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A CLASSIFICATION SYSTEM FOR REGOLITH IN WESTERN AUSTRALIA — AN UPDATE

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

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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A classification system for regolith in Western Australia — an update

by

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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 the Commonwealth Scientific and Industrial Research Organisation (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.

This update presents additions to primary, secondary and tertiary regolith codes, and information dealing with the storage of regolith codes in digital databases.

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 (Jackson, 1997). On Geological Survey of Western Australia (GSWA) maps, both superficial sediments and duricrust have been identified as separate regolith units. Duricrust in Western Australia is most commonly calcrete, silcrete, or ferruginous duricrust (such as ferricrete or lateritic residuum, often referred to as 'laterite') as defined by Anand and Paine (2002) and Eggleton (2001); see also the Appendix and Figure 1. There are few discussions of the regional extent and composition of regolith in Western Australia, apart from the comprehensive treatment of Yilgarn regolith by Anand and Paine (2002). This current Record is an expanded and updated version of Hocking et al. (2001), which discusses a classification system for regolith in Western Australia.

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) described and classified regolith according to its composition and position in an idealized landscape profile, and differentiated three major regimes: Residual,

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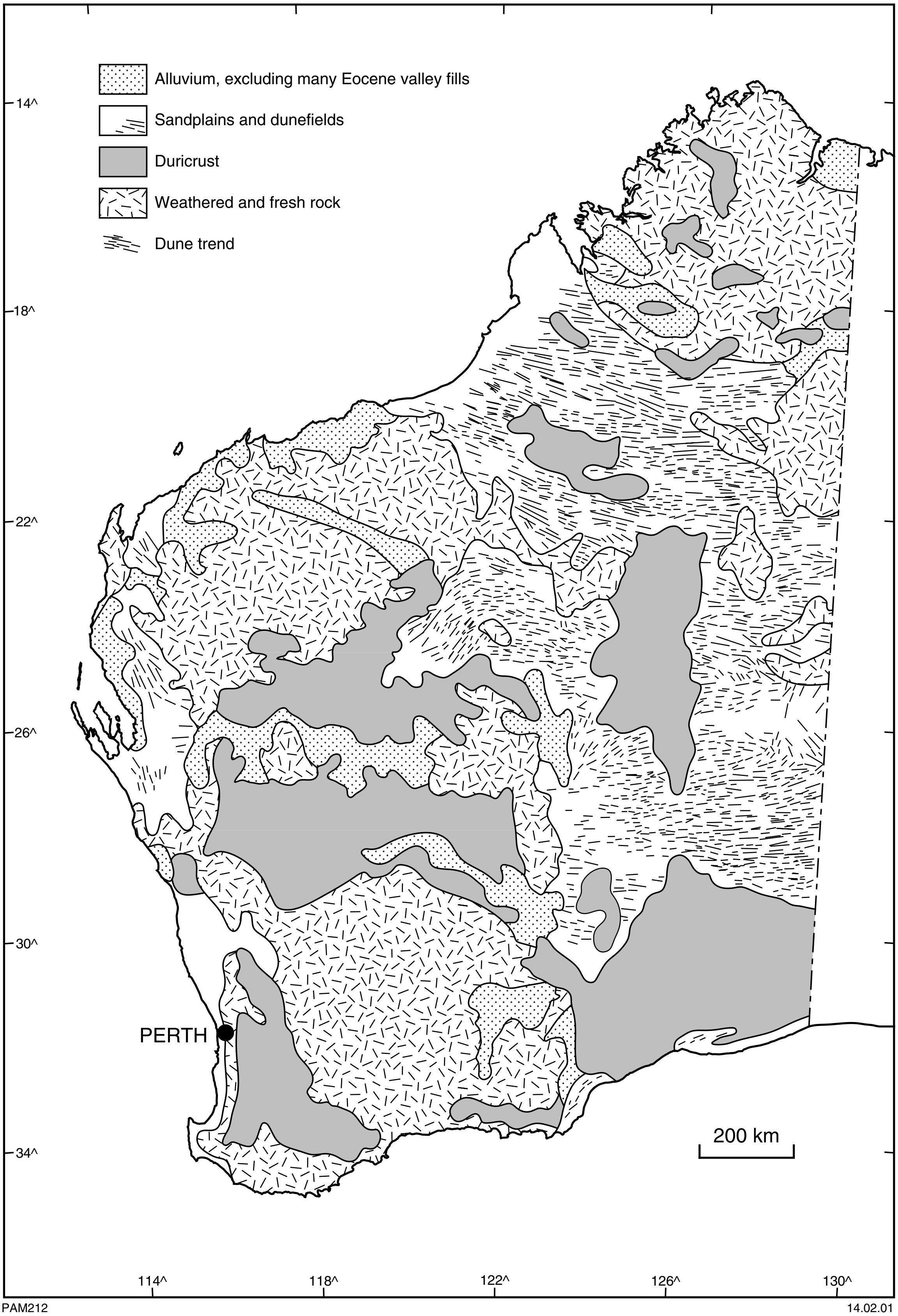


Figure 1. Generalized distribution of duricrust (ferruginous, siliceous, and calcareous), alluvium, eolian deposits, and weathered and fresh bedrock in Western Australia. After Hocking and Cockbain (1990, fig. 6-1)

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

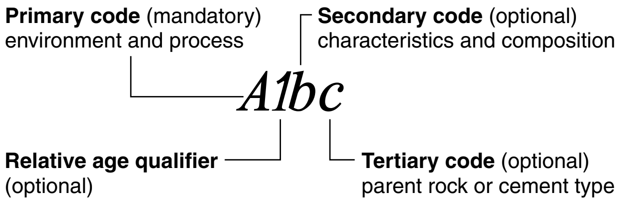
Regime	*Characteristics*	*Examples*
Residual	Remnant, reworked, or degraded materials derived from, and situated on, an ancient weathered land surface	Sand above granitic plateaus, duricrust-capped mesas, and siliceous cappings on the edges of breakaways
Erosional	Areas of erosion and removal of material 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. Depositional deposits can be many metres thick	Sheetwash plains, colluvial fans, saline playas, sandplains, and drainage channels

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 imagery, 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 landform (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 or the Terrane Custodian (Regolith).

GSWA produces an increasing number of products in digital form, and digital databases have taken on more importance. As such databases cannot store certain character attributes (including subscripted codes and italic characters), and some codes are used in both regolith and lithostratigraphic nomenclature (e.g. ‘A’ as a primary regolith code, and an Archaean age qualifier in lithological coding), it has been necessary to develop a system for unambiguous database storage of map codes. In Tables 2–5, each code is shown with its equivalent database code. To distinguish a regolith code from a lithostratigraphic code, the former is prefixed by an underscore (‘_’), and non-subscripted codes are prefaced by a hyphen (‘-’). Codes qualified by a subscript are not separated. For example, iron-rich alluvium, *Af*, has the database code _A-f, whereas an alluvial fan deposit (A_f) has the database code _Af. An Archaean felsic volcanic rock is database coded as

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 sheetflood) 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 freshwater 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

Af. Residual, iron-cemented pyritic carbonaceous material (i.e. $R_i r_y i$) is coded _Ri-ry-i in the database.

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 the Appendix 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. Residual or relict (*R*), exposed (*X*), and depositional (*D*) follow Anand et al.'s (1993a,b) RED scheme. The expansion of depositional (*D*) into nine codes corresponds broadly to the types of transported regolith found on GSWA maps.

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).

Landform code qualifiers

Optional subscripts can be used to achieve greater discrimination or precision for primary codes. The

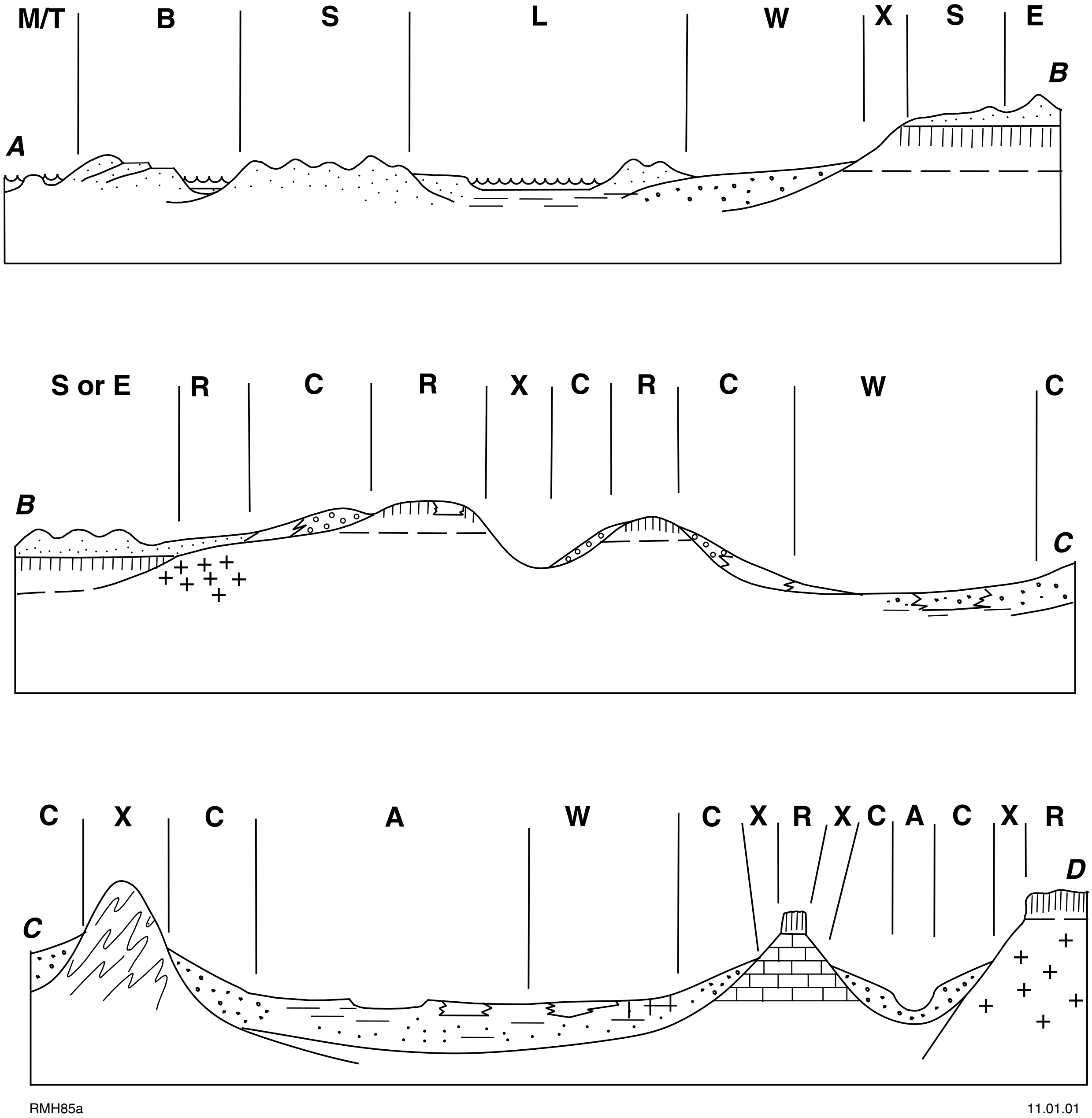


Figure 2. Diagrammatic relationships of regolith units in Western Australia, showing likely primary regolith codes (as listed in Table 2)

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 sandbars (A_s) and gravel bars (A_g) on the basis of their morphology as well as grain size. Some code subscripts are based on McDonald et al. (1990), whereas others are from Pain et al. (in prep.).

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 (but see Pillans, 1998a,b), absolute age

Table 3. Landform (primary code) qualifiers

Primary landform or process	*Landform element or pattern*	*Primary code, and subscript code*	*Database code*
Residual or relict		**R**	**_R**
	In situ weathered (residual)	R_i	_Ri
	Duricrust (residual or relict)	R_r	_Rr
	Sand (residual or relict)	R_s	_Rs
	Transported (relict)	R_t	_Rt
Exposed		**X**	**_X**
	Erosional plain (<9 m relief)	X_p	_Xp
	Rise (9–30 m relief)	X_r	_Xr
	Low hill (30–90 m relief)	X_l	_Xl
	Hill (>90 m relief)	X_h	_Xh
	Escarpment	X_e	_Xe
	Badlands	X_b	_Xb
Colluvium (proximal slope)		**C**	**_C**
	Colluvial fan	C_a	_Ca
	Cliff-foot slope	C_c	_Cc
	Pediment	C_e	_Ce
	Footslope	C_f	_Cf
	Rejuvenated pediment	C_j	_Cj
	Landslide	C_l	_Cl
	Scarp-foot slope	C_s	_Cs
	Talus	C_t	_Ct
Low-gradient slope (sheetflood, distal slope)		**W**	**_W**
	Transitional zone between pediment and transported regolith	W_e	_We
	Sheetflood fan	W_f	_Wf
	Playa, pan	W_p	_Wp
	Scarp-foot slope	W_s	_Ws
Alluvial		**A**	**_A**
	Alluvial plain	A_a	_Aa
	Stream bed	A_b	_Ab
	Stream channel	A_c	_Ac
	Drainage depression/swale	A_d	_Ad
	Delta	A_e	_Ae
	Floodplain	A_f	_Af
	Gravel bar	A_g	_Ag
	Channel bench	A_h	_Ah
	Floodplain with numerous claypans	A_i	_Ai
	Stream bank	A_k	_Ak
	Levee	A_l	_Al
	Meander plain	A_m	_Am
	Backplain	A_n	_An
	Playa, pan	A_p	_Ap
	Stream bar	A_r	_Ar
	Sandbar	A_s	_As
	Terrace	A_t	_At
	Superficial channel	A_u	_Au
	Fan/flood-out	A_v	_Av
	Swamp	A_w	_Aw
	Oxbow	A_x	_Ax
	Ovoid depression in eolian sandplain	A_y	_Ay
Lacustrine		**L**	**_L**
	Fringing dunes	L_d	_Ld
	Freshwater lake deposits	L_f	_Lf
	Fringing bedded deposits	L_g	_Lg
	Lake, excluding fringing deposits	L_l	_Ll
	Dune and playa terrain	L_m	_Lm
	Playa	L_p	_Lp
	Saline lake	L_s	_Ls
	Swamp deposits around lakes	L_w	_Lw
	Subcropping bedrock in lake	L_x	_Lx
Eolian		**E**	**_E**
	Parabolic dunefield	E_a	_Ea
	Blow-out	E_b	_Eb
	Dunefield	E_d	_Ed
	Dune	E_e	_Ee

Table 3. (continued)

Primary landform or process	*Landform element or pattern*	*Primary code, and subscript code*	*Database code*
	Longitudinal dunefield	E_l	_El
	Mobile dune	E_m	_Em
	Net-like dunefield	E_n	_En
	Sand and playa terrain	E_p	_Ep
	Sandplain overlying alluvial-playa plain	E_s	_Es
	Lunette	E_u	_Eu
	Interdune pavements	E_v	_Ev
	Swampy swale	E_w	_Ew
	Stabilized dune	E_z	_Ez
Sandplain; residual, uncertain, and mixed origin		**S**	**_S**
	Blow-out	S_b	_Sb
	Dune	S_d	_Sd
	Gravel deflation pavement	S_g	_Sg
	Longitudinal dunefield	S_l	_Sl
	Net-like dunefield	S_n	_Sn
	Sand and playa terrain	S_p	_Sp
	Undulating	S_u	_Su
Coastal (wave-dominated)		**B**	**_B**
	Beach (foreshore and backshore)	B_b	_Bb
	Cliffs	B_c	_Bc
	Foredune	B_d	_Bd
	Foreshore	B_f	_Bf
	Backshore	B_k	_Bk
	Back-barrier lagoon	B_l	_Bl
	Mobile dunes	B_m	_Bm
	Boulder beach	B_o	_Bo
	Beach ridge plain	B_r	_Br
	Storm beach gravels	B_s	_Bs
Coastal (tide-dominated)		**T**	**_T**
	Tidal bar, in channel	T_b	_Tb
	Tidal channel (subtidal base)	T_c	_Tc
	Tidal delta	T_d	_Td
	Estuary	T_e	_Te
	Tidal flat (intertidal and supratidal)	T_f	_Tf
	Chenier plain	T_h	_Th
	Intertidal flat	T_i	_Ti
	Lagoon	T_l	_Tl
	Mangrove flat	T_m	_Tm
	Superficial channel (intertidal)	T_s	_Ts
	Supratidal flat	T_u	_Tu
Marine		**M**	**_M**
	Coral reef	M_c	_Mc
	Shell bank	M_k	_Mk
	Plain, nearshore	M_n	_Mn
	Plain, offshore	M_p	_Mp
	Reef flat, backreef, or rock flat	M_r	_Mr
	Shoreface	M_s	_Ms
	Talus slope or footslope	M_t	_Mt
	Relict channel	M_v	_Mv

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 units 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, at least during the early stages of mapping, how many generations are present. In this situation, if the youngest deposit is given the highest

Table 4. Secondary codes and qualifiers for regolith composition

Secondary code	*Composition*	*Composition qualifier*		*Database code*
c	clay	c_b	black soil or gilgai	-cb
		c_c	chlorite	-cc
		c_g	glauconite	-cg
		c_k	kaolin	-ck
		c_i	illite	-ci
		c_m	montmorillonite	-cm
		c_s	smectite	-cs
d	undivided			-d
e	evaporite	e_a	anhydrite	-ea
		e_g	gypsum	-eg
		e_h	halite	-eh
f	ferruginous	f_g	gossan	-fg
		f_h	hematite	-fh
		f_l	limonite	-fl
		f_o	goethite	-fo
g	quartzofeldspathic			-g
h	heavy mineral	h_a	apatite	-ha
		h_g	garnet	-hg
		h_i	ilmenite	-hi
		h_l	leucoxene	-hl
		h_m	magnetite	-hm
		h_o	monazite	-ho
		h_r	rutile	-hr
		h_z	zircon	-hz
k	carbonate	k_a	aragonite	-ka
		k_c	calcite	-kc
		k_d	dolomite	-kd
		k_m	magnesite	-km
l	heterogeneous			-l
m	ferromagnesian			-m
q	quartz			-q
r	carbonaceous/organic	r_c	coal	-rc
		r_h	humus	-rh
		r_p	peat	-rp
		r_y	pyritic	-ry
t	lithic (rock fragments)			-t
u	ultramafic			-u
w*	weathered			-w
x	other mineral	x_a	aluminous/bauxite	-xa
		x_i	mica	-xi
		x_m	manganese	-xm
z	siliceous	z_o	opaline	-zo

NOTE: * 'w' can also be used as a subscript qualifier for all secondary codes

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 that 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.

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

Code	*Parent rock or cement*	*Qualifier*	*Database code*
a	aluminous cement		-a
c	chemical or biochemical sedimentary deposit	c_c chert	-cc
		c_d dolomite	-cd
		c_i iron formation	-ci
		c_l limestone	-cl
		c_t diatomite	-ct
g	glacial deposit		-g
i	iron cement		-i
k	carbonate cement		-k
l	heterogeneous		-l
m	metamorphic	m_n gneiss	-mn
		m_p pelite	-mp
		m_m psammite	-mm
		m_q quartzite	-mq
		m_s schist	-ms
o	fossiliferous		-o
p	plutonic	p_a alkali granite	-pa
		p_d diorite	-pd
		p_r gabbro	-pr
		p_g granite	-pg
		p_m monzogranite/monzonite	-pm
		p_o granodiorite	-po
		p_s syenogranite/syenite	-ps
		p_t tonalite	-pt
r	duricrust		-r
s	siliciclastic sedimentary rock	s_c conglomerate	-sc
		s_m mudstone, siltstone, shale	-sm
		s_s sandstone, arenite, wacke	-ss
u	ultramafic	u_d dunite	-ud
		u_k komatiite	-uk
		u_p peridotite	-up
		u_y pyroxenite	-uy
		u_s serpentinite/talc rock	-us
		u_t talc carbonate	-ut
v	volcanic	v_a andesite	-va
		v_b basalt	-vb
		v_d dacite	-vd
		v_r rhyolite	-vr
		v_t trachyte	-vt
		v_v volcaniclastic	-vv
w*	weathered	w_p saprolite	-wp
		w_r saprock	-wr
z	silica cement		-z

NOTE; * 'w' can also be used as a subscript qualifier for all tertiary codes

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. When a mapsheet comprises regolith units of both known and undetermined age, the latter are placed above the former in the map legend.

- Designating the relative age of regolith is restricted to the primary regolith code, which also avoids generation of excessively complex codes. For example, L_d1 and L_d2 can be used to designate younger and older dune deposits, fringing a lake system. Alternatively, $L1_d$ and $L2_m$ indicate that an older dune and playa terrain is found with younger fringing dune deposits. Two residual or relict carbonate units of different relative age are coded *R1k* and *R2k*.

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 code), and parent rock or cement type (tertiary code), 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 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 (with the appropriate database codes) are given below:

Akk (_A-k-k)	Carbonate-cemented calcareous alluvium (groundwater/phreatic calcrete, generally abbreviated to *Ak*)
A_pc (_Ap-c)	Claypan in alluvial system
Bh_z (_B-hz)	Heavy mineral-rich beach deposit (principally zircon)
Le_g (_L-eg)	Lacustrine deposit with evaporitic gypsum
Amv_b (_A-m-vb)	Alluvium derived from ferro-magnesian volcanic rock (basalt) fragments.

Note that 'w' is available as a qualifier for both secondary and tertiary codes, and as a tertiary code alone, to indicate weathering. The predominant usage of 'w' as a subscript is in areas of erosional regolith:

X_ld_w (_Xl-dw)	Low hill or rise of (undivided) weathered rock
X_bgp_w (_Xb-g-pw)	Badlands, composed of weathered granite

As a tertiary code, 'w' can be qualified to indicate the intensity of weathering:

X_rdw_p (_Xr-d-wp)	Rise of (undivided) saprolite
Xgw_r (_X-g-wr)	Quartzofeldspathic saprock.

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 materials 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 either that the nature of the regolith is unknown through direct observation (e.g. undivided colluvium is *Cd*), or that the unit is variable over a significant area (e.g., residual unit comprising both siliceous and ferruginous duricrust).

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. For these, 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 (Gradstein et al., 2004a,b), Tertiary is generally no longer used. Instead, Quaternary, Neogene and Palaeogene are used where a more precise age than Cainozoic is possible. The series is used after an 'N' or 'E' prefix to further proscribe the age, thus: *Q* Quaternary, *Ni* Pliocene, *Nm* Miocene, *Eo* Oligocene, *Ee* Eocene, and *Ep* Paleocene. The mnemonic letters for named units follow the scheme presently being introduced for rock units on GSWA maps and datasets, with a two letter capitalized code for a group, followed by a single letter code for a constituent formation (e.g. QKWt-kl on the map face, Q-KWt-kl in the database for the Tamala Limestone of the Kwinana Group), or a two letter code preceded by an underscore for an ungrouped formation (e.g. Qro-kl on the map face, Q-_ro-kl in the database for the Roe Calcarenite), and a trailing code separated by a hyphen for lithology, as shown above.

Regolith units derived from named rock units are locally distinguished on GSWA maps. In such cases, the code letter used for the formation can be used as the Tertiary code, analogous to the 'parent rock or cement', to indicate the specific named derivation. For example, colluvium derived from the Pallinup Formation (itself coded as Ee-PLp-sl) could be coded as _C-t-PLp (data code) and *Ct-PLp* (mapcode) if composed of fragments, or C-d-PLp and *Cd-PLp* if a more general code was sought. Limonitic wash from the Robe Pisolite (EN-_rb-cip) could be _W-fl-_rb and Wf_l*-rb*. Potential ambiguity is avoided by the description in the map reference, and in the corresponding narrative field of the database.

Regolith stratigraphy

This system for regolith classification is largely descriptive and does not rely on an interpretation of age, but an

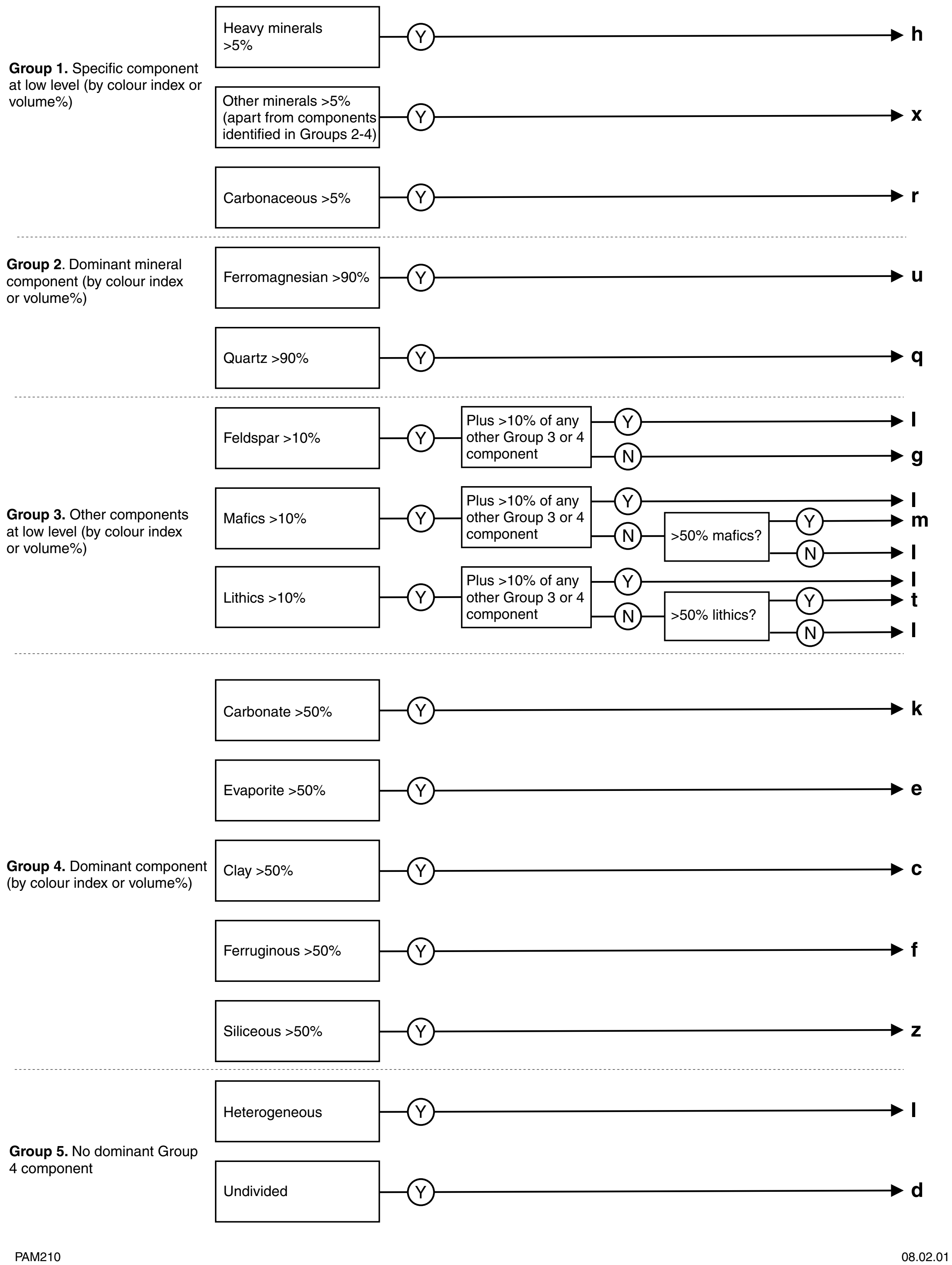


Figure 3. Selection of secondary codes (Y = yes, N = no)

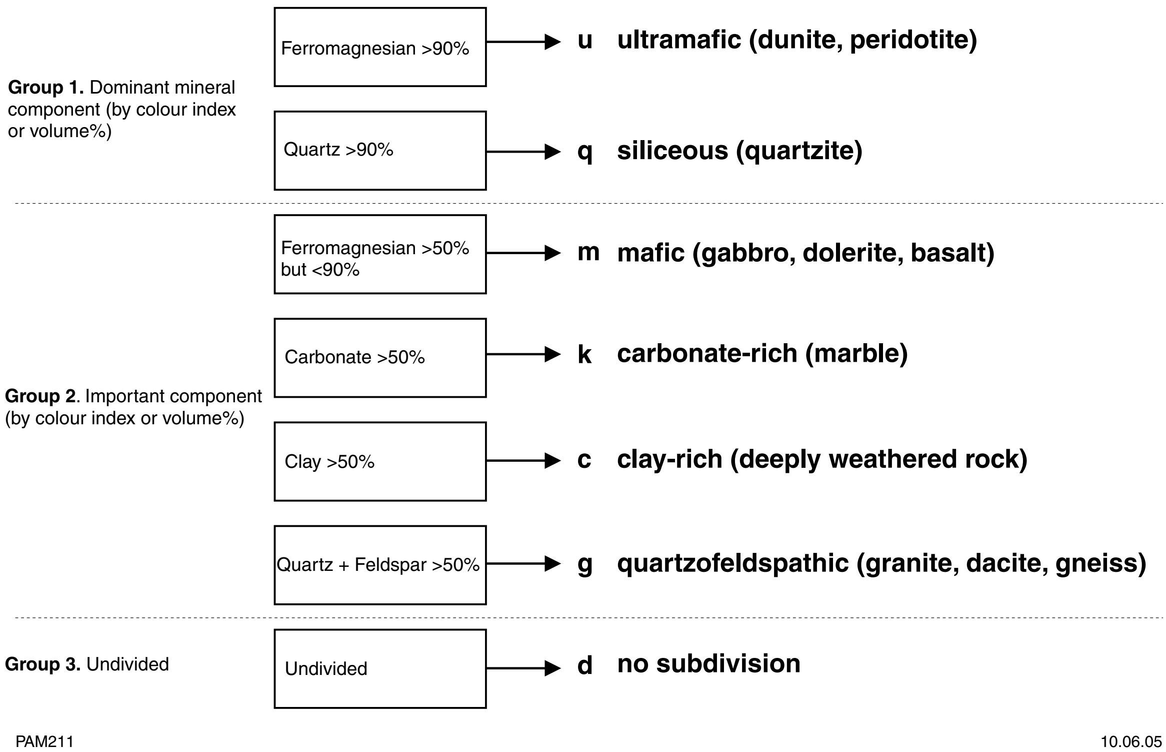


Figure 4. Selection of secondary codes for exposed regolith (*X*) derived from igneous and high-grade metamorphic rocks

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 (1998b) 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 (1978) used climatic models derived from sea-surface temperatures, land and sea positions, and the 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. Playford (2001) argued that the distribution of glacial landforms showed that much of Australia and parts of Gondwana were covered by thick ice sheets during the Early Permian.

Table 6. Summary of climatic and regolith changes from the Mesozoic to the present day. Absolute ages based on Gradstein et al. (2004b)

Age	*Climate*	*Regolith events*
Cretaceous (65–145 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
Late Oligocene – 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 dunefields 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

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 age in the Bight Basin and Cainozoic age in the overlying 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). Clarke et al. (2003) have carried out a detailed study into the Eocene stratigraphy of the Eucla, Bremer, and Polda Basins in Western and South Australia. They argued for a single depositional basin (which they termed the Eucla Basin) whose Eocene sediments were deposited in two transgressive episodes. Terminology here follows Bradshaw et al. (2003), who rationalized basin nomenclature in Western and South Australia, placed Mesozoic sediments in the Bight Basin and Cainozoic sediments in the Eucla Basin, and included the Cainozoic sediments of the Bremer Basin in the Eucla Basin.

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.

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

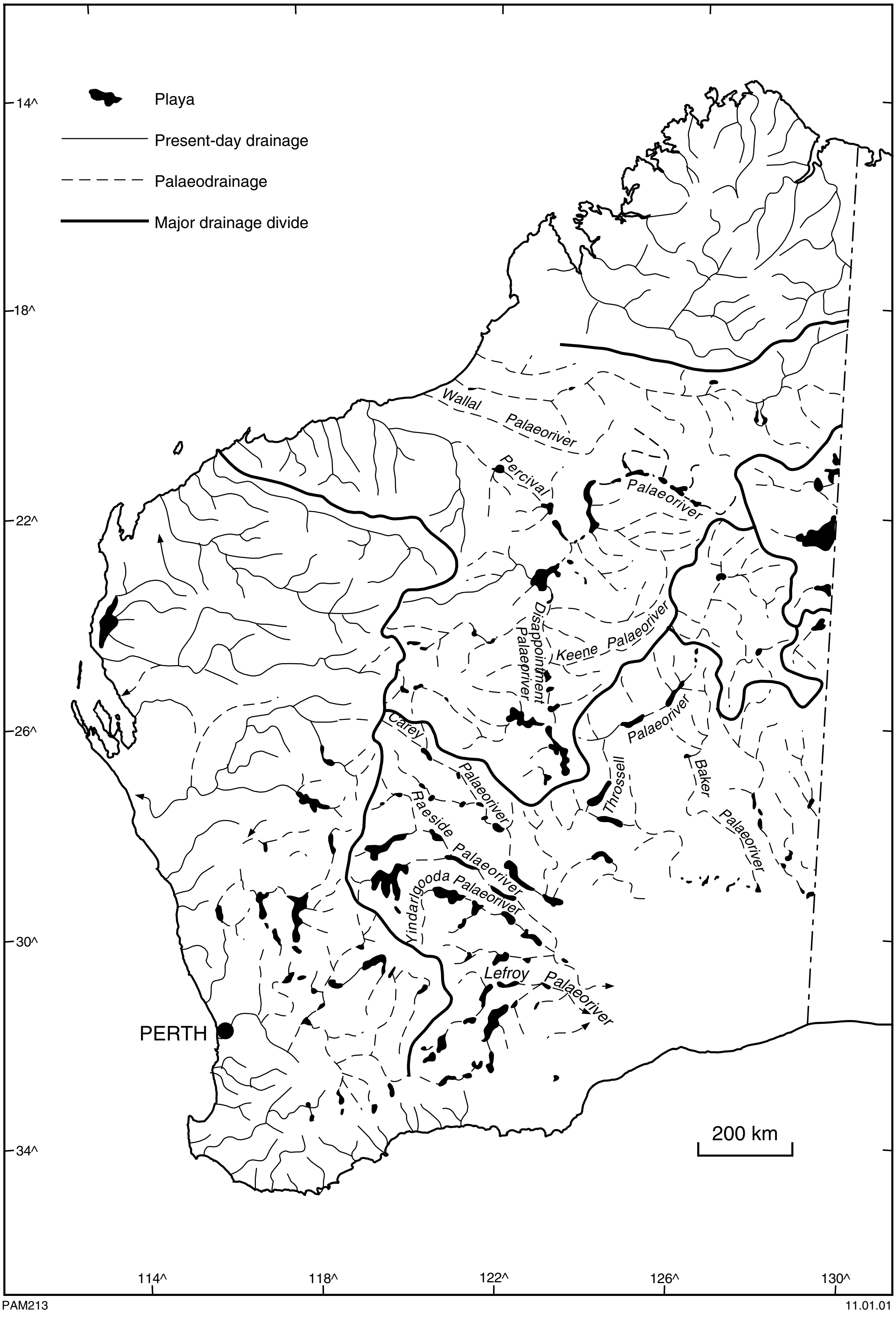


Figure 5. Palaeodrainage systems in Western Australia. Modified after van de Graaff et al. (1977)

dunes. Remnants of inland dunefields 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
calcrete	calcareous duricrust. Regolith carbonate accumulations, comprising variably cemented aggregates largely composed of calcium carbonate, but also including dolomite or magnesite.
coastal	located at or near the coast
colluvium	heterogeneous material of variable particle size (soil with or without rock fragments) accumulated on the lower parts of slopes. Transported by gravity, creep, sheetwash, rainwash, mudflows or solifluction
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	regolith material indurated by a cement, or the cement only. Includes silcrete, ferricrete, lateritic duricrust, calcrete, gypcrete, manganocrete, dolocrete, salcrete or a combination of these
eluvium	regolith originating in the place where found (in situ regolith)
eolian	transported and deposited by wind
erosional	pertaining to or produced by erosion
estuarine	deposited in estuaries
ferricrete	material formed by the in situ cementation of regolith by mainly goethite and hematite
fluvial	produced by the action of a stream or river
gibber	stony or pebbly plain, commonly formed by deflation
gilgai	microrelief associated with expansive clays, characteristically with a crabhole texture
hardpan	hard or impervious layer in the regolith lying at or near the surface. Resulting from cementation of soil particles by precipitation of mainly silica, with some iron oxide and carbonate
lacustrine	formed in a lake, on a lake margin; or a region characterized by lakes
lake	any inland body of water occupying a depression in the Earth's surface
laterite	regolith showing the character of all or the upper part of a laterite profile. Usually preserved as a hard commonly ferruginous surface characterized by variable colouring due to the distribution of iron and silica. An often abused term which should be used broadly and informally
mass wasting	downslope transport of material by gravity; not dominated by water
mottle	segregation of subdominant colour different from the surrounding region's colour
pediment	gently inclined to level landform pattern of extremely low relief, commonly with a thin veneer of detritus underlain by bedrock, characteristically lying downslope from adjacent hills with markedly steeper slopes
pisolith	spherical or ellipsoidal body resembling a pea in shape and limited in size between 2 and 64 mm in diameter. May have a concentric internal structure and/or a cortex or skin
playa	vegetation-free, flat area at the lowest part of an undrained desert basin, commonly underlain by stratified clay, silt, or sand, and in many places by soluble salts, but in places underlain by a rock surface that has minimal sedimentary cover. Dry most of the time
regolith	layer or mantle of loose, noncohesive 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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