A classification system for regolith in Western Australia

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A CLASSIFICATION SYSTEM FOR REGOLITH IN WESTERN AUSTRALIA

by R. M. Hocking, R. L. Langford, A. M. Thorne, A. J. Sanders, P. A. Morris, C. A. Strong, and J. R. Gozzard

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Abstract

This Record presents a comprehensive classification system for regolith units in Western Australia that can be used on a wide variety of map types and scales produced by the Geological Survey of Western Australia (GSWA). The system is based on the landform position and principal regolith-forming process, qualified by the composition of the regolith. The classification rationalizes previous GSWA schemes for Cainozoic units, and expands the RED (Residual–Erosional–Depositional) regolith–landform mapping scheme developed by CSIRO. The classification aims for a uniform, comprehensive, flexible, and reasonably intuitive approach to mapping regolith in Western Australia.

The classification has a defined set of primary codes that describe the landform setting and process: *R* (residual or relict), *X* (exposed), *C* (colluvial), *W* (sheetwash), *A* (alluvial), *L* (lacustrine), *E* (eolian), *S* (sandplain; mixed and eolian origins), *B* (beach, or wave-dominated coastline), *T* (tide-dominated coastline), and *M* (marine).

C, W, A, and *L* can be grouped into a higher level of *V* (valley); *B, T,* and *M* into *K* (coastal); and all of these into *D* (depositional), that, along with *R* and *X*, roll up to a simplified classification suitable for summary maps. Subdivision of the primary landform codes is achieved using subscripts.

Optional secondary codes specify regolith composition and, again, subscripts allow for more precise description. Tertiary codes, also optional, can be used to specify parent rock and cement type.

Numbers are employed to differentiate relative age of regolith.

The use of combined primary, secondary, and tertiary codes provides a flexible hierarchical system for description of the regolith in Western Australia, applicable to maps at many scales.

KEYWORDS: regolith, environmental setting, superficial sediments, residual sediments, Cainozoic, stratigraphy, palaeoclimatology, climatology

Introduction

Regolith is the layer of mineral and organic material, of diverse origin, that nearly everywhere forms the surface of the land and rests on bedrock. It is commonly unconsolidated, and comprises a wide range of materials, including alluvium, windblown deposits, accumulations of vegetation (such as peat), volcanic ash, glacial drift, and soil (Bates and Jackson, 1980). On Geological Survey of Western Australia (GSWA) maps, both superficial sediments and calcrete, silcrete, or ferricrete (hard ferruginous duricrust, also referred to as laterite; Appendix 1; Fig. 1) have been identified as separate regolith units.

Parameters that can be used to classify regolith include material type and properties, structural characteristics, landform slope and morphology, evidence of process, and evidence of relative or absolute age. Anand et al. (1993a)

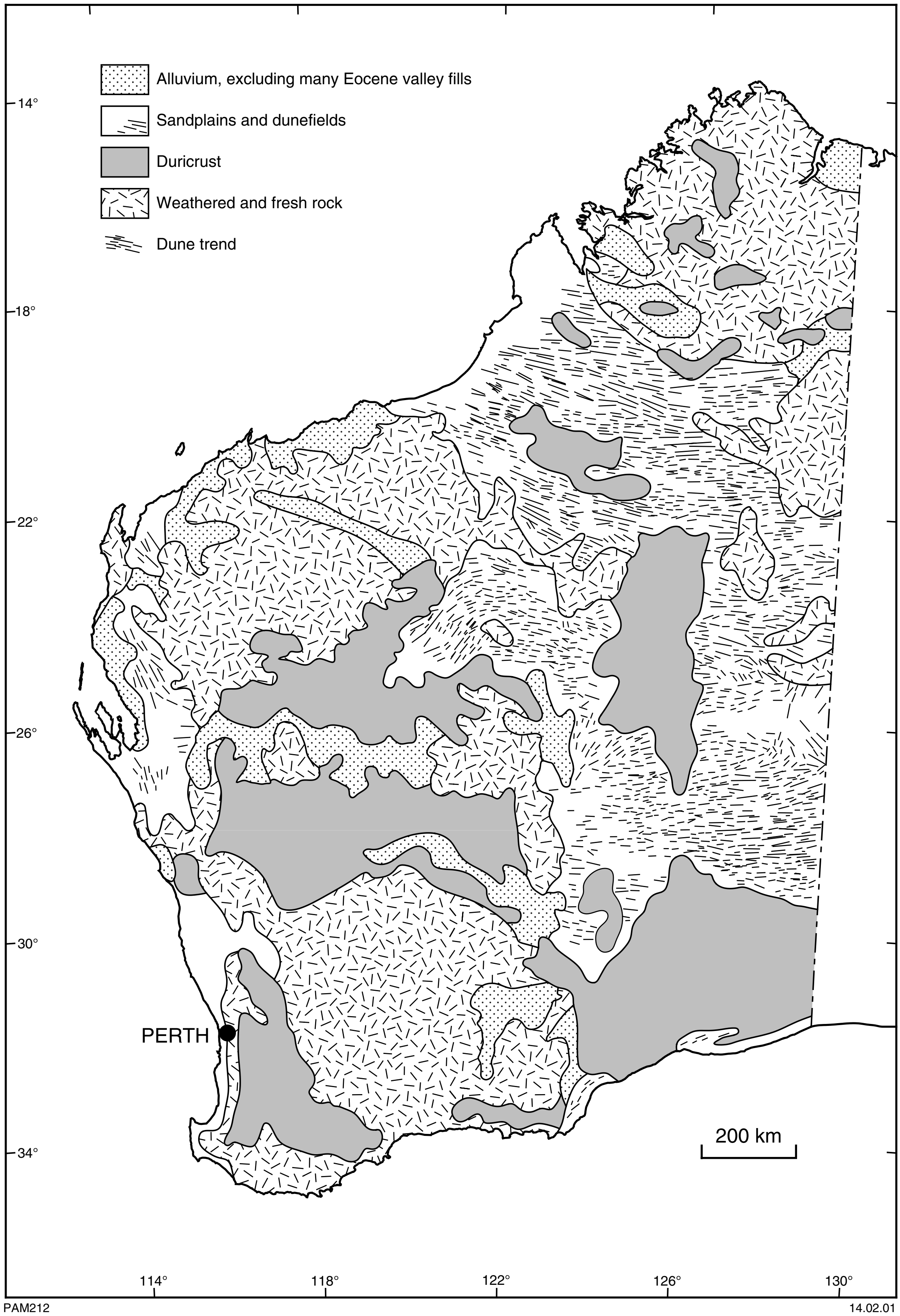


Figure 1. Generalized distribution of duricrust (ferricrete, silcrete, calcrete), alluvium, eolian deposits, and weathered and fresh bedrock in Western Australia. After Hocking and Cockbain (1990, fig. 6-1)

Table 1. Definitions of regimes in the RED scheme, adapted from Anand et al. (1993a,b)

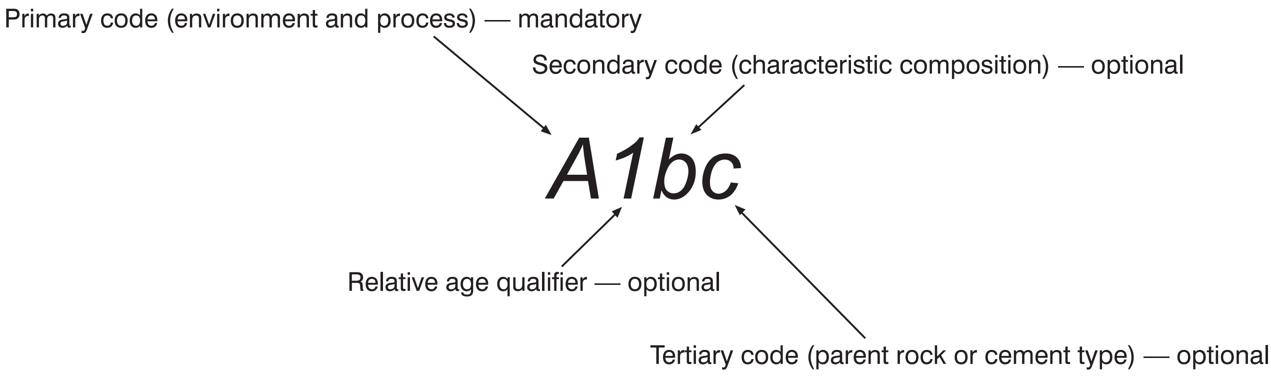
Regime	*Characteristics*	*Examples*
Residual	Remnant, reworked, or degraded materials derived both from, and situated on, an ancient weathered land surface	Sand above granitoid plateaus, ferricrete-capped mesas, and siliceous cappings on the edges of breakaways
Erosional	Areas of erosion and removal of material to a level where the mottled zone, clay zone, saprolite, or bedrock are exposed, concealed beneath thin soil, or concealed beneath locally derived, associated sediments	Scattered to abundant rock exposures and areas of relatively high relief, often covered with poorly sorted stony debris
Depositional	Widespread sediments that are increasingly reworked and redistributed relative to the residual or erosional source, and that can be many metres thick	Sheetwash plains, colluvial fans, saline playas, sandplains, and drainage channels

described and classified regolith according to its composition and position in an idealized landscape profile, and differentiated three major regimes: Residual, Erosional, and Depositional (RED scheme; Table 1; also see Fig. 1). Their classification was formulated in the arid interior of Western Australia, where an extensive, deeply weathered mantle above bedrock has been subsequently modified by erosion and deposition to form a variety of regolith types. Fundamental to their approach is the recognition of regolith–landform mapping units, which are areas characterized by a particular association of regolith materials, bedrock geology, and landforms. The GSWA classification extends the approach of Anand et al. (1993a) by expanding the depositional regime into its constituent categories (e.g. lakes, streams, and slope deposits), and specifies compositional and provenance attributes using optional secondary and tertiary codes.

Classification system

Regolith materials maps result from the synthesis of ground observations and remotely sensed data from sources such as aerial photographs and Landsat, and airborne radiometrics and magnetics, although the balance of direct observation and remote data interpretation varies between both maps and map series. A uniform regolith classification scheme for geological maps of Western Australia should be objective, simple, and logical, but also flexible enough to allow a detailed regolith subdivision when required. The scheme should also be compatible with published regolith classifications on GSWA maps wherever possible, and complement established formal lithostratigraphic nomenclature applied to named rock units.

Environment of formation and process (landform setting), composition, and relative age emerged as the most significant criteria for displaying regolith on most GSWA maps. This information is presented using a primary code letter for environment and process (Table 2), which can be subdivided using a series of subscripts (Table 3). A relative age number (increasing from 1) can be used where more than one generation of regolith is distinguished (see **Regolith age**). An optional secondary code can be used to designate regolith composition (Table 4), and an optional tertiary code indicates either parent rock type or cement (Table 5).



The primary, secondary, and tertiary codes summarize a broad range of environment and process plus compositional information. More detail or greater precision is available through subscript qualifiers.

$$A1_a\, b_b c_c$$

Each subscript qualifier ($_{a,\ b,}$ and $_c$) has a fixed position in the code string, and relates only to the preceding primary, secondary or tertiary code (*A*, *b*, and *c* in the above example). Thus, any regolith code could have a maximum of six letters (three of which are subscripted) plus one relative age qualifier. Only the primary code, describing the broad environmental setting or process, is compulsory. For universality, the primary, secondary, and tertiary codes, and many qualifiers, are predefined. These are presented in Tables 3 to 5. Additions to these codes are inevitable, and should be submitted to the GSWA Chief Geoscientist and the Regolith Database Custodian.

Landform codes (primary level)

The primary landform code (Table 2) specifies the environment (landform position) and/or process responsible for the formation or deposition of the regolith (e.g. alluvial, lacustrine, or tidal coastline). This is determined by identifying the slope and shape of the landscape, and the material present. Following from this is an assessment of whether the regolith reflects the current (active) climatic regime or is a relict of an older regime (Fig. 2). Most but not all relict features will be undergoing erosion. Patterns on aerial photographs and satellite images, remotely sensed geophysical data, and digital elevation models (DEMs) can all assist field observations in mapping these features.

Eleven primary code letters identify the dominant environment or process: *R* (residual or relict), *X* (exposed), *C* (colluvial), *W* (sheetwash), *A* (alluvial), *L* (lacustrine), *E* (eolian), *S* (sandplain; mixed and eolian origins), *B* (beach, or wave-dominated coastline), *T* (tide-dominated coastline), and *M* (marine). Three other letters are reserved for higher level groupings: *D* (depositional), *V* (valley) and *K* (coastal). These and other relevant terms are explained in Appendix 1 and Table 2. On 1:100 000- and 1:250 000-scale Geological Series maps, the order of the legend boxes should be as above and in Table 2, unless there are compelling extenuating reasons — such as stratigraphic position — for change.

Table 2. Primary regolith codes for GSWA maps

Primary landform code	*Environment and process*	*Notes*
R	Residual or relict	Remnant material overlying an ancient land surface. Residual material is derived by in situ weathering and shows no evidence of having undergone significant transport. Relict material comprises deposits of uncertain origin, either transported or residual, or a combination of both. The term relict should not be used if the original depositional process can be determined. In such cases the appropriate primary code (e.g. *A*, *C*, *W*), with a relative age qualifier, should be used instead
X	Exposed	Used for rock (optional) and weathered rock. Includes subcrop and bouldery lag
C	Colluvial	Proximal mass wasting deposits grading into sheetwash with a significant to perceptible slope
W	Low-gradient slope	Distal slope deposits (sheetwash and sheet flood) where the gradient is minimal, and drainage is not clearly defined
A	Alluvial/fluvial	Alluvium in channels and floodplains. Includes deltaic deposits
L	Lacustrine	Inland lakes, dune and playa terrain, and some coastal lakes. Includes saline and fresh-water playas and claypans, and minor eolian deposits directly associated with the lake system (e.g. fringing gypsiferous dunes)
E	Eolian	Eolian dunes, interdune areas, and sandplain
S	Sandplain	May be of mixed origin, including residual, sheetwash, and eolian sands
B	Coastal (wave-dominated)	Beaches, beach ridges, barrier bars and lagoons, and back-beach dunes, coastal cliffs and other erosional features (e.g. blowouts)
T	Coastal (tide-dominated)	Intertidal and supratidal flats and channels, estuaries, and mangrove flats
M	Marine	Subtidal, shoreface, and offshore marine deposits such as coralgal reefs, shell banks, and sea-grass banks
V	Valley	Higher level category; includes lacustrine, alluvial, floodplain, sheetwash, and colluvial
K	Coastal	Higher level category; includes wave- and tide-dominated coastal, and marine
D	Depositional	Highest level category; includes all depositional systems

The choice of primary code is largely determined by the amount and type of information available. Note that *R* is used for both residual or relict material. ‘Residual’ is used where regolith is a product of in situ weathering. ‘Relict’ is used for landforms (e.g. mesas) where regolith is of uncertain origin, either transported or residual. For relict material, in which the original process of formation *can* be determined, the unit should be classified with another appropriate primary code. For example, a dissected portion of an old alluvial terrace, should be classified as an older generation of alluvium or valley deposit (A2, A3, V2, etc).

It should be possible to reduce a regolith unit to primary code levels and thus produce a seamless join between maps, although inevitably there will be differences in the choice of some primary codes (e.g. *W* vs *C* vs *A*).

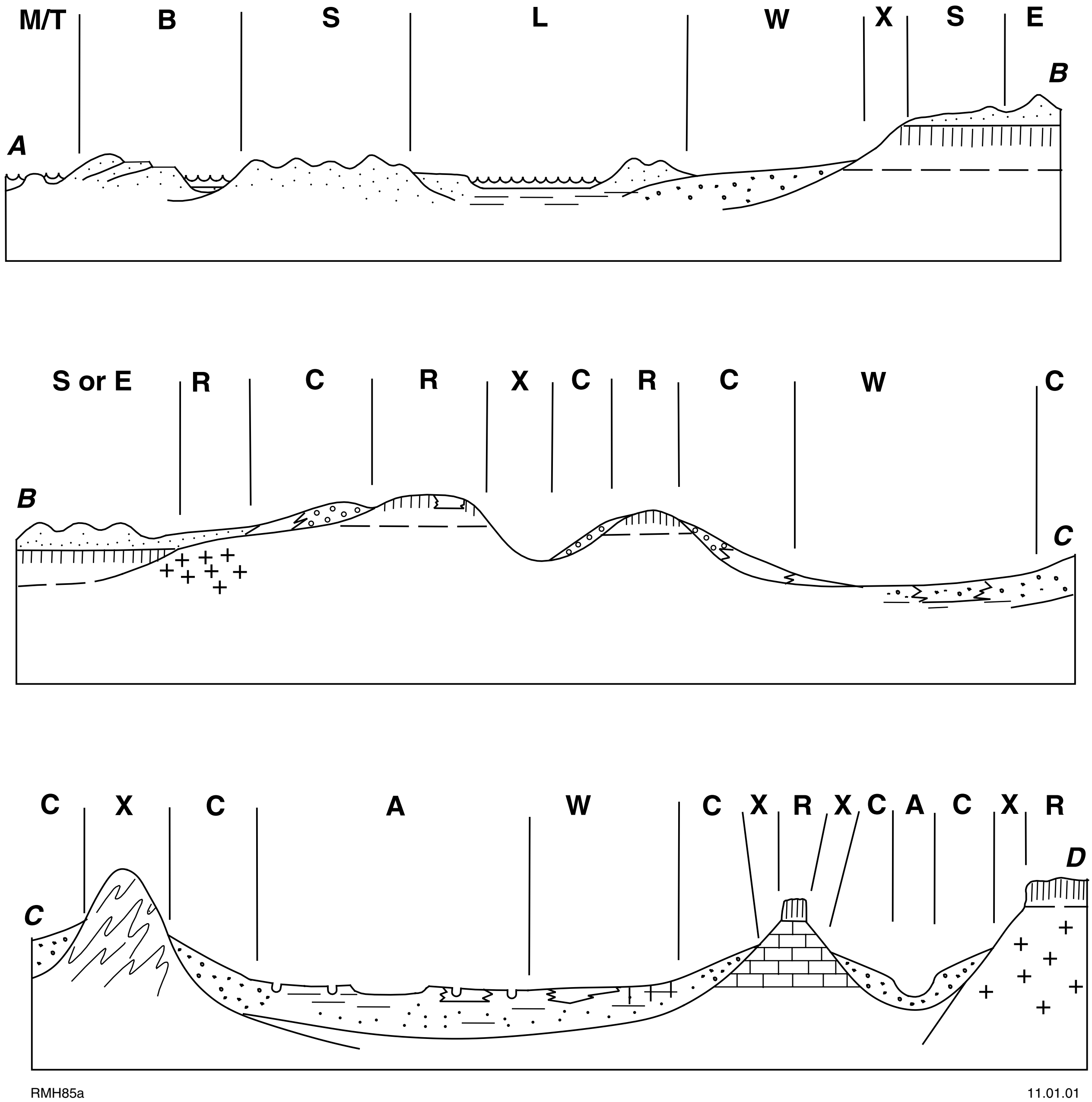


Figure 2. Diagrammatic relationships of regolith units in Western Australia, showing likely primary regolith codes

Landform code qualifiers

Optional subscripts can be used to achieve greater discrimination or precision for primary codes. The meaning of a subscript is set by its associated primary code, as shown by the examples in Table 3. Common usage of subscript letters between the primary landform elements is preserved where possible, but differences will arise. The system of subscript qualifiers also allows a summary of textural information, mostly grain size, to be shown on the map. This can be achieved where the information is specific to a certain landform and process sub-unit, as in an alluvial channel, where it would be possible to distinguish both sand bars (A_s) and gravel bars (A_g) on the basis of their morphology as well as grain size.

Table 3. Landform (primary) code qualifiers

Primary landform or process	*Landform element or pattern*	*Suggested primary and subscript code*	
Residual or relict		R	
	In situ weathered (residual)		R_i
	Duricrust (residual or relict)		R_r
	Sand (residual or relict)		R_s
	Transported (relict)		R_t
Exposed		X	
	Deeply weathered		X_w
Colluvial (proximal slope)		C	
	Cliff-foot slope		C_c
	Footslope		C_f
	Landslide		C_l
	Scarp-foot slope		C_s
	Talus		C_t
Low-gradient slope (sheet-flood, distal slope)		W	
	Sheet-flood fan		W_f
	Playa, pan		W_p
	Scarp-foot slope		W_s
Alluvial		A	
	Alluvial plain		A_a
	Stream bed		A_b
	Stream channel		A_c
	Drainage depression/swale		A_d
	Delta		A_e
	Floodplain		A_f
	Gravel bar		A_g
	Channel bench		A_h
	Stream bank		A_k
	Levee		A_l
	Meander plain		A_m
	Backplain		A_n
	Playa, pan		A_p
	Stream bar		A_r
	Sand bar		A_s
	Terrace		A_t
	Superficial channel		A_u
	Fan/flood-out		A_v
	Swamp		A_w
	Oxbow		A_x
Lacustrine		L	
	Fringing dunes		L_d
	Fringing bedded deposits		L_g
	Lake, excluding fringing deposits		L_l
	Dune and playa terrain		L_m
	Playa		L_p
	Saline lake		L_s
	Subcropping bedrock in lake		L_x
Eolian		E	
	Parabolic dunefield		E_a
	Blow-out		E_b
	Dunefield		E_d
	Dune		E_e
	Longitudinal dunefield		E_l
	Mobile dune		E_m
	Net-like dunefield		E_n
	Sand and playa terrain		E_p
	Lunette		E_u
	Interdune pavements		E_v
	Swampy swale		E_w

Table 3. (continued)

Primary landform or process	*Landform element or pattern*	*Suggested primary and subscript code*	
Sandplain; residual, uncertain, and mixed origin		S	
	Blow-out		S_b
	Dune		S_d
	Gravel deflation pavement		S_g
	Longitudinal dunefield		S_l
	Net-like dunefield		S_n
	Sand and playa terrain		S_p
	Undulating		S_u
Coastal (wave-dominated)		B	
	Beach (foreshore and backshore)		B_b
	Cliffs		B_c
	Foredune		B_d
	Foreshore		B_f
	Backshore		B_k
	Back-barrier lagoon		B_l
	Mobile dunes		B_m
	Boulder beach		B_o
	Beach ridge plain		B_r
	Storm beach gravels		B_s
Coastal (tide-dominated)		T	
	Tidal bar, in channel		T_b
	Tidal channel (subtidal base)		T_c
	Tidal delta		T_d
	Estuary		T_e
	Tidal flat (intertidal and supratidal)		T_f
	Chenier plain		T_h
	Intertidal flat		T_i
	Lagoon		T_l
	Mangrove flats		T_m
	Superficial channel (intertidal)		T_s
	Supratidal flat		T_u
Marine		M	
	Coral reef		M_c
	Shell bank		M_k
	Plain, nearshore		M_n
	Plain, offshore		M_p
	Reef flat, backreef, or rock flat		M_r
	Shoreface		M_s
	Talus slope or foot slope		M_t
	Relict channel		M_v

NOTE: These combinations should be followed where possible; however, the list is not exhaustive. Landform elements and patterns largely follow McDonald et al. (1990)

Regolith age

The age of regolith is commonly poorly constrained where marine sediments do not interfinger, and parts of the regolith (particularly relict) could be older than Cainozoic. On past GSWA maps, unconsolidated regolith generally has been designated as Quaternary whereas relict or residual material, or deposits known or suspected to include a significant thickness of both Quaternary and older Cainozoic material, have been grouped as undivided Cainozoic.

Because of the poor constraints on the absolute age of many regolith units, absolute age information is shown in the map reference but not included as a code letter in the map polygon label. This allows units to be assigned a specific age where this is known, or given an age range where dating is less precise. Where several generations of poorly dated regolith are present, relative ages can be specified more flexibly than before, by using a whole number (with 1 being the youngest) after the primary landform code letter; thus, the codes A1, A2, and A3 differentiate increasingly older alluvium. The rationale for assigning the number 1 to the youngest deposit is that these are usually the most widespread and easily recognized. The degree to which older deposits can be identified will vary across the mapped area, often making it difficult to assess how many generations are present during the early stages of mapping. In this situation, if the youngest deposit is given the highest number then all labels will have to be changed each time a new 'oldest' unit is recognized. Assigning 1 to the youngest deposit should ensure that this code, at least, is more likely to remain unchanged during any subsequent re-evaluation of regolith stratigraphy. Other features of this numbering system are:

- Regolith codes without a number are undivided in terms of relative age. Units in which relative ages can be recognized should always contain the number 1 for the youngest deposit i.e. use the sequence A1, A2, A3 and not A, A2, A3. In situations where several generations of a regolith type are recognized but where it is not always possible to assign each deposit to a particular generation, the unnumbered regolith code letter can be used as an unassigned category. For example, in areas where three generations of alluvial deposit (A1, A2, A3) are recognized, the code letter A could be used for alluvium which cannot be confidently assigned to any one of these three generations. The code list for alluvial deposits in this area would therefore be A, A1, A2, A3.
- There is no implied correlation between different regolith units with the same numerical age qualifier. Conversely, regolith units which are numbered differently may be of similar age. For example, a fluvial unit labelled A2 might be younger than a colluvial deposit labelled C2. In this case A2 would be placed above C2 in the map reference. On the other hand, the unit labelled C2 might be the same age as an older alluvial deposit, A3, and as such, would be shown alongside it on the reference.
- Care should be taken in the placement of the relative age number within the regolith code. In most cases the age qualifier immediately follows the primary code (e.g. A1g, $A2_c$q). In other situations, particularly when labelling residual units that require use of the secondary code to accurately convey the type of regolith, it may be more appropriate to place the number immediately after the secondary code, e.g. Rk1, Rk2. In this example, the number qualifier differentiates two ages of relict or residual carbonate-rich material, as the age qualifier relates directly to the code immediately to the left.

A broad, relative stratigraphy based on the climatic evolution of Western Australia is discussed below; this can help to establish local relationships for some regolith components.

Compositional codes (secondary and tertiary)

The compositional codes (Tables 4 and 5) are optional, but their use is encouraged where significant information is available. They are used to describe the characteristic composition (secondary), and parent rock or cement type (tertiary), of regolith material. In the map code, they appear to the right of the primary landform code and its qualifier. As with the landform code, they consist of a

Table 4. Secondary codes and qualifiers for regolith composition

Code	*Composition*	*Composition qualifier*	
c	clay	c_b	black soil/gilgai
		c_c	chlorite
		c_g	glauconite
		c_k	kaolin
		c_i	illite
		c_m	montmorillonite
		c_s	smectite
d	undivided		
e	evaporite	e_a	anhydrite
		e_g	gypsum
		e_h	halite
f	ferruginous	f_g	gossan
		f_h	hematite
		f_l	limonite
		f_o	goethite
g	quartzofeldspathic		
h	heavy mineral	h_a	apatite
		h_g	garnet
		h_i	ilmenite
		h_l	leucoxene
		h_m	magnetite
		h_o	monazite
		h_r	rutile
		h_z	zircon
k	carbonate	k_a	aragonite
		k_c	calcite
		k_d	dolomite
		k_m	magnesite
l	heterogeneous		
m	ferrogmagnesian		
q	quartz		
r	carbonaceous/organic	r_c	coal
		r_h	humus
		r_p	peat
		r_y	pyritic
t	lithic (rock fragments)		
u	ultramafic		
x	other mineral	x_a	aluminous/bauxite
		x_i	mica
		x_m	manganese
z	siliceous		

limited number of generic categories. A subscript qualifier may be used to give greater discrimination and precision or to extend the information offered. It is clear that no list of this sort will ever be complete; for example, the ‘other mineral’ category could contain a multitude of entries, but the aim is to cover most of the compositional variation seen in Western Australian regolith. Examples of the use of secondary and tertiary qualifiers are given below:

Table 5. Tertiary codes and qualifiers for parent rock or cement type

Code	*Parent rock or cement*	*Parent rock qualifier*	
a	aluminous cement		
c	chemical/biochemical sedimentary deposit	c_c	chert
		c_d	dolomite
		c_i	iron formation
		c_l	limestone
		c_t	diatomite
h	hypabyssal	h_d	dolerite
		h_p	porphyry
i	iron cement		
k	carbonate cement		
m	metamorphic	m_n	gneiss
		m_p	pelite
		m_m	psammite
		m_s	schist
o	fossiliferous	o_s	shells
		o_c	coral/coralgal
p	plutonic	p_a	alkali granite
		p_r	gabbro
		p_d	diorite
		p_g	granite
		p_m	monzogranite/monzonite
		p_o	granodiorite
		p_s	syenogranite/syenite
		p_t	tonalite
r	duricrust		
s	siliciclastic sedimentary rock	s_c	conglomerate
		s_m	mudstone, siltstone, shale
		s_s	sandstone, arenite, wacke
u	ultramafic	u_d	dunite
		u_k	komatiite
		u_p	peridotite
		u_y	pyroxenite
		u_s	serpentinite/talc rock
v	volcanic	v_a	andesite
		v_b	basalt
		v_d	dacite
		v_r	rhyolite
		v_t	trachyte
		v_v	volcaniclastic
z	silica cement		

Akk	Carbonate-cemented calcareous alluvium (groundwater/phreatic calcrete, generally abbreviated to Ak)
A_pc	Claypan in alluvial system
Bh_z	Heavy mineral-rich beach deposit (principally zircon)
Le_g	Lacustrine deposit with evaporitic gypsum
Amv_b	Alluvium derived from ferromagnesian volcanic rock (basalt) fragments.

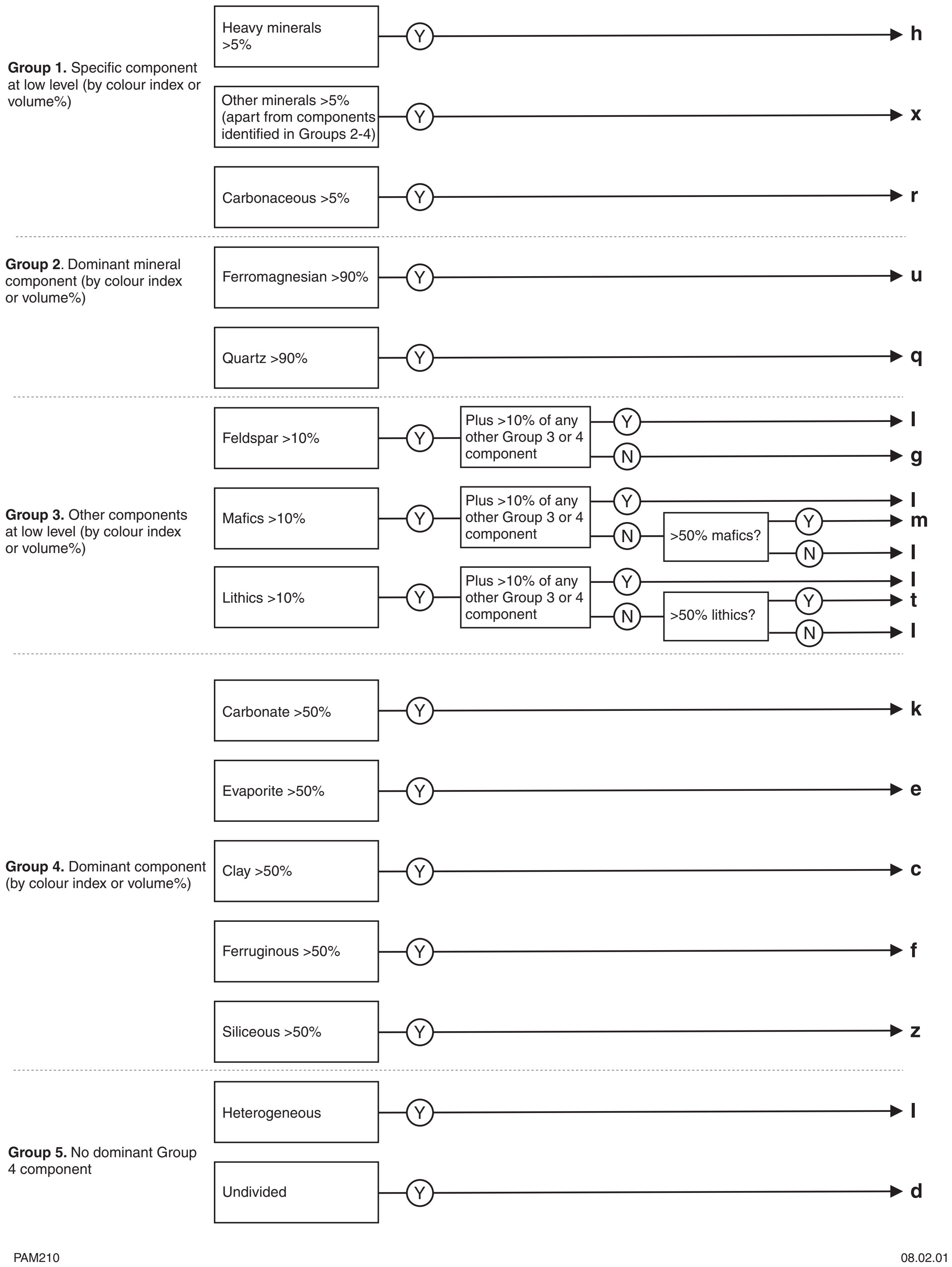


Figure 3. Selection of secondary code (Y = yes, N = no)

Assigning secondary codes

Assigning secondary codes relies on estimating the proportions of components in regolith. In order to emphasize the importance of some compositional elements, secondary codes are assigned in a hierarchical fashion, as detailed in Figures 3 and 4. The most common approach is that shown in Figure 3, but where there is a need to assign a regolith composition to exposed (X) igneous or high-grade metamorphic rocks, the classification system in Figure 4 should be used. It is intended for use in regolith material mapping, where a representation of the overall composition of the bedrock is required rather than its specific lithology. The secondary code 'd' (undivided) can be used to indicate that the nature of the regolith is known through direct observation (e.g. undivided colluvium is Cd).

Named lithostratigraphic units

Formally named lithostratigraphic units of Cainozoic age are common near the coast, and are also scattered through the interior of the State, and the conventions for coding lithostratigraphic rock units should be followed. The age of most of these units is reasonably constrained. Previously, Quaternary *Q* and Tertiary *T*, or less commonly Cainozoic *Cz*, have been used to specify age. In keeping with current IUGS recommendations, Tertiary is generally no longer used. However, Neogene and Palaeogene have not been adopted for GSWA maps pending widespread acceptance and usage of these divisions. Instead the series is used after a Cz prefix, thus: *Czi* Pliocene, *Czm* Miocene, *Czo* Oligocene, *Cze* Eocene, and *Czp* Paleocene. The mnemonic letters for named units are mostly well

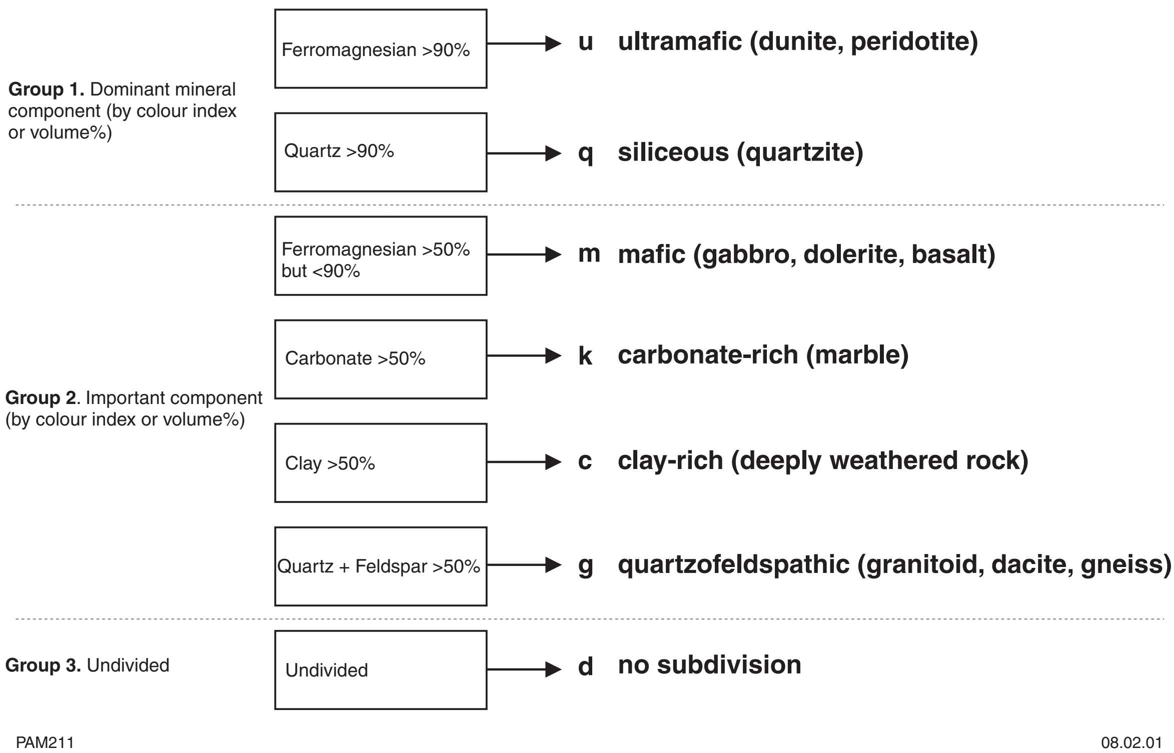


Figure 4. Selection of secondary codes for exposed regolith (*X*) derived from igneous and high-grade metamorphic rock

established from previously published maps. Formally named units get a lithostratigraphic code, and a different font so there can be no conflict with a primary process code as it does not form part of the code.

Units derived from named rock units are locally distinguished on GSWA maps. For example, colluvium derived from the Pallinup Siltstone, versus colluvium derived from granitoid rocks. In such cases, the code letter used for the formation can be used as a qualifier to the compositional code, to indicate the specific named derivation. Potential ambiguity is avoided by the description in the map reference.

Regolith stratigraphy

This system for regolith classification is largely descriptive and does not rely on an interpretation of age, but an understanding of the climatic development of Western Australia is necessary to utilize the scheme to its fullest, especially when two or more generations of regolith can be recognized. The relationship between two regolith units, in particular their relative ages, may be discerned if the possible or probable age of development of each can be established. In turn, the nature and relationships of two units may allow inferences about the prevailing climate of either or both. The following summary provides a guide as to where local observations on the regolith may fit in a broader, climatological context.

A broad stratigraphy for the regolith of Western Australia can be established using both dated horizons and intercalations, as well as known trends in Western Australia's climate since the end of the Mesozoic (Table 6). Unfortunately, even with this broad history, the age of development of an area's landscape is uncertain in many cases. The range in possible age for some regolith components in interior areas is from Pleistocene to Mesozoic, and there are some land surfaces (fossil and exhumed) in Western Australia that are known to be of Mesozoic or Palaeozoic age. Examples of these are: the present-day surface of the Devonian reef complexes of the West Kimberley, which is largely an exhumed Late Carboniferous (pre-Gondwana glaciation) surface (P. E. Playford, written comm. 1996); the Ashburton Surface in northern Australia, which is probably pre-Jurassic (Hays, 1967) and possibly even Cambrian–Precambrian (Stewart et al., 1986); and the oldest Hamersley Surface (Pilbara region), which Twidale et al. (1985) considered to be Mesozoic. Pillans (1998) has argued for subaerial exposure as far back as the Permian over parts of the Yilgarn Craton, and Pillans and Bateman (2000) used palaeomagnetism to date regolith components near Kalgoorlie as Late Cretaceous – Early Cainozoic, Jurassic, and Early Carboniferous. Taylor and Shirtliff (2000) concluded that the weathering process has been essentially continuous rather than episodic throughout the Phanerozoic. Suggestions by Finkl and Fairbridge (1979) that much of the surface of the Yilgarn Craton is of Permian or older age, refuted by van de Graaff (1981), have recently been supported by the work of Sircombe and Freeman (1999), who considered that the thick Perth Basin succession adjacent to the craton is in large part *not* derived from it, based on detrital zircon populations.

Churchill (1961, 1968, 1973) was the first to research Western Australia's climatic history. Later, Kemp (1978), and Christophel and Greenwood (1989) made advances in understanding Cainozoic climatic evolution, and a Quaternary chronology was developed through the work of Bowler (1976, 1977, 1986), Bowler et al. (1976), and Rognon and Williams (1977). Kemp used climatic models derived from sea-surface temperatures, land and sea positions, and the

Table 6. Summary of climatic and regolith changes from the Mesozoic to the present-day. Absolute ages based on Young and Laurie (1996)

Age	*Climate*	*Regolith events*
Cretaceous (65–141 Ma)	–	Marine deposits in the Eucla Basin, major marine transgression over most Phanerozoic basins
Late Cretaceous – Paleocene (c. 95–55 Ma)	–	Well-developed inland drainage (palaeodrainage) system. Undulating duricrust surface. Chains of playa lakes
Late Cretaceous – Early Miocene (c. 95–20 Ma)	–	Ferricrete and silcrete development in the interior of Western Australia
		Major palaeodrainage systems active
Paleocene–Eocene (c. 60–35 Ma)	Moist, temperate-tropical	Marine deposition on coastal plains
Eocene (55–34 Ma)	–	Hamersley Surfaces with pockets of pisolitic iron that could be remnants of a pre-Eocene surface
		Widespread marine deposition along southern margin
Middle–Late Eocene (c. 45–35 Ma)	–	Deposition in major palaeodrainages. Sea level up to 300 m above present-day
		Extensive silcrete and ferricrete development
Late Eocene (c. 40–35 Ma)	Beginning to dry out	Limestone in the Carnarvon Basin, deposited with numerous ferruginous pisoliths
Oligocene (c. 35–25 Ma)	Seasonally moist climate	Ferricrete and silcrete on the west coast and in the Pilbara
		Sea levels generally lower
Miocene (c. 25–12 Ma)	More seasonally extreme climate with significant variations in temperature. Last major transgression	Marine limestones in the Carnarvon and Eucla Basins
Late Miocene (c. 12–5 Ma)	Cooler, though still temperate	Eolian deposition in Carnarvon Basin and inner North West Shelf
Pliocene (5–2 Ma)	Prevailing continental climate appears to indicate increasing desiccation	Much pedogenic calcrete development
		Lacustrine carbonates of the Lawford and Nadarra Formations developed in stagnant drainages. Eolian sands and soils on the top of Kennedy Range and similar plateaus
Early–Middle Pleistocene	Predominantly dry with slightly wetter periods. Exposure of the continental shelf during glacial periods	Development of thick coastal dunes (Tamala Limestone and equivalents). Remnants of inland dune fields are preserved locally
		Calcrete formation continued, as did dissection of pre-existing calcrete surfaces
Late Pleistocene (more than 40 000 years BP)	Marginally drier and probably cooler than today	Dunes presumably active in Western Australia. Extensive alluvial deposition in the flood-dominated, arid environment of the Geraldton area
40 000 – 30 000 years BP	Onset of the last major glacial advance. Significantly wetter climate	High water levels in lakes and increased fluvial activity
25 000 – 15 000 years BP	Last glacial maximum	Lakes dried completely. Lunette development around playas was completed. Major unconsolidated dunefields of Western Australia developed
15 000 years BP – present-day	Transition from intense arid conditions to humid conditions	Mainly erosional
About 10 000 years BP	Temperatures slightly higher and rainfall substantially higher than today	Mainly erosional

extent of the Antarctic ice cap correlated with palynological data to reconstruct Paleocene to Miocene climates. Christophel and Greenwood (1989) used both palynological and megafossil floras to reconstruct Eocene to Pliocene–Pleistocene climates. Much of the following summary is drawn from a review by Cockbain and Hocking (1990).

Late Mesozoic – Early Cainozoic

In the Paleocene and Eocene, Western Australia had a moist, temperate to tropical climate. Australia and an ice-free Antarctica were still linked in the Paleocene, via Tasmania, and lay in high southern latitudes (Kemp, 1978). The oceans around Western Australia at these latitudes were warmer than those of today. High evaporation over this warmer sea surface resulted in deep inland penetration of rain-bearing westerly winds from the Indian Ocean. The climate would have been much warmer and wetter than today, and more typical of tropical to subtropical regimes (Churchill, 1973). Marine deposition extended onto the coastal plains in two depositional episodes; Paleocene – Early Eocene and Middle–Late Eocene. Sea level was about 300 m above the present-day level in the Middle–Late Eocene.

Marine deposits of Cretaceous and younger age in the Eucla Basin indicate that a westward-opening gulf existed along Western Australia's southern margin in the Cretaceous, prior to complete separation of Antarctica and Australia in the Eocene (McGowran, 1973, 1978). Fed by warm Indian Ocean waters, this gulf would have had a significant effect on the climate of southern Australia by producing summer storms that penetrated far inland (Kemp, 1978).

Inland, a well-developed drainage system (van de Graaff et al., 1977) was active over a land surface that developed in the Late Cretaceous or Paleocene (Fig. 5). The drainages were active prior to the Late Eocene, and significant flow ceased before the Late Miocene. They are outlined by undulating duricrust surfaces and by chains of playa lakes. Some drainage is now internal but, when active, all the networks drained externally. The present internal drainages were shown by van de Graaff et al. (1977) to have been affected by a gentle Cainozoic epeirogeny after they became inactive.

Extensive silcrete and ferricrete developed approximately coevally (van de Graaff, 1983) during the Middle to Late Eocene, although in some areas duricrusts were formed earlier. Van de Graaff et al. (1977) and Jackson and van de Graaff (1981) argued that ferricrete and silcrete in the interior of Western Australia developed while the major drainage systems were active. This gives a period of formation that spanned the Early Cainozoic, and may have extended from Late Cretaceous to Early Miocene. Twidale et al. (1985) suggested that the earliest of the Hamersley Surfaces (their 'upland surface', stripped in the Eocene) contained pockets of pisolitic iron that could be remnants of a pre-Eocene laterite surface.

Deposits in the major palaeodrainages of Western Australia are primarily Eocene, and are little dissected except in the Pilbara area. Adjacent to the Pilbara, Late Eocene limestone in the Carnarvon Basin contains numerous ferruginous pisoliths, but younger units do not. This suggests that Western Australia as a whole was beginning to dry out in the Late Eocene, and that major drainages in the interior mostly had stopped flowing regularly by the latest Eocene. However, Oligocene ferricrete and silcrete on the west coast (Hocking et al., 1987) and in the Pilbara (Butt, 1985) indicate a seasonally moist climate.

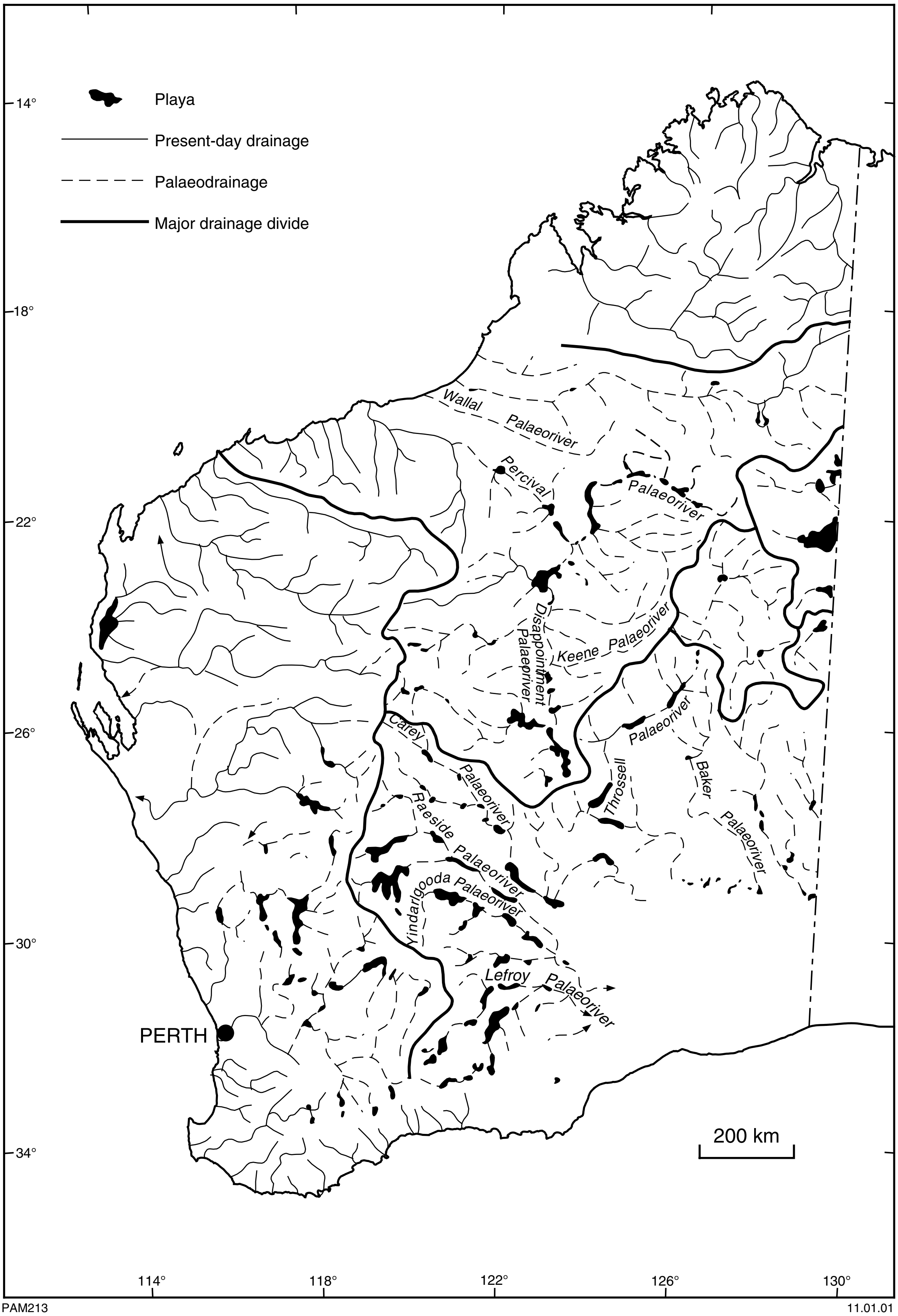


Figure 5. Palaeodrainage systems in Western Australia. Modified after van de Graaff et al. (1977)

Middle Cainozoic

Circum-polar circulation of ocean water was initiated during the Oligocene as Australia continued to move further northward, away from Antarctica (Kemp, 1978). This drift continued during the Miocene. This, and the growing Antarctic ice cap, caused a deterioration to a more seasonally extreme climate with significant variations in temperature. The southern half of Australia became increasingly arid as general levels of precipitation decreased and temperatures fell. The last major transgression to affect near-coastal areas took place in the Middle Miocene, when marine limestones were deposited in the Carnarvon and Eucla Basins. In the Late Miocene, the climate became even cooler, though still temperate, as the Antarctic ice-sheet extended 300 to 400 km beyond its present limits (Kemp and Barrett, 1975). The Late Miocene cooling was short-lived, and temperatures in the Southern Ocean subsequently increased rapidly.

Late Cainozoic (Pliocene and Quaternary)

The climate of the Pliocene is less well known. The sparse data on the prevailing continental climate appear to indicate increasing desiccation (Bowler, 1976; Galloway and Kemp, 1977). We infer that much pedogenic calcrete development took place at this time. Other depositional episodes that probably occurred in the Pliocene are the widespread lacustrine carbonates of the Lawford Formation (Kimberley) and the Nadarra Formation (Carnarvon Basin), which developed in stagnant drainages, and the consolidated eolian sands and soils at the top of Kennedy Range and similar plateaus, which pre-date the present dissection of the plateaus.

During the Early to Middle Pleistocene the climate seems to have been predominantly dry (Galloway and Kemp, 1977), although slightly wetter periods, when the climate was not very different from the climate of today, are inferred from palaeosols in the coastal Tamala Limestone sequence. Periods of alternating aridity and humidity were caused largely by glacial maxima and minima. Near the coast, exposure of the continental shelf during glacial periods resulted in extensive, thick, coastal dunes. Remnants of inland dune fields are preserved locally. Calcrete formation continued, as did dissection of pre-existing calcrete surfaces.

In the Late Pleistocene (c.800 000–40 000 years BP) conditions were marginally drier and probably cooler than today. In eastern Australia there are indications of eolian activity at 300 000 and 120 000 years BP (Bowler, 1976), although the extent of activity and degree of aridity is less than in the period between 25 000 and 13 000 years BP; dunes were presumably also active in Western Australia. Wyrwoll (1979) considered that aridity in central coastal areas may have begun about 80 000 years BP. Extensive alluvial deposition occurred in a flood-dominated, arid environment in the Geraldton area between 80 000 and 40 000 years BP (Wyrwoll, 1984).

The period from 40 000 to 30 000 years BP represents the onset of the last major glacial advance, during which southern Australia experienced a significantly wetter climate. Regolith processes are dominated by both high water levels in lakes and increased fluvial activity.

The last period of significant activity of dunefields was during the last glacial maximum, between 25 000 and 15 000 years BP (Bowler, 1976; Wyrwoll, 1979). Maximum aridity was between 17 500 and 16 000 years BP, when lakes dried completely, lunette development around playas was completed, and the major unconsolidated dunefields of Western Australia developed (Bowler, 1976).

Conditions generally remained dry between 15 000 and 10 000 years BP, but precipitation increased slightly as temperatures slowly rose (Bowler, 1976). This period is essentially transitional between the earlier intense arid conditions and later humid conditions nearer to those of today. About 10 000 years BP, temperatures were slightly higher and rainfall was substantially higher than today. This peak was followed by drier conditions culminating in today's climate.

Rognon and Williams (1977) disagreed slightly with Bowler's (1976) chronology by placing maximum aridity between 17 000 to 12 000 years BP, but they confirmed the general sequence. Wyrwoll (1979) noted that the climatic record for the period from 10 000 years BP to the present is very incomplete. He suggested that from 7400 to 6000 years BP the northwest underwent a humid phase, with higher rainfall than today. Between 6000 and 4500 years BP there was an arid phase in the southwest. In the extreme southwest there was higher rainfall between 6000 and 5000 years ago, followed by drier conditions until 2500 BP.

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Appendix

Glossary

alluvium	unconsolidated detrital deposit formed in a stream or floodplain; deposited by a stream or running water (adj. alluvial)
black soil	grey to black clayey and silty soil, commonly with expansive clays; may have a gilgai pattern
breccia	a coarse-grained clastic rock composed of angular, broken rock fragments, either cemented or with a matrix
calcrete	calcareous duricrust
chemical rock	formed by precipitation; non-clastic; <50% detritus
coastal	located at or near the coast
colluvium	a) loose soil or rock fragments deposited by mass wasting at the base of a steep slope; b) alluvium deposited by runoff and sheet erosion at the base of a slope
debris	loose material detached from rock masses by chemical or mechanical means, consisting of rock fragments, soil material and sometimes organic matter
deflation	removal of clay- and silt-size particles by wind action. A form of wind erosion
detritus	loose material derived by mechanical erosion from older rocks and moved from its place of origin (adj. detrital)
duricrust	hard layer in the soils of semiarid climates formed by precipitation; see also ferricrete, silcrete, and calcrete
eluvium	a) fine soil deposited by wind; b) weathering residue (adj. eluvial)
eolian	transported and deposited by wind
erosional	pertaining to or produced by erosion
estuarine	deposited in estuaries
ferricrete	ferruginous duricrust
fluvial	produced by the action of a stream or river
gibber	stony/pebbly plain, commonly formed by deflation
gilgai	microrelief associated with expansive clays
lacustrine	formed in a lake, on a lake margin; or a region characterized by lakes
mangrove swamp	marine swamp characterized by mangrove vegetation
marine sediments	dominated by marine processes or provenance
mass wasting	down-slope transport of material by gravity; not dominated by water
regolith	layer or mantle of loose, non-cohesive or cohesive rock material comprising rock wastes of all sorts
relict	surviving landform, after decay and disintegration
residual	a) feature remaining after erosion; b) material left after weathering
residue	accumulation of rock debris formed by weathering, essentially in place, with soluble components removed (syn. residuum)
rubble	loose mass of angular rock fragments, commonly overlying outcropping rock; the unconsolidated equivalent of a breccia
sandplain	sand-covered plain of uncertain, or mixed eolian and residual, origin
scree	loose talus; loose fragmental material lying on or mantling a slope
sheetwash	material transported by the water of a sheetflood
silcrete	siliceous duricrust
talus	loose rock fragments at the base of a steep slope, deposited chiefly by gravitational falling, rolling or sliding
transported	carried by natural agents

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