to hard and insoluble blackish-red ferruginous duricrusts (ferricretes). Iron oxide precipitates within weathering profiles can therefore have expression in the landscape like a soft saprolite, or like an erosion-resistant silcrete (such as in the Pilbara Channel Iron). Iron-rich precipitates were once considered to be parts of laterite profiles which were understood in a simplistic fashion: ferricrete or ironstone on the top, a red oxidised zone grading down through a mottled zone to a bleached white pallid zone, overlying saprolite. While these elements remain important elements of many deep weathering profiles, the complete picture is much more intricate. Ferricretes and iron-rich duricrusts can often be intimately co-located with silcretes and siliceous duricrusts, in a way that suggests overlapping or coeval conditions of formation. This is a complex question and outside the scope of this report. Ferricretes, iron-rich rocks and iron-rich desert varnish are widespread in the colour of the study area's landscapes, and therefore are important to its aesthetic appeal. Where they are hard and erosion-resistant, iron-rich regolith plays the same landscape role as silcretes, however silcretes are generally far more abundant.

	Feature	Other Duricrusts and Regolith Precipitates
	Theme (subtheme)	Regolith (Gypcrete, Calcrete, Ferricrete)
NHL Criteria	Events and Processes	As a general statement, duricrusts and regolith precipitates will be specific to their formative conditions of host rock, groundwater chemistry and climate, therefore marking one or more stages in the local landscape evolution. Phreatic duricrusts in particular may give clear indications of groundwater location and conditions, and gypsum crystal habit can indicate palaeogeography.
	Rarity	Duricrusts are common in drylands Australia but no particular sites have been identified in which their heritage values are identified.
	Research	Analysis of duricrust formation can contribute to understanding an area's landscape evolution.
	Principle characteristics of a class	There are likely to be many sites where the characteristic features of various duricrusts are demonstrated.
	Aesthetics	-
	Creative or technical achievement	-
	Social	Some calcretes develop karstic voids, and are associated with freshwater springs along palaeodrainages. These are locally important economically and ecologically and were likely to be important in pre-European times.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	N
	Unusual (Australia)	N
	Multiple geomorphic themes	-
	Site's value with respect to significance threshold	-
	Integrity	Y
	Authenticity	Y
	Cross-reference: the feature occurs at these sites.	Specific sites: Ferricretes are associated with the Eastern Goldfields Palaeodrainages and the Pilbara channel iron. Calcretes are mentioned as being present in the Eastern Goldfields Palaeodrainages. General associations: Ferricretes may be found in conjunction with saprolite in a complete (lateritic) weathering profile, and are often in association with silcretes. Calcretes are a widespread element in desert soils, and are commonly found along the margins of palaeodrainages and playa lakes. Calcretes are also an important part of mound springs.
	IBRA region	Multiple.
	Status	Calcretes, gypcretes, and most ferricretes are not in themselves sufficiently prominent landscape elements to rate as natural heritage landscapes. However, they are important components in, and may contribute to the heritage values of, landscapes dominated by other geomorphic themes.

Table 33 Other duricrusts

3.8 Watercourses

The watercourses theme includes all landforms associated with moving water across the surface of the land. This sounds obvious, however two landform sub-themes discussed here are not usually recognised as being fluvial because they transmit unchannelled sheetflow (floodouts, and banded vegetation sheetflow plains), and two others (megaflood landforms, palaeodrainages) may not be immediately clear to the observer because of their age and the scale of their features.

Australia's drylands rivers are in some ways unlike other desert rivers described in the literature: they are less arid than those of the Middle East, and with more irregular flow regimes than many in the western USA (because of that area’s orographic precipitation). They flow through catchments that are (in comparison to other parts of the world) unusually full of fine regolith. Consequently, descriptions of drylands river form and process which fit other parts of the world are sometimes a poor fit here. Although there has been some excellent research done on Australian drylands rivers, their remote and difficult locations make adequate research funding difficult to acquire, and there are relatively few researchers working on them. There is certainly insufficient recognition of their various special landforms, and more work yet to be done.

A quantity of water, and a slope for that water to move down, are the usual requirements for a river system to exist. In Australia's inland, both those components are in short supply: rainfall is limited, and most of the drylands are very low-gradient. Where watercourses exist they must either be adjusted to a short, intermittent flow pattern, or they must be in a position where they can receive exogenous water (rainfall from outside the arid zone). The fluvial landforms described here are the different mechanisms that have evolved to cope with these limiting factors.

Australia’s drylands rivers are diverse, and in this report the watercourses landforms are divided into 12 sub-themes. These subthemes are not intended to encompass all features of all Australian drylands rivers, but rather to highlight and clarify the geomorphic processes relevant to this heritage discussion. Amongst the present-day channelled watercourses are

- sand bed rivers,
- discontinuous ephemeral streams (DES), and
- anabranching rivers.

Notable components of present-day channelled watercourses are

- mud-aggregate floodplains,
- fresh-water basins, and
- mound springs.

Unchannelled present-day watercourses include

- banded vegetation sheetflow plains, and

- floodouts.

Large-scale old watercourses are

- palaeodrainages, or
- megaflood landforms.

Finally, there are

- playa lakes and associated megalake deposits, and
- post-European channel incision.

Sand-bed rivers

Sand-bed rivers are wide, relatively shallow sandy river beds, occurring where uplands provide an abundant supply of coarse sediments (sand, gravel, boulders) to the drainage network. They are typically single-thread channels with a nearly straight or a gently curved planform. The abundance and coarse texture of the sediment requires high energy to transport the bedload: the channel geometry makes the best use of the limited stream power. In fluvial process studies, low-sinuosity rivers are associated with low slope, low stream power, and low capacity for sediment transport (Tooth 2000a, Nanson and Huang 2008). In the past, sand bed rivers were considered to be typical of deserts (e.g. Mabbutt 1977), however this is probably an oversimplification on a world scale, and certainly underestimates the diversity of Australian drylands rivers (this document, and see Tooth 2000a). Low-sinuosity rivers have been described in fluvial literature since at least the 1950s (e.g. Leopold and Wolman 1957, Schumm 1977), but relatively little attention has been paid to documenting their real-world fluvial processes.

Sand-bed river bedforms can form in response to either peak-flow high-energy or waning-flow low-energy flow conditions (see Wakelin-King and Webb 2007b). When seen in their normal condition (dry, between flows) the bedforms are typically flat bedding or 2D dunes, low-energy forms deposited during waning flow (Fig. 28). The fluvial architecture of sand-bed rivers' depositional units marks extreme to 'ordinary' flow events, and can be very complex (Bourke 1994, Bourke and Pickup 1999). Sand-bed responses to changing conditions include flooding out with downstream decreases in discharge, or developing anabranching when a tributary brings in increased moisture and sediment (Mabbutt 1977, Tooth 1999, Tooth and Nanson 2004).

The flat white sandy and gravelly riverbeds stand out against the orange-red of the nearby rocks and floodplains. Their aesthetic is a highly valued part of the tourist and local experience, so they are important both economically and socially. The soil and groundwater conditions of sand-bed rivers often support River Red Gums (*Eucalyptus* *camaldulensis*), which are similarly important. Sand-bed rivers are a common theme in the work of artist Albert Namatjira.

Sand-bed rivers are characteristic of central Australia's Amadeus Basin ranges e.g. rivers arising from the MacDonnell Ranges (the Todd, Hale, Plenty, Finke, Hay and others) or those in the Northern Plains (the Sandover, Bundey, Woodforde and others). They will also occur wherever eroding uplands contain quartz-rich lithologies, e.g. the Flinders Ranges. In the study area, sand-bed rivers contribute value to a number of sites (Table 6).

	Feature	Sand-bed rivers
	Theme (subtheme)	Watercourses (sand bed rivers)
NHL Criteria	Events and Processes	Channel geometry balances the high energy needed to transport their bedload against the river's low discharge and/or periodic flow regime.
	Rarity	-
	Research	Have potential to increase understanding of low-energy low-sinuosity fluvial systems; currently under-researched.
	Principle characteristics of a class	Within the study area reaches will exist that can demonstrate the characteristics of this type of river.
	Aesthetics	The beauty of sandy river beds and their river red gums are highly valued, and are important in the tourist economy and local amenity.
	Creative or technical achievement	
	Social	
	Significant people	A common theme in the work of artist Albert Namatjira.
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y?
	Unusual (Australia)	N
	Multiple geomorphic themes	This feature contributes value to complex sites.
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: feature occurs at these sites	Simpson Desert floodouts, Wilkatana fan complex/central Flinders Ranges, Sandover-Bundey confluence floodout, Amadeus Basin/MacDonnell Ranges, Amadeus Basin/Rodinga Range, Ross-Todd confluence.
	Status	Contributes value to places listed under other geomorphic themes; indicative area.

Table 34 Sand-bed rivers

Fig. 28 Flat bedding in the channel of a sand-bed river (Trephina Gorge)

Discontinuous Ephemeral Streams; Fowlers Creek

Discontinuous ephemeral streams (DES) are small (<~70 km in length) dry creeks, which include both channelled and unchannelled reaches. They are characteristic of many parts of rangeland Australia. They consist of spatially linked source-transport-sink reaches, in which an upstream reach is often characterised by erosion, a central reach with an established channel transports sediment, and a downstream unchannelled reach is a site of sediment deposition (Bull 1997). Depending on topography, the creek system as a whole may consist of a single source-transport-sink unit, or several. Discontinuous ephemeral streams can occur within different landscape contexts, including low, regolith-covered hills, and drainage lines extending out from range fronts and into flat depositional plains.

Systems such as this in Australia have been described as erosion cells (Pickup 1988, 1991), and in the western USA as discontinuous ephemeral streams (Bull 1997). Where rainfall is episodic but sometimes occurs in short high-intensity bursts, sediments scoured from a channel may be transported only a short distance before being redeposited (Pickup 1985, 1988). Usually the channel is large compared to the amount of sediment transported, and sediment is deposited in-channel. Where the channel is small, or terminates, a sediment lobe will be deposited at the channel's downstream end: this is a floodout (see *3.8 Watercourses: floodout*s). The floodouts of erosion cells and discontinuous ephemeral streams are ecologically valuable because they are likely to be well-vegetated, and may retain water when the rest of the area is in drought. Such streams are maintained by a self-reinforcing feedback system, promoting either aggradation (and floodout maintenance) or channel entrenchment, depending on the balance between stream power and valley-floor strength along the flow path (Bull 1997, Wakelin-King and Webb 2007a).

Discontinuous ephemeral streams are typically found in low regolith-covered hills with fairly randomly-oriented valleys, a topographic context which does not allow them to form large well-connected drainage networks that transport significant amounts of water (as opposed to e.g. the Amadeus Basin ranges in Central Australia which have steeper hills, good hillslope-creek connectivity and valleys which are spatially integrated with one another). Because they are small and volumetrically insignificant in terms of their water resources, they have received little research attention, and (c.f. larger rivers carrying perennial flow) tend to be a lower priority for poorly-resourced catchment management authorities. Nonetheless, DES are the framework upon which local ecosystems are built. For example, in the Barrier Ranges the DES host the surface water resources which are critical to the local pastoral industry and local inhabitants' amenity, and which are a significant contributor to the tourist experience.

Discontinuous ephemeral streams present special challenges in land management and water rights regulation. Landholders' water rights are defined in terms of the size of watercourse that they wish to extract water from. For example, under the New South Wales Water Management Act 2000 (Harvestable Rights) (NSW 2006a), a landholder may dam a first- or second-order stream, as defined with reference to certain topographic maps (NSW 2006b). The topographic map is created by airphoto interpretation, in which visible stream channels are traced. If the unchannelled floodout reaches of DES are large and poorly vegetated, it is not uncommon that they are not recognised on the topographic maps as part of a drainage network. In that case, the upstream channelled reaches may be given a different name to the downstream channelled reaches, effectively separating the drainage network into two. In such a case, it is legally possible for a landholder to dam a third- or higher-order channel (because it resembles a first- or second-order stream), which occludes a larger proportion of the catchment than they are entitled to.

Discontinuous ephemeral streams are a common fluvial type in some parts of the study area, for example the Western Division of New South Wales (an area that includes the Barrier Range) and parts of South Australia's Arid Lands region. It is likely that DES are also found in e.g. the Great Victoria and Great Sandy dunefields, and elsewhere. Nonetheless, this fluvial style has received very little research attention.

Fowlers Creek is proposed here as a watercourse with high potential geoheritage values in multiple areas. This creek is 54 km long and is located ~100 km ENE from Broken Hill, western New South Wales. Its lower-order reaches are set in the low rolling uplands of the Barrier Range. The creek exits the uplands, crossing the eastern rangefront, and traverses the Bancannia Plain towards its terminal floodout.

The upper reaches of Fowlers Creek are located within what was Corona Station, a major pastoral station for which meteorological and historical records have been kept since early European settlement. Its central reaches and most of its floodout are located within the Fowlers Gap Research Station, currently owned by the University of New South Wales. A centre of research since the 1950s, Fowlers Gap Research Station is a place where independent research topics address overlapping themes and geographies, to the benefit of all. This is an almost unique situation in the Australian arid zone. It is consequently one of the best-researched arid zone rivers in Australia, with local research projects including fluvial process (including key research on post-European valley floor incision and on banded vegetation landforms), hillslope processes, vegetation, soil, aeolian deposits, pre- and post European history. Earth science research publications based in and around the Fowlers Gap research station include Dunkerley (1992, 2008a, 2008b), Graeme and Dunkerley (1993), Dunkerley and Brown (1995, 1999a, 1999b), Hill and Roach (2003, 2005) MacDonald et al.

Fig. 29 A lower-order channel in Fowlers Creek ;1 m scale (arrowed)

(1999), Mabbutt and Sullivan (1973), Wakelin-King (2011), Wakelin-King and Webb (2007a, 2007b); and see the entries under *3.8 Watercourses: Post-European Drainage Incision*. An extensive range of ecological and agricultural investigations has also taken place; on-site research is noted in the Fowlers Gap annual reports. The geology of the Fowlers Creek area is described in *inter alia* Ward and Sullivan (1973), Cooper et al. (1975), Neef et al. (1995) and Mills and David (2004).

Fowlers Creek exhibits several different fluvial styles and its catchment includes other landforms of interest (Wakelin-King 2005). Its lower-order reaches are discontinuous ephemeral streams (Fig. 29) (with tributary-confluence intermediate floodouts) set in the low rolling uplands of the Barrier Range. The creek crosses a significant geological fault at the eastern Barrier Range where it exits the uplands; the spatial relationships of faults, uplands and outcrops of sedimentary rock (expressive of shallow tectonics or Cainozoic uplift), and outcrops of medium- to high-grade metamorphic rock (expressive of deep tectonics and long-term uplift) have the potential to contribute significantly to understanding evolution of the Australian plate. The reaches on either side of the eastern rangefront are anabranching; they differ in many respects from other described anabranching rivers. The creek diminishes as it flows across the Bancannia Plain towards its terminal floodout. The hillslopes surrounding the upland reaches are banded vegetation (stony gilgai) which is characteristic of some parts of western New South Wales, and is key to the biological productivity of the hillslopes. The stony gilgai is based on red-clay vertisols, and these contribute to Fowlers Creek's dominantly mud-aggregate sediment load, imparting some unusual flow characteristics (Wakelin-King and Webb 2007b). Mud aggregates are important in the sedimentary record, and Fowlers Creek is one of only two places in the world where mud-aggregate fluvial sedimentology is described (see *3.8 Watercourses: Mud-Aggregate Floodplains*). The Fowlers Creek sedimentary record demonstrates important points about pre- and post-European landscape evolution (see *3.8 Watercourses: Post-European Drainage Incision*). In the upstream reaches, many discontinuous ephemeral streams with intermediate floodouts are currently threatened by channel-floor incision resulting from early styles of grazing management.

Fowlers Creek is representative of this collection of landforms. It is possible that other catchments in western New South Wales may have some of these features developed to a better degree, but Fowlers Creek is by far the best researched, and currently contains the best-documented of the principal characteristics of many of the landforms it contains.

Table 35 Fowlers Creek

	Place	Fowlers Creek	
	Theme (subtheme)	Watercourses (discontinuous ephemeral streams)	Watercourses (post-European drainage incision)
NHL Criteria	Events and Processes	Discontinuous watercourses are important components of Australian drylands' patch dynamics. Tributary confluence floodouts (a component of discontinuous ephemeral streams) are ecologically important, and are sometimes refugia. They are also likely to be relic from very large flow events.	Post-European changes to land management practices has led to channel entrenchment in some previously unincised valley floors. They mark historical events in which human activities have changed fluvial processes: river systems have crossed a threshold boundary from one stable state to another.
	Rarity	Discontinuous ephemeral streams, and drainages that have suffered post-European incision, are not rare but their values are currently unrecognised. The tributary confluence floodouts are threatened by the post-European channel incision.	
	Research	Discontinuous watercourses are not well recognised in rangelands management: better understanding of the processes which form and maintain them will lead to better management of erosion and better preservation of 'sweet spot' patch ecosystems.	Investigation of instances of valley floor incision will lead to better land management practices. Distinguishing between 'natural' and post-European causes of valley floor incision is important to understand fluvial processes in discontinuous ephemeral streams, and is also important in assessing range condition and setting rehabilitation targets. Fowlers Creek contains both incised and unincised valley-floors, and extensive records and allied research: it is a highly suitable research site in which to investigate this process.
	Principle characteristics of a class	Likely to contain good examples of the principal characteristics of many of the landforms it contains.	
	Aesthetics	-	
	Creative or technical achievement	-	
	Social	In law, lack of recognition of the discontinuous nature of these watercourses is likely to lead to water rights disputes.	Fowlers Creek is the site of important and influential measurements of post-European erosion.
		Fowlers Creek is one of Australia’s best-researched drylands rivers. It is important to the research community as a place where interdisciplinary research addresses overlapping themes and geographies, to the benefit of all.	
	Significant people	-	

	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	Y
	Multiple geomorphic themes	Yes: as well as Discontinuous Ephemeral Streams and Post-European Drainage Incision (this table), Fowlers Creek contains landforms from the Watercourses: Floodouts, Watercourses: Anabranching Rivers, Watercourses: Mud Aggregate Floodplains and Watercourses: Banded Vegetation Hillslopes themes. The banded vegetation hillslopes are based on red vertisols; they are critical to local ecosystems and play an important role in mediating hillslope runoff. The mud aggregate floodplains are currently one of only two described modern analogues of an important lithotype. Part of the Barrier Range; though some distance from the Mundie Mundi rangefront, Fowlers Creek's rangefront has formed in response to the same tectonic context (tectonics; faulting). Tributary-junction floodouts (watercourses; floodouts) are integral parts of discontinuous ephemeral streams. Fowlers Creek is anabranching in its middle reaches, in a way that is dissimilar to other well-known anabranching rivers. Research into its processes in these reaches will contribute to better understanding of anabranch processes. Rangefront faulting is expressive of deep crustal relationships.
	Value with respect to significance threshold	Likely
	Integrity	Y
	Authenticity	The degree to which some parts of the creeks have been altered in post-European times has been a subject for discussion in the literature. However, that dialogue is important for understanding appropriate land management, and the discussion does not detract from the heritage value of the site.
	Cross-reference to other places	Barrier Range/Mundi Mundi rangefront
	Status	Specific area

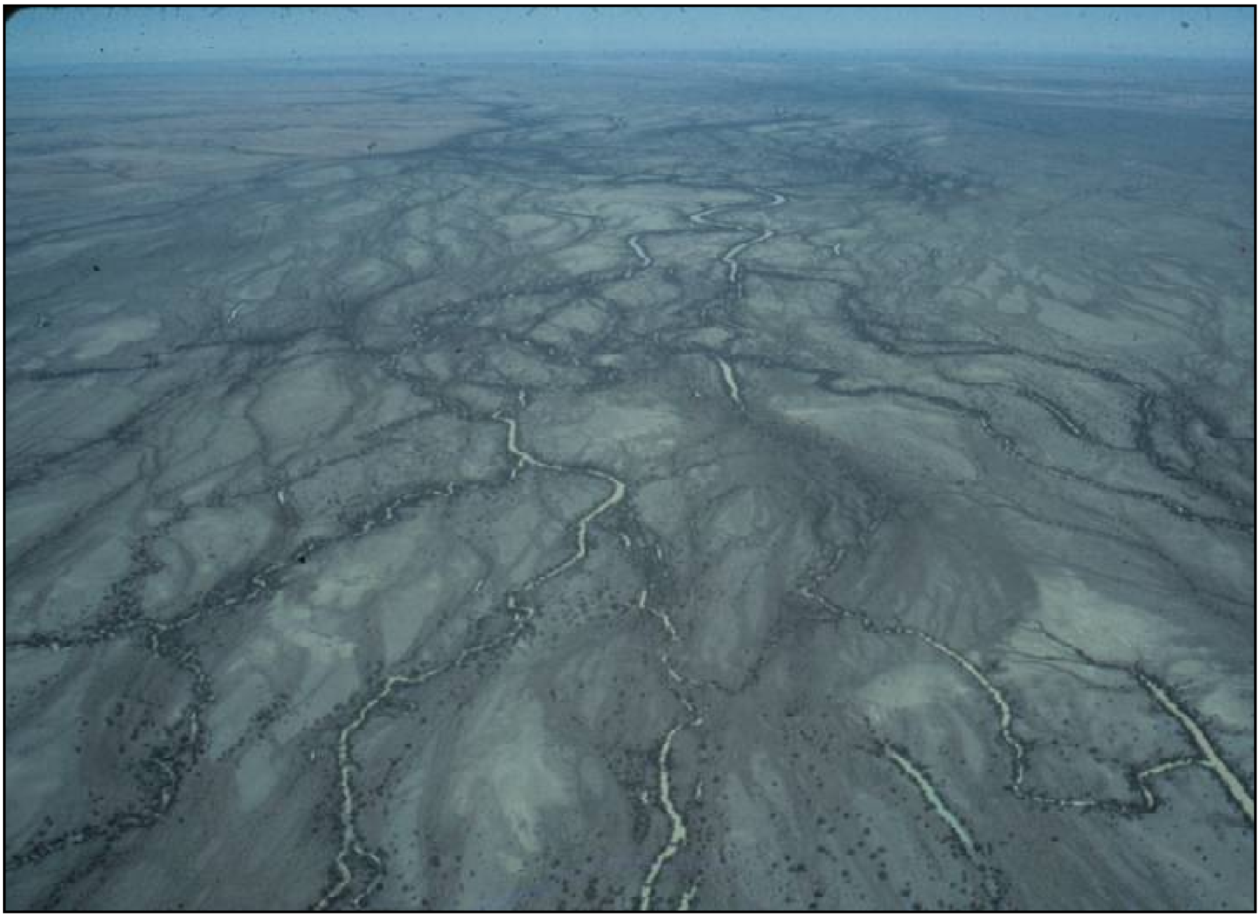


Fig. 30 Cooper Creek's anabranching channels

The large anabranching channels host waterholes. The mud-aggregate floodplains show shallow anastomosing floodways around braid-like bars. Photo: Gerald Nanson; looking downstream.

Anabranching Rivers; Cooper Creek (Windorah to Nappa Merrie)

An anabranching river has multi-thread channels in which each channel is hydraulically independent and separated by stable, floodplain-height vegetated bars. They are a response to low stream power: dividing a given discharge of water into several channels increases flow depth and therefore stream power in each channel, allowing a greater grain size and/or amount of water and sediment to be transported (Nanson and Knighton, 1996; Nanson and Huang, 1999, 2008). Anabranching is an outstanding demonstration of fluvial adaptability to Australia's low-energy watercourses in the flat, dry inland (see Tooth and Nanson 2000). Bank strength is a key component of the anabranching process (Tooth and Nanson 2004). In addition to the references cited here, anabranching systems are also described in Gibling et al (1998), Nanson and Tooth (1999), Nanson et al. (1986), Sheldon and Thoms (2006), Tooth and Nanson (2000).

Anabranching is not uncommon in Australian rivers, but its heritage values are not presently recognised. Outside the present study area, significant anabranching occurs in rivers of the Macquarie fan (e.g. Thoms et al. 2006), and the Murray River. Within the study area, anabranching occurs in (*inter alia*) Fowlers Creek, the Neales Catchment, the northern plains of central Australia, and the Channel Country of the Lake Eyre Basin (LEB): the Georgina and Diamantina Rivers, and Cooper Creek. (Rust and Nanson 1986, Nanson et al. 1988, Nanson and Knighton 1996, Tooth and Nanson 1999, Wakelin-King 2005, Wakelin-King 2011a). The most extensive and spectacular examples occur in the reaches of Cooper Creek from Windorah to Nappa Merrie Waterhole (Fig. 30), in south-east Queensland, here proposed as an area of high potential geoheritage value. It is an area of considerable geomorphic complexity (e.g. Nanson et al., 1986; Nanson and Tooth, 1999), containing outstandingly good examples of landforms from three Watercourses subthemes (Table 4). For more than thirty years this area has been a research focus by the influential Nanson research group (University of Wollongong): it is one of Australia’s best-researched arid rivers.

Cooper Creek is, for Australia, an extremely large river (>1000 km long). Its headwaters are up north in the Black Soil Plains (see *3.7 Regolith: Vertisol Plains and Slopes*), where they can receive monsoonal rains. It traverses some of Australia's driest country and many of its channels are usually dry. However, its flow regime is extremely variable (Knighton and Nanson 2001) and it flows or floods often (several times a decade to several times a year, depending on which part of the drainage network you are considering) (Costelloe 2008, 2013). In a good (usually La Niña) year, the river in flood can occupy the entire wide floodplain, and the flood front can take months to reach its end in Kati Thanda - Lake Eyre.

Cooper Creek is constrained between silcrete-crested uplands (see *Tectonics: Flexure* and *Regolith: Silcrete*). Between Windorah and Nappa Merrie Waterhole the creek occupies a very low-gradient, very broad floodplain (Fig. 31) which hosts a complex array of different landforms and features. The main channels are a network of primary, secondary, and sometimes discontinuous minor channels linked as anabranches (Nanson et al. 1988, Nanson and Tooth 1999). Though channel relocation and infilling are known from other LEB anabranching systems (Wakelin-King 2010), Cooper Creek's major channels appear to be stable in the long term (Knighton and Nanson 2000). The channels are relatively narrow and deep with steep banks, and many host waterholes (see *3.8 Watercourses : Freshwater Basins*). The floodplain sediments are dominantly mud aggregates (see *3.8 Watercourses: Mud Aggregate Floodplains*). During flooding, overbank flow is carried in shallow floodways forming an anastomosing network around low-relief braid-like bars. This suite of landforms is dependent on the valley context (low-gradient and laterally unconstrained). The river changes its character at Nappa Merrie Waterhole (~50 km upstream from Innamincka), where it enters the Innamincka Dome (see *3.5 Tectonics: Innamincka Dome, Cooper Creek Valley*).

The disposition of the Channel Country’s drainage network links the monsoonal north with the arid inland. The anabranching nature of the channels and the geometry of the waterholes promote sufficient stream power to maintain channel depth; these factors occur in all Channel Country rivers but are most common in Cooper Creek (Windorah to Nappa Merrie). Together, these key features allow floods into penetrate deeply into arid areas, maintaining refuge waterholes and terrestrial ecosystems, permitting rich ecosystems to exist in the arid interior. Furthermore, the Channel

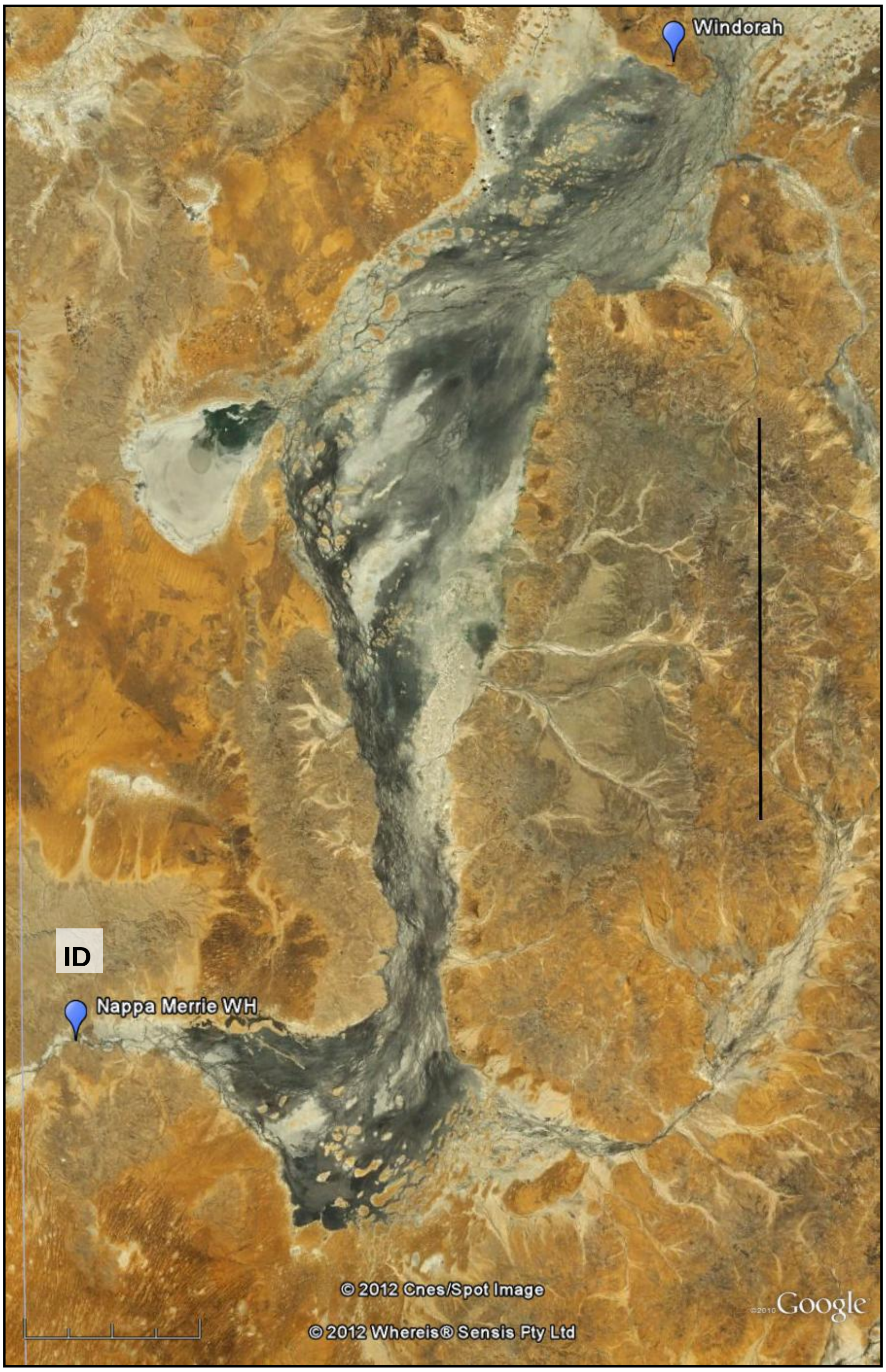


Fig. 31 The Cooper's wide floodplain between Windorah and Nappa Merrie Waterhole

The floodplain is pale grey (sand and mud), and dark grey to black (dense vegetation: frequent inundation), between the orange and grey-brown of the stony deserts and sandplains. ID, the Innamincka Dome; north to top, black scale bar is 100 km.

Country’s access to water and biological productivity have been key to the development of the pastoral industry in post-European settlement Australia, important economically and the inspiration for many of the songs and stories Australians tell about ourselves (for example, the songs *Waltzing Matilda* and *Diamantina Drover*, or the Longreach Stockman's Hall of Fame). The Channel Country’s strong aesthetic appeal is also an important element in the present-day local tourist economy.

Cooper Creek’s Windorah to Nappa Merrie Waterhole reaches are spatially linked to other sites of potential geomorphic geoheritage: the Black Soil Plains (upstream), the Innamincka Dome (immediately downstream), the Cooper distributaries in the Strzelecki Desert (further downstream), and Kati Thanda - Lake Eyre (further downstream).

Table 36 Cooper Creek (Windorah to Nappa Merrie)

	Place	Cooper Creek (Windorah to Nappa Merrie)	
	Theme (subtheme)	Watercourses (anabranching rivers)	Watercourses (freshwater basins)
NHL Criteria	Events and Processes	The channel network is an outstandingly good demonstration of fluvial equilibrium in an extremely low gradient, laterally unconfined, high variability system. Anabranching allows monsoonal floodwaters to penetrate deep into the arid zone, governing ecosystem distribution over an extremely wide area. Anabranch patterns govern ecosystem placement and viability.	Waterhole distribution maps the occurrence of high-energy conditions in otherwise low-energy flows. Refuge waterholes are critically important to ecosystems on a catchment scale.
	Rarity	Anabranching is not uncommon but its heritage values are not presently recognised.	Waterholes are a common feature of Channel Country rivers, but the Windorah to Nappa Merrie reach has a greater number of larger and more densely clustered waterholes in comparison to other Channel Country rivers. Their heritage values are currently unrecognised.
	Research	Anabranching is only relatively recently recognised as a type of river, with important implications for understanding fluvial process.	Waterholes have potential to expand understanding of drylands fluvial processes especially during high-volume flows, and to reveal information about landscape evolution.
	Principle characteristics of a class	This is the classic area for Lake Eyre Basin anabranching, being the locations of the original research. The width of floodplain and scale of the anabranching are the best	The Windorah to Nappamerry reaches of Cooper Creek are the classic areas for waterholes.

		examples within the Channel Country rivers.	
	Aesthetics	The multiplicity of channels across the wide floodplain is the feature for which the Channel Country is named.	Waterholes are very important to the channel country aesthetic.
	Creative or technical achievement	-	
	Social	One of the best-studied rivers in drylands Australia, and an important contributor to worldwide understanding of this channel type.	Waterholes are popular camping spots and an important contributor to the local tourist economy. The Channel Country's strong aesthetic appeal and links to Australian pastoral history have inspired the songs and stories we tell about ourselves.
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and Context	Unusual (world)	Y	
	Unusual (Australia)	N	
	Multiple geomorphic themes	Yes: as well as Anabranching Rivers and Freshwater Basins (this table), this area contains landforms from the theme *Watercourses: Mud Aggregate Floodplains*. Within that theme, the mud aggregate floodplains are a relic of a substantial change to fluvial style. Rare on a world scale (although not rare in Australia) they are very well-researched, having already delivered information on Australian Quaternary climate change, and with strong potential for further information. They demonstrate the principle characteristics of the class insofar as this is the place where mud aggregate floodplains and their particular bedload transport characteristics were first described; they are still the best-described. The mud aggregate floodplains are important on a world scale: they are one of only two modern analogues that have been described for an important lithotype. The spatial relationship between Cooper Creek and the Black Soil Plains allows delivery of vertic muds to the Cooper Creek floodplain: this is a rare combination of circumstances. The wide valley and its low gradient (which are strong influences on the fluvial style) are governed by *Tectonics: flexure*.	
	Value with respect to significance threshold	Clear	
	Integrity	Y	
	Authenticity	Y	
	Cross-reference	The site Cooper Creek (Windorah to Nappa Merrie) is spatially linked to these sites: Black Soil Plains, Innamincka Dome with Cooper Creek valley, Cooper Distributaries (Strzelecki Desert), Kati Thanda - Lake Eyre.	
		As a feature, anabranching occurs at the sites Neales River Catchment, Fowlers Creek.	
	Status	Specific area, or possibly indicative area.	

Mud-Aggregate Floodplains

In earth science textbooks, mud in fluvial transport is described as behaving in a certain way related to its fine grain size: transported as grains or flocs in suspended load, deposited in low-energy conditions. However, mud aggregate particles formed from vertic soils behave differently. (Other kinds of aggregated muds also exist, and are known soil components, but it is not the intent of this report to review that literature.) Vertic mud aggregates behave like sands under fluvial transport: they are robust pellets that are capable of being transported as bedload, and are deposited in moderate to moderately high energy conditions (Maroulis and Nanson 1996, Wakelin-King and Webb 2007b). The first observations of this mode of sediment behaviour, were only recently brought to the attention of the geological community (e.g. Nanson et al. 1986), and were received with interest and astonishment.

There are presently only two mud aggregate fluvial systems described in the literature, both in drylands Australia: Cooper Creek and Fowlers Creek. In both, vertic mud aggregate sediments are a dominant floodplain material (Maroulis and Nanson 1996, Wakelin-King and Webb 2007a). The presence of vertic floodplain sediments is probably related to vertisols in the surrounding hillslopes and/or the hinterland. The floodplain soils display significant shrink-swell behaviour leading to gilgai landforms including cracking, heave, and deep macropores. Because vertic soils have a high capacity to retain water, and floodplains are placed to receive water, mud aggregate floodplains in drylands rivers can be relatively water-rich landforms that play a critical role in ecosystem support. The tough cohesive muds also contribute to stability of steep waterholes banks and fluvial processes that promote anabranching (Nanson and Knighton 1996, Knighton and Nanson 2000).

Cooper Creek and Fowlers Creek differ in some ways. Cooper Creek is a black-earth vertisol and Fowlers Creek is a red-earth vertisol (see *3.7 Regolith: Vertisol Plains and Slopes*), reflecting their different catchment contexts. The Cooper Creek floodplain displays heavy degrees of cracking and self-mulching so the soil surface is often loose and friable, whereas the Fowlers Creek floodplain is either hard and compacted or loose and silty (Wakelin-King 2005, Wakelin-King 2015b). The Fowlers Creek floodplain landforms are relatively simple arrangements of channel-floodplain-valley margin set within a context of discontinuous ephemeral streams. The Cooper Creek floodplain is complex, with braid-like low-relief emergent bars separated by an anastomosing network of shallow floodways (Fig. 30). The floodplain's distribution of braid-like areas and gilgai swamps relates to its inundation patterns (Fagan and Nanson 2004). The floodways are independent of, but coexisting with, the main anabranching channel system (Nanson et al. 1986), in a way that is characteristic of the Channel Country rivers but otherwise very unusual on a world scale.

Cooper Creek is the area in which mud aggregate braid -like floodplains were first described (e.g. Rust and Nanson 1986). It has been used as a modern analogue for an important lithotype: massive mudrock, which is common in the geological record, and economically important as seal in the North Sea and other hydrocarbon provinces. The Australian mud aggregate floodplains are therefore important to the geological community on a world scale. Fowlers Creek is also a modern analogue for massive mudrock, however much of its descriptions are as yet unpublished, whereas Cooper Creek is unusually well-researched and extensively published.

Table 37 Mud-aggregate floodplains

	Feature	Mud-aggregate floodplains
	Theme (subtheme)	Watercourses (mud aggregate floodplain)
NHL Criteria	Events and Processes	Because of their high capacity to retain water, they play a critical role in supporting drylands river ecosystems.
	Rarity	Mud aggregate floodplains are common in the Channel Country rivers and in western New South Wales, but their heritage values are currently unrecognised.
	Research	Further investigation of the Cooper Creek floodplain, publication of the Fowlers Creek research, and investigation into other mud aggregate floodplains has potential to increase understanding of the lithotype massive mudrock.
	Principle characteristics of a class	The mud aggregate floodplain at Cooper Creek (Windorah to Nappa Merrie) is the area where the geomorphological and sedimentological characteristics of mud aggregate floodplains were first and best described.
	Aesthetics	-
	Creative or technical achievement	-
	Social	The Australian mud aggregate floodplains are amongst of the few researched modern analogues for a lithotype that is geologically important on a world scale.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	N
	Multiple geomorphic themes	Not applicable
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: feature occurs at these sites	Cooper Creek (Windorah to Nappa Merrie); Fowlers Creek.
	Status	Contributes value to places listed under other geomorphic themes

Freshwater Basins

In the context of this study, freshwater basins are declivities in the ground surface which retain fresh water for some time after the close of flow events or rainfall events. They include waterholes, lakes, and swamps. In the study area freshwater basin landforms contribute significant value to four sites: the Neales River catchment (Fig. 32), and Cooper Creek: Windorah to Nappa Merrie, Innamincka Dome, and the Strzelecki Desert distributaries.

The importance of these freshwater basins is that they support the terrestrial and aquatic ecosystems through periods of drought, providing seeds or spawn to renew their catchments' ecosystems when the next flows or rains occur (e.g. McNeil et al. 2011). The degree of their importance depends on the volume of water that they hold versus the recurrence interval of freshening flows, in the context of local evaporation rate and flow regime variability. For example, in the lower reaches of the Lake Eyre Basin, a water body that receives approximately annual flows needs to have a cease-to-flow depth of >4 meters in order to provide near-permanent aquatic habitat (Costelloe 2011).

The term 'waterhole' is widely used in drylands Australia to refer to places where water remains after a river's close of flow; it covers a variety of different landforms. In the Amadeus Basin ranges deep waterholes occur in the 'gaps' where creeks cut through rocky outcrops. In central Australia's sand-bed rivers away from the ranges, waterholes are in-channel places where the channel bed is of extremely low elevation (Wakelin-King 2015a). The present report considers waterholes as they occur in the Lake Eyre Basin's Channel Country rivers (the Georgina, Diamantina River, Cooper catchments). Waterholes are one of the few channel features likely to be specific to the drylands (Nanson et al., 2002).

Channel Country waterholes are channel segments which are deeper and usually wider than the upstream and downstream continuations of the same channel, and/or than other nearby channels. They occur as part of the dominant system of anabranching channels, in complex relationships with the multiple flow paths, and also as isolated channel segments in less-frequently inundated parts of the floodplain (Knighton and Nanson 1994, Gibling et al. 1998). They are often marked by dense riparian vegetation (usually River Red Gum or coolibah [*Eucalyptus coolabah*] trees, with bushy and grassy understory) making them visible from a distance and from above (aerial photographs, Google Earth) (Figs. 30 and 32). Waterhole distribution and Channel Country rivers is irregular. Cooper Creek between Windorah and Nappa Merrie has an unusually high number of significant waterholes (Silcock 2009), and waterholes here have been a research focus for the influential University of Wollongong research group.

The wide valleys of Channel Country rivers have complex floodplains, including many locations with dry swamps (densely vegetated, often with narrow reticulate channels and strong gilgai development (e.g. Fagan and Nanson 2004). In the Strzelecki Desert, long-term interrelationships between Cooper Creek's distributary flow paths and the dunefield have created lakes and swamps along the river, including significant refuge ecosystems such as the Ramsar-listed Coongie Lakes. The landform assemblage of coexisting channels, swamps, waterholes, lakes, and dunefield is highly unusual on a world scale.

Generally speaking, freshwater basins are 1) the geomorphic relics of rare large flow events, or 2) created in response to locally high-energy flow conditions (e.g. flow constriction), or 3) other types of geomorphic processes intersecting the fluvial network. Waterholes are formed and maintained by variable stream power within an overall low-power context (Knighton and Nanson, 2000); their distribution therefore marks patterns of turbulence across floodplains. Lakes and swamps in the Strzelecki Desert have complex origins involving intersecting aeolian, fluvial, and lacustrine geomorphic processes (Wakelin-King 2013).

Fig. 32 Algebuckina Waterhole, in the Neales River

	Feature	Freshwater basins
	Theme (subtheme)	Watercourses (freshwater basins)
NHL Criteria	Events and Processes	Waterholes, swamps and lakes which retain fresh water during drought are critical to the continuance of catchment ecosystems. LEB-type waterholes demonstrate the distribution of turbulence and/or zones of higher stream power across floodplains during high-level flows. Lakes and swamps in the Strzelecki Plain arise from complex fluvial-aeolian interactions over time, in a context of increasing aridity during glacial cycles.
	Rarity	Waterholes are common in the study area's larger rivers, but their heritage values are currently unrecognised. The Coongie Lakes in the Strzelecki Plain are recognised as a Ramsar wetland, but the heritage values of the landforms are not recognised
	Research	Depending on the location, freshwater basins are likely to have potential to expand understanding of drylands fluvial processes, and/or to reveal information about landscape evolution.
	Principle characteristics of a class	The waterholes at Cooper Creek (Windorah to Nappa Merrie) and the swamps and lakes of Cooper Creek's distributaries in the Strzelecki Plain demonstrate the principle characteristics of those landform types. Excellent examples of other kinds of freshwater basins are likely to be identifiable elsewhere.
	Aesthetics	The LEB waterholes and lakes generally have high aesthetic value. The Coongie Lakes (in the Strzelecki Desert) and waterholes in Cooper Creek (Innamincka Dome) and Cooper Creek distributaries (Strzelecki Desert) are particularly valued.
	Creative or technical achievement	-
	Social	Waterholes lakes and swamps generally have been important in pre- and post-European settlement Australian history, including development of the pastoral industry with its attendant songs and legends. The Coongie Lakes (in the Strzelecki Desert) and waterholes in Cooper Creek (Innamincka Dome) and Cooper Creek distributaries (Strzelecki Desert) are an important part of local amenity and tourist attraction.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	N
	Unusual (Australia)	Y
	Multiple geomorphic themes	Not applicable
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: the feature occurs at these sites.	Cooper Creek (Windorah to Nappa Merrie), Innamincka Dome with Cooper Creek valley, Cooper Creek (North West Branch Strzelecki Plain), Neales Catchment.
	Status	Contributes value to places listed under other geomorphic themes

Table 38 Freshwater basins

Mound Springs

Mound springs occur where artesian water comes to the surface and forms a permanent or semipermanent pool. Around the edge, dissolved solids precipitate, and damp cryptogam films may also trap sediments; the edges become raised into a mound. Depending on the rate of discharge versus the local rate of evaporation, the discharge of water will flow downslope in a 'tail'. Mound springs in drylands are valuable sources of permanent water and support groundwater-dependent ecosystems.

The study area’s best-known mound springs occur along the edges of the Eromanga Basin (Great Artesian Basin, GAB), whose artesian aquifers will leak water to the surface wherever the overlying aquilude is removed by erosion, or fractured by tectonic activity (Clarke and Bourke 2011, Habermahl 1982, Keppel et al. 2011, Mudd 2000). Where tectonic activity has raised the elevation of the spring outlet, or where human use of the groundwater resource has lowered the piezometric surface, the spring may cease to flow. Mound springs are not especially unusual in the Great Artesian Basin but are not common elsewhere. The largest and most complex cluster of mound springs, Witjira-Dalhousie Springs (Fig. 33), is currently listed on the NHL. However, its geomorphological values should be added to the existing listing.

Fig. 33 Witjira-Dalhousie Springs

White salts, pale saprolite and dark vegetation distinguish the springs from the surrounding red-brown gibber plain and sand plain. Google Earth image, white scale bar = 10 km.

	Place	Witjira-Dalhousie Springs
	Theme (subtheme)	Watercourses (mound springs)
NHL Criteria	Events and Processes	Artesian water flowing to surface expresses continent-wide relationships between aquifer hydrology and tectonics. Mound spring geomorphology supports groundwater-dependent ecosystems, especially in places that are isolated from river flows.
	Rarity	The Dalhousie Springs complex is the biggest and most complex mound springs group in Australia. It has a number of abandoned and currently-active mound springs, some of which are very large.
	Research	Mound springs are an important record of Cainozoic groundwater and surface climate interactions. Abandoned mounds also record changes to the piezometric surface and/or local uplift. The Dalhousie Springs complex brings together many mound springs of different ages, and has the potential to contribute to the understanding of the Lake Eyre Basin landscape evolution and climate change.
	Principle characteristics of a class	Dalhousie Springs complex is likely to contain landforms which exhibit the principal characteristics of their class.
	Aesthetics	
	Creative or technical achievement	
	Social	The line of mound springs up the western side of the Lake Eyre Basin was an important source of water in otherwise dry areas. The location of the springs directed the direction of travel of explorers and settlers, including the Afghan cameleer is who are such an important part of 19th-century Australian settlement, and the later steam trains.
	Significant people	
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	Y
	Multiple geomorphic themes	N
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference	-
	IBRA region	
	Status	Dalhousie Springs is currently on the National Heritage List, but its geomorphic values could be added to its listed attributes.

Table 39 Witjira-Dalhousie Springs

Banded vegetation sheetflow plains

Banded vegetation sheetflow plains (also known as tiger bush, or vegetation mosaic) are gently-sloping plains marked by (usually contour-parallel) bands of well-vegetated and poorly-vegetated ground (bands and interbands, respectively), sometimes with more evenly-vegetated water lanes (Fig. 34). Except in cases of gullying or valley-floor incision (see *3.8 Watercourses: post-European drainage incision*) banded vegetation plains usually lack channelised drainage. For this reason, this landform is almost never recognised by land and catchment managers as a watercourse. Nonetheless, in banded vegetation plains water moves downslope as unchannelled sheetflow, alternately shed from the bare areas, and trapped and retained in the vegetated bands or patches. Greater biological productivity is possible with the vegetation segregated in this way, in comparison to the vegetation being distributed evenly. Thus, it is key to terrestrial ecosystems over wide areas. Banded vegetation can be an important animal habitat, and its behaviour that promotes infiltration indicates it may play a significant role in local water table recharge (English 1998).

The vegetation is not the landform, it is the most visible expression of the landform and its processes (the sheetflow plains) (Wakelin-King 1999). Banded vegetation occurs where there is a gentle slope and some degree of clay in the soil; it is often associated with vertisols and gilgai (such as banded Mitchell Grass plains, or stony

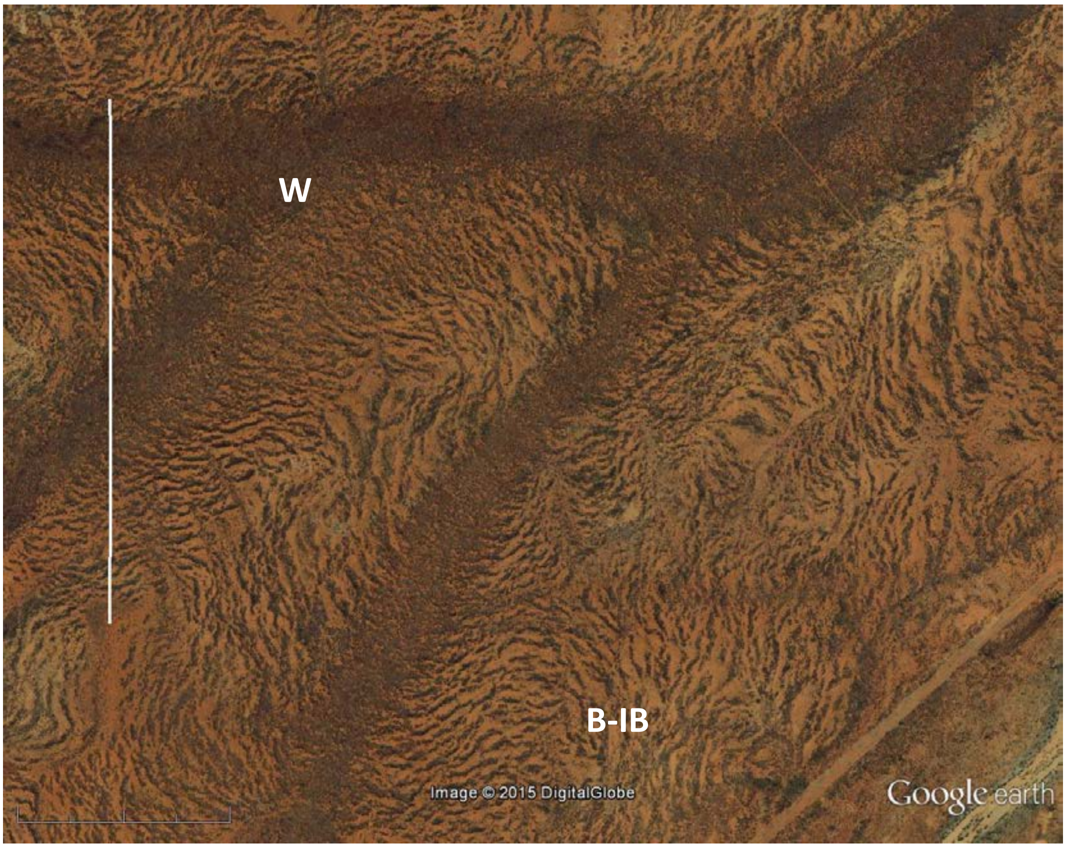


Fig. 34 Banded vegetation

W, water lanes; B-IB, bands and interbands; Google Earth image of an area ~110 km north north-east of Alice Springs, NT; white scale bar = 3 km.

gilgai chenopod plains, both in the Barrier Range near Broken Hill, Dunkerley and Brown 1995, 1999a). It is also found in red-earth soils, such as in the Burt Plain (Northern Territory), or in Western Australia (Mabbutt and Fanning 1987, Dunkerley 2002a). The vegetation banding is a naturally occurring water-harvesting system consisting of alternate runoff/runon bands. It a biophysical response to water-limited ecologies: soil, topography, and vegetation structure combine in the process (Wakelin-King 1999). Microtopography is important to the physical process: often the unvegetated areas appear steeper than the vegetated bands, although the truth is more complex (Dunkerley and Brown 1995, 1999a, 2002).

The scale and attributes of banded vegetation sheetflow plains vary according to soil type, slope, and physical scale of the dominant vegetation (Wakelin-King 1999). It is widespread in the study area, including –

- the mulga grove country of the Gibson Desert (e.g. Uluru – Kata Tjuta National Park), central Australia (e.g. the Burt Plain IBRA region), and the Murchison and Gascoyne IBRA Regions, especially between Wiluna and Meekatharra (WA),
- chenopod communities in the stony gilgai of western New South Wales, such as the Barrier Range, and Fowlers Creek,
- some Mitchell Grass communities e.g. in western New South Wales.

In banded vegetation sheetflow plains, a key component of the process is that the sheetflow is sufficiently low-energy that it does not cut channels through the bands of water-retaining vegetation. Where that occurs, the landform becomes ‘leaky’, less functional, and less biologically productive (e.g. Tongway and Hindley 2004). Banded vegetation sheetflow plains are vulnerable to desiccation by gullying and/or valley-floor incision, especially along the 'water lanes' where sheetflow collects and is most deep (Fig. 34). Gullying and valley floor incision can occur during extreme flow events, however can also result from land management actions (e.g. earthworks, dams, culverts, or heavy grazing pressure). Banded vegetation landforms are widely compromised in western New South Wales, and in areas where mulga communities have been destroyed by fire or thinned by grazing.

Nonetheless, many banded vegetation sheetflow plains remain. It is a critically important but unprotected landform. Because of its great variety, wide distribution, lack of recognition as a watercourse, and the relatively few places in which it has been studied, it is not possible in this report to identify specific sites of potential heritage value. Possibly, it may be best protected as an additional landform of heritage value within other sites.

Aside from the works cited above, banded vegetation landforms or communities, or rangeland ecosystem patch dynamics, are discussed in Mabbutt (1963),Ollier (1966), Tongway and Ludwig (1994), Valentin and D’herbes (1996), Dunkerley (2000), Tongway and Ludwig (2001), Dunkerley (2002b), Wakelin-King (2011b).

	Feature	Banded vegetation sheetflow plains
	Theme (subtheme)	Watercourses (banded vegetation sheetflow plains)
NHL Criteria	Events and Processes	Demonstrates a biophysical response to water-limited ecologies in low-gradient settings with clayey or loamy soils. Outstandingly important to terrestrial ecosystems and pastoral productivity as a principal landform for intercepting and managing runoff from rainfall.
	Rarity	It is widespread across the study area, but its identity as a watercourse landform and its heritage values are unrecognised.
	Research	Understanding it as a water-carrying landform will be an important step in recognising qualitative differences between perennial and drylands watercourses. Banded vegetation's wide variety of forms and geological contexts has potential to provide information on processes of biophysical interaction in general, and site-specific ecological relationships in particular.
	Principle characteristics of a class	Within the study area, there will certainly be areas that demonstrate the principle characteristics of this landform. The best examples will where there is little post-European modification to drainage networks.
	Aesthetics	-
	Creative or technical achievement	-
	Social	The biological productivity of this landform is important to the ecosystems and pastoral economies of the area.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Not widely reported except for Africa.
	Unusual (Australia)	N
	Multiple geomorphic themes	Not applicable
	Site's value with respect to significance threshold	Not applicable
	Integrity	Vulnerable to desiccation by gullying and/or valley floor incision, and widely compromised in parts of the study area.
	Authenticity	Because these plains are of wide extent and gentle gradient, their identity as a landform is poorly recognised. Because they carry water without channelised landforms, and because they are typically inaccessible during wet weather, their watercourse nature is largely unrecognised.
	Cross-reference : the feature occurs at these sites.	Widespread across the study area, including Uluru – Kata Tjuta National Park, the Barrier Range, the catchment of Fowlers Creek, the Sandover-Bundey confluence floodout.
	Status	Contributes value to places listed under other geomorphic themes

Table 40 Banded vegetation sheetflow plains

Fig. 35 Sandover River channel (right) and floodout (centre). Photo: Stephen Tooth

Floodouts

At floodouts, water travelling downvalley along a drainage network flows as sheetflow across an unchannelled reach – essentially, a reach that is 100% floodplain (Tooth 1999). Floodouts occur where a river's capacity to transport sediment declines to the point where the channel ceases to exist and water spreads out either as sheetflow, or as a network of small distributary swales. Some floodouts occur where the drainage terminates, for example where the central Australian sand-bed rivers flood out amongst the Simpson Desert sand dunes. Some occur within the drainage network (intermediate floodouts, Tooth 1999), such that there is an unchannelled reach separating two channelled reaches (for example see *3.8 Watercourses: discontinuous ephemeral streams*).

The fluvial processes of floodouts involve a positive feedback loop in which flowing water is retained in the floodout and nurtures dense vegetation, while the vegetation density acts to slow the flow and reduce its stream power (Bull 1997, Wakelin-King and Webb 2007a). Floodouts are therefore often biologically productive, and can be drought refugia. As reliable sources of feed and water, they have been important in Australia's post-European history (explorers and pastoral development), and undoubtedly important in pre-European times as well.

Floodout integrity depends on the valley-floor strength being sufficient to resist erosion. If a channel incises through an intermediate floodout, establishing continuity between the upvalley and downvalley channels, flow bypasses the floodout reach without watering the floodplain, and the floodout ecosystem will diminish or die (Bull 1997, Wakelin-King and Webb 2007a). They are vulnerable therefore to extreme flood events, and to management activities which act to promote stream power or reduce valley-floor strength (e.g. constriction of the flow path, overgrazing, tracks or cleared fencelines). Because floodouts are largely unchannelled, their fluvial nature may go unrecognised. The consequences are firstly that this may create ambiguities with respect to landholder's water rights (see *3.8 Watercourses: discontinuous ephemeral streams*), and secondly that it may not be understood that the area should be managed as a riparian zone and protected from erosion.

The noun 'floodout' (verb: 'to flood out') is in general use in Australia's rural population, reflecting the fact that floodouts are widespread throughout the study area (e.g. Pickup 1985, Pickup 1991, Tooth 1999, Gore et al. 2000, Tooth 2000b, Wakelin-King and Webb 2007b). The term has existed in geomorphological literature for more than 35 years (e.g. Mabbutt 1977). However, detailed research into floodout processes and landforms is only recent (e.g. Tooth 1999). Floodouts may be one of the few fluvial features that are truly characteristic of the arid zone (Nanson et al. 2002). Australia's tectonic and climatic history has promoted low-relief regolith-choked drainage networks traversed by underfit rivers, conditions very favourable to floodout development (Wakelin-King and Amos, *submitted*).

Despite being widespread, floodouts' geomorphic heritage values are not currently recognised. They occur in a wide variety of types and scales, from large (the Sandover-Bundy system, in the Northern Plains of central Australia, e.g. Tooth 2005) to small (such as the tributary-confluence floodouts in Fowlers Creek, Wakelin-King and Webb 2007a). In the present study, floodouts contribute geomorphic value to the north-western Simpson Desert (see *3.2 Sand Deserts*) and Fowlers Creek (see *3.8 Watercourses: discontinuous ephemeral streams*), and are likely to occur in other locations also.

One of the most thoroughly researched floodouts is at the confluence of the Sandover and Bundey Rivers (NT) (Tooth 1999, 2005), ~270 km northeast from Alice Springs in the Northern Plains section of the Lake Eyre Basin. Here, a large floodout has developed where the river moves away from its catchment area and tributaries and out into the plains: river capacity declines through transmission loss and with declining slope. The Sandover River channel diminishes and disappears, and its water spreads out into the plain. The Sandover River is a sand-bed river, and its channels terminate abruptly, spreading sandy splays across the plain (Fig. 35). The water continues to travel downslope, and as it approaches the Bundey River it reforms into channelised flow.

In addition to the references cited above, floodouts are considered in Pickup (1988), Nanson and Tooth (1999), Hollands et al. (2006), Wakelin-King (2011a, 2015a).

	Place / Feature	Sandover-Bundey confluence floodout
	Theme (subtheme)	Watercourses (floodouts)
NHL Criteria	Events and Processes	Floodouts are important to local ecology because of their capacity to retain moisture, and to fluvial processes because of their role in mediating erosion. They represent the changing face of the fluvial network, as increasing aridity reduced the river's ability to reach base level.
	Rarity	Floodouts are not rare within the study area, but their heritage values have not been recognised. Intermediate floodouts are often not recognised as a fluvial landform, because they lack channels and sometimes lack obvious signs of a primary flow path.
	Research	Some research has taken place but has only covered a small part of the diversity of this landform. The present research is largely in the geomorphic literature: there is great potential to translate knowledge across into the sedimentological literature (from these modern analogues into sedimentary facies which would be recognisable in the rock record) and develop sustainable land management practices. The comparison between the present-day drainage network and the palaeorivers which once connected the Sandover and the Bundey Rivers is likely to provide information on landscape evolution and past climate change.
	Principle characteristics of a class	The intermediate floodout at the Sandover/Bundy River confluence exemplifies larger-scale floodouts.
	Aesthetics	-
	Creative or technical achievement	-
	Social	The Sandover-Bundey confluence floodout is one of the best-researched of the large floodouts.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Y
	Unusual (Australia)	N
	Multiple geomorphic themes	Yes: the Sandover river is a sand-bed river.
	Value with respect to significance threshold	
	Integrity	Y
	Authenticity	Y
	Cross-reference: as a feature, occurs at these sites	As a feature, intermediate floodouts are part of discontinuous ephemeral streams, and are found in the Barrier Ranges, and Fowlers Creek. Terminal floodouts contribute value to the north-west Simpson Desert Dunefield.
	Status	Sandover-Bundey confluence floodout is a specific area defined in this study. Floodouts as a feature contribute to the heritage values of sites listed under other geomorphic themes.

Table 41 The Sandover-Bundey confluence floodout

Palaeodrainages

Palaeodrainages are what remains after a watercourse or drainage network has moved away or been greatly changed. In the context of this report's drylands study area, palaeodrainages are watercourses that existed during Australia's previous wetter climates, but which currently no longer exist as active fluvial systems or no longer exist in their previous state. In the study area, types of palaeodrainages include those now completely buried by post-fluvial sediments (e.g. in the Gibson Desert, see English 1998), low-relief palaeovalleys (such as the Eastern Goldfields Palaeodrainages, see *3.7 Regolith*), and those now existing in a state of topographic inversion (the Mirackina Conglomerate in the Neales River Catchment, see *3.5 Tectonics*; the Pilbara Channel Iron, see *3.7 Regolith*). Palaeodrainages are widespread across the study area. Since the preservation depends in part of Australia's continental stability and lack of glaciations, it is probable that the number and degree of development of our palaeodrainages is unusual on a world scale.

Palaeodrainages which are now buried may be socially important as sources of groundwater (English 1998, Magee 2009). There is likely to be a continuum of the degree of surface expression between buried palaeodrainages with little or no surface expression and palaeovalleys with clear surface expression (see Magee 2009).

Fig. 36 Chains of playa lakes in the Yilgarn palaeodrainages

White scale bar = 20 km.

Palaeovalleys in which the post-fluvial sediments have partially filled but not totally obscured the topography (see Magee 2009) are now expressed as semi-linear low-relief features. They can have clear surface expression, such as the Eastern Goldfields Palaeodrainages with their chains of playa lakes (Van de Graff et al. 1977) (Fig. 36). Low-relief palaeodrainages are widespread in many parts of the study area. They may contain groundwater resources (see Magee 2009). Additionally, they may be importance to local ecosystems as the low-elevation areas in which water collects.

Palaeodrainages in which a combination of weathering and tectonic activity has cemented channel sediments but removed surrounding softer lithologies leads to topographic inversion, in which deposits that were once along the lowest points of the valley (the river bottom) are now expressed as semi-linear hills. As uplands, these strongly influence locations of present-day drainage networks, and those with surfaces that rapidly shed rainwater are important sources of water for local downslope ecosystems. Some topographically inverted palaeodrainages contain important mineral resources (the Pilbara Channel Iron).

Research into the sedimentary and weathering history of palaeodrainages has potential to yield important information on palaeoclimates, especially with respect to climate zone behaviour during times of climate change; data on this is extremely scarce in the inland. Palaeodrainage topography can be an important and unambiguous data point in investigating neotectonic activity, for example uplift locations are indicated by reversed slopes in the Yilgarn palaeodrainages (WA) (Van de Graff et al. 1977, Clarke 2005). The social importance of palaeodrainages as the creators of wide swathes of countryside is harder to calculate, but no less real. It is interesting to speculate on the role of these landforms in the internationally recognised art of, for example, Balgo (WA).

In addition to the references cited above, palaeodrainages are discussed in Langford-Smith 1983, Arakel et al. 1989, Arakel 1991, Morgan 1993, Twidale and Campbell 1993, Harper and Gilkes 2004, de Broekert and Sandiford 2005, Hou et al. 2005, Johnson and McQueen 2005, Craddock et al. 2010, Glasby et al. 2010.

	Feature	Palaeodrainages
	Theme (subtheme)	Watercourses (palaeodrainages)
NHL Criteria	Events and Processes	Palaeodrainages are an extremely important contributor to the present-day landscape over many parts of the study area
	Rarity	Palaeodrainages are not rare, however their heritage values are not presently recognised.
	Research	The sedimentary and weathering history of palaeodrainages has potential for the research on palaeoclimates and groundwater evolution. The topography of palaeodrainage networks can provide important information on post-fluvial tectonic activity.
	Principle characteristics of a class	Within the study area, there will certainly be areas that demonstrate the principle characteristics of these landforms.
	Aesthetics	-
	Creative or technical achievement	-
	Social	Palaeodrainages can contain important groundwater and mineral resources. Palaeodrainages are fundamental architectural elements for wide swathes of countryside so they are likely to be important to those aspects of local society with close relationships to those landscapes.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	Possibly: palaeodrainage preservation relies on continental stability.
	Unusual (Australia)	N
	Multiple geomorphic themes	Not applicable
	Site's value with respect to significance threshold	Not applicable
	Integrity	Y
	Authenticity	Y
	Cross-reference: as a feature, occurs at these sites	Pilbara channel iron, Eastern Goldfields Palaeodrainages, Neales River Catchment; Also likely in the Great Sandy and Great Victoria Dunefields.
	Status	Contributes value to places listed under other geomorphic themes

Table 42 Palaeodrainages

Megaflood landforms

Drylands rivers experience flow variability, and it is not unusual for a river which is dry most of the time to overtop its channels with above-floodplain level flow on a regular basis. Flow variability is expressed in terms of event recurrence intervals (e.g. ‘a one in 20 year flood’) or the more technically correct percentage likelihood that a flow greater than a level will occur in any given year (e.g. ‘annual exceedance probability 5%’). Human structures such as bridges are usually designed to withstand a ‘one in 100 year flood’ (the ‘design flood’).

Extremely large flood events (megafloods) also occur, on timescales measured in centuries and millennia. They leave permanent marks on the landscape: carved channels, valleys and plains scoured to bedrock, and deposited sediments; later flows of smaller size may flow along and deposit sediments within the megaflood channels, but they are unlikely to remove or greatly modify megaflood landforms (Gupta 1983, Bourke and Pickup 1999, Tooth 2000b, Tooth & Nanson 2000, Shannon et al. 2002, Webb et al. 2002). If a present-day river exists at a megaflood site, its flow path and landforms will have developed within the context of the megaflood landforms. In this way, sand-bed rivers develop a hierarchy of landforms with variable surface morphology and complex subsurface sedimentary relationships (Bourke and Pickup 1999). Megaflood landforms provide the context within which are set the deposits of smaller flows; they have strong influence over present-day rivers.

Megaflood landforms provide important information about palaeoclimates and long-term fluvial variability. Australia’s short recorded history and high degree of flow variability means that we don’t know how big our ‘design floods’ should be (Finlayson and McMahon 1988). Recognition of megaflood landforms helps clarify flood size and frequency: critical for land-use planning (e.g. population centres) or infrastructure design for potentially toxic industries (e.g. low-level nuclear waste dumps). In Australia, megaflood research sites include Katherine Gorge, the Finke River, and the Ross and Todd Rivers in the NT (Baker et al. 1983a, 1983b; Pickup et al. 1988, Pickup 1991, Bourke and Pickup 1999), Sandy Creek in NSW (Jansen and Brierley 2004, Jansen 2006), and the Lockyer Valley in Queensland (Thompson and Croke 2103). Likely megaflood landforms are also noted in the Sandover River, NT, (Tooth 1999), the Rodinga Range area, NT, (Hollands et al 2006), and in the Neales and Cooper catchments, SA (Wakelin-King 2011a, 2013). However, generally megaflood landforms are insufficiently recognised, and there are likely to be many in the study area.

The Ross and Todd Rivers (Northern Territory) are two sand-bed rivers which flow from the MacDonnell Ranges. Their confluence, just south of where the Ross River emerges from the MacDonnell Ranges ~63 km east of Alice Springs, contains a well-researched (Patton et al 1993, Bourke 1994) suite of megaflood landforms in an irregular area extending ~11.5 km south, and ~15 km southeast from the gap where Ross River exits the ranges. Three extreme floods have taken place in this area. Firstly, a 10 km wide flood covered the entire floodplain, truncating alluvial fan toes and depositing low-amplitude transverse bars which are still present today (these are referred to on the webpages of fluvial geomorphologist Geoff Pickup as megaripples, but this phrase is technically ambiguous). Later, between 1500 and 750 years ago, other floods created a braided palaeochannel more than three times the width of the modern river (Patton et al. 1993).

Table 43 Megaflood landforms

	Place	Ross-Todd confluence
	Theme (subtheme)	Watercourses (megaflood landforms)
NHL Criteria	Events and Processes	Megaflood landforms record rare high-volume floods. Near the confluence of the Ross and Todd rivers, megaflood landforms record three extreme flood events. Megaflood deposits can strongly influence the style and location of present-day rivers. Where megafloods carve channels along a drainage line, smaller flows deposit sediments within those spaces. Megaflood sediments are deposited in places that are not within the reach of ordinary fluvial processes; smaller flows are unable to materially affect those deposits, and so must work around them.
	Rarity	As a class of landform, megaflood traces are rarely described, so their heritage values are largely unrecognised. The Ross-Todd confluence includes unusual features such as truncated alluvial fan toes and flood-deposited transverse bedforms. The field of transverse bedforms is vulnerable to erosion such as may occur after inappropriate land use, drought, or fire.
	Research	As a feature, megaflood landforms include datable material (e.g. slackwater deposits) which can be used to establish socially important long-term flood records (flood frequency vs flood size). The Ross-Todd confluence has been the site of influential studies on Australian fluvial process, and provides a dated flood record for this part of central Australia.
	Principle characteristics of a class	The Ross-Todd confluence demonstrates a number of landforms which are characteristic of megafloods, and was the research area for an influential study on the relationships between modern sand-bed river geomorphology and megaflood landforms. Other locations in the study area may have characteristic megaflood landforms.
	Aesthetics	-
	Creative or technical achievement	-
	Social	In order to manage risk for land use planning and infrastructure design, it is critical to know an area's flow regime. However, drylands Australia has almost no flow records and amongst the world's highest flow variability. Megaflood landforms are an extremely important way of understanding a river's long-term flood history.
	Significant people	-

	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	?
	Unusual (Australia)	?
	Multiple geomorphic themes	Yes: the Ross and Todd Rivers are sand-bed rivers.
	Site's value with respect to significance threshold	Likely
	Integrity	Y
	Authenticity	Y
	Cross-reference	The Ross-Todd confluence occurs in the plains between Amadeus Basin uplands.
		Megaflood landforms also occur at or near the Sandover river, the Neales catchment, Cooper Creek in the Innamincka Dome and Amadeus Basin ranges including the Rodinga Range. It is likely that megaflood landforms are found elsewhere also.
	Status	The Ross-Todd confluence is a specific area defined in this study. As a feature, megaflood landforms can contribute to the heritage values of sites listed under other geomorphic themes .

Playa lakes and associated megalake remnants; Kati Thanda - Lake Eyre

Playa lakes are usually-dry lake beds where less water enters the lake than is lost through evaporation. Some playa lake beds are characterised by thick layers of evaporite minerals (such as halite), covering wet black muds in which large crystals of gypsum or other evaporite minerals are growing. Some lake beds have firm floors that look as if they are only brown mud (although many are actually mud with fine-grained gypsum). Many playa lakes are associated with calcrete scarps around their margins, and gypsum dunes, gypcrete, and lunettes around the margins and downwind. Some playa lakes have springs of relatively fresh water at their edges.

Because the current climate is considerably more arid than previous climates, many playa lakes are set within older landforms created in a wetter context. The Yilgarn's chains of playa lakes occur along palaeodrainages (Magee 2009). The chain of playa lakes southeast of Lake Amadeus occupy a river valley that used to flow into the Finke River (Wakelin-King 1989). Other playa lakes are the shrunken remnants of once much-larger bodies of fresh water (e.g. English et al. 2001, Cohen et al. 2011). Unless obscured by later sediments (such as sand dunes), these old megalake deposits are expressed in the landscape as wide, very flat mud plains. The megalake countryside around playa lakes is both a relic of the lake's previous pluvial state, and a present-day influence on landform suites characterised by very low gradients, deflation pans, and disorganised drainage.

Playa lakes have potential to contribute to a better understanding of climate change in the Australian inland, by research into the timing and degree of change during increasing aridity. The study area has many playa lakes of all sizes, which have potential to contribute value to their different landscapes. Some of the most notable which are also well-studied are playas in the Eastern Goldfields Palaeodrainages (Clarke 1994c), Lake Lewis (English et al. 2001), Lake Amadeus (Jacobson 1988a, 1988b; Chen et al. 1993), and Kati Thanda - Lake Eyre.

Kati Thanda - Lake Eyre (South Australia) (Fig. 37) is probably Australia's largest lake (however there don't appear to be systematic comparisons of its size to other large Australian playas). Measured using GIS software, based on the shoreline defined in the Geosciences Australia topographic datasets, its dimensions are ~186 km (north to south) and ~85 km (west to east), and it is 9,445 km^2 in extent. It is the depocentre for the Lake Eyre Basin (LEB), Australia's largest drainage basin and one of the world's largest endoreic drainage basins. As the LEB depocentre, it is the base level (and therefore fundamental topographic driver) for the Channel Country rivers (including Cooper Creek), the Neales Catchment, and the rivers which used to flow from Central

Fig. 37 The edge of Lake Eyre

Australia (Craddock et al. 2010) and which now flood out in the Simpson Desert dunefields. It has a number of interesting geomorphic features including mound springs in the lake bed and various kinds of duricrust around the lake margins.

Kati Thanda - Lake Eyre has experienced repeated lake level fluctuations over geological time. It was once linked with Lakes Gregory, Callabonna, Blanche, and Frome in an enormous megalake system which has left behind beach ridges at an elevation of +10 m AHD; present-day maximum lake fills reach -10 m AHD (DeVogel et al. 2004, Cohen et al. 2011, Habeck-Fardy and Nanson 2014). Kati Thanda - Lake Eyre and its surrounding megalake remnants (shorelines, links to Lake Gregory, and abandoned lake-floor plains) mark the differences between previous wetter climates and present day aridity. Since Kati Thanda - Lake Eyre receives rain from both the northern (monsoonal) and southern weather systems (Cohen et al. 2012), its sedimentary and landform history integrates continent-scale climatic signals. It has the potential to be extremely important in research into climate change, climate zones, and ENSO weather patterns.

The Lake Eyre Basin is a continental-scale intra-cratonic sag; tectonic forces have caused an extremely widespread but not very deep (on a world scale) subsidence. The basin is asymmetrical: the lowest-elevation area in Lake Eyre South (-15.6 m AHD) is very close to the southern basin margin, including some of the LEB's highest-elevation places. The Cainozoic geological record indicates a north-to-south shift in the basin depocentre, and a nearby reversal of topography in which a Neogene lake has been uplifted and now lies along the drainage divide between Kati Thanda - Lake Eyre and Lake Torrens (Callen and Cowley 1998, Callen et al. 1998, Moussavi-Harami and Alexander 1998). The tectonic undulation of land surfaces (Sandiford et al. 2009) is a key feature governing landscapes throughout the Lake Eyre Basin (see *3.5 Tectonics: Flexure*). Recent research (Schellart and Spakman 2015) indicates that the LEB subsidence and migration of the basin depocentre results from deep-crustal processes related to subduction of a slab of New Guinea continental crust. Thus, Kati Thanda - Lake Eyre is an outstanding geomorphic relic of significant earth events, with potential to contribute to an understanding of Australia's continental evolution and the behaviour of the Australian tectonic plate.

In addition to the references cited above, playa lakes are discussed in Al-Farraj (2008), Alley (1998), Arakel (1986), Chen (1997), Chen and Barton (1991), Chen et al. (1991), Cohen et al. (2012), Cupper (2005), Davey and Hill (2009), Dulhunty (1982), English (2005), Humphreys et al. (2009), Jacobson and Janowski (1989), Jacobson et al. (1988, 1989, 1991), Leon and Cohen (2012), Magee et al. (1995), McLaren and Wallace (2010), Wopfner and Twidale (1967).

Table 44 Kati Thanda-Lake Eyre

	Place	Kati Thanda – Lake Eyre	
	Theme (subtheme)	Watercourses (playa lakes)	Tectonics (flexure)
NHL Criteria	Events and Processes	Kati Thanda - Lake Eyre and its surrounding megalake remnants mark the differences between previous wetter climates and present-day aridity. In previous geological ages it truly was an inland sea.	The migration of Kati Thanda - Lake Eyre's depocentre to its present location is an outstanding marker of deep-crustal processes.
		Kati Thanda – Lake Eyre is the base level of a catchment which extends over ~20% of the Australian mainland.	
		As a feature, playa lakes are often relics of previous lakes or river systems. If they control local groundwater base level and outcrop (springs), they may have strong influence on local ecosystems.	
	Rarity	Kati Thanda - Lake Eyre is highly unusual in its size, catchment size, and low elevation.	
		Playa lakes are not rare but their heritage values are unrecognised.	
	Research	Kati Thanda - Lake Eyre's sediments record climates over large parts of Australia, and have the potential to provide useful information on the movement of climate zones during climate change.	The development and migration of the Lake Eyre Basin's depocentre is critically important to understanding Australian continental evolution and Australia's relationships with other tectonic plates.
		Many playa lakes have potential to reveal an area's Cainozoic climate history.	
	Principle characteristics of a class	Kati Thanda - Lake Eyre is one of the best-known and most accessible examples of a large playa lake. Playa lakes in other locations are also likely to demonstrate characteristics of their class. There are likely to be differences between playa lakes which are megalake remnants, and those which are developed in palaeodrainages.	
	Aesthetics	Kati Thanda - Lake Eyre is an iconic Australian landscape, celebrated in artworks (e.g. www.nationalgeographic.com; or the Salt documentary www.saltdoco.com). It is a strong tourist drawcard especially during lake-full episodes.	
	Creative or technical achievement	-	
	Social	-	
	Significant people	-	
	Indigenous	(Not within the scope of the authors of this study.)	
Comparative and	Unusual (world)	Y: Kati Thanda - Lake Eyre is unusual in its catchment scale.	
	Unusual (Australia)	Y: Kati Thanda - Lake Eyre is unusual in the scale of lake and continent-spanning catchment; in being able to receive water from both the northern	

		monsoonal and the southern winter-rainfall weather systems.
	Multiple geomorphic themes	Yes: as well as Watercourses: Playa Lakes and Tectonics: Flexure (this table), Kati Thanda - Lake Eyre has features from Watercourses: Mound Springs (mound springs within the lake bed), and Regolith (the lake margins include various duricrusts). As a feature, playa lakes are often associated with duricrusts around the lake margins, especially calcretes and gypcretes.
	Value with respect to significance threshold	Clear
	Integrity	Y
	Authenticity	Y
	Cross-reference	Kati Thanda - Lake Eyre is adjacent to the Simpson Desert Dunefield and the Neales Catchment, and forms the base level for that ultimately drives Cooper Creek.
		Playa lakes are found in the Acraman Impact Structure, the Eastern Goldfields Palaeodrainages, and the Cooper Creek Distributaries (Strzelecki Desert).
	Status	Kati Thanda - Lake Eyre is a specific area defined in this study. Playa lakes as a feature contribute to the heritage values of sites listed under other geomorphic themes.

Post-European Drainage Incision

Where a fluvial valley has only a small channel or no channel (such as floodout, a banded vegetation landscape, or a broad swaley drainage network), the natural fluvial process may work to allow runoff waters to be retained in the valley floor. These processes can include e.g. dense communities of vegetation that reduce flow speed and increase valley-floor resistance to erosion, low gradient that reduces flow speed, macropores that promote infiltration. The fluvial landforms are stable, and the well-watered valley floors support viable ecosystems.

However, if circumstances increase stream power or decrease valley floor strength, valley-floor incision may be promoted, creating entrenched channels which are efficient in transporting runoff away. This switches fluvial behaviour over to a different stable state, in which the valley floors cease to be watered, the floodplain becomes desiccated and its vegetation diminishes or dies (Bull 1997, Wakelin-King and Webb 2007a). While this transition can happen in response to non-human factors, in some circumstances, post-European land management has created the conditions for change, e.g. by swamp drains, overgrazing, infrastructure construction, or the use of stock routes (e.g. Prosser 1991, Grant 1994, Pickard 1994, Fanning 1999). The change can be very rapid; in many cases it is held to have occurred during early settlement before the land’s original state was documented. While this problem has occurred throughout Australia (e.g. Wasson et al. 1998), the arid zone is particularly vulnerable. The Barrier Range has been a focus of research, and some very high erosion rates have been documented near the Mundi Mundi Fault Scarp, and at Fowlers Creek (Wasson and Galloway 1986, Fanning 1994).

It is extremely important to understand the triggers (both natural and human-created) of this process, so land management practices can be improved to reduce the risk of its occurrence. The initial research on the topic has not fully examined its possibilities, nor has the information made a useful transfer to management practice (e.g. Pringle and Tinley 2003). Sustainable rangelands management depends on further information about these processes. Distinguishing between 'natural' and post-European causes of valley floor incision is important to understanding fluvial processes in discontinuous ephemeral streams, and to assessing range condition and setting rehabilitation targets.

Channel incision is not particularly uncommon, but its heritage values are unrecognised. This is a “negative” heritage value – valley-floor incision is a poor outcome, but it is nonetheless proper to recognise it as the latest potent force to affect the landscape in the study area. Though valley-floor incision diminishes the integrity of the original fluvial landforms, the landforms of the drainage incision itself can have high degrees of integrity.

The authenticity of valley-floor incision is regarded as contentious in some circles. Where valley floor incision events took place during the early years of European settlement, both the event and the landform's pre-European state are undocumented. Because of the political ramifications (potentially setting the pastoral industry in conflict with environmental groups or government regulatory bodies), recognition of valley floor incision is an emotive and difficult issue.

	Feature	Post-European Drainage Incision
	Theme (subtheme)	Watercourses (Post-European Drainage Incision)
NHL Criteria	Events and Processes	A change from unincised valley floor to an incised and continuous channel means the watercourse has moved to a new state of fluvial behaviour.
	Rarity	Post-European valley floor incision is common in the study area, but frequently unrecognised. Its heritage value has not previously been considered. It is proper to recognise these landforms as representative of the latest potent force on the study area.
	Research	Reliable recognition of post-European drainage incision and wider understanding of its triggers and processes would be extremely beneficial to rangelands management.
	Principle characteristics of a class	Within the study area, there will certainly be areas that demonstrate the principle characteristics of this landform.
	Aesthetics	-
	Creative or technical achievement	-
	Social	Valley-floor incision usually results in floodplain desiccation, and stress to or death of the riparian ecosystem. There can be long-term negative outcomes for ecosystems, productivity, biodiversity, and prosperity.
	Significant people	-
	Indigenous	(Not within the scope of the authors of this study.)
Comparative and Context	Unusual (world)	N
	Unusual (Australia)	N
	Multiple geomorphic themes	-
	Site's value with respect to significance threshold	not applicable
	Integrity	Post-European drainage incision indicates damage to pre-existing fluvial landforms, however the drainage incision itself can have high degrees of integrity.
	Authenticity	Contentious: valley floor incision is demonstrated in scientific literature, but in specific landscapes it may be disputed or ignored. It is a politically sensitive issue.
	Cross-reference: feature occurs at these sites	Fowlers Creek; Barrier Ranges; and undoubtedly elsewhere in the study area.
	IBRA region	(multiple)
	Status	As a feature, post-European drainage incision detracts from the heritage values of fluvial landforms in sites listed under other geomorphic themes. However, where examples of post-European drainage incision are well-documented and unambiguous in their cause and effect, and/or demonstrate the principle characteristics of this feature, and/or have the potential to contribute important information into understanding its nature, these examples may contribute to the heritage value of a site (for example, Fowlers Creek).

Table 45 Post-European drainage incision

4 Conclusions

In this study, the landforms within a defined area of Australia's drylands are reviewed and assessed against the National Heritage List criteria. The assessment process relies on comparisons, not only between each landscape and the NHL criteria, but between a range of like landscapes with respect to each of the NHL criteria: a complex undertaking. Since the study area is huge and diverse in type and scale of its landforms, a matrix-style methodology was developed to facilitate fair comparisons. The methodology explicitly recognises values of complexity. This was a desktop study, sourcing information from published and unpublished literature, and from the field experience of members of the Australian geomorphology community. This present report is the second edition, rewritten for clarity and lightly revised in the light of peer reviews of the two papers that arose from the first edition.

The client brief called for the best examples of landforms that demonstrate the history and development of Australia's characteristic desert landscapes. Contrary to our initial expectations, aridity was not the prime determinant of landscape character in the study area. Rather, Australia's relative landscape stability allows long-term exposure to palaeoclimates and geological processes, and preserves the results to the present day; the onset of aridity in recent geological times is a powerful driver in landscape development, but it is not the only driver. The agents of geomorphic activity operate within that framework of stability, palaeoclimates, inheritance and aridity. Landscapes in this study are discussed in terms of their most relevant class of geomorphic process: either by their processes of formation (for example, extra-terrestrial impact in *Astroblemes*), or by their present-day function in the landscape (for example, unchannelled sheetflow in the *Banded Vegetation Sheetflow Plains*).

The 28 sites or areas identified in this report are those which have either met or have potential to meet the NHL criteria. However, this project, covering such a large and sparsely settled area, is to be expected to have unaddressed knowledge gaps. As well as the three identified gap areas (the Great Sandy and Great Victoria dunefields, and the Murchison-Davenport uplands) about which very little is published, the sites or areas that are currently sufficiently well-known that we have assessed their significance will yet have presently undiscovered features. For example, decades-long research in the Nullarbor Plain has revealed a great deal over vast areas, yet the expanses north of the railway are virtually unexplored and therefore their geomorphic heritage values are unknown. In summary, later investigations may add to or change the list of 28 geoheritage sites or areas presented in this report. Other sites may be found to be worthy of inclusion; new sites with values of higher significance than ones currently known may bump present sites off the list; better knowledge of these present sites may change the values presented here; it cannot be predicted.

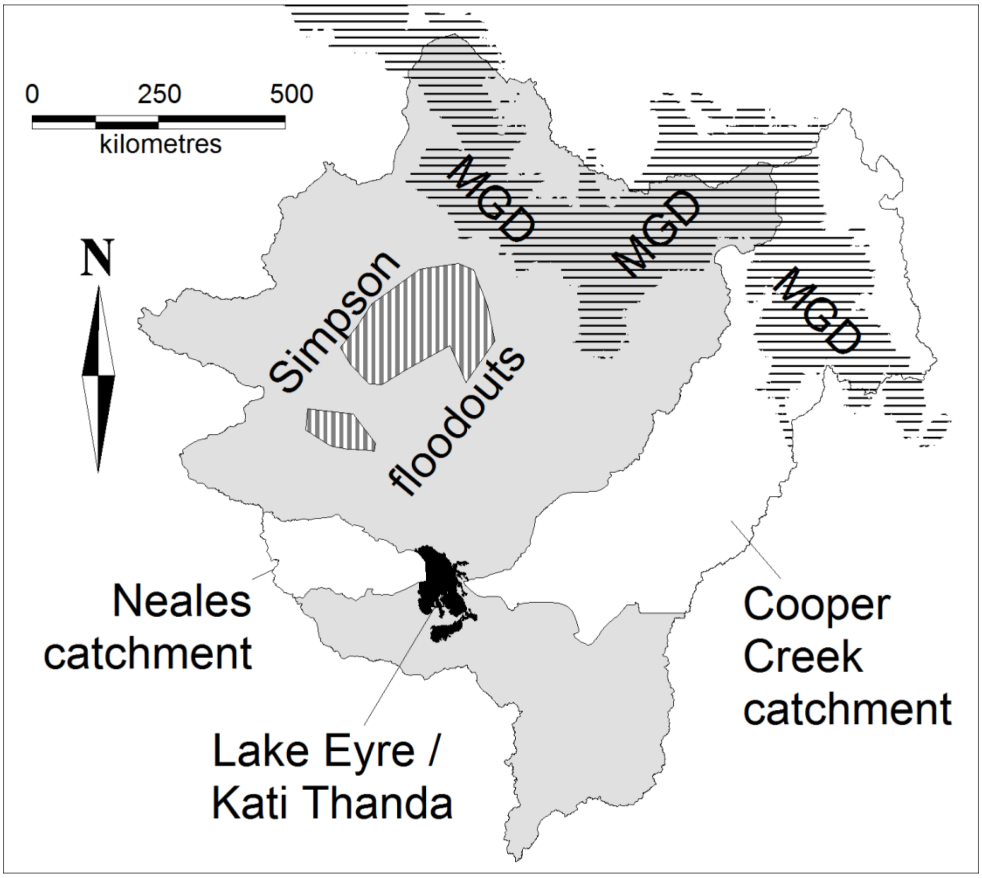


Fig. 38 Lake Eyre Basin (grey) and its areas of geomorphic heritage

Compilation of the sites and areas map (Fig.1) demonstrated that some groups of sites are geographically linked in a way that indicates connection to an underlying continent-scale landscape element.

- Amadeus Basin: The sites Gosses Bluff , Uluru-Kata Tjuta, the MacDonnell and Rodinga Ranges, the sand-bed rivers with their confluences and floodouts, are all distributed along the geological framework of the Amadeus Basin and owe some of their attributes to that geology.
- Cooper Creek: the Cooper Creek catchment contains sites linked by their position within modern drainage network: black-soil plains in the upper catchment feed mud aggregates to the mud–aggregate floodplains, and the Innamincka Dome influences the Cooper upstream(Windorah to Innamincka) and downstream (Strzelecki Desert).
- Lake Eyre Basin: Cooper Creek itself is part of an even larger group of sites, related to the huge intracratonic sag that is the Lake Eyre Basin (Fig. 38). As well as Cooper Creek, the Lake Eyre Basin contains the Neales Catchment, Lake Eyre and the Simpson Desert, all correlated to the same developmental, tectonic and/or climatic factors.

Recognition of these site clusters may be of benefit in coordinated research, documentation or administration.

The inclusion of locations in the present report does not constitute nomination for heritage status. Nomination requires engagement with an administrative process (see http://www.environment.gov.au/heritage). NHL listing does not preclude multiple land uses as long as the use does not compromise the values for which the place is listed. A site's heritage listing may imply greater protection, calling for increased understanding and leading to the allocation of resources for research or management. It may also be an opportunity for development of new income streams for local communities.

5 Bibliography

** denotes references important in observations or concept development, but which may have been superseded by later works.*

Al-Farraj, A., 2008. Desert pavement development on the lake shorelines of Lake Eyre (South), South Australia. Geomorphology 100: 154–163.

Allen, A.D., 1993. Hydrogeology of Cape Range. In: Humphreys W.F., (ed.), The Biogeography of Cape Range. Records of the Western Australian Museum, Supplement 45. Western Australian Museum, Perth: pp. 25-38.

Allen, H., Holdaway, S., Fanning, F. and Littleton, J., 2008. Footprints in the sand: appraising the archaeology of the Willandra Lakes, western New South Wales, Australia. Antiquity 82: 11-24.

Alley, N.F., 1998. Cainozoic stratigraphy, palaeoenvironments and geological evolution of the Lake Eyre Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 144: 239–263.

Anand, R.R. 2005. Weathering history, landscape evolution, and implications for exploration. In: Anand, R.R. and de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 2-40.

Anand, de Broekert, P. (eds.), 2005. Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia;

Anand, R.R., King, J.D. and Robertson, I.D.M., 2005. Mt Magnet District, Western Australia. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 328-332.

Arakel, A.V., 1986. Evolution of calcrete in palaeodrainages of the Lake Napperby area, central Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 54: 283-303.

Arakel, A.V., 1991. Evolution of Quaternary duricrusts in Karinga Creek drainage system, Central Australian groundwater discharge zone. Australian Journal of Earth Sciences 38 (3): 333-347.

Arakel, A.V. and McConchie, D., 1982. Classification and genesis of calcrete and gypsite lithofacies in paleodrainage systems of inland Australia and their relationship to carnotite mineralization. Journal of Sedimentary Petrology 52 (4): 1149-1170.

Arakel, A.V., Jacobson, G., Salehi, M. and Hill, C.M., 1989. Silicification of calcrete in palaeodrainage basins of the Australian arid zone. Australian Journal of Earth Sciences 36 (1): 73-89.

Australian Heritage Council, 2009. Guidelines for the Assessment of Places for the National Heritage List. Department of the Environment, Water, Heritage and the Arts, Canberra. URL http://www.environment.gov.au/resource/guidelines-assessment-places-national-heritage-list [accessed 7 October 2015].

Australian Government Department of the Environment, no date. National Heritage List criteria. URL http://www.environment.gov.au/heritage/about/national/national-heritage-list-criteria [accessed 19 January 2015].

Bagas, L., 1989. Geology of Kings Canyon National Park. Report 4; Northern Territory Geological Survey, Department of Mines and Energy, Darwin.

Baker, V.R. Pickup, G., Polach, H.A., 1983a. Desert palaeofloods in Central Australia. Nature (London) 301 (5900): 502-504.

Baker, V.R., Kochel, R.C., Patton, P.C. and Pickup, G., 1983b. Palaeohydrologic analysis of Holocene flood slack-water sediments. In: Collinson, J.D. and Lewin, J. (eds.), Modern and Ancient Fluvial Systems; Special Publications of the International Association of Sedimentologists 6: pp. 229-239.

Barnes, L.C. and Pitt, G.M., 1976. The Mirackina Conglomerate. Geological Survey of South Australia Quarterly Geological Notes 59: 2-6.

Beard, J.S., 1982. Late Pleistocene aridity and aeolian landforms in Western Australia. In: Barker, W.R. and Greenslade, P.J.M., (eds.), Evolution of the flora and fauna of arid Australia. Peacock Publications, Adelaide, pp. 101-106.

Belton, D.X., Brown, R.W., Kohn, B.P., Fink, D. and Farley, K.A., 2004. Quantitative resolution of the debate over antiquity of the central Australian landscape: implications for the tectonic and geomorphic stability of cratonic interiors. Earth and Planetary Science Letters 219: 21-34.

Berg, S.S. and Dunkerley, D.L., 2004. Patterned mulga near Alice Springs, central Australia, and the potential threat of firewood collection on this vegetation community. Journal of Arid Environments 59 (2): 313-350.

Bierman, P.R. and Caffee, M. 2002. Cosmogenic exposure and erosion history of Australian bedrock landforms. Geological Society of America Bulletin 114(7): 787-803.

Blake, D.H., Stewart, A.J., Sweet, I.P. and Hone, I.G., 1987. Geology of the Proterozoic Davenport province, central Australia. Bulletin 226, Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Bourke, M.C., 1994. Cyclical construction and destruction of flood dominated flood plains in semiarid Australia. In: Olive, L.J., Loughran, R.J. and Kesby, J.A. (eds.), Variability in stream erosion and sediment transport; IAHS-AISH Publication 224. Proceedings of the Canberra Symposium. International Association of Hydrological Sciences, Louvain, pp.113-123.

Bourke, M.C. and Pickup, G., 1999. Fluvial form variability in arid central Australia. In: Miller, A.J. and Gupta, A. (eds.), Varieties of Fluvial Form. John Wiley and Sons, Chichester, pp. 249-271.

Bourman, R.P., 2006. A composite regolith profile at Ceduna, South Australia. Transactions of the Royal Society of South Australia 130: 197-205

Bourman, R.P. and Milnes, A.R., 1985. Australian Landform Example 48: Gibber Plains. Australian Geographer 16 (3): 229-232.

Bourman, R.P., Ollier, C.D. and Buckman, S., 2009. Mount Augustus Geology and Geomorphology. Geographical Research 48 (2): 111–122.

*Bourne, J.A. and Twidale, C.R., 1998. Pediments and alluvial fans; genesis and relationships in the western piedmont of the Flinders Ranges, South Australia. Australian Journal of Earth Sciences 45 (1): 123-135.

Bowler, J.M., 1978. Quaternary climate and tectonics in the evolution of the Riverine Plain, southeastern Australia. In: Davies, J.L. and Williams, M.A.J., (eds.), Landform evolution in Australia. Australian National University, Canberra, pp. 149-172.

Bowler, J.M., 1982a. Aridity in the late Tertiary and Quaternary of Australia. In: Barker, W.R. and Greenslade, P.J.M., (eds.), Evolution of the flora and fauna of arid Australia. Peacock Publications, Adelaide, pp. 35-46.

Bowler, J.M., 1982b. Australian salt lakes: a palaeohydrologic approach. Hydrobiologia 82 (1): 431-444.

Brookfield, M., 1970. Dune trends and wind regime in Central Australia piedmont plains and sand-formations in arid and humid tropic and subtropic regions. Zeitschrift fuer Geomorphologie 10: 121-153.

Brown, K.J. and Dunkerley, D.L., 1996. The influence of hillslope gradient, regolith texture, stone size and stone position on the presence of a vesicular layer and related aspects of hillslope hydrologic processes; a case study from the Australian arid zone. Catena (Giessen) 26 (1-2): 71-84.

Brocx, M. and Semeniuk, V., 2010. Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying geodiversity and sites of significance in Western Australia. Journal of the Royal Society of Western Australia 93(2): 81-113.

Bull, W.B., 1997. Discontinuous ephemeral streams. Geomorphology 19:227-276.

Bullard, J.E. and Livingstone, I., 2002. Interactions between aeolian and fluvial systems in dryland environments. Area 34(1): 8-16.

Burnett, S., Webb, J. and White, S., 2013. Shallow caves and blowholes on the Nullarbor Plain, Australia -- flank margin caves on a low gradient limestone platform. Geomorphology 201: 246-253.

Butt, C.R.M., Robertson, I.D.M., Scott, K.M. and Cornelius, M., 2005. Regolith expression of Australian ore systems. CRC LEME, Perth. Online availability only, http://crcleme.org.au/Pubs/Monographs/RegExpOre.html; accessed October 2015.

Callen, R.A., and Bradford, J., 1992. Cooper Creek fan and Strzelecki Creek – hypsometric data, Holocene sedimentation, and implications for human activity. Mines and Energy Review 58: 052-057; South Australia Department of Mines and Energy, Adelaide.

Callen, R.A. and Cowley, W.M. 1998. Billla Kalina Basin. In: Drexel J. F. & Preiss W. V. (eds.), The Geology of South Australia, Volume 2, The Phanerozoic. Geological Survey of South Australia Bulletin 54; pp. 195–198.

Callen, R.A., Alley, N.F. and Greenwood, D.R., 1998. Lake Eyre Basin. In: Drexel J. F. and Preiss W. V. (eds). The Geology of South Australia; Volume 2, The Phanerozoic. Geological Survey of South Australia Bulletin 54; pp. 188-195.

Carlisle, D., Merifield, P.M., Orme, A.R., Kohl, M.S. and Kolker, O., 1978. The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability; based on a study of deposits in Western Australia and South West Africa (Namibia). Technical report, University of California, Los Angeles.

Cattle, S.R., McTainsh, G.H. and Elias, S., 2009. Aeolian dust deposition rates, particle-sizes and contributions to soils along a transect in semi-arid New South Wales, Australia. Sedimentology 56 (3): 765-783.

Chen, X.Y., 1997. Pedogenic gypcrete formation in arid central Australia. Geoderma 77 (1): 39-61.

Chen, X.Y. and Barton, C.E., 1991. Onset of aridity and dune-building in central Australia; sedimentological and magnetostratigraphic evidence from Lake Amadeus. Palaeogeography, Palaeoclimatology, Palaeoecology 84 (1-4): 55-73.

Chen, X.Y., Bowler, J.M. and Magee. J.W., l99l. Gypsum ground: a new occurrence of gypsum sediment in playas of central Australia. Sedimentary Geology. 72: 79-95.

Chen, X.Y., Bowler, J.M. and Magee, J.W. 1993. Late Cenozoic stratigraphy and hydrologic history of Lake Amadeus, a central Australian playa. Australian Journal of Earth Sciences 40 (1): 1-14.

Chen, X.Y., Lintern, M.J. and Roach, I.C., 2002. Calcrete: characteristics, distribution and use in mineral exploration. Cooperative Research Centre for Landscape Environments and Mineral Exploration, CSIRO, Kensington, Western Australia.

Clarke, J.D.A., 1994a. Geomorphology of the Kambalda region, Western Australia. Australian Journal of Earth Sciences 41: 229-239.

Clarke, J.D.A., 1994b. Evolution of the Lefroy and Cowan palaeodrainage, Western Australia. Australian Journal of Earth Sciences 41: 55-68.

Clarke, J.D.A., 1994c. Lake Lefroy, a palaeodrainage playa in Western Australia. Australian Journal of Earth Sciences 41: 417-427.

Clarke, J.D.A., 2005. Complex depositional landscapes of the Western Australian wheat belt. In Roach, I.C. (ed.), Regolith 2005 – Ten Years of CRC LEME. CRC LEME, Canberra, pp. 49-54.

Clarke, J.D.A. and Bourke, M.C., 2011. Travertine and tufa from Dalhousie Springs (Australia)—Implications for recognizing Martian springs. Geological Society of America Special Papers 483: 231-247.

Cohen, T.J., Nanson, G.C., Jansen, J.D., Jones, B.G., Jacobs, Z., Treble, P., Price, D.M., May, J-H., Smith, A.M., Ayliffe, L.K. and Hellstrom, J.C., 2011. Continental aridification and the vanishing of Australia's megalakes. Geology (Boulder) 39 (2): 167-170.

Cohen, T.J., Nanson, G.C., Jansen, J.D., Jones, B.G., Jacobs, Z., Larsen, J.R., May, J.-H., Treble, P., Price, D.M. and Smith, A.M., 2012. Late Quaternary mega-lakes fed by the northern and southern river systems of central Australia: varying moisture sources and increased continental aridity. Palaeogeography, Palaeoclimatology, Palaeoecology 356–357: 89–108.

Cohen, T., Nanson, G., Jones, B. and Nansen, J., 2009. Channel/floodplain profiles of Cooper Creek and the discrepancy with lake levels on Lake Eyre. In: Anonymous, Programme with Abstracts - International Geomorphology Conference, vol. 7, Melbourne, Victoria, Australia, July 6-11, 2009. International Association of Geomorphologists, Abstract no. 706.

Cohen, T.J., Nanson, G.C., Larsen, J.R., Jones, B.G., D.M. Price, M. Coleman , and T.J. Pietsch, 2010. Late Quaternary aeolian and fluvial interactions on the Cooper Creek Fan and the association between linear and source-bordering dunes, Strzelecki Desert, Australia. Quaternary Science Reviews 29, 455-471.

Cooper, P.F., Tuckwell, K.D., Gilligan, L.B. and Meares, R.M.D. 1975. Torrowangee Fowlers Gap 1:100,000 Geological Sheet. Geological Survey of New South Wales, Sydney.

Costelloe J.F., 2008. Updating and analysis of the ARIDFLO water level data in the Lake Eyre Basin. Report to the South Australian Department of Water, Land and Biodiversity Conservation, Adelaide.

Costelloe J.F., 2011. Hydrological assessment and analysis of the Neales Catchment. Report to the South Australian Arid Lands Natural Resource Management Board, for the Critical Refugia project, Caring For Our Country Program 2009/10, Adelaide.

Costelloe, J.F. 2013. Hydrological assessment and analysis of the Cooper Creek catchment, South Australia. A report to the South Australian Arid Lands Natural Resource Management Board, Port Augusta.

Craddock, R.A., Hutchinson, M.F. and Stein, J.A., 2010. Topographic data reveal a buried fluvial landscape in the Simpson Desert, Australia. Australian Journal of Earth Sciences 57 (1): 141-149.

Croke, J., 1997. Australia. In: Thomas, David S. G. (ed.), Arid zone geomorphology; process, form and change in drylands. John Wiley and Sons, Chichester, pp. 563-573.

CSIRO, 2008. Sustainability in Australia's arid lands. Commonwealth Scientific and Industrial Research Organisation. http://www.csiro.au/Outcomes/Water/Rural-and-regional-water/arid-landsustainability.aspx. Accessed 2 September 2014.

Cupper, M.L., 2005. Last glacial to Holocene evolution of semi-arid rangelands in southeastern Australia. Holocene 15 (4): 541-553.

Davey, A., 1986. Themes in prehistory of the Nullarbor Caves, semi-arid southern Australia Cave history. Helictite 24 (1-2): 53-59.

Davey, A.G., Gray, M.R., Grimes, K.G., Hamilton-Smith, E., James, J.M. and Spate, A.P., 1992. World heritage significance of karst and other landforms in the Nullarbor region. Report prepared for the Australian Dept. of the Arts, Sport, the Environment and Territories; Canberra.

Davey, J. and Hill, S., 2009. Modern evolution of continental interiors: tectonostratigraphic and palaeogeographical reconstructions of the Lake Frome Embayment. In: Anonymous, 2009, Programme with Abstracts - International Geomorphology Conference, vol. 7, Melbourne, Victoria, Australia, July 6-11, 2009. International Association of Geomorphologists, Abstract no. 1040.

de Broekert, P. and Sandiford, M., 2005. Buried inset-valleys in the eastern Yilgarn Craton, Western Australia; geomorphology, age, and allogenic control. Journal of Geology 113 (4): 471-493.

de Broekert, P., 2005. Lady Bountiful extended gold deposit, Western Australia. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 312-316.

Derriman, M.D.J., 1988. Geology of the Alice Springs Telegraph Station Historical Reserve. Report 5; Northern Territory Geological Survey, Department of Mines and Energy, Darwin.

DeVogel, S.B., Magee, J.W., Manley, W.F. and Miller, G.H., 2004. A GIS-based reconstruction of late Quaternary paleohydrology; Lake Eyre, arid central Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 204 (1-2): 1-13.

Dickson, M., 2009. Rocky coasts workshop July 2009, Melbourne. Convened by the Department of the Environment, Water, Heritage and the Arts, Canberra, ACT.

Doelman, T., Webb J.A. and Domanski, M., 2001. Source to discard: patterns of lithic raw material procurement and use in Sturt National Park, northwestern NSW. Archaeology Oceania 36: 15–33.

Doerr, S.H. and Davies R., 2007. Combining remote sensing, geophysical and "old-school" geomorphological tools to assess weathering rates of the world's largest exposed carbonate platform; the Nullarbor Plain, Australia. Geological Society of America, 2007 Annual Meeting Abstracts With Programs - Geological Society of America 39(6): 248.

Drysdale, R.N. and Gale, S.J., 1997. The Indarri Falls Travertine Dam, Lawn Hill Creek, northwest Queensland, Australia. Earth Surface Processes and Landforms 22: 413–418.

Dulhunty, J.A., 1982. Holocene sedimentary environments in Lake Eyre, South Australia. Journal of the Geological Society of Australia 29: 437–442.

Dunkerley, D.L. 1992. Channel geometry, bed material, and inferred flow conditions in ephemeral stream systems, Barrier Range, western N.S.W., Australia. Hydrological Processes, 6: 417-433.

Dunkerley, D.L. 2000, Hydrologic effects of dryland shrubs: defining the spatial extent of modified soil water uptake rates at an Australian desert site. Journal of Arid Environments 45: 159–172.

Dunkerley, D.L., 2002a. Infiltration rates and soil moisture in a groved Mulga community near Alice Springs, arid central Australia: evidence for complex internal rainwater redistribution in a runoff–runon landscape. Journal of Arid Environments 51, 199–219.

Dunkerley, D.L. 2002b, Systematic variation of soil infiltration rates within and between the components of the vegetation mosaic in an Australian desert landscape. Hydrological Processes 16: 119–131.

Dunkerley, D.L., 2008a. Bank permeability in an Australian ephemeral dry land stream; variation with stage resulting from mud deposition and sediment clogging. Earth Surface Processes and Landforms 33 (2): 226-243.

Dunkerley, D., 2008b. Flow chutes in Fowlers Creek, arid western New South Wales, Australia; evidence for diversity in the influence of trees on ephemeral channel form and process. Geomorphology 102 (2): 232-241.

Dunkerley, D.L., 2011. Desert soils. In: Thomas, D.S.G. (ed.) Arid Zone Geomorphology: Process, Form and Change in Drylands (3rd Edn). Wiley-Blackwell, Chichester; pp 101-129.

Dunkerley, D.L. and Brown, K.J. 1995. Runoff and runon areas in a patterned chenopod shrubland, arid western New South Wales, Australia: characteristics and origin. Journal of Arid Environments 30: 41–55.

Dunkerley, D.L. and Brown, K.J. 1999a. Banded vegetation near Broken Hill, Australia: significance of surface roughness and soil physical properties. Catena 37: 75–88.

Dunkerley, D. and Brown, K. 1999b. Flow behaviour, suspended sediment transport and transmission losses in a small (sub-bank-full) flow event in an Australian desert stream. Hydrological Processes, 13: 1577-1588.

Dunkerley, D.L. and Brown, K.J. 2002 Oblique vegetation banding in the Australian arid zone: implications for theories of pattern evolution and maintenance. Journal of Arid Environments 51: 163–181.

*Dury, G.H., 1970. Morphometry of gibber gravel at Mt Sturt, New South Wales. Journal of the Geological Society of Australia 16 (2): 655-665.

Edgoose, C.J., 2005. Barkly Tableland region, Northern Territory. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 148-150.

Edgoose, C.J., Camacho, A., Wakelin-King, G.A. and Simons, B.A., 1993. Kulgera SG53-5; 1: 250,000 Geological sheet and explanatory notes. Northern Territory Geological Survey, Darwin.

Eliot I., Gozzard J.R., Eliot M., Stul T. and McCormack G., 2012. The Coast of the Shires of Shark Bay to Exmouth, Gascoyne, Western Australia: Geology, Geomorphology & Vulnerability. Prepared by Damara WA Pty Ltd and Geological Survey of Western Australia for the Department of Planning and the Department of Transport; Perth.

English, P., 1998. Cainozoic geology and hydrogeology of Uluru-Kata Tjuta National Park. AGSO (Australian Geological Survey Organisation), Canberra.

English, P.M., 2001. Lake Lewis basin, central Australia: environmental evolution and OSL chronology. Quaternary International 83–85: 81–101.

English, P.M., 2005. Lake Lewis, Northern Territory . In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 160-165.

English, P., Spooner, N.A., Chappell, J., Questiaux, D.G. and Hill, N.G., 2001. Lake Lewis Basin, central Australia; environmental evolution and OSL chronology. Quaternary International 83-85: 81-101.

Fagan, S.D. and Nanson, G.C., 2004. The morphology and formation of floodplain-surface channels, Cooper Creek, Australia. Geomorphology 60 (1-2): 107-126.

Fanning, P., 1994. Long-term contemporary erosion rates in an arid rangelands environment in western New South Wales, Australia. Journal of Arid Environments 28: 173-187.

Fanning, P.C., 1999. Recent landscape history in arid western New South Wales, Australia; a model for regional change. Geomorphology 29 (3-4) 191-209.

Fanning, P.C., Holdaway, S.J., Rhodes, E.J., 2008. A new geoarchaeology of Aboriginal artefact deposits in western NSW, Australia: establishing spatial and temporal geomorphic controls on the surface archaeological record. Geomorphology 101 (3): 524-532.

Fink, D., 2006. Unravelling the landscape evolution process of sedimentary sand sheets and stony deserts in Australia with in situ cosmogenic nuclide depth profiles. Abstracts of the 16th annual V. M. Goldschmidt conference. Geochimica et Cosmochimica Acta 70 (18S): A173.

Finlayson, B.L. and McMahon, T.A., 1988. Australia v. the World; a comparative analysis of streamflow characteristics. In: Warner, R.F. (ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney, pp. 17-40.

Firman, J.B., 1994. Paleosols in laterite and silcrete profiles; evidence from the south east margin of the Australian Precambrian shield. Earth-Science Reviews 36 (3-4): 149-179.

Fitzsimmons, K., 2007. Morphological variability in the linear dunefields of the Strzelecki and Tirari Deserts, Australia. Geomorphology 91 (1-2): 146-160.

Folk, R.L., 1971. Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia; 1 Geomorphology and grainsize relationships. Sedimentology 16: 5-54.

Forman, D.J., 1966. The geology of the south-western margin of the Amadeus Basin, central Australia. Bureau of Mineral Resources, Australia, Report 87; Canberra.

Fujioka, T., Chappell, J., Honda, M., Yatsevich, I., Fifield, K. and Fabel, D., 2005. Global cooling initiated stony deserts in central Australia 2-4 Ma, dated by cosmogenic 21Ne-10Be. Geology 33: 993-996.

Fujioka, T., Chappell, J., Fifield, L.K. and Rhodes, E.J., 2009. Australian desert dune fields initiated with Pliocene-Pleistocene global climatic shift. Geology (Boulder) 37 (1): 51-54.

Gale, S.J., Drysdale, R.N., Scherrer, N.C. and Fischer, M.J., 1997. The Lost City of north-west Queensland; a test of the model of giant grikeland development in semi-arid karst. Australian Geographer 28(1): 107-115.

Gardner, R. and Pye, K., 1981. Nature, origin and palaeoenvironmental significance of red coastal and desert dune sands. Progress in Physical Geography 5: 514.

Geomorphology Conference, vol. 7, Melbourne, Victoria, Australia, July 6-11, 2009. International Association of Geomorphologists, Abstract no. 1040.

Geoscience Australia, no date. All Australian earthquakes located up to 2011 (map); Geoscience Australia website, URL: http://www.ga.gov.au/scientific-topics/hazards/earthquake/basics/where, accessed 14 July 2015. Map reproduced in this report under the Creative Commons License.

Gibling, M.R., Nanson, G.C. and Maroulis, J.C., 1998. Anastomosing river sedimentation in the Channel Country of central Australia. Sedimentology 45: 595-619.

Gibson, D.L., 1997. Recent tectonics and landscape evolution in the Broken Hill region. AGSO Research Newsletter, 26: 17-20.

Gibson, D.L., 1998. Regolith and its relationship with landforms in the Broken Hill region, western NSW. Geological Society of Australia: special publication 20; pp. 80-86.

Gibson, D.L., 1999. Explanatory notes for the Broken Hill and Curnamona Province 1:500,000 regolith landform maps. CRC LEME open file report 77; Perth.

Gibson, D.L., 2000. Post-Early Cretaceous landform evolution along the western margin of the Bancannia Trough, western NSW. The Rangeland Journal 22:32-43.

Gibson, D.L., 2005a. Northern Barrier Ranges region, New South Wales. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 96-100.

Gibson, D.L., 2005b. Wonnaminta 1:100,000 map sheet, New South Wales. In: Anand, R.R., and de Broekert, P. (eds.), Regolith Landscape Evolution Across Australia; A Compilation of Regolith Landscape Case Studies with Regolith Landscape Evolution Models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp 126-129.

Gillieson, D., 1997. Environmental change and human impact on the arid karst of the Nullarbor Plain, Australia. In: Jeannin, P-Y., (ed.), Proceedings of the 12th International Congress of Speleology, Symposium 8, La Chaux-de-Fonds, Switzerland; pp. 327-330.

Glasby, P., O'Flaherty, A. and Williams, M.A.J., 2010. A geospatial visualisation and chronological study of a late Pleistocene fluvial wetland surface in the semi-arid Flinders Ranges, South Australia. Geomorphology 118 (1-2): 130-151.

Glassford, D.K. and Semeniuk, V., 1995. Desert-aeolian origin of late Cenozoic regolith in arid and semi-arid southwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology, 114: 131-166.

Gore, D., Brierley, G., Pickard, J. and Jansen, J., 2000. Anatomy of a floodout in semi-arid eastern Australia. In: Pfeffer, K.H (ed.), Holocene geomorphology, Zeitschrift fuer Geomorphologie. Supplementband 122: pp. 113-139.

Goudie, A.S., 2002. Great Warm Deserts of the World: Landscapes and Evolution. Oxford University Press, Oxford.

Goudie, A.S., Viles, H.A., Allison, R.J., Day, M., Livingstone, I. and Bull, P., 1990. The geomorphology of the Napier Range, Western Australia. Transactions, Institute of British Geographers, New Series 15 (3): 308-322.

Graeme, D. and Dunkerley, D.L. 1993. Hydraulic resistance by the River Red Gum, Eucalyptus camaldulensis, in ephemeral desert streams. Australian Geographical Studies 31: 141-154.

Grant, A.R. 1994. Landscape morphology and processes in the upper Todd River catchment, central Australia, and their implications for land management. CCNT Technical Memorandum Number TM94/2, Land Conservation Unit, Conservation Commission of the Northern Territory, Alice Springs

Gravestock, D.I., Callen, R.A., Alexander, E.M. and Hill, A.J., 1995. Explanatory Notes, 1:250,000 Geological Series – Strzelecki, SH/54-2. Geological Survey of South Australia, Adelaide.

Gray, M., 2005. Geodiversity and geoconservation: what, why and how? The George Wright Forum 22: 4–12.

Grimes, K.G., 1988. The Barkly Karst Region, North-west Queensland. Conference Proceedings: 17th Australian Speleological Federation: pp. 16-24.

Gupta, A., 1983. High-magnitude floods and stream channel response. In: Collinson, J.D. and Lewin, J. (eds.), Modern and Ancient Fluvial Systems; Special Publications of the International Association of Sedimentologists 6: 219-227.

Habeck-Fardy, A. and Nanson, G.C., 2014. Environmental character and history of the Lake Eyre Basin, one seventh of the Australian continent. Earth-Science Reviews 132: 39-66.

Habermahl, MA. 1982. Springs in the Great Artesian Basin, Australia – their origin and nature. BMR Report 235. Australian Government Publishing Service, Bureau of Mineral Resources, Geology and Geophysics; Canberra.

Haines, P.W., 2005. Impact cratering and distal ejecta: the Australian record. Australian Journal of Earth Sciences 52 (4): 481-507.

*Hallsworth E.G. and Beckmann, G.G., 1969. Gilgai in the Quaternary. Soil Science 107: 409-420.

Harper, R.J. and Gilkes, R.J., 2004. Aeolian influences on the soils and landforms of the southern Yilgarn Craton of semi-arid, southwestern Australia. Geomorphology 59 (1-4): 215-235.

Hearty, P. J. and O'Leary, M. J., 2008. Carbonate eolianites, quartz sands, and Quaternary sea-level cycles, Western Australia: a chronostratigraphic approach. Quaternary Geochronology 3(1): 26-55.

Heimsath, A.M., Chappell, J., Hancock, G.R., Fink, D. and Fifield, K., 2008. Eroding Australia; slowly. Abstracts of the 18th annual V. M. Goldschmidt conference. Geochimica et Cosmochimica Acta 72 (12S): A363.

Hesse, P., 2010. The Australian desert dunefields; formation and evolution in an old, flat, dry continent. In: Bishop, P. and Pillans, B. (eds.), Australian Landscapes. Geological Society Special Publications 346: pp.141-164.

Hesse, P.P. and McTainsh, G.H., 2003. Australian dust deposits; modern processes and the Quaternary record. Quaternary Science Reviews 22(18-19): 2007-2035.

Hesse, P.P. and Simpson, R.L., 2006. Variable vegetation cover and episodic sand movement on longitudinal desert sand dunes. Geomorphology 81 (3-4): 276-291.

Hill, S.M., 2005. Regolith and landscape evolution of Far Western New South Wales. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 130-145.

Hill, S.M. and Roach, I.C. 2003. The regolith-landforms of Sandstone Paddock, Fowlers Gap, western NSW. In Roach, I.C. (ed.), Advances in Regolith. CRC LEME, Canberra, pp. 193-200.

Hill, S.M. and Roach, I.C. 2005. The regolith-landforms of northern Lake Paddock, Fowlers Gap Arid Zone Research Station, western NSW. In Roach, I.C. (ed.), Regolith 2005 – Ten Years of CRC LEME. CRC LEME, Canberra, pp. 139-145.

Hill, S.M., Eggleton, R.A. and Taylor, G., 2003. Neotectonic disruption of silicified palaeovalley systems in an intraplate, cratonic landscape; regolith and landscape evolution of the Mulculca range-front, Broken Hill Domain, New South Wales. Australian Journal of Earth Sciences 50 (5): 691-707.

Hill, S.M., West, D.S., Shirtliff, G., Senior, A.B., Maly, B.E.R., Jones, G.L., Holzapfel, M., Foster, K.A., Debenham, S.C., Dann, R. and Brachmanis, J., 2005. Southern Barrier Ranges - Northern Murray Basin, New South Wales. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 104-109.

Hollands, C.B., Nanson, G.C., Jones, B.G., Bristow, C.S., Price, D.M. and Pietsch, T.J., 2006. Aeolian-fluvial interaction; evidence for late Quaternary channel change and wind-rift linear dune formation in the northwestern Simpson Desert, Australia. Quaternary Science Reviews 25 (1-2): 142-162.

Hou, B., Frakes L.A., Sandiford M., Worrall L., Keeling J. and Alley N.F., 2008. Cenozoic Eucla Basin and associated palaeovalleys, southern Australia - Climatic and tectonic influences on landscape evolution, sedimentation and heavy mineral accumulation. Sedimentary Geology 203: 112–130.

Hou, B., Frakes, L.A. and Alley, N.F., 2005. Palaeochannel evolution, Northwestern Gawler Craton, South Australia. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 226-229.

Hubble, G.D., 1984. The cracking clay soils: definition, distribution, nature, genesis and use. In: McGarity, J.W., Hoult, E.H. and So, H.B. (eds.), The Properties and Utilisation of Cracking Clay Soils: Reviews in Rural Science 5. University of New England, Faculty of Rural Science, Armidale; pp.3-13.

Hudec, M.R. and Jackson, M.P.A., 2007. Terra infirma: Understanding salt tectonics. Earth-Science Reviews 82: 1–28.

Humphreys, W.F. (ed.), 1993. The Biogeography of Cape Range, Western Australia: Proceedings of a Symposium Held Under the Auspices of the Western Australian Museum in Perth on 21 November 1992 at the Art Gallery of Western Australia. Western Australian Museum. Records of the Western Australian Museum, Supplement 45.

Humphreys, W.F., Watts, C.H.S., Cooper, S.J.B. and Leijs, R., 2009. Groundwater estuaries of salt lakes: buried pools of endemic biodiversity on the western plateau, Australia. Hydrobiologia 626 (1): 79-95.

*Hutton, J.T., Twidale, C.R. and Milnes, A.R., 1978. Characteristics and origin of some Australian silcretes. In: Langford-Smith, T., (ed.), Silcrete in Australia. Department of Geography, University of New England, Armidale; pp. 19-40.

Jacobsen, G., 1988. The hydrology of Lake Amadeus, a groundwater discharge playa in central Australia. BMR Journal of Australian Geology and Geophysics 10: 301-308.

Jacobson, G. and Jankowski, J., 1989. Groundwater-discharge processes at a central Australian playa. Journal of Hydrology 105 (3-4): 275-295.

Jacobson, G., Arakel, A.V. and Yijian, C., 1988. The central Australian groundwater discharge zone: Evolution of associated calcrete and gypcrete deposits. Australian Journal of Earth Sciences 35 (4): 549-565.

Jacobson, G., Jankowski, J. and Chen, X.Y., 1991. Solute budget for an arid-zone groundwater system, Lake Amadeus, central Australia. Australian Journal of Earth Sciences 38 (1): 1-14.

Jacobson, G., Lau, G.C., McDonald, P.S. and Jankowski, J., 1989. Hydrogeology and groundwater resources of the Lake Amadeus and Ayers Rock region, Northern Territory. Australia, Bureau of Mineral Resources, Geology and Geophysics; Bulletin 230.

James, J.M., 1989. Tietkens Plains karst, Maralinga In: Gillieson, D.S. and Smith, D.I. (eds.), Resource management in limestone landscapes; International Perspectives. Proceedings of the International Geographical Union Study Group Man's Impact on Karst. Special Publication - Australian Defence Force Academy, Dept. of Geography and Oceanography: pp. 101-110.

James, N.P., Bone, Y., Carter, R.M. and Murray-Wallace, C.V., 2006. Origin of the Late Neogene Roe Plains and their calcarenite veneer: implications for sedimentology and tectonics in the Great Australian Bight. Australian Journal of Earth Science 53(3): 407–419.

Jansen, J.D., 2006. Flood magnitude-frequency and lithologic control on bedrock river incision in post-orogenic terrain. Geomorphology 82 (1-2): 39-57.

Jansen, J.D. and Brierley, G.J., 2004. Pool-fills: a window to palaeoflood history and response in bedrock-confined rivers. Sedimentology 51(5): 901-925.

*Jennings, J.N., 1967. Some karst areas of Australia. In: Jennings, J.N and Mabbutt, J.A. (eds.) Landform Studies from Australia and New Guinea. Australian National University Press, Canberra; pp. 256-292.

*Jennings, J.N., 1968. A revised map of the desert dunes of Australia. Australian Geographer 10(5): 408-409.

*Jennings, J.N., 1971. Karst (An Introduction to Systematic Geomorphology: 7). Australian National University Press, Canberra.

* Jennings, J.N., 1985. Karst geomorphology. Basil Blackwell, Oxford. (a revised and expanded edition of Jennings 1971)

Johnson, C.B. and McQueen, K.G., 2005. Gold-bearing palaeochannel sediments at Gidji, Western Australia. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 284-289.

Johnson, D.P., 1982. Sedimentary facies of an arid zone delta; Gascoyne Delta, Western Australia. Journal of Sedimentary Petrology 52 (2): 547-563.

Keppel, M.N., Clarke, J.D., Halihan, T., Love, A. J. and Werner, A.D., 2011. Mound springs in the arid Lake Eyre South region of South Australia: a new depositional tufa model and its controls. Sedimentary Geology, 240(3): 55-70.

Killick, M.F., Churchward, H.M. and Anand, R.R., 2005. Hamersley Iron Province, Western Australia. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 295-299.

Knighton, A.D. and Nanson, G.C., 1994. Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 9: 311-324.

Knighton, D. and Nanson, G., 1997. Distinctiveness, diversity and uniqueness in arid zone river systems . In: Thomas, D.S.G. (ed.), Arid Zone Geomorphology; Process, Form And Change In Drylands. John Wiley and Sons, Chichester; pp. 185-203.

Knighton, A.D. and Nanson, G.C. 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 35 (1-2): 101-117.

*Langford-Smith, T., 1978a (ed.), Silcrete in Australia. Department of Geography, University of New England, Armidale.

*Langford-Smith, T., 1978b. A select review of silcrete research in Australia. In: Langford-Smith, T., (ed.), Silcrete in Australia. Department of Geography, University of New England, Armidale, pp. 1-12.

*Langford-Smith, T., 1983. New perspectives on the Australian deserts. Australian Geographer 15 (5): 269-284.

Larsen, J., Cendón, D., Nanson, G. and Jones, B., 2009. Surface and groundwater hydrology of arid-zone billabongs (waterholes) in Queensland, Australia. In: Anonymous, 2009, Programme with Abstracts - International Geomorphology Conference, vol. 7, Melbourne, Victoria, Australia, July 6-11, 2009. International Association of Geomorphologists, Abstract no. 462.

Leon, J.X. and Cohen, T.J., 2012. An improved bathymetric model for the modern and palaeo Lake Eyre. Geomorphology 173–174: 69–79.

Leopold, L.B. and Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. U.S. Geological Survey Professional Paper 282-B. U.S. Geological Survey, Reston.

Lindsay, J.F., 1987. Upper Proterozoic evaporites in the Amadeus basin, central Australia, and their role in basin tectonics. GSA Bulletin 99 (6): 852-865.

Lipar, M. and Ferk, M., 2015. Karst pocket valleys and their implications on Pliocene–Quaternary hydrology and climate: Examples from the Nullarbor Plain, southern Australia. Earth-Science Reviews 150: 1-13.

Lowry, D.C., 1967. The origin of blow-holes and the development of domes by exsudation in caves of the Nullarbor Plain. Geological Survey of Western Australia, Record 12: 40-44.

Lowry, D.C. and Jennings, J.N., 1974. The Nullarbor karst, Australia. Zeitschrift fuer Geomorphologie 18(1): 35-81.

Ludwig, J.A., Tongway, D.J. and Marsden, S.G., 1999. Stripes, strands or stipples: modelling the influence of three landscape banding patterns on resource capture and productivity in semi-arid woodlands, Australia. Catena 37 (1-2): 257-273.

Mabbutt, J.A., 1963. Wanderrie banks; micro-relief patterns in semiarid Western Australia. Geological Society of America Bulletin 74 (5): 529-540.

Mabbutt, J.A., 1967. Denudation chronology in central Australia; structure, climate, and landform inheritance in the Alice Springs area. In: Jennings, J.N. and Mabbutt, J.A., (eds.), Landform studies from Australia and New Guinea. Cambridge University Press; pp. 144-181.

*Mabbutt, J.A., 1977. Desert Landforms (An Introduction to Systematic Geomorphology: 2). Australian National University Press, Canberra.

*Mabbutt, J.A., 1978. Lessons from pediments. In: Davies, J.L. and Williams, M.A.J., (eds.), Landform evolution in Australasia. Australian National University Press, Canberra, pp. 331-347.

Mabbutt J.A. and Fanning P.C., 1987. Vegetation banding in arid Western Australia. Journal of Arid Environments 12: 41–59.

Mabbutt, J.A. and Sullivan, M.E. (eds.) (1973), Lands of Fowlers Gap Station, New South Wales. University of New South Wales Research Series No. 3; Sydney.

MacDonald, B.C.T., Melville, M.D. and White, I. 1999. The distribution of soluble cations within chenopod-patterned ground, arid Western New South Wales Australia. Catena, 37: 89-105.

MacDonald, F.A., Bunting, J.A. and Cina, S.E., 2003. Yarrabubba; a large, deeply eroded impact structure in the Yilgarn Craton, Western Australia. Earth and Planetary Science Letters 213 (3-4): 235-247.

Magee, J.W., 2009. Palaeovalley groundwater resources in arid and semi-arid Australia – a literature review. Geoscience Australia Record 2009/03, Geoscience Australia, Canberra.

Magee, J., Bowler, J.M., Miller, G.H. and Williams, D.L.G., 1995. Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 113 (1): 3-42.

Maroulis, J.C. and Nanson, G.C., 1996. Bedload transport of aggregated muddy alluvium from Cooper Creek, central Australia; a flume study. Sedimentology 43 (5): 771-790.

Maroulis, J.C., Nanson, G. ., Price, D. and Pietsch, T., 2007. Aeolian–fluvial interaction and climate change: source-bordering dune development over the past∼ 100ka on Cooper Creek, central Australia. Quaternary Science Reviews, 26 (3): 386-404.

Marshall, T.R. and Dyson I.A., 2007. Halotectonics – a key element of Amadeus Basin development and prospectivity. In: Munson TJ and Ambrose GJ (editors), 2007. Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005. Northern Territory Geological Survey, Special Publication 2, pp. 119-135.

Marshall, T.R. and Wiltshire, R.G., 2007. Evaporite flow folds: Characterisation and mechanics from outcrop in the Amadeus Basin, central Australia. In: Munson TJ and Ambrose GJ (editors), 2007. Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005. Northern Territory Geological Survey, Special Publication 2, pp. 147-171.

McLaren, S. and Wallace, M.W., 2010. Plio-Pleistocene climate change and the onset of aridity in southeastern Australia. Global and Planetary Change 71 (1-2): 55-72.

McNeil, D.G, Schmarr, D.W. and Rosenberger A. E. 2011. Climatic variability, fish and the role of refuge waterholes in the Neales River Catchment: Lake Eyre Basin, South Australia. Report by South Australian Research and Development Institute (Aquatic Sciences) to the South Australian Arid Lands NRM Board, Port Augusta.

McTainsh, G.H. and Lynch, A.W., 1996. Quantitative estimates of the effect of climate change on dust storm activity in Australia during the last glacial maximum Response of aeolian processes to global change. Geomorphology 17 (1-3): 263-271.

Mills, K.J. and David, V. 2004. The Koonenberry Deep Seismic Reflection Line and Geological Modelling of the Koonenberry Region, western New South Wales. Geological Survey of New South Wales Open File Report GS2004/185 (unpublished), Sydney.

*Milnes, A.R. and Twidale, C.R., 1983. An overview of silicification in Cainozoic landscapes of arid central and southern Australia. Australian Journal of Soil Research 21 (4): 387-410.

Morgan, K.H., 1993. Development, sedimentation and economic potential of palaeoriver systems of the Yilgarn Craton of Western Australia. Sedimentary Geology 85 (1-4): 637-656.

Moussavi-Harami, R. and Alexander, E., 1998. Tertiary stratigraphy and tectonics, Eromanga Basin region. MESA Journal 8, 32-36; Mines and Energy South Australia, Adelaide.

Mudd, G.M., 2000. Mound springs of the Great Artesian Basin in South Australia: a case study from Olympic Dam. Environmental Geology 39(5): 463-476.

Nanson, G.C. and Huang, H.Q., 1999. Anabranching rivers; divided efficiency leading to fluvial diversity. In: Miller, A.J. and Gupta, A. (eds.), Varieties of Fluvial Form. John Wiley and Sons, Chichester, pp. 477-494.

Nanson, G.C. and Huang, H.Q., 2008. Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels. Earth Surface Processes and Landforms 33(6): 923-942.

Nanson, G.C. and Knighton, A.D., 1996. Anabranching rivers; their cause, character and classification. Earth Surface Processes and Landforms 21: 217-239.

Nanson, G.C. and Tooth, S., 1999. Arid-zone rivers as indicators of climate change. In: Singhvi, A.K. and Derbyshire, E. (eds.), Palaeoenvironmental Reconstruction in Arid Lands. A.A. Balkema, Rotterdam, pp. 175-216.

Nanson, G.C., Price, D.M., Jones, B.G., Maroulis, J.C., Coleman, M., Bowman, H., Cohen, T.J., Pietsch, T.J. and Larsen, J.R., 2008. Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia. Geomorphology 101 (1-2): 109-129.

*Nanson, G.C., Rust, B.R. and Taylor, G., 1986. Coexistent mud braids and anastomosing channels in an arid-zone river; Cooper Creek, central Australia. Geology (Boulder) 14 (2): 175-178.

Nanson, G.C., Tooth, S. and Knighton, A.D., 2002. A global perspective on dryland rivers: perceptions, misconceptions, and distinctions. In: Bull, L.J. and Kirkby, M.J. (eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. John Wiley & Sons, Chichester; pp. 17-54.

Nanson, G.C., Young, R.W., Price, D.M. and Rust, B.R., 1988. Stratigraphy, sedimentology and late-Quaternary chronology of the Channel Country of western Queensland. In: Warner, R.F. (ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney; pp. 151–175.

Neef, G., Bottrill, R. S. and Ritchie, A., 1995. Phanerozoic stratigraphy and structure of the northern Barrier Ranges, western New South Wales. Australian Journal of Earth Sciences, 42: 557-570.

NSW, 2006a. Water Management Act 2000, Order under Section 54, Harvestable Rights-Western Division. New South Wales Government Gazette, 31 March 2006, pp. 1628-1630.

NSW, 2006b. Water Management Act 1912, Order (definition of a river). New South Wales Government Gazette, 24 March 2006, pp. 1500-1509.

*Ollier, C.D., 1966. Desert gilgai. Nature (London) 212 (5062): 581-583.

Pain, C., Gregory, L., Wilson, P. and McKenzie, N., 2011. The physiographic regions of Australia – Explanatory notes. Australian Collaborative Land Evaluation Program and National Committee on Soil and Terrain. CSIRO (Canberra), and the Australian Department of Agriculture, Fisheries and Forestry (DAFF) (Canberra). Dataset available at URL http://www.asris.csiro.au/themes/PhysioRegions.html#PhysioRegions_Downloads, accessed 22 Jan. 2105.

Patton, P.C., Pickup, G. and Price, D.M., 1993. Holocene paleofloods of the Ross River, central Australia. Quaternary Research 40 (2): 201-212.

Pell S.D., Chivas A.R. and Williams I.S., 2000. The Simpson, Strzelecki and Tirari deserts: development, and sand provenance. Sedimentary Geology 130: 107–130.

Pickard, J., 1994. Post-European changes in creeks of semi-arid rangelands, Polpah Station, New South Wales. In: Millington, A.C. and Pye, K., (eds.), Environmental change in drylands; biogeographical and geomorphological perspectives. John Wiley and Sons, West Sussex; pp. 271-283.

Pickup, G., 1985. The erosion cell - a geomorphic approach to landscape classification in range assessment. Australian Rangeland Journal 7: 114-121.

Pickup, G., 1988. Modelling arid zone soil erosion at the regional scale. In: Warner, R.F. (ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney, pp. 105-127.

Pickup, G., 1991. Event frequency and landscape stability on the floodplain systems of arid central Australia. Quaternary Science Reviews 10 (5): 463-473.

Pickup, G., Alan, G. and Baker, V.R., 1988. History, palaeochannels and palaeofloods of the Finke River, central Australia. In: Warner, R.F., (ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney, pp. 177-200.

Pillans, B., 2005. Geochronology of the Australian regolith. In: Anand, R.R., and de Broekert, P., (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; pp. 41-52.

Pillans, B., 2007. Pre-Quaternary landscape inheritance in Australia. Journal of Quaternary Science 22 (5): 439-447.

Pralong, J.-P., 2005. A method for assessing the tourist potential and use of geomorphological sites. Géomorphologie: Relief, Processes, Environment 3: 189–196.

Pringle, H.J.R., and Tinley K.L., 2003. Are we overlooking critical geomorphic determinants of landscape change in Australian rangelands? Ecological Management and Restoration 4: 180-186.

Prosser, I.P. 1991. A comparison of past and present episodes of gully erosion at Wangrah Creek, Southern Tablelands, New South Wales. Australian Geographical Studies, 29: 139-154.

Quigley, M.C., Cupper, M.L. and Sandiford, M., 2006. Quaternary faults of south-central Australia: palaeoseismicity, slip rates and origin. Australian Journal of Earth Sciences 53: 285-301.

Quigley, M.C., Sandiford, M., and Cupper, M.L., 2007a. Distinguishing tectonic from climatic controls on range-front sedimentation. Basin Research 19: 491-505.

Quigley, M., Sandiford, M., Fifield, K. and Alimanovic, A., 2007b. Bedrock erosion and relief production in the northern Flinders Ranges, Australia. Earth Surface Processes and Landforms 32 (6): 929-944.

Quigley, M.C., Clark D, and Sandiford, M., 2010 Tectonic geomorphology of Australia. In: Bishop, P., Pillans, B. (eds.), Australian Landscapes. Geological Society, London, Special Publications, 346; pp. 243-265.

Ramanaidou, E.R., Morris, R.C. and Horwitz, R.C., 2003. Channel iron deposits of the Hamersley Province, Western Australia. Australian Journal of Earth Sciences, 50 (5): 669-690.

Rosengren, N., 2009. Rocky coasts workshop July 2009, Melbourne. Convened by the Department of the Environment, Water, Heritage and the Arts.

*Rust, B.R. and Nanson, G.C., 1986. Contemporary and palaeo channel patterns and the late Quaternary stratigraphy of Cooper Creek, Southwest Queensland, Australia. Earth Surface Processes and Landforms 11 (6): 581-590.

Sandiford, M., 2007. The tilting continent: a new constraint on the dynamic topographic field from Australia. Earth and Planetary Science Letters 261(1): 152-163.

Sandiford, M., 2010. A slow divorce: tectonic signals in an ancient continent. The Australian Geologist 157: 29-31.

Sandiford, M., Quigley, M., De Broekert P. and Jakica, S., 2009. Tectonic framework for the Cenozoic cratonic basins of Australia. Australian Journal of Earth Sciences 56 (Supplement 1): S5-S18.

Schellart, W.P. and Spakman, W., 2015. Australian plate motion and topography linked to fossil New Guinea slab below Lake Eyre. Earth and Planetary Science Letters 421: 107-116.

Schmarr, D.W., Mathwin, R., Cheshire, D.L. and McNeil, D.G., 2012. Aquatic ecology assessment and analysis of the Cooper Creek catchment: Lake Eyre Basin, South Australia. Report to the South Australian Arid Lands Natural Resource Management Board. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2012/000442–1. SARDI Research Report Series No. 679.

Schumm, S.A. 1977. The Fluvial System. John Wylie and Sons, New York.

Semeniuk V., 1993. The Pilbara Coast: a riverine coastal plain in a tropical arid setting, northwestern Australia. Sedimentary Geology, 83: 235-256.

Semeniuk , V., 1996. Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology year 123 : 49-84.

Shannon, H., 2010 (unpublished). Alexandra Station. Report of Alexandra Station Sinkhole (Alex09 Cave, 8BK-34); Victorian Speleological Association, Inc.; Melbourne.

Shannon, J., Richardson, R. and Thornes, J., 2002. Modelling event-based fluxes in ephemeral streams. In Bull, L.J, & Kirkby, M.J. (eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. John Wiley & Sons, Chichester, pp. 128-172.

Sheldon, F. and Thoms, M.C., 2006. In-channel geomorphic complexity; the key to the dynamics of organic matter in large dryland rivers? Geomorphology 77 (3-4): 270-285.

Silcock, J., 2009. Identification of permanent refuge waterbodies in the Cooper Creek and Georgina-Diamantina River catchments for Queensland and South Australia. Report to the South Australian Arid Lands Natural Resource Management Board. South Australian Arid Lands Natural Resource Management Board, Port Augusta.

Smith, K.G., Smith, J.W. and Stewart, J.R., 1961. The regional geology of the Davenport and Murchison ranges, Northern Territory. Report 58, Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Sniderman, J.K., Woodhead, J.D., Hellstrom, J., Jordan, G.J., Drysdale, R.N., Tyler, J.J. and Porch, N., 2016. Pliocene reversal of late Neogene aridification. Proceedings of the National Academy of Sciences 113(8): 1999-2004.

Stidolph, P.A., Bagas, L., Donnellan, N., Walley, A.M., Morris, D. G. and Simons, B., 1988. ELKEDRA SF53-7 1: 250,000 geological map series and explanatory notes. Northern Territory Geological Survey, Darwin

Sweet, I.P., Stewart, A.J. and Crick, I.H., 2012. Uluru and Kata Tjuta: a geological guide. Geoscience Australia, Canberra.

Thiry, M., Milnes, A.R., Rayot, V. and Simon-Coincon, R., 2006. Interpretation of palaeoweathering features and successive silicifications in the Tertiary regolith of inland Australia. Journal of the Geological Society of London 163 (4): 723-736.

Thompson, C. and Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia. Geomorphology 197: 156-169.

Thompson, R.B., 1995. A guide to the geology and landforms of central Australia. Northern Territory Geological Survey, Department of Mines and Energy, Darwin.

Thoms, M.C., Beyer, P.J. and Rogers, K.H., 2006. Variability, complexity and diversity; the geomorphology of river ecosystems in dryland regions. In: Kingsford, R., (ed.), Ecology of desert rivers, Cambridge University Press, New York, pp. 47-75.

Tongway, D.J. and Hindley, N.L., 2004. Landscape function analysis: procedures for monitoring and assessing landscapes. CSIRO Sustainable Ecosystems, Canberra.

Tongway D.J. and Ludwig J.A., 1994. Small-scale resource heterogeneity in semi-arid landscapes. Pacific Conservation Biology 1: 201–208.

Tongway, D.J. and Ludwig, J.A., 2001. Theories on the origins, maintenance, dynamics, and functioning of banded landscapes. In: Tongway, D.J., Valentin, C. and Seghieri, J., (eds.), Banded vegetation patterning in arid and semiarid environments: Ecological processes and consequences for management. Springer, New York: pp. 20-31.

Tooth, S., 1999. Floodouts in central Australia. In: Miller, A.J. and Gupta, A., (eds.), Varieties of Fluvial Form. John Wiley and Sons, Chichester, pp. 219-247.

Tooth, S., 2000a. Process, form and change in dryland rivers; a review of recent research. Earth-Science Reviews 51 (1-4): 67-107.

Tooth, S., 2000b. Downstream changes in dryland river channels; the Northern Plains of arid central Australia. Geomorphology 34: 33-54.

Tooth, S., 2005. Splay formation along the lower reaches of ephemeral rivers on the Northern Plains of arid central Australia. Journal of Sedimentary Research 75 (4): 636-649.

Tooth, S. and Nanson, G.C., 1999. Anabranching rivers on the Northern Plains of arid central Australia. Geomorphology 29 (3-4): 211-233.

Tooth, S. and Nanson, G.C., 2000. Equilibrium and nonequilibrium conditions in dryland rivers. Physical Geography 21 (3): 183-211.

Tooth, S. and Nanson, G.C., 2004. Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel-pattern discrimination and prediction. Geological Society of America Bulletin 116 (7-8): 802-816.

Trewin, B., 2006. Australian deserts, climatic aspects of Australia's deserts. Australian Bureau of Statistics © 1301.0 - Year Book Australia, 2006. http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/1301.0Feature%20Article22006?open. Accessed 2 Sept 2014.

*Twidale, C.R., 1967. Hillslopes and pediments in the Flinders ranges, South Australia. In: Jennings, J.N. and Mabbutt, J.A., (eds.), Landform studies from Australia and New Guinea. Australian National University Press, Canberra, pp. 95-117.

Twidale, C.R., 1980. The Devil's Marbles, central Australia. Transactions of the Royal Society of South Australia 104 (3-4): 41-49.

Twidale, C.R. and Bourne, J.A., 1998. The use of duricrusts and topographic relationships in geomorphological correlation; conclusions based in Australian experience. Catena (Giessen) 33 (2): 105-122.

Twidale, C.R. and Campbell, E.M., 1993. Australian landforms; structure, process and time. Gleneagles Publishing, Adelaide.

Upton, G., 1983. Genesis of crabhole microrelief at Fowlers Gap, western New South Wales. Catena 10: 383-392.

Valentin C. and D'herbes J-M. 1996. Impact of water harvesting variations along a climatic transect in Niger upon productivity and patterns of tiger bush. In: Banded Vegetation Patterning in Arid and Semi-arid Environment, Symposium, Paris, France, April 1996, pp. 37-38. Institut Francais de Recherche Scientifique pour le Developpement en Cooperation.

Van de Graaff, W.J.E., Crowe, R.W.A., Bunting, J.A. and Jackson, M.J., 1977. Relict early Cainozoic drainages in arid Western Australia. Zeitschrift fuer Geomorphologie 21 (4): 379-400.

Vanderstaay, A.G.B., 2000. WQ32—soils of western Queensland. Technical notes, western Queensland best practice guidelines. Queensland Government Department of Main Roads; http://www.tmr.qld.gov.au/~/media/busind/techstdpubs/Western%20Queensland%20Best%20Practice%20Guidelines/WQ32.pdf, accessed 31 October 2014.

Waclawik, V.G., Lang, S.C. and Krapf, C.B.E., 2008. Fluvial response to tectonic activity in an intra-continental dryland setting; the Neales River, Lake Eyre, central Australia. Geomorphology 102 (1): 179-188.

Wakelin-King, G.A., 1989. Geology of Simpsons Gap National Park. NTGS Report 6; Northern Territory Geological Survey, Department of Mines and Energy, Darwin.

Wakelin-King, G.A., 1989. Investigations of playa lakes on the Kulgera 1:250,000 map sheet. NTGS Technical Report 1989/012, Department of Mines and Energy, Darwin.

Wakelin-King, G.A., 1999. Banded mosaic ('tiger bush') and sheetflow plains: a regional mapping approach. Australian Journal of Earth Sciences 46: 53–60.

Wakelin-King, G.A., 2005. Modern fluvial process and prior landscape history in an arid-zone river: Fowlers Creek, New South Wales, Australia. Doctoral dissertation, La Trobe University.

Wakelin-King, G.A., 2011a. Geomorphological assessment and analysis of the Neales Catchment: A report to the South Australian Arid Lands Natural Resources Management Board. Wakelin Associates, Melbourne. 128pp., 2 maps.

Wakelin-King, G.A. 2011b. Using geomorphology to assess contour furrowing in western New South Wales, Australia. The Rangeland Journal: 33, 153–171.

Wakelin-King, G.A., 2013. Geomorphological assessment and analysis of the Cooper Creek catchment (SA section). Report by Wakelin Associates to the South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Wakelin-King, G.A., 2015a. Geomorphology of Finke River and Arckaringa Creek: the bedload rivers. Report by Wakelin Associates to the South Australian Department of Environment, Water and Natural Resources; Lake Eyre Basin River Monitoring Project. DEWNR Technical report 2015/xx; Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Wakelin-King, G.A., 2015b. Geomorphology of the Thomson River, Queensland: overview and comparison with Cooper Creek. Report by Wakelin Associates to the South Australian Department of Environment, Water and Natural Resources; Lake Eyre Basin River Monitoring Project. DEWNR Technical report 2015/xx; Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Wakelin-King, G.A., (in prep. 2015). Length of Australia's arid cliffed coasts.

Wakelin-King, G. and Amos, K., (submitted 2015). A time-slice of the Lake Eyre Basin: sand/mud depositional geometries in a diverse lowstand endorheic drylands setting. Submitted to proceedings of the Eastern Australian Basins Symposium, Melbourne, September 2015.

Wakelin-King, G.A. and Webb, J.A., 2007a. Threshold-dominated fluvial styles in an arid-zone mud-aggregate river: the uplands of Fowlers Creek, Australia. Geomorphology 85 (1-2): 114-127.

Wakelin-King, G.A. and Webb, J.A., 2007b. Upper-flow-regime mud floodplains, lower-flow-regime sand channels: sediment transport and deposition in a drylands mud-aggregate river. Journal of Sedimentary Research 77: 702–712.

Wakelin-King, G.A. and White, S.Q. 2011. Potential geoheritage values of Australian desert landscapes (Edn 1). Report to the Commonwealth Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Wakelin-King, G.A. and White, S. 2015 (in print; online publication January 2015). The National Heritage potential of landscapes within the Australian drylands. Geoheritage : doi 10.1007/s12371-014-0140-x

Ward, C.R., and Sullivan, M.E. 1973. Geology of Fowlers Gap Station. In: Mabbutt, J.A. and Sullivan, M.E. (eds.), Lands of Fowlers Gap Station, New South Wales. Research Series No. 3, University of New South Wales, pp. 67-84.

Wasson, R.J., 1979. Sedimentation history of the Mundi Mundi alluvial fans, western New South Wales. Sedimentary Geology 22 (1-2): 21-51.

Wasson, R.J., 1982. Landform development in Australia. In: Barker, W.R. and Greenslade, P.J.M., 1982, (eds.), Evolution of the flora and fauna of arid Australia. Peacock Publications, Adelaide, pp. 23-34.

Wasson, R.J. and Galloway, R.W. 1986. Sediment yield in the Barrier Range before and after European settlement. Australian Rangeland Journal 8: 79-90.

Wasson R.J. and Hyde R., 1983. Factors determining desert dune type. Nature 304: 337-339.

Wasson, R.J., Mazari, R.K., Starr, B. and Clifton, G., 1998. The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. Geomorphology 24: 291-308.

Watson, A. and Nash, D.J., 1997. Desert crusts and varnishes In: Thomas, D.S.G., (ed.), Arid zone geomorphology; process, form and change in drylands. John Wiley and Sons, Chichester; pp. 69-107.

Webb, J.A. and Golding, S.D., 1998. Geochemical mass-balance and oxygen-isotope constraints on silcrete formation and its paleoclimatic implications in southern Australia. Journal of Sedimentary Research 68 (5): 981–993.

Webb, J.A. and James, J.M., 2006. Karst evolution of the Nullarbor Plain, Australia. In: Harmon, R.S. and Wicks, C.M. (eds.), Perspectives on karst geomorphology, hydrology, and geochemistry; a tribute volume to Derek C. Ford and William B. White. Special Paper - Geological Society of America 404: 65-78.

Webb, J.A. and White, S., 2013. Karst in deserts. In: Shroder, J. (Editor in Chief) and Frumkin, A. (ed.), Treatise on Geomorphology, Vol. 6, Karst Geomorphology. Academic Press, San Diego, CA, pp. 397–406.

Wells, A.T., Forman, D.J., Ranford, L.C. and Cook, P.J., 1970. Geology of the Amadeus Basin, central Australia. Bureau of Mineral Resources, Australia, Bulletin 100; Canberra.

White, S. and Wakelin-King, G.A., 2014. ESCoM, a comparative method for geoheritage assessment. Geographical Research. 52(2): 168–181; doi: 10.1111/1745-5871.12062.

White, S., King, R.L., Mitchell, M.M., Joyce, E. B., Cochrane, R.M., Rosengren N. J. and Grimes K.G., 2003: Conservation and heritage registering sites of significance. In: Birch W.D.(ed.), Geology of Victoria. Geological Society of Australia Special Publication 23. Geological Society of Australia (Victoria Division); pp. 703–711.

Williams G. E. and Gostin V. A. 2005. The Acraman – Bunyeroo impact event (Ediacaran), South Australia, and environmental consequences: 25 years on. Australian Journal of Earth Sciences 52: 607 – 620.

Williams, G.E. and Wallace, M.W., 2003. The Acraman asteroid impact, South Australia; magnitude and implications for the late Vendian environment. Journal of the Geological Society of London 160 (4): 545-554.

Witford, J.R., 2005. Granites-Tanami region, Northern Territory. In: Anand, de Broekert, P. (eds.), Regolith landscape evolution across Australia; a compilation of regolith landscape case studies with regolith landscape evolution models. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Bentley, West Australia; 151-155.

*Woolnough, W.G., 1927. Presidential address Part 1, The chemical criteria of peneplanation; Part 2 The duricrust of Australia. Journal of the Proceedings of the Royal Society of New South Wales 61:1-53.

*Wopfner, H., 1978. Silcretes of northern South Australia and adjacent regions. In: Langford-Smith, T., (ed.), Silcrete in Australia. Department of Geography, University of New England, Armidale, pp. 93-142.

*Wopfner, H. and Twidale, C.R., 1967. Geomorphological history of the Lake Eyre Basin . In: Jennings, J.N. and Mabbutt, J.A., (eds.), Landform studies from Australia and New Guinea. Australian National University Press, Canberra, pp. 118-143.

Wyrwoll, K-H., Kendrick, G.W. and Long, J.A., 1993. The geomorphology and Late Cenozoic geomorphological evolution of the Cape Range - Exmouth Gulf region. In: Humphreys, W.F., (ed.), The biogeography of the Cape Range. Records of the Western Australian Museum. Western Australian Museum, Perth, supplement 45: 1-23.

Young, D N., Duncan, N., Camacho A., Ferenczi, P.A. and Madigan T.L.A., 2002. Ayers Rock, Northern Territory, 1:250,000 Geological Series (2nd edition). Northern Territory Geological Survey, Explanatory Notes; Darwin.

Young, W.J. and Kingsford, R.T., 2006. Flow variability in large unregulated dryland rivers. In: Kingsford, R., (ed.), Ecology of desert rivers, Cambridge University Press, New York; pp. 11-46.