GEOCHEMICAL DISPERSION, PROCESS AND EXPLORATION MODELS

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INTRODUCTION

The surface geochemical signature of each mineral deposit is always unique in some respects, due to differences in geological, geomorphological and environmental settings. Nevertheless, many similarities in dispersion characteristics may be displayed over extensive regions, either generically, for many commodities, or more specifically, for one commodity. These similarities are best portrayed and synthesized in the form of conceptual process and methodological models that represent data and interpretations of relevance to geochemical exploration (Bradshaw, 1975). Such models attempt to illustrate the spatial (and genetic) relationships between geochemical dispersion processes and the formation and evolution of regolith, landforms and landscapes, and to apply these to the optimization of exploration procedures. Ideally, it should be possible to use such models productively when planning surveys to anticipate mechanisms of dispersion, to select appropriate sample media and to estimate the nature and significance of anomalies. Correctly applied, they may serve to direct, supplement or replace orientation surveys – the last option an important factor in exploration in covered, poorly known terrain, or for new styles of mineralization.

Thus, the geochemical models are intended to illustrate the nature and origin of the surface expression of mineralization. In regolith-dominated terrains, as in much of Australia, they must account for relict features as well as active processes. To be valid, and useful, they must:

- Provide systematic, summarized descriptions of geochemical dispersion in a regolith-landform context.
- Indicate the nature of geochemical anomalies - element associations, dispersion mechanisms and host materials.
- Indicate appropriate exploration procedures - sample media, sampling intervals, analysis and interpretation.

MODEL SYSTEM AND CLASSIFICATION

Model system

Secondary geochemical dispersion patterns associated with bedrock mineralization are the cumulative product of the successive weathering episodes under differing climatic regimes. The broad effects of this weathering history are recorded in the landforms and regolith, hence these form an appropriate basis for describing and interpreting the patterns. The models are based on the premise that bedrock over much of Australia has been subjected to deep weathering, under humid, probably warm, sub-tropical to tropical conditions. The resultant regolith has been preserved, or partially to wholly eroded during later weathering episodes, which, over much of the continent, have been much drier. The models are defined and classified according to relief, the degree of development or preservation of the deeply weathered regolith and the effects of later physical and chemical modifications under changed environmental conditions including, importantly, the presence of transported overburden or other cover sequences. This scheme, in effect, assumes that the landscape evolved in two or three stages, which is clearly a gross oversimplification. Some areas of the Precambrian shields have been exposed to sub-aerial weathering since at least the late Proterozoic (Daniels, 1975; Butt, 1989), and much of the continent since the late Mesozoic (See: Weathering History, this volume). During these long periods of exposure, there were several significant changes in climate and weathering conditions, so that very different dispersion processes have operated at different times. In general, however, only the most extreme, longest-lasting or currently active climatic episodes will have had significant impacts on geomorphology, regolith formation and geochemical dispersion. The chemical modifications resulting from changes in element mobilities under recent more arid climates are commonly minor in comparison to the profound mineralogical and geochemical alterations that occurred during the early episodes of deep weathering under humid conditions. Accordingly, the influence of the earlier events, represented by the deep regolith, is paramount to understanding geochemical dispersion, although the geochemical significance of each episode of deep weathering is not known or recognized. Currently active processes are also very significant, particularly with respect to geochemical signatures in 'transient' media such as vegetation, soil and groundwater. Consequently, despite their relative simplicity, the models provide a suitable context for portraying and interpreting the geochemical expression of mineralization by highlighting the principal factors influencing element dispersion, and give a framework for comparison between terrains.

Classification of models

A model classification similar to that used by Butt and Zeegers (1992) has been adopted for this volume and is shown in Table 1, and the relationship between the models and information that may be obtained from a three-dimensional regolith-landform map is illustrated in Figure 1. Mineralization at sites having similar regolith and landform characteristics, as expressed in the models and model codes, would be expected to have a similar geochemical expression, and hence be amenable to similar exploration procedures. The criteria upon which the classification is based are as follows: -

Relief. Local and regional relief control the degree of preservation of the profile. In areas of low to moderate relief, physical erosion is mostly slow and inefficient, so that deep regoliths may develop and any pre-existing regolith may be preserved wholly or in part; geochemical dispersion tends to be dominated by chemical mechanisms, active now or in the past. Conversely, in areas of moderate to high relief, the rates of physical erosion exceed those of chemical weathering even in humid climates, precluding preservation or formation of thick regoliths. Where uplift and rejuvenation of drainage have led to the dissection of uplifted plateaux, pre-existing regoliths are rogressively eroded and destroyed. Accordingly, geochemical dispersion in these areas is dominated by currently active, and mostly physical, processes. In general, therefore, due to the reduction in the importance of chemical dispersion, both past and present, the greater the relief, the greater is the similarity in geochemical expression of mineralization, in all environments. In Australia, majority of case histories and models relate to areas of low to moderate relief.

Present climate. This governs active weathering and dispersion processes, including the formation of soil from the exposed horizons of the pre-existing regolith. The amount and seasonality of the rainfall strongly influence the degree to which the profile is modified, *e.g.,* by leaching or precipitation of introduced components. However, as relief increases and active physical erosion becomes the dominant dispersion process, the influence of the present climate declines.

Preservation of the regolith profile. This largely determines the importance of geochemical and mineralogical characteristics inherited from previous weathering episodes, for example, enrichments of Al, Fe, Ni and Au, and depletions of Na, K, Ca, Mg, Cu and Zn. It also determines the nature of the uppermost residual horizon, whether modified as soil or buried beneath transported overburden.

"A" type models are those in which the regolith profiles are fully preserved. The uppermost residual horizon is commonly ferruginous lateritic residuum, or soils developed over or from it.

"B" type models are those in which there is no lateritic residuum, because either it did not develop or the profile is partially truncated. Saprolite, with quite different geochemical characteristics from the ferruginous horizon, forms the uppermost horizon and the parent material of residual soils.

"C" type models are those in which there is no earlier regolith, either because it did not form or it has been entirely eroded. Here bedrock outcrops at surface, has residual soils forming directly from it or is buried by transported overburden.

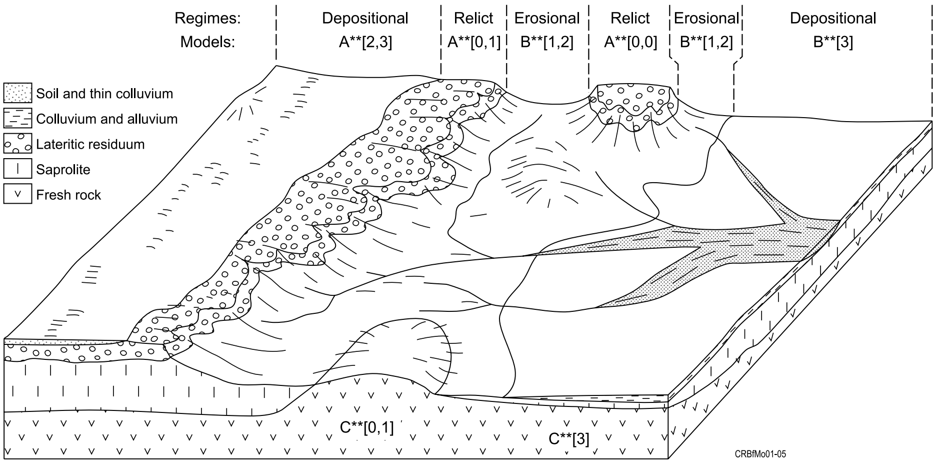


Figure 1. The relationship between mappable regolith-landform regimes and geochemical models. Model codes (see Table 1) refer to presence of lateritic regolith: A, preserved; B, partially truncated; C, absent. Surface: [0], outcrop; [1], residual soil; [2], semi-residual soil; [3], transported overburden (after Butt and Zeegers, 1992).

TABLE 1
CLASSIFICATION OF GEOCHEMICAL DISPERSION MODELS FOR TROPICALLY WEATHERED TERRAINS
(after Butt and Zeegers, 1992).

Present Climate		Savanna (seasonally humid; Aw, Cwa#)
		Rainforest (humid; Af, Am, Cwb#)
		Warm arid (BSh, BWh#)
(# Köppen classification)		
Modifications to pre-existing profile within each climatic zone.		
Pre-existing Profile	A:	Mostly preserved
	B:	Partly truncated
	C:	Fully truncated
Recent alteration	0:	Minor
	1:	Low
	2:	Moderate
	3:	Strong
Recent accumulation, cementation or neoformation	0:	None
	Al:	Al oxides
	AS:	Al silicates
	Ca:	Ca-Mg carbonates (calcrete)
	Gy:	Gypsum (gypcrete)
	Fe:	Iron oxides (ferricrete)
	Si:	Silica (silcrete)
	Sm:	Smectites
Overburden on pre- existing profile	0:	None
	1:	Residual soil
	2:	Semi-residual
	3:	Transported
Examples:		
A*Ca[0,1]:		lateritic residuum, with pedogenic carbonate; outcropping or beneath residual soil.
B*Si[3]:		truncated profile, silicified, transported overburden.
B**[3]:		buried truncated profile.

An asterisk * is used for generalized models for which a characteristic is not diagnostic or identified.

The assumption that a 'complete' profile previously existed is not critical. If it did not, and no lateritic residuum formed, B (or C) models apply, since it is the absence of the characteristics of the lateritic residuum that are important.

Recent alteration. Butt and Zeegers (1992) attempted to indicate the degree of chemical alteration that had occurred since earlier deep weathering, under the present climate or during an intermediate period, *e.g.,* due to increased leaching or to the neoformation or accumulation of secondary minerals. These alterations may be cumulative and hence produce complex geochemical responses. However, the estimate is subjective and has not been used in this volume.

Neoformation or accumulation of minerals. In some environments, the formation and accumulation of specific phases becomes significant, mainly due to changes in the degree of leaching. Examples include the formation of gibbsite in regions of high rainfall, and the retention of silica or carbonates, as silcrete and calcrete, in arid regions.

Presence and nature of overburden. The nature of the surface horizons is commonly critical in determining the most appropriate exploration sample media. There may be no overburden, so that untransformed regolith materials (*e.g.,* lateritic residuum, saprolite) or fresh bedrock may outcrop, or the overburden may be *in situ* (as residual soil), a semi-residual mixture (*e.g.,* residual soil plus aeolian silt and clay, or colluvial sheetwash), or transported (*e.g.,* alluvium, aeolian sand, talus). A distinction is made between 'transported overburden', which generally refers to sediments of continental origin (*e.g.,* colluvium, alluvium, palaeochannel sediments) and other cover rocks, whether these are part of a mineralized sequence or are later units of volcanic or sedimentary origin (*see* Transported overburden, *in* Sample Media, *this volume*). The latter are commonly thicker and more lithified than transported overburden, and may have much the same weathering history as the prospective rocks. However, the distinction is somewhat arbitrary with respect to some channel and estuarine sequences, glacial deposits and miscellaneous, poorly exposed sediments of uncertain age and origin.

The classification in Table 1 summarizes the characteristics of each deposit or prospect as a code. For example, a prospect in an arid area of low relief, model code B*Ca [1], has a truncated profile, calcrete and residual soil developed from saprolite. (N.B. The degree of recent alteration is not estimated, and the presence of recently neo-formed minerals and cements has been indicated only when specifically reported or known to exist; these fields are indicated by an asterisk if unfilled).

The relationships between landform and models are clear in Relict and Erosional regimes (Figure 1). However, in Depositional regimes, each of the principal types of dispersion model may be present beneath the transported cover but, in most cases, it will not be possible to identify them without 'stratigraphic' drilling of the regolith. Irrespective of which model applies, the most critical observation is that the sediments are present, so that surface sampling will generally be ineffective. Sedimentation may have pre-dated deep weathering, be contemporaneous with it or post-date it, so that identification of the sediments and their relationship with the different weathering phases can be very important (*see* Sample Media: *this volume*).

Commodity

Although many features are common, there are sufficient critical differences in geological settings and/or geochemical behaviours of major ore elements to derive specific models for different commodities and deposit types. Accordingly, models are proposed for Ni sulphides and PGE-Cu-Ni deposits, associated with mafic and ultramafic rocks, base metal (VMS, other volcanic/hydrothermal and sediment-hosted), Au and Cu-Au deposits (including Cu-Au-Mo porphyries). These include variants related to climate, environmental features and the nature and thickness of cover sequences. For example, for Au, distinctions are drawn between regions with non-saline and saline groundwaters and on the presence or absence of pedogenic carbonate, because these characteristics greatly influence the mobility and distribution of Au in the regolith and the nature of the geochemical expression of mineralization. There are insufficient examples to derive specific models for U deposits, although a model for calcrete U deposits is given by Deutscher *et* *al*., 1980. Similarly, many other deposit types described in the Chapter on Ore Deposits Types (*this volume*) are not represented herein by case histories, although many observation summarized in the relevant commodity model will apply.

EXPLORATION MODELS FOR NICKEL SULPHIDE AND PGE-Cu-Ni DEPOSITS

Weathering of nickel sulphides

Known Ni sulphide mineralization in Australia is dominated by komatiite-hosted (or -associated) deposits (see Ore Deposit Types, *this volume*) in semi-arid environments in the Yilgarn Craton, with potential in the Pilbara-Fortescue and Gawler Craton. Deposits in layered intrusions occur in the Pilbara, Kimberley and Musgrave Blocks. These deposits all occur in semi-arid regions that have undergone past deep weathering.

Massive and matrix sulphide deposits (pentlandite-millerite-pyrrhotite-chalcopyrite-pyrite) undergo electrochemical weathering to form, firstly, supergene sulphides (violarite-pyrite), with a moderate enrichment of Ni, and, subsequently, are further oxidized to form gossans, dominated by goethite and hematite. Towards the land surface, the gossans thin and commonly only form discontinuous, rubbly outcrop. Carbonate and sulphate minerals are present at the transition between the supergene and oxide zones, at the base of the gossan. The total depth of weathering, as indicated by supergene sulphides, may extend many tens of metres below the present water-table. Formation of the gossan involves considerable leaching of Ni. Disseminated Ni sulphide deposits undergo similar reactions, but because there is no electrical connection between individual sulphide grains, the overall depth of weathering is less. Despite strong leaching during gossan formation, there is no significant lateral dispersion of Ni into the wallrocks. Any enrichment is minor in comparison with that due to lateritic weathering of the host komatiites and is not evident in other lithologies, whether these are basalts in the footwall or felsic rocks in structurally emplaced sulphide bodies. The only other metals associated with Ni sulphide mineralization are Cu and PGE. None appears to have any significant mobility during weathering and, hence, they do not have appreciable secondary dispersion haloes in saprolite. However, they are absent in barren olivine cumulates and are generally effective indicators of mineralized rocks (*see* Gossans and Ironstones *in* Sample Media, *this volume*).

Weathering of ultramafic rocks

Olivine-rich ultramafic rocks and their serpentinized equivalents commonly form one or both wall-rocks to massive and matrix Ni sulphide deposits and are the host rocks to disseminated deposits. However, even where sulphides are absent, the regolith formed on ultramafic rocks, other than talc carbonates, is commonly strongly enriched in Ni, in places forming Ni laterites. It is generally very difficult to distinguish such lateritic enrichments, in which the Ni is derived from silicates, from those in which it is derived from sulphides. Although gossans directly intersected by drilling may be recognized, the weathered equivalents of ultramafic rocks proximal to flow units hosting massive, matrix sulphides or disseminated sulphides have very similar geochemical and mineralogical characteristics to those adjacent to barren units. Accordingly, knowledge of the characteristics of Ni laterites is essential for the interpretation of geochemical data.

Olivine, especially forsteritic olivine ($>Fo_{75}$) commonly contains 0.16-0.40% Ni (Fleet *et al.,* 1977), which accumulates in the regolith during weathering. Economically exploitable reserves of Ni are found where the weathered ultramafic rocks, principally dunite and olivine-pyroxene peridotite, outcrop over a wide area and the regolith is well preserved. The Ni concentrations generally occur in one or more horizons or units within the profile and the ores can be classified according to their mineralogy (Brand *et al.,* 1998): -

Oxide: dominated by Fe oxyhydroxides, principally goethite, forming the mid- to upper saprolite and extending to the pedolith. Manganese oxides (*e.g.,* asbolan, lithiophorite) are commonly abundant and are enriched in both Co and Ni. Deposits developed over dunites (adcumulates) may contain abundant secondary silica. Mean grades are about 1.0-1.6% Ni. Australian examples include Cawse, Ravensthorpe and Syerston (see Brand *et al.,* 1998; Freyssinet *et al.,* 2005.) There is a similar profile at the Mt. Keith MKD5 deposit (*this volume*), but although stockpiled, this is not regarded as a Ni laterite source.

Clay silicate: dominated by Ni-rich smectites such as nontronite and saponite, commonly in the mid to upper saprolite and pedolith. Nickel in these minerals is fixed between structural layers or substitutes for ferric iron in the octahedral layer, with concentrations up to 4% Ni. Mean grades are generally 1.0-1.5% Ni. The deposits form from peridotites (mesocumulates and orthocumulates). Murrin Murrin (*this volume*) and Bulong (Burger, 1996) are examples.

Hydrous Mg silicate: dominated by hydrous Mg-Ni silicates in the lower saprolite. The silicates are mainly nickeloan varieties of serpentine, talc, chlorite and sepiolite, many of which are poorly defined and are known informally as "garnierite". Globally, these ores have the highest grades (mean 1.8-2.5% Ni), and are typically found in areas of high relief. The Greenvale and Marlborough deposits (Qld) are of this type (Burger, 1979; Golightly, 1981).

The deposits formed during the main periods of lateritic weathering under humid climates in the Cretaceous to mid-Tertiary. Except for those in Queensland, most now occur in semi-arid environments. They have commonly been modified by precipitation of secondary silica (especially over dunites) and magnesite in saprolite.

The high concentrations of Ni developed during weathering are a considerable hindrance to Ni sulphide exploration. Indeed, higher concentrations occur in the regolith developed on barren adcumulates in the Siberia-Ora Banda region (Smith, 1977) than on the disseminated mineralization in the Mt. Keith adcumulate and disseminated-to-matrix mineralization at Perseverance, as noted by Butt and Nickel (1981). Secondary enrichment is commonly focussed along fractures and shears, and the geochemical data alone may simulate the distributions associated with weathered sulphide mineralization and associated wall-rock. At Cawse, secondary Ni enrichments >2%, mostly in clay, are aligned along shears through the ferruginous saprolite (Brand *et al.,* 1998). Discrimination of enrichments due to mineralization can be made by use of abundances and ratios of pathfinder elements such as Cu and PGE (*see* Gossans and Ironstones *in* Sample Media – *this volume*), the outcomes are not unique.

Relict landform regime – pre-existing profile preserved (A-type models)

This regime generally typifies upland areas of an undulating landscape. The complete weathered profile is preserved (A-type models) and the surface exposure consists of lateritic residuum, including pisolitic and nodular gravels and lateritic duricrusts, or a semi-residual soil overlying these materials. However, there are no significant Ni sulphide deposits described from this landform regime and hence no examples of the expression of Ni sulphide mineralization in outcropping lateritic residuum, although shallowly-buried residuum over weak mineralization occurs S of Mt. Keith (Butt and Nickel, 2005). The closest analogues are PGE-(Cu-Ni) mineralization at Ora Banda and Yarawindah Brook (both *this volume*), although the host rocks and style of mineralization are different.

The Ni distribution in saprolite on ultramafic rocks in relict landform regimes is similar to that in Ni laterites, with the greatest concentrations in Fe saprolite over dunites and in smectitic clays over peridotites. Nickel abundances may exceed 1%, with concentrations >2% associated with Mn oxides, commonly as sub-horizontal zones representing perched water-tables, and with Fe and Mn oxides and clays along faults and shears, with a sub-vertical attitude that may resemble mineralization. Conversely, strong silicification, in the mid to lower saprolite, causes dilution. Differentiation between sulphide-bearing and barren ultramafic rocks would be expected to be on the basis of elevated Cu and PGE abundances, with the highest concentrations of these elements in mottled and ferruginous clays.

Lag and outcropping lateritic residuum (nodular duricrust and gravels) over PGE-(Cu-Ni)-bearing pyroxenites of the Ora Banda Sill show some enrichment in Pt (400 ppb), Pd (150 ppb) and Cu (590 ppm),

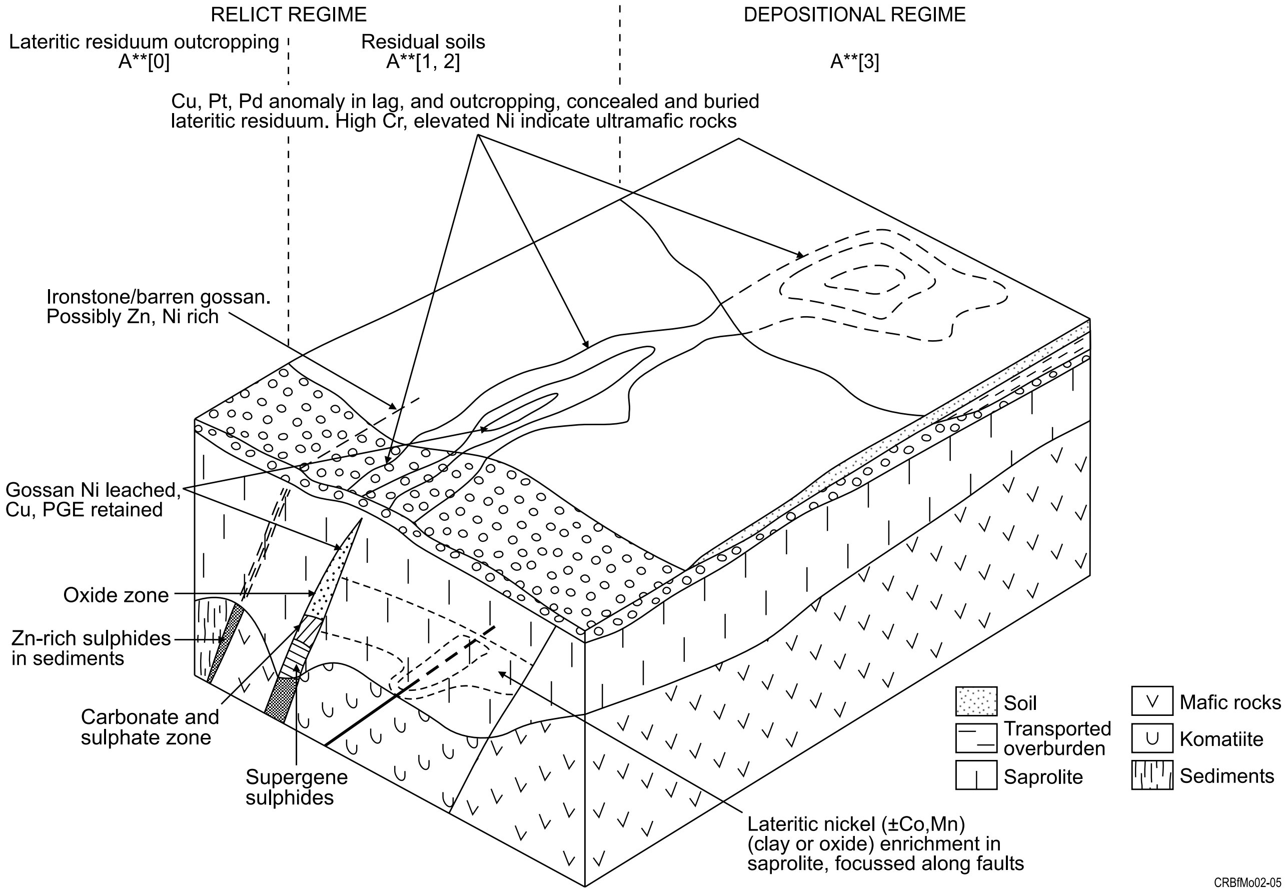


Figure 2. Anticipated Type A dispersion model from Ni sulphide deposits in relict and depositional landform regimes, having preserved profiles with lateritic residuum outcropping or concealed beneath residual soil or transported overburden.

TABLE 2
SELECTED ELEMENTS IN GOSSANS AND OTHER IRONSTONES FROM THE YILGARN CRATON, WESTERN AUSTRALIA[#]

	Jan Shoot, Kambalda	Lunnon Shoot, Kambalda	Mt. Clifford	Windarra	Perseverance 1A Shoot (mean)	Dunite association	Mafic association	Sediments in volcanic ultramafic rocks	Other gossans in sediments	Duricrusts on barren ultramafic rocks *
N =	6	5	10	10	>20	9	12	5	9	21
Au (ppb)	4-18	100-1100	1-1600	2	nd	1-30	0.6-166	1-9.2	1.2-237	0.1-400
Co (ppm)	40-1400	295-1625	<10-660	70-110	55	65-1900	10-1900	190-340	60-670	120-2960
Cr (ppm)	600-1800	70-1080	20-10000	175-7000	5710	220-2800	515-13900	150-3700	55-2600	1030-24500
Cu (ppm	500-20200	1700-1.18%	175-14000	330-2500	1410	200-2900	700-50500	900-2300	200-3700	<100-1400
Fe (%)	8.9-54.1	7.4-43.0	1.9-50.0	31.5	51.5	3-54	6-56.5	31.6-54.5	24.55	9.2-54
Ir (ppb)	145-1980	165-600	70-345	37	nd	6-70	<0.1-435	25-55	0.2-8.0	0.3-17
Mn (ppm)	30-460	30-180	30-540	90-160	400	205-885	50-4100	70-590	70-1375	310-4400
Ni (ppm)	240-27800	1200-11400	200-25000	2000-3000	125	900-1.7%	100-27000	2800-9300	200-4200	400-9200
Pd (ppb)	180-1940	75-340	60-1700	1360	nd	20-335	6-2500	70-415	<1-90	1.5-50
Si (%)	1.4-38.0	8.2-4.03	2.7-44.4	30.7	4.6	5-390	2-38.2	1-20.8	2.4-27.4	1-32.6
Zn (ppm)	40-60	40-100	10-90	30-90	90	45-360	45-750	110-1285	30-875	80-785

nd: not determined. *: includes lateritic duricrusts and silicified saprolite. [#]From Travis *et al*., 1976; data for Perseverance 1A Shoot from Thornber *et al*., 1981, illustrating extreme leaching of Ni; Windarra from Smith *et al*., 1980.

TABLE 3.
NICKEL GOSSANS AND OTHER IRONSTONES FROM THE YILGARN CRATON, WESTERN AUSTRALIA#

	Gossans		Ironstones	
	N = 103		N = 69	
	Median (ppm)	Range (ppm)	Median (ppm)	Range (ppm)
Ag	2	<3-11	<2	<2
As	25	20-300	25	20-30
Au	<0.15	-	bld	-
Bi	45	20-60	15	~15
Co	280	200-400	480	200-800
Cr (s)	750	200-2000	600	100-1800
Cu	1000	800-3000	90	80-150
Mn	300	200-400	1400	800-2000
Mo	<5	-	10	~10
Ni	3000	1500-5000	1500	800-2500
Pb	35	30-40	30	10-40
Pd	0.15	0.1-0.3	bd	-
Pt	0.15	0.1-0.5	bd	-
Sb	30	20-40	bd	-
Se	35	20-40	<2	-
Zn	140	50-200	800	200-1500

Cr(s): acid soluble Cr ($HClO_4$, HNO_3); bd: below detection limit (0.02ppm);
N = number of samples (20 for PGE; Au). Range = normal range, 15-85 percentiles.
#After Moeskops (1977).

but loss in Ni (520 ppm), relative to fresh rock. There is also strong enrichment in Cr, Fe and Al. In part, the enrichments are relative, due to loss of Mg and other mobile elements. Nickel in fresh pyroxenite (mean 1110 ppm) is hosted by silicates (probably olivine) and its distribution in the regolith is similar to that in Ni laterites, although maximum enrichments, in clay saprolite, are only about 2000 ppm. However, much of the Cu (mean 210 ppm, locally >600 ppm) is hosted by chalcopyrite, hence the response has some similarities to that over disseminated Ni sulphide mineralization. Copper accumulation in upper, ferruginous zones of the regolith is similar to Mt. Keith. In the regolith, most PGE are in the <2 µm fraction, mainly in Fe oxides; Pt is hosted by hematite and some Pd by Al-rich goethite. This separation may reflect differences in primary host minerals, with Pt in an unstable phase (*e.g.,* a sulphide) that weathered to hematite and Pd in a more stable phase, associated with later formation of goethite. The Pt distribution, therefore, may also be analogous to that over Ni sulphide mineralization. This response, however, closely resembles that expected of disseminated Ni sulphides, representing a complexity in discrimination.

In comparison, at Yarawindah Brook, in the more humid Mediterranean environment of the northern Darling Range (530 mm pa rainfall), Pt and Pd are more strongly enriched in saprolite than lateritic residuum. In lateritic residuum, Ni and Cu abundances are low relative to saprolite and bedrock, but nevertheless there is a Ni-Cu-Cr-Sc dispersion halo of 1000-2000 m around the ultramafic unit and at a threshold of 5 ppb Pt+Pd the deposit would be detected at a sampling interval of up to 500 m.

In summary, the dispersion model shown in Figure 2 has the following characteristics: -

- *Gossan*: poorly preserved or absent in lateritic residuum and upper saprolite; where present, strongly leached, with elevated PGE contents.
- *Lateritic residuum*: commonly highly ferruginous and strongly indurated, with Ni and Cr abundances similar to or higher than soil, indicating ultramafic rocks. Elevated Cu (>100 ppm) and PGEs, may indicate sulphides and, in loose pisoliths, give haloes 10x to 100x target outcrop width due to clastic dispersion of fragments of gossans or enriched Fe oxides.
- *Lower lateritic residuum, ferruginous saprolite*: horizons with maximum Cu and PGE abundances on disseminated mineralization. Minor lateral dispersion, especially in lateritic residuum.
- *Saprolite*: mid- to upper saprolite hosts zone of maximum Ni enrichment, in Fe oxides or smectite clays. No significant difference in Ni abundances over barren or mineralized komatiites, but Cu and PGE abundances will be greater. No lateral dispersion of Ni, Cu or PGE from either massive or disseminated deposits into wall rocks. Because Cu-PGE and Ni concentrate in different horizons, ideally data from these different horizons should be compared.
- *Leaching of PGE*, with accumulation in saprolite, evident in humid environments.

Erosional regime - pre-existing profile truncated or absent (B-type models)

This regime typically occurs in areas of moderate relief where erosion has truncated the profile to the mottled zone or saprolite, including silicified saprolite (silica cap-rock) on dunites/adcumulates (B-type models) or fresh rock (C-type models). This is the landform regime in which gossan search and soil sampling are most appropriate and have led to the initial discoveries in most districts. Gossan search by ironstone sampling formed an integral part of all exploration programmes during the "nickel boom" (1967-1972). There is a considerable overlap in compositions between Ni sulphide gossans and other ironstones (Tables 2 and 3); the multivariate procedures developed to distinguish them are discussed under Gossans and Ironstones *in* Sample Media (*this volume*). In many places, the gossans are so degraded at surface that they were discovered by soil sampling, *e.g.,* several deposits at Kambalda (Mazzucchelli, 1972) and Carnilya Hill, (Arndt, 1980). These surveys commonly utilized the fine fractions of soils, *i.e.,* <175 µm, although Mazzucchelli (1972) noted that the 75-175 µm fraction had the lowest Ni and Cu concentrations, with the highest concentrations in the >2 mm fraction, which is dominated by ferruginous fragments. At Redross (C.R. Dalgarno and A.R. Knowles, written communication, 1973) and in the Forrestania area (Leggo and McKay, 1980), both fine (<180 and <150 µm, respectively) and coarse (500-2000 µm) fractions of soils were used, with the latter giving higher concentrations and anomaly definition, especially for Cu. Subsequently, Carver *et al.,* (1987) noted that ferruginous lag (2-6 mm) gave higher abundances and greater contrasts than the <200 µm soil fraction at the Blair deposit. Lag also gave the best response over (uneconomic) disseminated mineralization (0.9% Ni) at Maggie Hays South (*this volume*), with coincident Ni, Cu and Ni/Cr anomalies; a comparison showed lag > total soil > minus 2 mm soil, although each gave similar patterns. Nevertheless, at Pioneer, S of Kambalda, Cox (1975) observed that the fine fraction (<180 µm) of mostly calcareous soils gave better response for Ni, Cu, Co and Cr than the coarse fraction (although giving no comparative data). The contrast, however, is very subdued, with a nearly tenfold decrease in abundance but only minor lateral dispersion, in comparison with data from weathered bedrock, mostly at 1 m depth. The low concentrations in topsoil are probably due to dilution by carbonates, aeolian sand and sheetwash. In summary, the coarse fraction is preferred, with a true total analysis (*e.g.,* HF based) giving more reliable data than other mixed acids (Gedeon *et al.,* 1977).

An important feature is the small areal extent of surface geochemical anomalies. There has been little lateral dispersion during weathering. Accordingly, where saprolite or fresh rock outcrop, or are the parent material for residual or semi-residual soils, dispersion haloes are very restricted, limited to a few tens of metres from outcrop or subcrop of the source. The Ni data alone cannot be used to distinguish between the host ultramafic rocks and the mineralization; indeed, moderate dissection may expose a lateritic Ni enrichment in saprolite, to give far higher concentrations than might occur in gossans. Generally, the Cu distribution more accurately reflects the presence of mineralization, but dispersion is rarely more than a few tens of metres. However, it may extend to 100 m or more in the lag or soil coarse fraction due to physical dispersion of gossan fragments by sheetwash (Forrestania: Leggo and McKay, 1980; Blair: Carver *et al.,* 1987). Copper derived from other

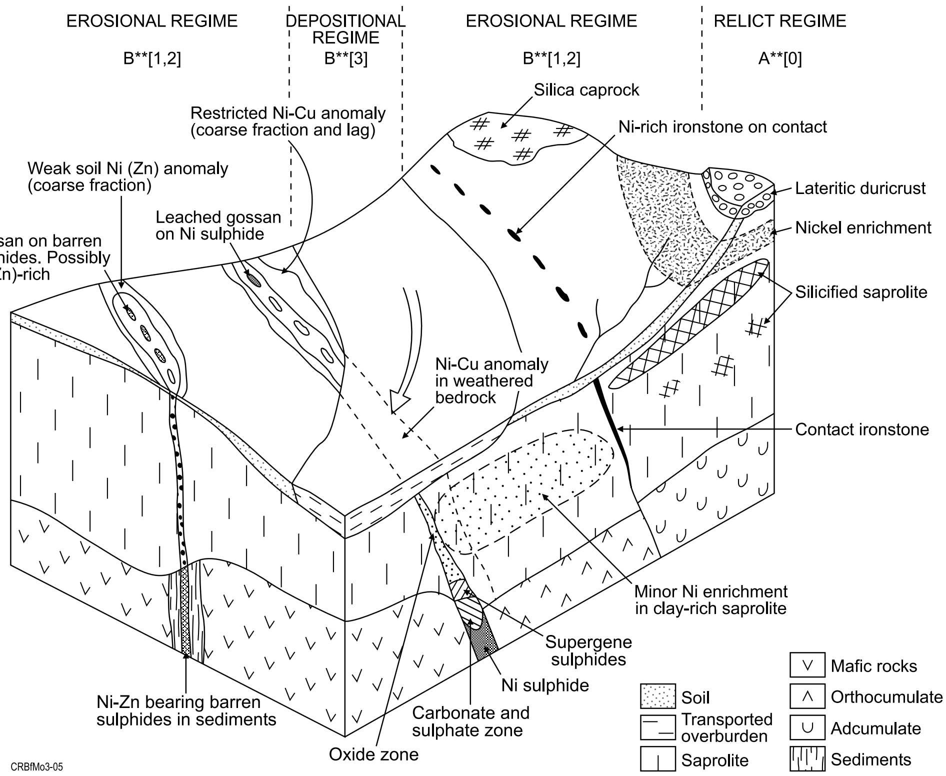


Figure 3 Dispersion model, Type B, for Ni sulphide deposits with incomplete or truncated profiles, with saprolite (or fresh rock) outcropping, or concealed by residual soil or shallow transported overburden.

sources, such as gossans on sulphidic sediments (which may also be enriched in Ni), some high Mg metabasalts and Proterozoic dolerite dykes, can cause difficulties in interpretation, having abundances similar to those for gossans themselves.

Where disseminated mineralization is associated with dunitic adcumulates, intense silicification of saprolite commonly results in the outcrop of a "silica cap". The silica acts as a strong diluent (see Butt and Sheppy, 1975), hence Ni and Cu abundances in soil can also be depressed. In many places, however, the silica does not readily degrade, and any overlying unconsolidated 'soil' is probably transported. Leggo and McKay (1980) concluded that coarse fraction soil sampling was preferred, as finer fractions are subject to dilution by transported components, but found it difficult to distinguish ferruginous or silicified gossan fragments from silicified saprolite, even using partial extraction procedures. They considered the greatest use for soil sampling was as a mapping tool. None of the published studies on soil geochemistry has used PGE as pathfinders, mainly due to the previous lack of suitably sensitive, reliable and inexpensive analytical techniques.

The dispersion model for erosional terrains has the following characteristics (Figure 3): -

- Mineralization forms a restricted surface target. It may consist of outcropping gossan, gossan detritus or leached and possibly silicified saprolite formed from ultramafic rocks containing disseminated sulphides, and fragments of these dispersed in soil and shallow colluvium. The widespread haloes associated with lateritic residuum are absent.
- *Gossans*: commonly poorly preserved at surface and outcrop may consist only of discontinuous ferruginous masses or scattered cobbles. Gossans are highly variable in composition, but commonly leached of Ni and, when emplaced in felsic lithologies, also leached of Cu. They may retain pseudomorphs of primary and secondary sulphides, especially when derived from pentlandite-pyrrhotite ore. Physical characteristics and chemical and mineralogical composition may resemble other ironstones, including gossans on barren sulphides. Ironstone surveys require multi-element analysis for Ni, Cu, Cr, Co, Mn, PGE (especially Pt, Pd and Ir) and Te for identifying Ni gossans.
- *Soil*: best response generally from coarse fractions and lag, since these contain fragments of gossan and ferruginous nodules. However, anomalies rarely exceed a few tens of metres and high Ni abundances alone may represent exhumed lateritic enrichment. High Cu contents (50->100 ppm) may reflect sulphide mineralization.
- *Saprolite (weathered bedrock)*: silicified saprolite may vary from massive outcrop in which original primary fabric, including oxide spotting after sulphides, is well preserved, through to highly porous silica boxworks, with voids after olivine. There is essentially no lateral dispersion of sulphide-derived Ni, Cu or PGE into weathered wallrocks.
- When 'bottom-of-hole', maximum abundance or composite sampling are used for deep sampling of saprolite, high Ni concentrations may be obtained from ferruginous or clay-rich mid- to upper saprolite, possibly with high Co and Mn, resulting from lateritic enrichment. However, Cu and PGE will be at background abundances. Conversely, intense silicification may dilute abundances of all other elements. Accordingly, deeper sampling may be preferred, but is costly and the target size is small.

Depositional regimes - pre-existing profiles preserved, partly truncated or absent

Buried lateritic profile complete (A-type model)

Ultramafic rocks in this environment have residual profiles with characteristics generally similar to those described for relict environments. However, mineralized examples are rare. About 10-15 km S of Mt Keith MKD5 (*this volume*), dispersion of PGE and Cu for up to 500 m from low-grade disseminated Ni sulphide mineralization occurs in buried lateritic residuum (Butt *et al*., 2005). Such dispersion, indicated for the depositional regime in Figure 3, is typical of that observed for A-type models for other base metal and Au deposits. At East Scotia, about 3 m of colluvium overlies a weakly cemented ferruginous zone, interpreted to be lateritic duricrust (Smith, 1977). There are no recognizable bedrock features above 10 m. Nickel abundances decline from >5000 ppm in bedrock to <500 ppm in saprolite and the ferruginous zone (Figure 4). Copper is less strongly leached, and relatively high concentrations (125-250 ppm) are maintained in the ferruginous zone, especially when developed from talc-carbonate rocks. Dispersion is limited to about 10 m. Copper enrichment associated with sulphidic meta-sediments is similarly anomalous, but may be distinguished by high Cr abundances.

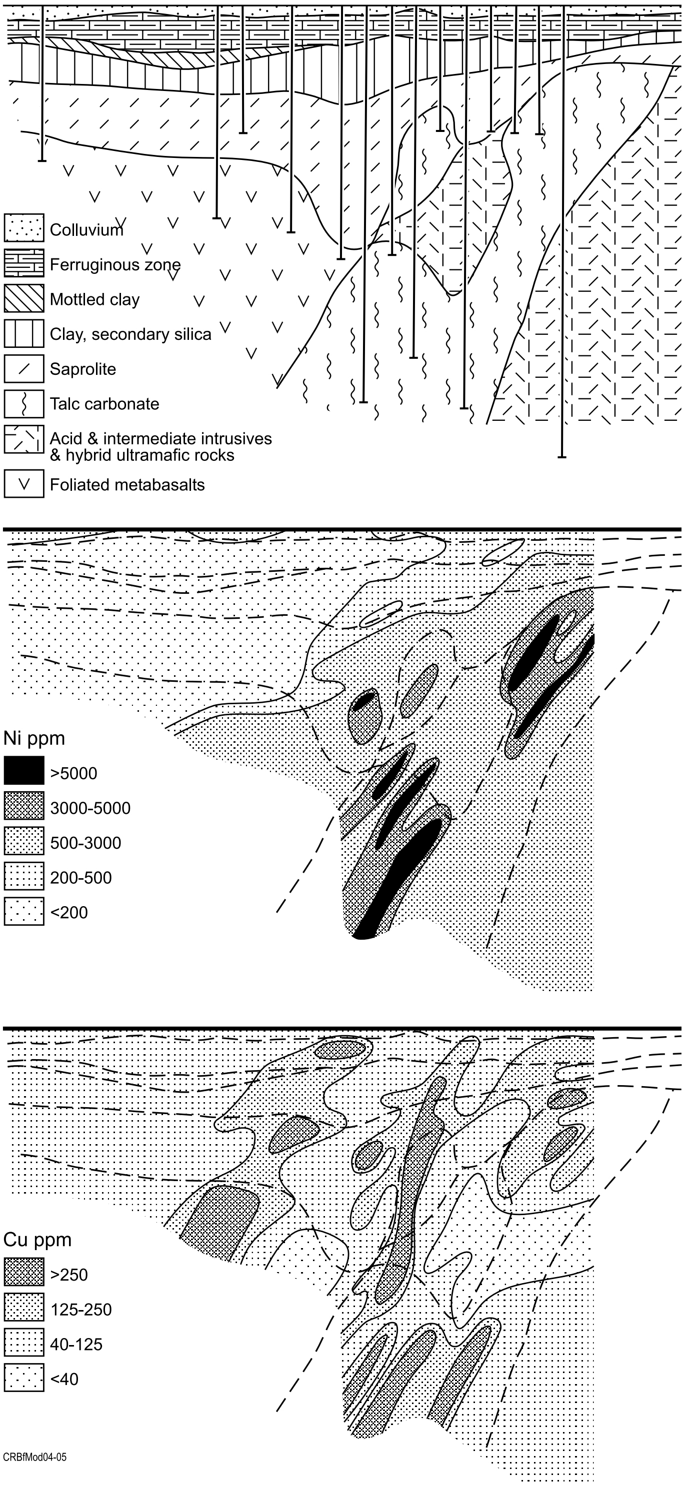


Figure 4. Geology, and nickel and copper geochemistry, East Scotia (after Smith, 1977).

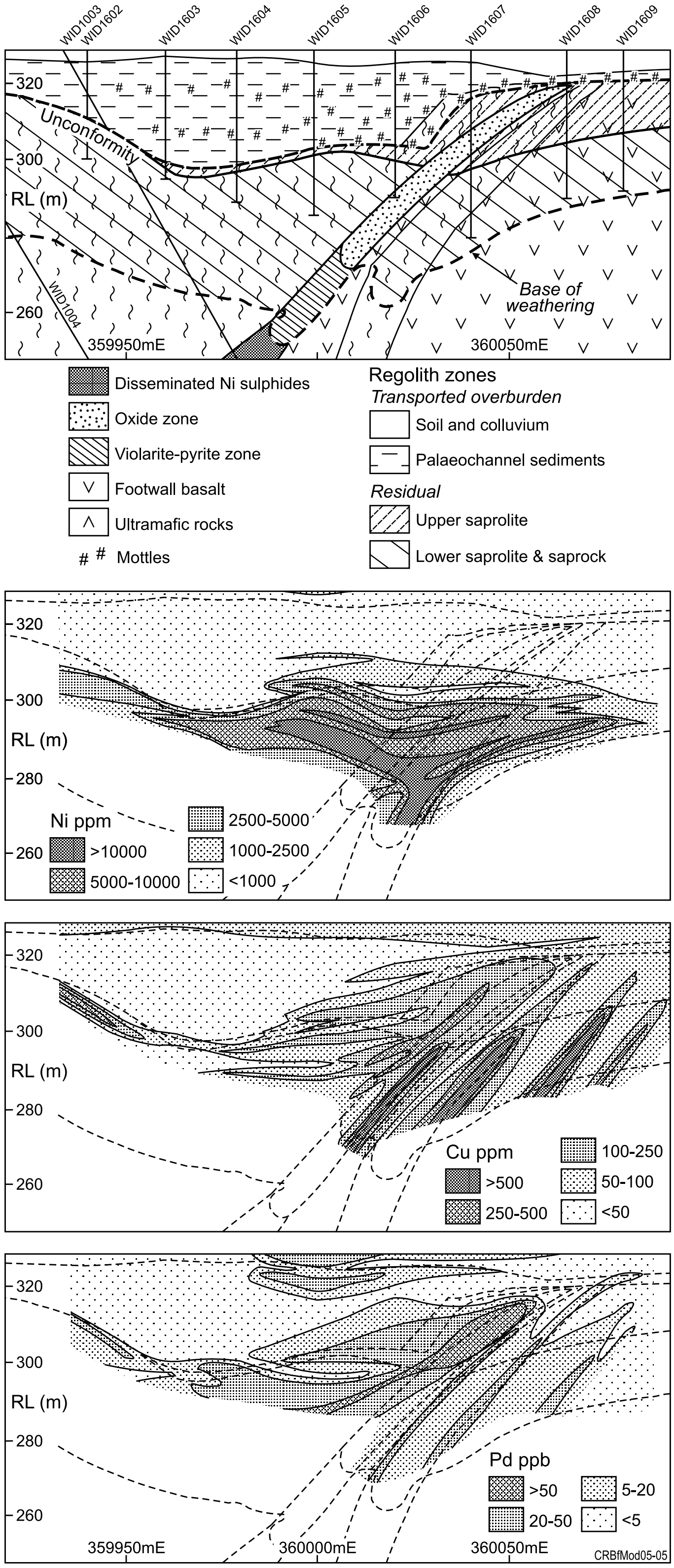


Figure 5. Moore deposit, Widgiemooltha. Geology, and nickel, copper and palladium geochemistry (after Brand, 1977).

Some specific characteristics include: -

- *Soil:* no response to underlying bedrock or mineralization unless transported overburden is less than two metres thick.
- *Colluvium, alluvium and other sediments:* no response to underlying mineralization but elevated Ni and Cr abundances may reflect ultramafic country rocks.
- *Lateritic residuum, ferruginous zone:* similar to relict regimes if well developed; preferred sample medium if available.

Buried lateritic profile truncated (B- and C- type models)

Transported overburden effectively eliminates the possibility of a surface expression for mineralization. Possible mechanisms of dispersion into transported overburden include clastic dispersion at the old land-surface prior to sedimentation, and later mixing by bioturbation, biogeochemical cycling by vegetation and hydromorphic dispersion by shallow groundwaters along the unconformity or into the sediments. However, none have been shown to yield significant anomalies. Most studies have concluded that soil sampling is ineffective. Considerable dilution by aeolian and water-borne sediment has occurred even in 1-1.5 m thick, apparently 'residual' soil at Pioneer (Cox, 1975). Lag, total (augered) soil and <2 mm soil were all ineffective in detecting mineralization at the concealed Main and North deposits at Maggie Hays (*this volume*), which are concealed by 5 to 20 m of colluvium, respectively. Main is also probably blind and North faulted into felsic volcanic rocks. There are some broad peaks in Ni at both sites, with other elements (Cu, Co, Zn) and Ni/Cr showing local variation, but at best these probably reflect the ultramafic provenance of some of the colluvium. Similarly, at Windarra (Smith *et al.,* 1980) and Forrestania (Leggo and McKay, 1980), exploration has depended on drilling to bedrock at intervals as close as 60 x 7 m and 30 x 3 m over carefully defined magnetic targets. This interval was necessary because of the narrow targets; at Windarra, the positions of the various ore shoots were clearly indicated, but dispersion haloes were only about 1400 x 50 m for Ni and 1000 m x 25 m for Cu.

Dispersion into older sediments themselves, rather than the overlying soil, is evident over truncated regolith. At Redross, the possible dispersion of Ni and Cu from buried, oxidized Ni sulphide mineralization into shallow (6 m) alluvium has been reported (C.R. Dalgarno and A.R. Knowles, written communication, 1973; see Butt and Zeegers, 1992, p. 358). Auger sampling showed an anomaly in alluvium, defined by the 100 ppm Cu and 200 ppm Ni contours, extending about 50 m downslope. At Moore (Brand, 1997), oxidized disseminated sulphides subcrop beneath about 10 m of alluvial and colluvial sediments on the flanks of a 25-30 m deep palaeochannel. The regolith on the komatiites is mostly truncated to lower saprolite; the unconformity is sharp, with little or no mixing. There is some minor dispersion of Cu (100-200 ppm), Cr (locally >1500 ppm), Pt and Pd (both 20-50 ppb) into the sediments close to the sub-cropping mineralization and komatiites (Figure 5). At best, these could be interpreted to indicate an ultramafic source for the sediment. The most prominent dispersion is shown by As, with concentrations >500 ppm in a lower mottled clay horizon extending 100 m into the channel. Nickel, however, is strongly depleted from the upper oxide zone/saprolite over mineralization, but shows prominent sub-horizontal enrichment in lower saprolite and saprock. This occurs over olivine adcumulates, where it is probably residual, but also extends over the footwall basalt for about 30 m from the contact. There is probably little direct exploration significance in the dispersion observed into the sediments, given the complexities of identifying transported regolith units and in interpreting Cu-Ni data from weathered ultramafic rocks, but it illustrates that some dispersion has taken place. Overall, there is little evidence for significant hydromorphic dispersion into saprolite or sediments, except possibly at Moore.

At Mt. Keith (*this volume*), up to 35 m of transported overburden overlie a partly complete lateritic profile on the MKD5 deposit. It is possible that the oldest sediments are contemporaneous with deep weathering; younger channel clays were weathered during a later episode. Nickel, Cu and the PGEs are all enriched in the residual regolith, but not in the same horizons. Nickel contents remain high at the base of the collapsed ferruginous saprolite, associated with Fe oxides and Mn oxides, but decline sharply upwards, whereas Cu and PGE contents reach their maximum concentrations in the collapsed ferruginous saprolite and transitional zone at the base of the mottled clays. Apart from the Cu-PGE enrichment of the basal transitional horizon, the geochemical composition of the sediments gives no indication of the underlying deposit. Concentration in the upper saprolite and collapsed ferruginous saprolite appears to be equivalent to that commonly seen in ferruginous horizons, including lateritic residuum. However, lateral dispersion extends only over the adjacent barren adcumulates, and for Ni is largely due to residual enrichment of silicate-derived Ni.

Groundwater sampling has rarely been attempted for Ni exploration, but may have application in depositional areas where water-tables are relatively shallow. Available data show that Ni and Cr contents of groundwaters indicate the presence of ultramafic rocks (Gray, 2001; 2003), and Gray *et al.,* (1999) reported very high Ni-Co concentrations in groundwaters from drill holes intersecting Ni sulphide mineralization (0.25-140 ppm Ni). However, it remains uncertain whether such mineralization gives a significant, recognizable dispersion halo, either in Ni alone, or with Cu, PGE and, possibly, S isotope data, in groundwater from holes near, but not intersecting, sulphide mineralization.

In summary, the dispersion model (Figure 6) indicates there is little scope for a definitive expression of concealed mineralization through or within transported overburden and similar constraints on anomaly dimensions in residuum apply as for B and C models in erosional regimes.

- *Soil:* Except where transported overburden is very thin (<2 m) and there is the possibility of bioturbation, soil sampling is unlikely to be successful. There is no reliable, published evidence for the successful use of partial extraction analysis to reveal otherwise concealed mineralization.
- *Transported overburden (colluvium, alluvium):* High Ni and Cr abundances reflect ultramafic provenance. In addition, Cu (Redross) and Cu and PGE (Moore) anomalies indicate sub-cropping Ni sulphide mineralization and give relatively broad targets, but are probably too difficult to identify to be a reliable guide.
- *Basal sediment – upper residuum transition:* At Mt. Keith, a clay-rich transitional mixing zone has characteristics of both the sediment and the ultramafic bedrock, due largely to physical churning. Elevated Cu and PGE abundances may distinguish mineralized from barren bedrock.
- *Interface sampling:* Where there is no mixing zone, clastic and hydromorphic dispersion close to or along the unconformity between sediments and saprolite has been successful as a sampling target for Au exploration. For Ni, separation of ferruginous mottles and gravel would be the most promising approach, emulating lag and coarse fraction soil sampling of equivalent erosional terrain.
- *Saprolite:* This is the most common sample medium in this terrain. Lateral dispersion in saprolite is minimal, as in all other situations, hence close interval drilling is essential. As elsewhere, ferruginous or clay-rich mid- to upper saprolite may yield very high Ni contents due to lateritic enrichment (*e.g.,* as at Moore), so that saprock sampling may be required to define diamond drilling targets. Copper, and possibly PGE, may be present in part as native metals. Data interpretation must account for Cu-PGE and Ni being concentrated in different horizons.

EXPLORATION MODELS FOR BASE METAL SULPHIDE DEPOSITS

Occurrence and weathering of base metal sulphides

Volcanic-hosted massive sulphide (VMS) Cu-Zn-Pb deposits and sediment-hosted Zn-Pb-Ag, Au-Cu-Ag-Pb-Zn, Fe-Cu-Au and Cu deposits occur in a wide variety of environments. These include temperate regions of moderate to high relief in western Tasmania, Victoria and New South Wales, savanna climates with moderate relief in NE Queensland, semi-arid regions of mostly low relief in New South Wales and Western Australia, and semi-arid to savanna regions of moderate to high relief in the NW of Queensland and Western Australia. Many of these have undergone deep weathering; some have been buried, either before or following deep weathering, whereas others, principally in areas of high relief, show little or no weathering. These factors considerably influence their surface expression, which may be dominated by either past or present dispersion processes, or be a combination of both. Deposits of all types are broadly similarly weathered and are described below. Despite the differences in genesis of VMS and sediment-hosted deposits, the dispersion models have many common features. (Models for epithermal Cu-Au and porphyry Cu-Au±Mo deposits are discussed separately).

The dominant minerals in base metal deposits are chalcopyrite, sphalerite, galena and pyrite. In lateritic environments, weathering may extend to depths of 100 m or more, well below the present (or past) water-table. Sulphide weathering commences by replacement of chalcopyrite by supergene Cu sulphides (*e.g.,* covellite, chalcocite). Subsequently, sphalerite, galena, pyrite and chalcocite are dissolved, commonly leaving cavities that, slightly higher in the profile, are occupied by a wide variety of secondary Cu-Pb-Zn-Ag minerals, including native metal (Cu, Ag), carbonates and sulphates (Nickel, 1984). Higher still, these minerals dissolve or are further oxidized to form gossans, dominated by goethite and hematite. Towards the land surface, the gossans thin and commonly only form discontinuous, rubbly outcrop; boxwork fabrics after sulphides are rare. Although there may be some absolute enrichment of Cu in the supergene sulphides (*e.g.,* Whim Creek (WA), *this volume*), Cu and Zn tend to be strongly leached throughout a mature gossan profile; similar depletion affects associated stringer and disseminated mineralization. Conversely, Pb is retained and may be enriched. VMS deposits, in particular, may contain a range of pathfinder elements including As, Bi, Sb, Sn and W, which also tend to be retained during

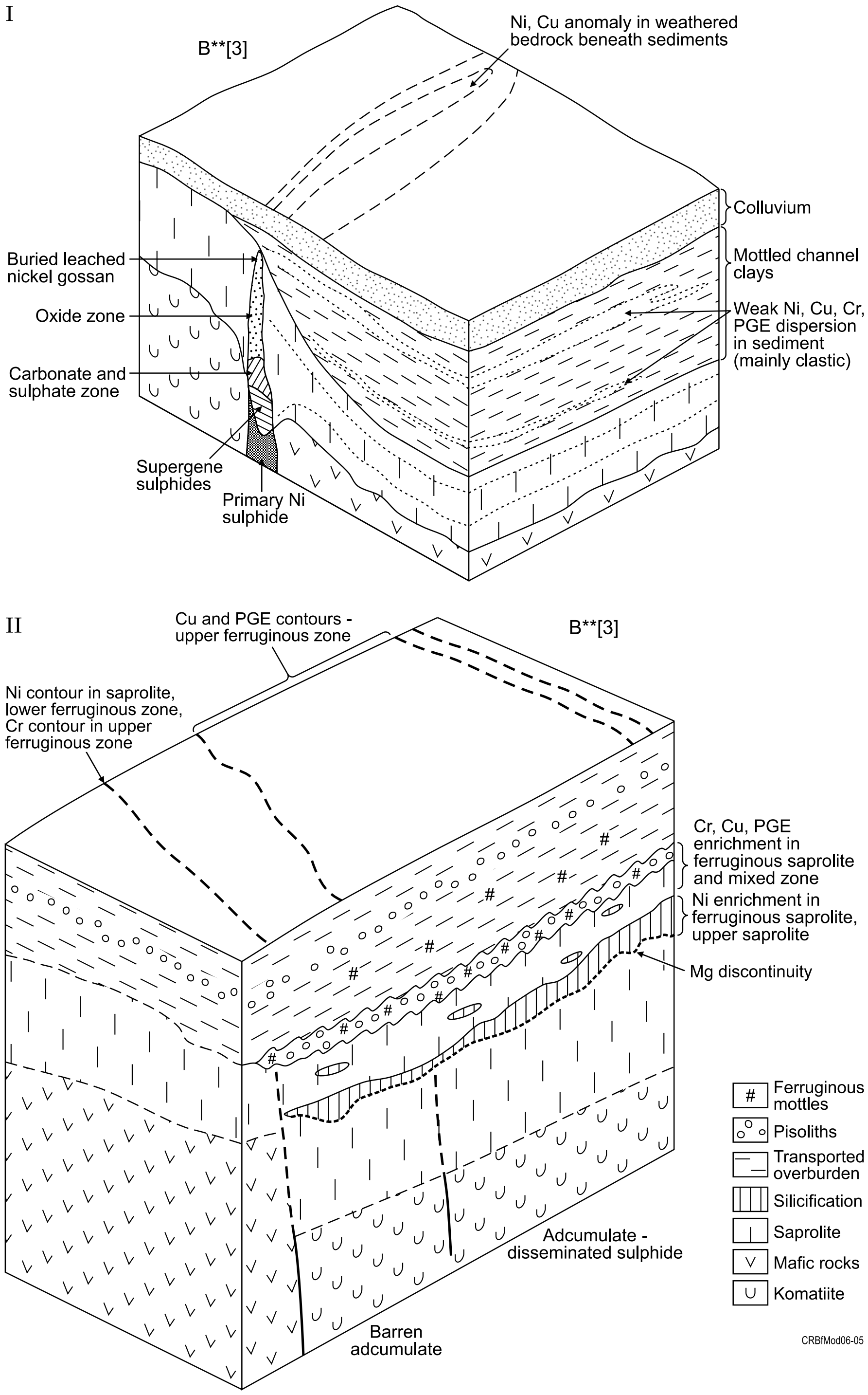


Figure 6. Dispersion model for Ni sulphide deposits , Type B, in depositional terrain having incomplete or truncated profiles, with saprolite or fresh rock buried by transported overburden. I: enrichment of proximal alluvial sediments, mainly by clastic lateral dispersion. II: regolith over adcumulate indicating position of mixed zone and separation of Cu-Cr-PGE and Ni enrichments.

weathering; because cassiterite is largely unaffected by weathering, Sn becomes residually enriched towards the surface.

Despite strong leaching during weathering and gossan formation, significant lateral dispersion from VMS or other base metal deposits rarely occurs. However, there is limited dispersion of Pb and Zn at Teutonic Bore in the Yilgarn Craton (Greig, 1983; see Butt and Zeegers, 1992; Butt, 1985) and Pb at Woodcutters, NT (Taube, 1978) is reported to extend up to 200 m laterally in saprolite, confined to narrow, sub-horizontal, zones. Similarly, at Elura (*this volume*), a Pb anomaly (>100 ppm) extends for over 500 m in shallow saprolite beneath a palaeochannel.

Prior or contemporary burial restricts the intensity of weathering, but permits the possibility of dispersion into the sediments. At Osborne (*this volume*), multi-element chemical dispersion into Mesozoic sediments is interpreted to have resulted from weathering and diagenesis during or after burial, whereas at Pajingo (*this volume*), anomalous horizons formed by largely clastic dispersion during erosion and local deposition. If burial has post-dated the main period of weathering, dispersion into sediments is less likely, especially in arid areas, unless past or present water-tables have been relatively high, especially close to the unconformity (*e.g.,* Thalanga: Granier *et al.,* 1989; Waterloo, Dalgaranga: both *this volume*).

Where the earlier weathering profiles have been truncated or are absent, the geochemical expression is largely due to active dispersion, either from the remnant oxidized mineralization (*e.g.,* Mons Cupri, *this volume*) or the sulphides themselves (*e.g.,* Hall's Peak and Hercules, both *this volume*).

Relict landform regime – pre-existing profile preserved (A-type models)

This regime is generally typical of upland areas with an undulating landscape in which the complete weathered profile is preserved. The surface exposure consists of lateritic residuum, including pisolitic and nodular gravels and lateritic duricrusts, or a semi-residual soil overlying these materials. Residual accumulation and lateral dispersion together

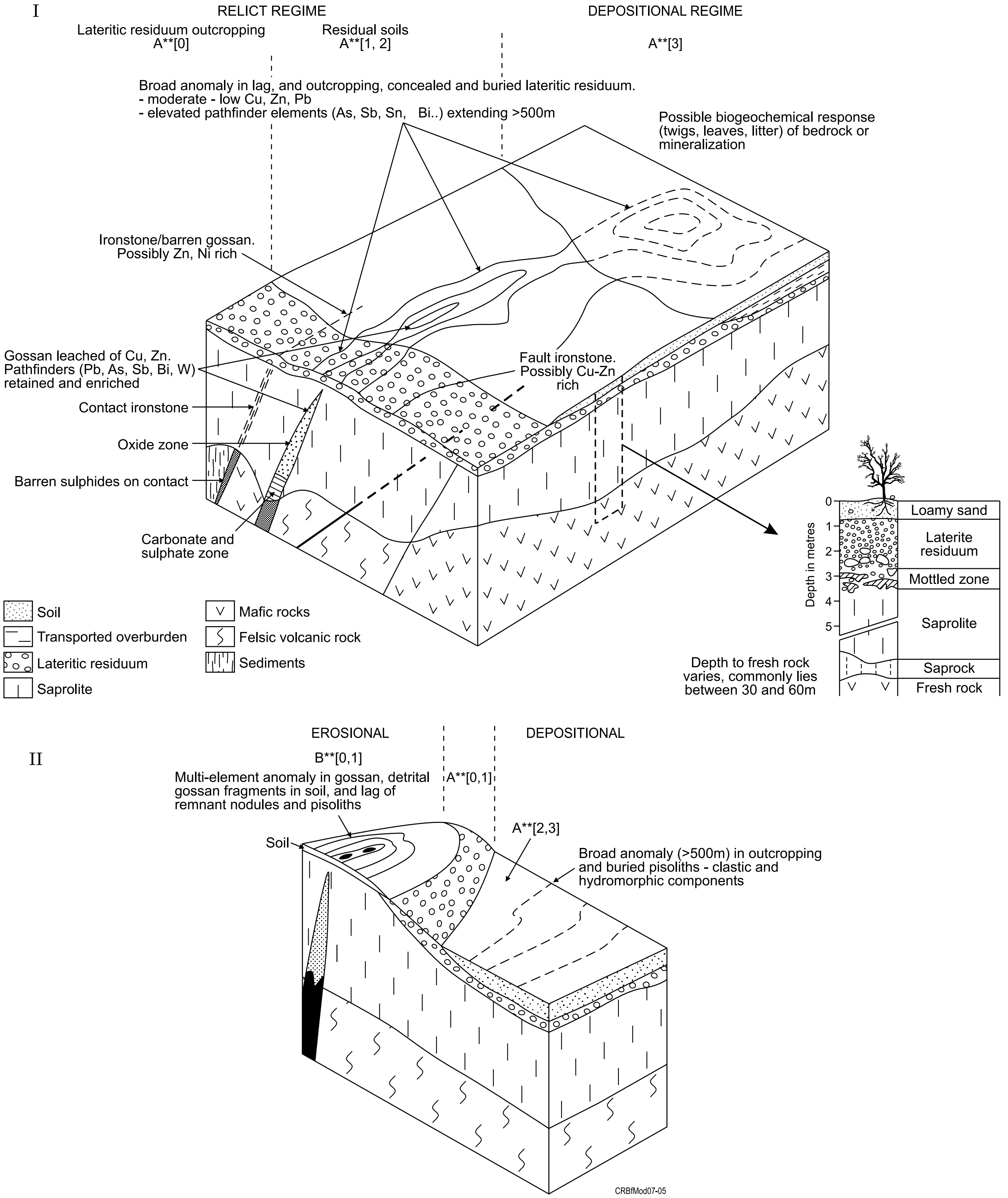


Figure 7. Dispersion model for base metal deposits, Type A, relict and depositional terrains; preserved profile, with lateritic residuum outcropping, or concealed beneath residual soil or shallow transported overburden. I: undulating, low relief. II: site with gossans outcropping on low hill.

can cause widespread geochemical and mineralogical patterns related to concealed mineralization derived from resistant primary minerals and fragments of gossan incorporated within it.

The principal example of dispersion from a VMS deposit in lateritic residuum is from Golden Grove (WA) (*this volume*; Smith and Perdrix, 1983). Nevertheless, the relationship between gossan formation and disintegration, and pisolith formation and lateral dispersion remains uncertain. The principal gossans at Golden Grove outcrop on a prominent hill (Gossan Hill), whereas the laterite anomaly is on the flanks of the hill and in the surrounding plain. Pisoliths and nodules contain gossan fragments, but it is not certain that the hill was completely covered by pisolitic laterite or, if so, whether this predated the first exposure of the gossans. Consequently, it cannot be assumed that gossans form at the same sites as pisoliths or, therefore, that pisoliths will contain gossan fragments. At the Scuddles deposit, 4 km N of Gossan Hill, the terrain is subdued and no gossans are exposed. Pisolith sampling showed that both Cu and Zn are at background abundances. Several pathfinder elements (As, Sb, Bi, Se, Sn and Mo) are anomalous for up to 1.5 km from the projected sub-crop of the mineralized zone. Dispersion has been both hydromorphic and mechanical; the latter possibly as individual minerals, such as cassiterite, rather than as gossan fragments. Similar dispersion in lateritic residuum occurs at Freddie Well (WA) (*this volume*), expressed as weak Zn, Bi, In and Mo anomalies,

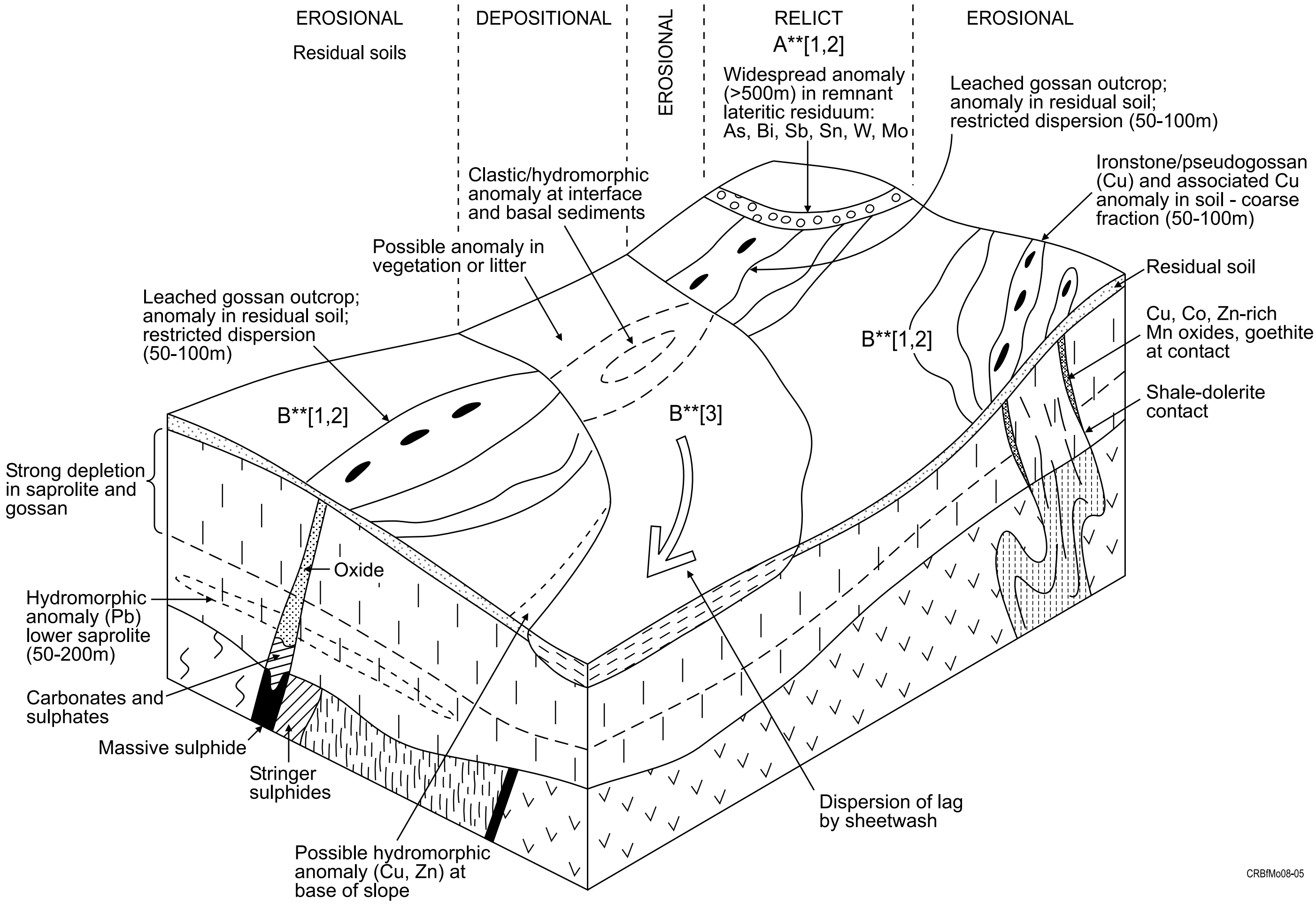


Figure 8. Dispersion model for base metal deposits, Type B, mainly erosional terrain, low to moderate relief; incomplete or truncated profile, with saprolite or fresh rock outcropping, beneath residual soil or shallow transported overburden. (For legend: see Figure 7).

and in remnant duricrust at Lady Loretta (Qld), in which Pb-Zn-As±Ag anomalies show dispersion haloes of >600 m (Anand *et al.,* 1997).

The dispersion model (Figure 7A) has the following characteristics:

- *Gossan*: poorly preserved or absent at surface in lateritic residuum and upper saprolite, but may be exposed in erosional windows.
- *Lateritic residuum*: commonly pisolitic or nodular, cemented with depth. Widespread (500-1500 m) multi-element anomalies, especially in pathfinder elements (Ag, As, Bi, In, Mo, Pb, Sb, Sn); Cu and Zn abundances (generally <1000 and <200 ppm) strongly leached compared to gossans and sulphides, but anomalous with appropriate low thresholds. Dominantly clastic dispersion as gossan fragments and resistant minerals.
- *Gossans and wall-rock saprolite*: strong leaching of Cu and Zn is anticipated in, with minimal lateral dispersion. Lead, As, Sb, Sn and other pathfinders retained in gossan. Secondary oxidate minerals present lower in gossan profile, overlying supergene and primary sulphides.

Erosional regime - pre-existing profile truncated (B-type models)

This regime typically occurs in areas of low to moderate relief where the uppermost horizon of the profile is saprolite (B-type models), locally eroded to fresh rock (C-type models). In arid areas, the soil is generally poorly developed and may be strewn with ferruginous lag where less deeply truncated (Figure 8). Truly residual soils are probably restricted in extent, especially where the relief is low; sheetwash and aeolian input result in the addition of exotic material to give semi-residual soils or a thin cover of essentially transported material even in erosional landscapes. It is the landform regime in which gossan search is most appropriate and led to the initial discoveries in most base metal districts. Ironstone, soil and lag sampling are the most common procedures for gossan search and have proved to be effective procedures in these environments. Because of the potential for secondary enrichment in iron-

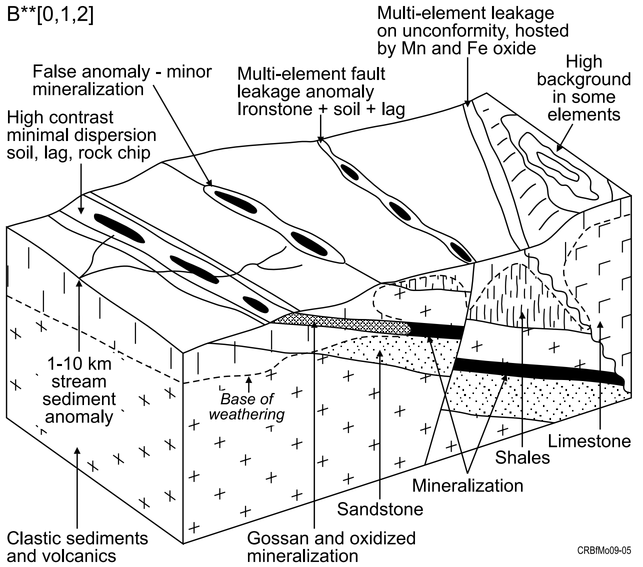


Figure 9. Dispersion model for stratabound base metal deposits, Type B, erosional terrain, semi-arid environment; incomplete or truncated profile, with saprolite (locally fresh rock) outcropping or beneath residual soil. Illustrates different types of gossans and ironstones and associated soil anomalies.

stones of various origins, such as at Killara (*this volume*), pathfinder elements (*e.g.,* As, Bi, Mo, Sb, Sn, W) are important discriminants (see Gossans and Ironstones *in* Sample Media, *this volume*), but cannot readily be used to identify ironstones (as depicted in Figure 9) enriched by leakage from buried, significant mineralization, or gossans developed on minor mineralization (*e.g.,* see Century *this volume*). Where saprolite outcrops, or is the parent material for residual or semi-residual soils, dispersion haloes are very restricted, limited to a few tens of metres from outcrop or subcrop of the source, in contrast to the extensive anomalies in lateritic residuum. Examples in the Yilgarn Craton

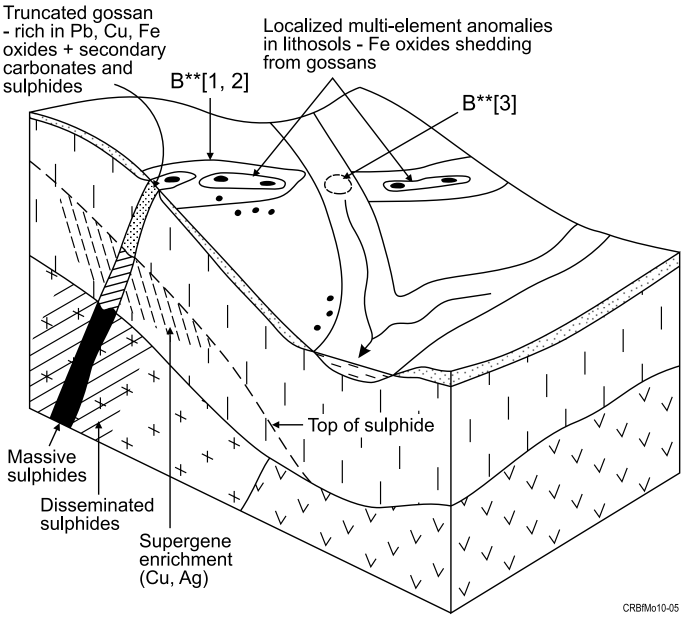


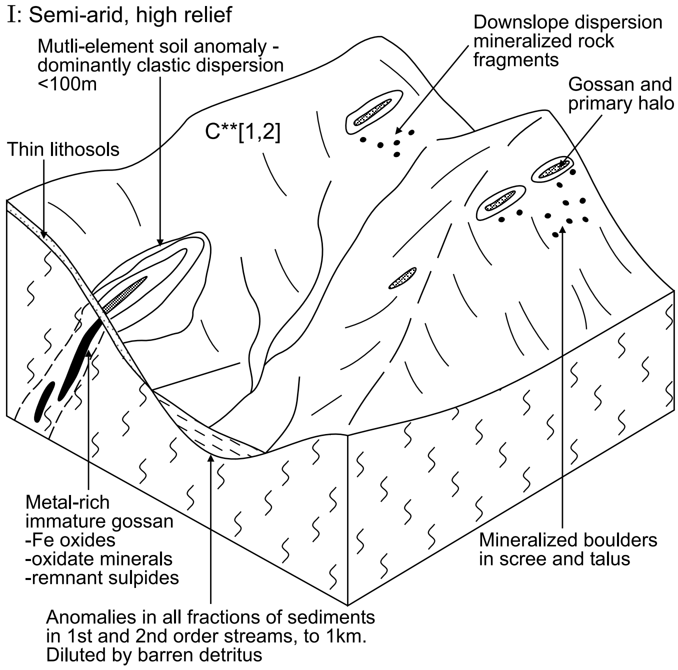
Figure 10. Dispersion model for base metal deposits, Type B, erosional terrain, moderate relief, semi-arid environments; incomplete or truncated profile, with saprolite or fresh rock outcropping or beneath residual soil. (For legend: see Figure 7).

are the Freddie Well Cu-Zn deposit (200 m; *this volume*, and Smith *et al.,* 1976), the Killara pseudogossan (50 m; *this volume*) and the Teutonic Bore Cu-Zn deposit (minimal halo, Greig, 1983). Base metal mineralization of various styles in the Cobar region, NSW (*e.g.*, Elura, CSA, both *this volume*) similarly have haloes that generally extend less than 100 m in residual soils. Even where there has been greater erosion and gossans have high base metal contents, (*e.g.,* Whim Creek, Mons Cupri, Pilbara Craton, and Century, Mt Isa, all *this volume*) the haloes have similar dimensions (Figure 10). Greater dispersion, extending to 200-300 m, may occur where there is high relief, such as the Hilton-George Fisher deposits (Mt. Isa, *this volume*). In each case, the anomalies have ferruginous outcrops as secondary sources and the geochemical patterns in soil result from mainly mechanical dispersion of ironstone and gossan fragments. Lady Loretta (Qld) however, is an exception. Lead and Ag are not strongly leached from the gossan and Pb, especially, shows minimal dispersion. In contrast, Zn is strongly leached and the highest concentrations occur about 500 m downslope, presumably due to hydromorphic dispersion under earlier, more humid conditions (Cox and Curtis, 1977). More widespread anomalies may be detected in drainage sediments if streams erode high contrast anomalies (*e.g.,* up to 10 km at Century). Lag may also give extensive multi-element signatures when incorporated in colluvium or entering drainage channels. In general, these are probably related to mineralized systems rather than individual deposits, although Pb anomalies were detected for 5 km down drainage from Elura (NSW) (Dunlop *et al.,* 1983).

Leaching and depletion, especially of Cu and Zn, may extend to depths of 10-30 m or more (>100 m at Lady Loretta), and any chemical dispersion or supergene enrichment in saprolite is generally below these depths, possibly below the water-table. Lateral dispersion of Pb, such as that noted above at Teutonic Bore (WA), Woodcutters (NT) and Elura (NSW), offers the potential for wider targets, but cannot be relied upon. If present, multi-element analysis of all (or composited) samples from RAB or RC drilling at (say) 50 x 100 m spacings, searching for such haloes, should be more effective than drilling for a direct intersection of oxidized mineralization.

The dispersion model (Figures 8, 9 and 10) has the following characteristics: -

- Mineralization forms a restricted surface target, derived from outcropping gossan and gossan detritus.
- *Gossans:* commonly poorly preserved at surface and outcrop may consist only of discontinuous ferruginous masses or scattered cobbles. Gossans are commonly leached of Cu and Zn, but may retain high concentrations of associated Pb, As, Bi, In, Mo, Sb, Sn, if originally present. Their physical characteristics and chemical and mineralogical composition may resemble other ironstones, including fault and contact ironstones, but gossans may be distinguished using this pathfinder element suite. More strongly truncated gossans at sites with moderate to high relief have higher abundances of ore metals and may have visible secondary carbonates and sulphates.



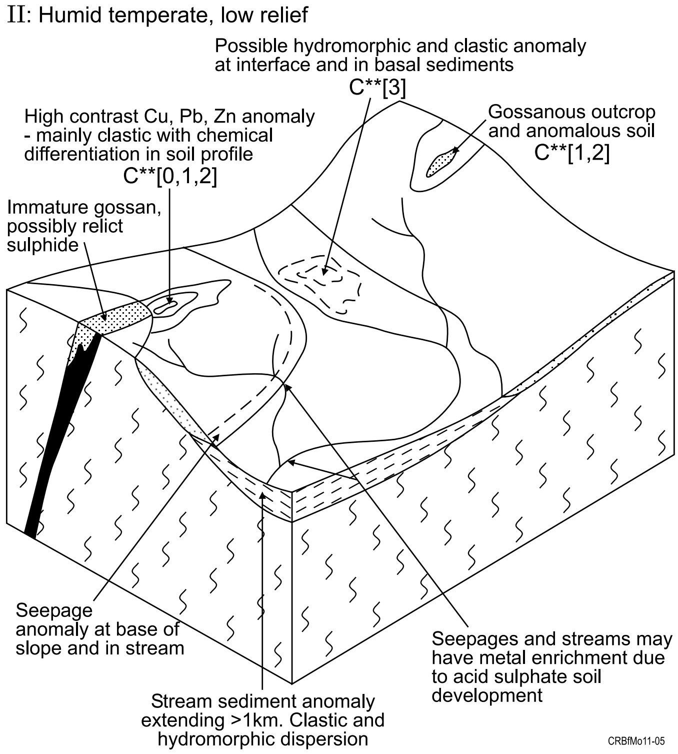


Figure 11. Dispersion model for base metal deposits, Type C, erosional terrain, no deep weathering profile, with fresh rock outcropping or beneath residual soil. I: high relief, semi-arid environments; II: moderate relief, temperate humid environment. (For legend: see Figure 7).

- *Soil and lag:* best response generally given by coarse fractions of soil and lag, since these contain fragments of gossan and ferruginous nodules. However, dispersion rarely exceed 50-100 m, even in regions with moderate to high relief, and may be of low contrast, reflecting strong leaching of gossans. Metal associations are commonly related to dominant soil and lag mineralogy, (*e.g.,* hematite: Fe-As-Pb± Sb±Bi±W; goethite: Fe-Cu-Zn; Mn oxides: Mn-Co-Zn±Cu±Ni), with possibility of developing false anomalies, especially with partial extractions.

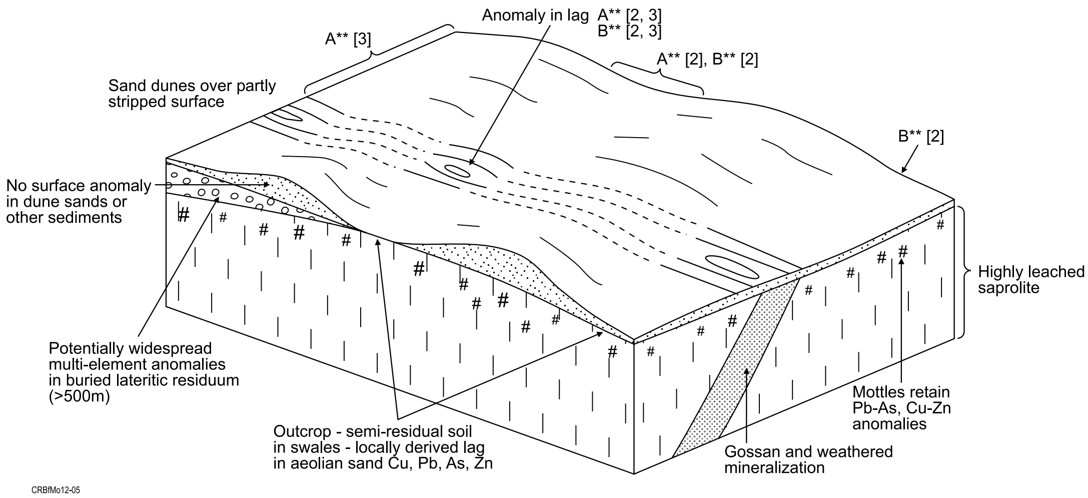


Figure 12. Dispersion model for base metal deposits, Types A and B, mainly depositional, desert terrain. Lateritic residuum or upper saprolite mainly concealed by dune sands, with subcrop or semi-residual soil in swales.

- *Calcrete*: generally dilutes existing metal abundances and reduce anomaly contrasts. However, it may provide an alkaline environment and stabilize normally mobile elements like Cu and Zn (see below).

- *Saprolite:* mottles in upper saprolite may show metal associations with hematite and goethite (above), but saprolite is commonly strongly leached (especially in Cu and Zn) to depths of 10-30 m, possibly to below the water-table. Secondary enrichment may occur in the zones of oxidate minerals and secondary sulphides over massive and stringer mineralization. Lateral dispersion, especially in Pb, can be evident for 50-200 m, generally in specific zones. Enrichments of Co, Cu, Zn, As and/or Ni with Mn oxides or goethite at redox-fronts (*e.g.,* faults, contacts, perched water-table) need careful assessment as they may be unrelated to mineralization.

Erosional regime - pre-existing profile eroded or not developed (C-type models)

Apart from small, localized areas of outcrop in mostly deeply weathered erosional terrain, sites where there is no significant preservation of a pre-existing regolith occur in areas of moderate to high relief. In hills and mountains in semi-arid areas (*e.g.,* McDonnell Ranges, NT), due to the slow rate of chemical weathering and soil formation, dispersion is dominantly mechanical, with ore-related elements hosted by gossan fragments and resistant minerals such as cassiterite. Gossans themselves are generally immature and not strongly leached, possibly with secondary oxidate minerals and remnant sulphides in outcrop. Gossan search is effective but, because gossans may be less resistant than country rock, they may be buried in depressions; gossan fragments may be found in talus. Downslope dispersion may result in quite broad, high contrast soil anomalies, but will be attenuated by dilution in outwash fans and sand spreads in valleys and plains. At Oonagalabi, NT (*this volume*), Cu-Pb-Zn-Ag anomalies in <75 µm soils extend over 200 m from outcropping mineralization. Stream sediment anomalies in all size fractions show distinct but short dispersion trains due to dilution, rarely reaching beyond second order streams.

The dispersion model for arid areas of moderate to high relief (Figure 11A) shows: -

- *Immature gossans:* high metal contents, possibly with secondary oxidate minerals (*e.g.,* malachite), remnant sulphides.

- *Immature lithosols,* with high contrast, multi-element anomalies, in all size fractions, with dominantly clastic dispersion 200 m or more downslope. Total analysis preferred.

- *Stream-sediment* anomalies in first and second order streams, all size fractions, total analysis.

In humid, mostly temperate, areas, such as along the hill belts of the eastern seaboard from NE Queensland to Tasmania, more active weathering has resulted in the formation of deeper, differentiated soils, generally with stronger anomalies and greater dispersion, especially in stream sediments, than in arid areas. In the heavily dissected northern tablelands of New South Wales, immature gossans and soils have high metal abundances, and stream sediments are anomalous for up to 40 km downstream – possibly, in part, due to contamination from old workings (Hall's Peak, *this volume*). Dispersion commonly has a significant hydromorphic component. At Benambra (Vic), this has not only contributed to soil and stream sediment anomalies, but has also formed secondary solution-deposited gossans as ferricretes at seepages and contributed metal-rich groundwaters directly to streams (Robbins and Chenoweth, 1984). Only up-dip stringer mineralization outcrops, and metal abundances are reduced (*e.g.,* maximum 1200 ppm Cu, 670 ppm Zn at Wilga), but anomalous responses extend 50-200 m downslope in soil and up to about 750 m in stream sediments. In the Mt Lofty Ranges (SA), environmental change has led to the development of acid sulphate conditions, in which chemical mobilization and scavenging of metals have resulted in high concentrations of base metals in soils, seepages, stream sediments and waters. At Mt. Torrens (*this volume*), the drainage anomalies extend for over 1 km. Similar processes are active across much of southern Australia, so that acid saline soils and seepages have broad potential as a sample medium. Where rainfall is very high, as in western Tasmania, soils may be strongly differentiated, so that sampling a consistent horizon is essential. The Ao and C horizons are generally recommended, but anomalies may be attenuated due to strong leaching (Skey and Young, 1980; Farrell and Orr, 1980).

The dispersion model for temperate humid areas of moderate to high relief (Figure 11B) shows: -

- *Mostly immature gossans:* high metal contents, possibly with secondary oxidate minerals (*e.g.,* malachite) and remnant sulphides. Dissolution of sulphides and secondary minerals results in metal-rich groundwaters, with precipitation of ore metals with Fe and Mn oxides in seepages and streams. Solution gossans (and precipitates) without pathfinder elements (*e.g.,* Sn, W) originally hosted by resistant minerals.

- *Differentiated soils:* high contrast, multi-element anomalies in all size fractions; dispersion up to 200 m downslope. Sampling of consistent horizon essential; organic Ao horizon gives good response in very humid areas. Recommended intervals 40 x 400 m, closing to 20 x 100 m. Total analysis preferred.

- *Stream-sediments:* anomalies in first, second and higher order streams; sample density 3-5 per km^2. Potentially contaminated by old workings in many areas. Total analysis of fine fractions preferred.

- *Groundwater, seepages and stream waters*: all potentially have anomalous base metal contents.

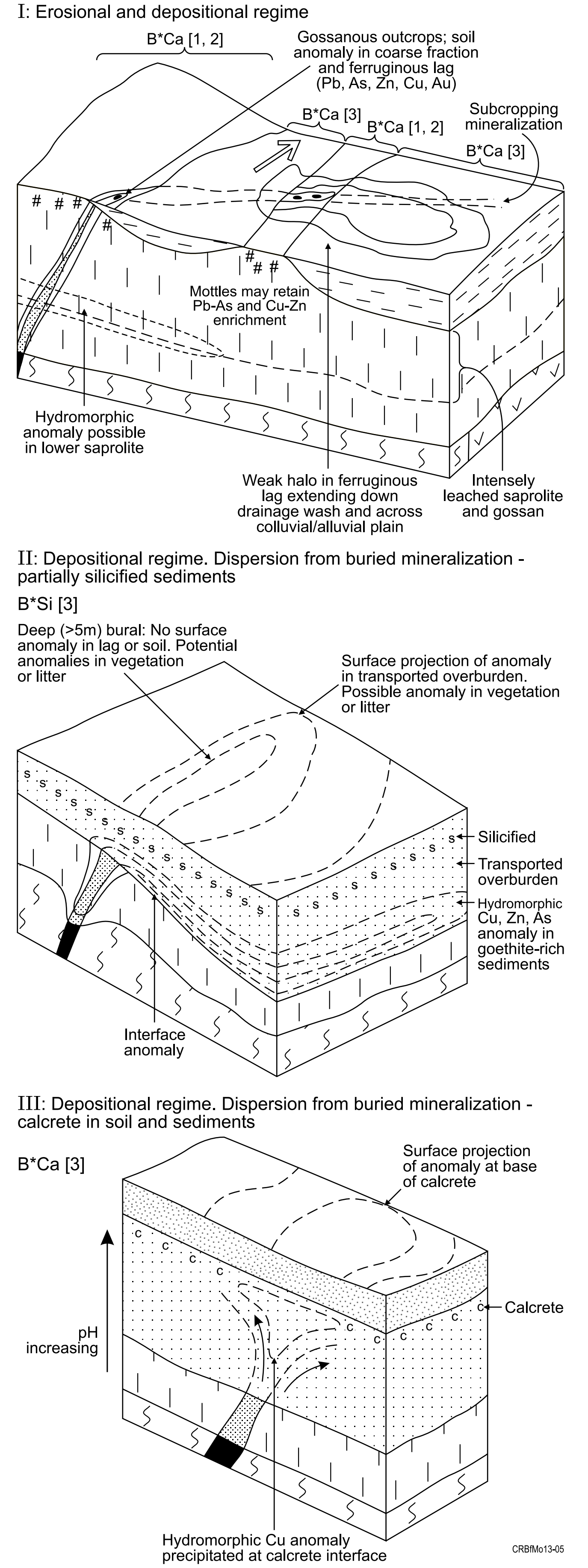


Figure 13. Dispersion model for base metal deposits, Type B, mainly depositional terrain, moderate relief, semi-arid environments. Incomplete or truncated profile, with saprolite concealed by transported overburden. I: hydromorphic dispersion in saprolite, clastic dispersion (lag) from outcrop into surficial sediments. II: clastic and hydromorphic dispersion along interface and lower sedimentary units. III: hydromorphic dispersion through sediments, precipitating at a pH barrier. (For legend: see Figure 7).

Depositional regimes - pre-existing profiles preserved, partly truncated or absent

Buried lateritic profile complete (A-type models)

Deposits in this environment have residual profiles with characteristics generally similar to those described for relict environments. The principal examples are Golden Grove (Gossan Hill, *this volume*; Smith and Perdrix, 1983) and Freddie Well (*this volume*), where laterally extensive lateritic residuum continues from outcrop to beneath overlying colluvium and sandplain sediments (Figure 7B). There is a similar situation at Nifty (WA) (*this volume*), with poorly developed and partially eroded lateritic residuum buried beneath sand dunes. This unit is partly exposed in swales, allowing sampling of ferruginous lag. The potential for biogeochemical sampling has not been effectively tested. The relevant dispersion model is illustrated in Figure 12.

- *Soil:* no response to underlying bedrock or mineralization unless transported overburden is less than two metres thick and bioturbation or other mechanisms have introduced anomalous regolith components such as lag.
- *Colluvium, alluvium and other sediments:* no response to underlying mineralization.
- *Lateritic residuum:* similar to relict regimes if well developed; preferred sample medium if available, allowing wide spaced sampling.

Buried lateritic profile truncated or absent (B- and C- type models)

The presence of transported overburden generally greatly reduces or eliminates the surface geochemical expression of mineralization. Possible dispersion mechanisms include clastic dispersion at the old landsurface prior to sedimentation, and later mixing by bioturbation, biogeochemical cycling by vegetation, and hydromorphic dispersion by shallow groundwaters along the unconformity or into the sediments. However, rarely have these been shown to yield significant anomalies in surface media if the cover is greater than about 3 m thick, generally less, with partial analysis offering no obvious advantage.

Lag sampling may show considerable dispersion (*e.g.,* 5 km down drainage from Elura (NSW): Dunlop *et al.,* 1983), but is generally most effective in semi-residual soils closer to the source (P4 anomaly and Pipeline Ridge, Cobar (NSW); Nifty (WA); all *this volume*). Lag sampling is much less effective where cover is thicker and, at best, may result in district scale anomalies that require drilling to saprolite for local target definition. Elsewhere, there is no relationship between surface lag and basement rock concealed by colluvium (*e.g.,* see also Quasar Au deposit (WA) (*this volume*). Partial extraction analysis of lag, such as at P4 and LP3, near Cobar (*this volume*), does not appear to provide advantages over total analysis, and may repress strongly bound elements. Higher leachable Cu, Zn, Tl and Sb concentrations at P4, and Ag, Hg, Mo at LP3, may reflect different host minerals rather than downslope hydromorphic dispersion. Similarly, soil sampling is generally ineffective in areas of colluvial-alluvial cover (*e.g.,* Little Eva (Qld) *this volume*), although vegetation (Freddie Well (WA); Flying Doctor (NSW); both *this volume*) and, particularly, litter sampling show promise. There is a significant multi-element response (Zn, Cu, Pb, Cd, Ag, In) in litter at the Jaguar VMS deposit (WA), where the up-dip extension of mineralization is concealed by 15 m of colluvium (Anand and Cornelius, 2005). Degradation of the litter does not appear to contribute these metals to the soil.

The hydromorphic dispersion anomalies at the unconformity and in cover sediments at Waterloo (Qld) (*this volume*), Thalanga, Qld (Granier *et al.,* 1989), Dalgaranga, WA (*this volume*), Moonta, SA (Mazzucchelli *et al.,* 1980) and Poona, SA (*this volume*) offer broad targets that may be encountered in scout drilling. The anomalies at Waterloo, Moonta and Poona are related to metal precipitation at the pH barriers of horizons rich in carbonate. In their absence, however, drilling to saprolite is the only option, with the provisos related to equivalent erosional terrain, *i.e.,* narrow targets and strong depletion to 10-30 m, but with the possibility of lateral dispersion at greater depth.

The dispersion models relevant to truncated residual regolith in depositional terrains are summarized in Figures 13 A, B and C: -

- *Vegetation and litter:* multi-element responses possible, but not necessarily present everywhere.
- *Soil and lag:* response unlikely in arid areas unless part of the mineralized sequence is concealed by less than about 2 m of transported overburden. Lag anomalies may extend 1-5 km down-drainage from outcrop or near-outcrop. Partial analysis does not appear to convey advantage.
- *Seepage areas*: downslope hydromorphic dispersion into soil developed from overburden may occur in humid areas or where the water-table is near surface, at or above the unconformity. Such enrichment may be highlighted by partial analysis if currently active.
- *Overburden:* enrichment in ore-derived elements is possible if accreting sediments are derived from erosion of adjacent mineralized rocks, or by hydromorphic dispersion from ongoing weathering of mineralization sub-cropping at the unconformity. Hydromorphic enrichment is most probable at redox boundaries – *e.g.,* past or present water-table, and at or above the interface/unconformity.
- *Interface:* mechanical dispersion before and during sedimentation, and hydromorphic dispersion at or above the interface/unconformity potentially provide an optimal sampling target.
- *Calcrete:* carbonate precipitated in the overburden will dilute existing response, but Cu and Zn dissolved in acid groundwater may themselves precipitate at the pH barrier of the lower contact.

EXPLORATION MODELS FOR BASE METAL DEPOSITS – TERRAIN DOMINATED BY BASIN SEDIMENTS

Geological setting

Sedimentary (and volcanic) rocks that overlie mineralized basement present a considerable barrier to exploration in many regions of Australia. Examples include Proterozoic sequences overlying the northern continuation of the Archaean Yilgarn Craton, the Middle Proterozoic Kombolgie Sandstone overlapping U-mineralized Lower Proterozoic schists in the Alligator Rivers region, NT (*this volume*), and Cambrian to Cretaceous sediments concealing mineralized Proterozoic rocks in the Mt. Isa Region (Qld), and the Curnamona (NSW, SA) and Patterson (WA) Provinces. The cover sequences may have partially or wholly buried the basement rocks; subsequently, some sediment cover has been eroded. The weathering history is also complex, with some prior to sedimentation, but the strongest weathering occurring after uplift and exposure, during the late-Cretaceous to early Tertiary and subsequent periods. These episodes affected both the sediments and the underlying basement, offering the potential for hydromorphic dispersion of ore-related metals into the cover sequences. Contemporaneous erosion has partially exhumed the basement rocks, exposing them directly to weathering at different stages. The result is a landscape having: -

continuously exposed, exhumed and buried basement rocks that have undergone varying intensities of weathering and, in eroded areas, partial stripping;

weathered and locally eroded cover sequences;

areas with younger transported overburden of various types, including black soil plains, concealing basement and cover rocks.

The basement rocks that have been continuously exposed may have complete or truncated weathering profiles, and mineralization will have a surface expression similar to those in terrains with no cover sediments. The regolith on exhumed basement is characterized by truncated profiles, similar to those on continuously exposed rocks. However, if sedimentary cover dominates the region, and there is extensive, younger transported overburden, exhumed rocks may be difficult to recognize. The cover sequence may also have complete or truncated weathering profiles, which may influence any geochemical expression of buried mineralization.

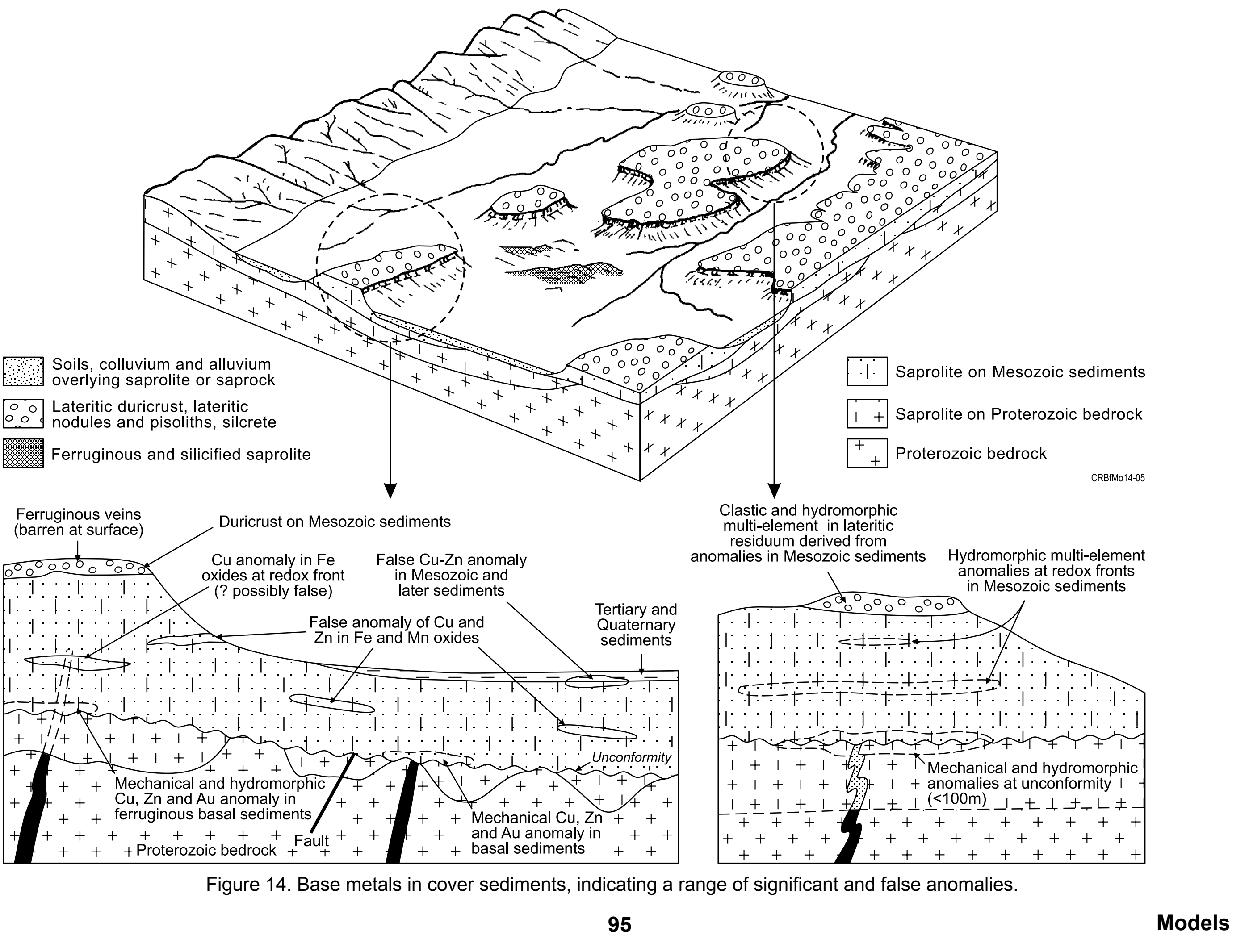


Figure 14. Base metals in cover sediments, indicating a range of significant and false anomalies.

Fresh and weathered basement rocks concealed by weathered sedimentary rocks

Geochemical exploration in covered areas depends on the possible presence of dispersion through the sediments or leakage along faults or fractures, but may be complicated by the presence of high metal backgrounds in the sediments themselves. The best documented examples from such terrains are of base metal and Cu-Au mineralization in the Mt. Isa Region, concealed by up to100 m or more of Mesozoic sediments, which serve as the basis for the model. Anomalous concentration of base metals and Au in the sediments may be exposed by erosion or encountered during drilling as a follow-up of geophysical targets. Some of the most prominent anomalies occur at Osborne (*this volume*), interpreted to be due largely to weathering of sulphide mineralization that continued during submergence in a marine environment, with hydromorphic dispersion into the sediments as they accumulated. Further mobilization occurred during diagenesis and, following emergence, sub-aerial weathering. This has resulted in sub-horizontal zones of enrichment (Cu, Au, Ag, Zn, Mo, Co) at and below the present landsurface, at ferruginous horizons representing redox fronts in the sediments, and at the unconformity. It is uncertain how widely this process has occurred the region.

Accumulation and further lateral dispersion in uppermost mottled saprolite and lateritic residuum on the sediments emulates A-type models on emergent residual terrain. Re-working under recent conditions has given rise to responses to partial extraction techniques. Similar accumulation of Cu and Zn with Fe oxides within the sediments, though not at surface, was noted in the same region at Brumby (Anand *et al.,* 1997). Multi-element (Cu, As, Zn, Sb, Au) anomalies occur in basal sediments and at the unconformity at Eloise (*this volume*) and Brumby. The multi-element responses in the basal sediments, due to a combination of clastic and hydromorphic dispersion, represent a useful target for exploration sampling, especially where the sediments (and the underlying Proterozoic rocks) are fresh or little weathered. Metal-rich horizons in weathered sediments, higher in the sequence, can also be targeted, particularly by specifically sampling ferruginous units and fragments. However, these are less certainly related to mineralization. Zinc and Cu, concentrated in Fe (and Mn) oxides at redox fronts, may be derived by leaching from the sediments, and be unrelated to any basement mineralization. This is seen at Tringadee (*this volume*) and possibly at Brumby. Such anomalies may be distinguished as false by regression analysis or by the absence of a multi-element signature – but with no certainty if the primary mineralization itself lacks other elements, or only Cu and Zn have been mobilized. Conversely, the sediments themselves may have a high, multi-element background, or contain low grade mineralization: this is the case for Cambrian sediments NW of Mt. Isa, which yield strong surface anomalies from economically insignificant sources (*e.g.,* at Century (*this volume*) and the Blinder and Drifter prospects, Anand *et al.,* 1997).

The Bowdens Ag-Pb-Zn deposit (*this volume*), in humid temperate New South Wales, has an equivalent setting. Where mineralization is concealed by only a thin (<5 m) cover of marine sandstones, soils show weak total and partial extraction anomalies; where the sediments are thicker, the response is equivocal.

The dispersion characteristics for terrains dominated by later sediments, summarized in Figure 14, are: -

- *Soils:* where the cover sequence is partly eroded, soils may give surface expression to any base metal concentrations in sediments, including low grade intraformational mineralization, enrichment derived from buried mineralization or accumulations due to weathering.
- *Lateritic residuum on cover sequence:* potentially gives surface expression to ore-derived metals dispersed into cover sequence.
- *Cover sequence:* ferruginous veining and mottling, mainly at redox fronts, may host multi-element anomalies resulting from syngenetic and epigenetic dispersion during sedimentation, diagenesis and weathering. Leaching of Zn and Cu, with co-precipitation with Fe and/or Mn oxides, may give distal hydromorphic anomalies, or false anomalies, at redox fronts.
- *Unconformity and basal sediments:* may host multi-element anomalies due to clastic and hydromorphic dispersion from mineralization during and after sediment deposition.
- *Sedimentary cover rocks:* generally weathered throughout, but not strongly towards the base, especially if > 60m thick. The sediments themselves may have high background metal abundances or host low grade mineralization.
- *Basement rocks:* fresh at unconformity, or variably weathered. Secondary dispersion probably minimal in weathered basement. Mineralization is concealed, with no direct surface expression.

EXPLORATION MODELS FOR GOLD DEPOSITS

Occurrence and weathering

Gold deposits, of different types and age, occur in a wide variety of environments throughout Australia. Many of them have undergone deep weathering, others are the products of deep weathering or erosion, whereas some, principally in areas of high relief, are almost unweathered. Many are exposed at surface; others have been buried, before, during or after deep weathering. These factors have considerable influence on their surface expression, which may be dominated by past or present dispersion processes, or be a combination of several dispersion processes. Variations in Au distribution in deeply weathered, lateritic regoliths in different environments are due to the similarities imposed by the initial deep weathering and differences in the modifications imposed by later events, principally those that have affected the salinity of the groundwater.

Gold mobility during lateritic deep weathering

The formation and evolution of deeply weathered, lateritic regoliths may result in the mobilization and redistribution of Au and have considerable significance to the surface expression of mineralization (Butt, 1988; Gray *et al.,* 1992). During lateritization in seasonally humid, warm to tropical climates, oxidation at the weathering front deep below the water-table produces neutral to acid conditions, with lower pH favoured by felsic rocks and high sulphide contents. Gold associated with tellurides or held in the lattice of the sulphides and other minerals may be released, but the free metal remains largely immobile due to the absence of suitable complexing ligands. Thiosulphate ions, which can complex Au, are formed only by sulphide oxidation in neutral to alkaline conditions, and concentrations of chloride ions and organic matter are very low. Accordingly, although some corrosion and reduction of size occurs, primary Ag-rich grains persist through the saprolite and into the ferruginous zone, and lateral dispersion into saprolitic wallrocks is minimal. Gold (and Ag) may be mobilized, however, if high concentrations of carbonate are present in the primary mineralization, because the oxidation of pyrite in such an alkaline environment produces thiosulphate. Lateral dispersion of Au is evident towards the top of the profile, particularly in the lateritic residuum and mottled horizons. This is due to (i) residual concentration, colluvial transport and surface wash of Au grains during landsurface reduction and (ii), to mobility, either in solution or as particulates (*e.g.,* colloids or very fine grains of free metal). Some Au may also be contributed directly to the soil in litter after uptake by plants. Reduction of the complexes results in incorporation of fine-grained Au with low Ag contents in Fe oxides, particularly in the lower part of the lateritic residuum and in the mottled zone. The resultant Au distribution in the residual regolith is typical of deposits in the humid tropics (Mborguéné, Cameroun, and Banankoro, Mali: Freyssinet *et al.,* 1989 a,b; Freyssinet *et al*., 2005).

Such mechanisms can account for the formation of lateritic Au deposits and Au anomalies, with their mixture of high and low fineness Au, and the presence of ore-grade oxidized mineralization through the saprolite. This distribution is preserved under other conditions, including arid climates, if the groundwater remains non-saline (*e.g.,* Bronzewing, *this volume*). However, if factors such as the lowering of the water-table, dehydration of the upper horizons and poor drainage under arid conditions cause sufficient concentration of alkalis and alkaline earths for salinity to develop, they may permit considerable mobility and redistribution of Au in the regolith through the formation of soluble Au halide (mainly chloride) complexes. Widespread salinity is a feature of semi-arid Australia, approximately S of latitude 30ºS; further N, salinity is restricted to major drainages. The cause of this distribution is uncertain, but may be a function of climate (*e.g.,* winter versus summer rainfall), gradients and drainage (Butt *et al.,* 1977; Gray, 2001), and it is in these southern regions that supergene Au mobility is most marked. The change from humid savanna to arid climates over much of Australia has occurred since the mid-Miocene or earlier, but with several reversals to humid climates, temporarily restoring conditions conducive to deep weathering. Accordingly, lowering of the water-table has been punctuated by still-stands or temporary rises. Such events have great significance for, under these circumstances, the increased rainfall leaches precipitated salts and recreates redox conditions suitable for ferrolysis, thus producing acid and saline groundwaters which, if strongly oxidizing, become capable of dissolving Au (Mann, 1983, 1984). In the eastern Darling Range (WA), for example, recent humidity has resulted in active ferrolysis and leaching by saline waters; in nearby agricultural districts, a rise in water-table caused by clearing has mimicked such climatic change. During these humid periods, therefore, Au may be dissolved and mobilized from upper regolith horizons, precipitating at depth in response to a rise in pH, dilution of the chloride concentration or reduction of the Au chloride by ferrous iron. Each of these reactions may occur when solutions percolating through the unsaturated zone reach the water-table. Ferrous iron oxidation may also occur at the interface between an upper oxidized aquifer and a lower reduced aquifer, resulting in enrichment below the water-table. The secondary Au is typically of very high fineness, containing 0.5% Ag or less.

These mechanisms account for strong Au depletion from the upper horizons of the regolith (below lateritic residuum) and enrichment deeper in

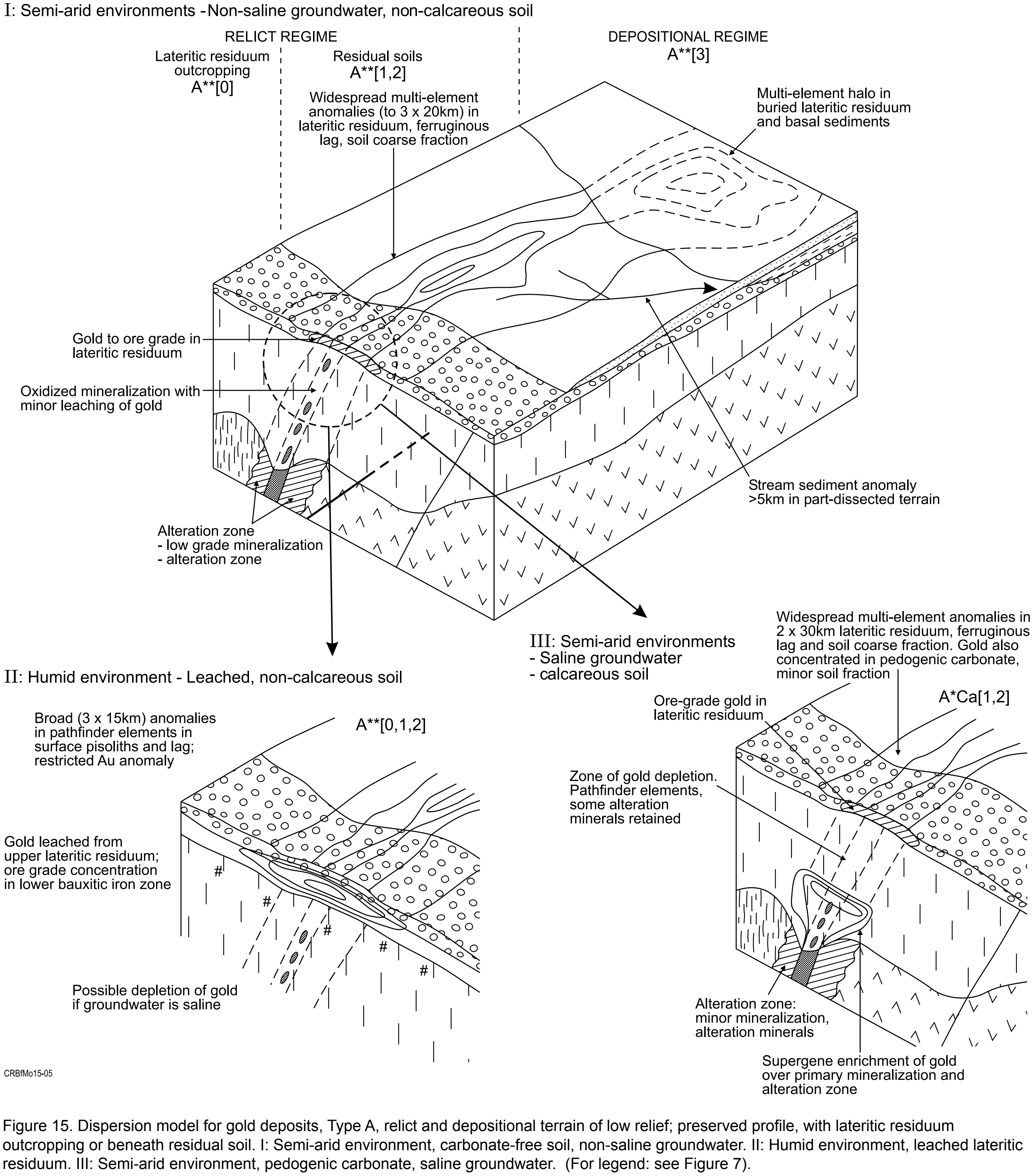


Figure 15. Dispersion model for gold deposits, Type A, relict and depositional terrain of low relief; preserved profile, with lateritic residuum outcropping or beneath residual soil. I: Semi-arid environment, carbonate-free soil, non-saline groundwater. II: Humid environment, leached lateritic residuum. III: Semi-arid environment, pedogenic carbonate, saline groundwater. (For legend: see Figure 7).

the saprolite of primary mineralization and the alteration zone. Despite earlier indications to the contrary (*e.g.,* Butt, 1989), there is generally little lateral Au dispersion in saprolite. The flat-lying zones of supergene enrichment are coincident with the mineralization and associated alteration zone. Lateral dispersion is most probable in highly saline environments, especially in palaeochannels, where supergene enrichment may be in oxidizing or reducing sediments, or in the saprolite beneath the channel, although generally proximal to primary mineralization in bedrock.

Where the profile has been preserved, the widespread halo in the lateritic residuum is retained, whether at surface or buried (*e.g.,* Boddington, Mt Gibson: both *this volume*). Where the regolith has been truncated, leaching of the upper horizons may still have occurred, so the near-surface expression of mineralization is minimal, although the supergene enrichment is present (*e.g.,* Panglo, *this volume*). In semi-arid regions, pedogenic carbonates typically occur where there is pervasive salinization of groundwater. Recent mobility of Au and accumulation in carbonates may give surface expression to concealed mineralization, even where there has been strong depletion and a thin cover of transported overburden.

Relict landform regime – pre-existing profile preserved (A-type models)

This regime generally typifies upland areas of an undulating landscape in which the complete weathered profile is preserved. The surface exposure consists of lateritic residuum, including pisolitic and nodular gravels and lateritic duricrusts, or a semi-residual soil overlying these materials. Residual accumulation and lateral dispersion have resulted in widespread geochemical patterns in soil, lateritic residuum and mottled zone related to concealed mineralization. These may be due to hydromorphic processes during weathering (especially As, Au), or clastic dispersion, during and after deep weathering, of primary and secondary Au grains and pathfinder elements (*e.g.,* As, Sb, Sn, W) hosted by resistant minerals or gossan fragments. Examples include Mt. Dimer and Mt. Gibson (both *this volume*); Nimary-Jundee, WA, (Lewington 1995 and Wright and Herbison, 1995); Redback-Dogbolter, NT (Henderson *et al.,* 1995), at each of which the lateritic residuum itself has been a mineable resource. At Boddington (*this volume*), the pathfinder elements give a stronger and more extensive anomaly than Au. The surface expression closely resembles those of deposits in the humid tropics because, under the present humid conditions, Au is strongly leached from soil and the upper horizons of lateritic residuum (means 80-150 ppb), and concentrated deeper within it, in the bauxite horizon (mean 2 ppm). At both Boddington and Plutonic, WA (Bucknell, 1975), which is in an arid area, the dispersion haloes extend for up to 5 and 12 km, respectively, in stream sediments containing lateritic debris. In southern, semi-arid areas, Au is hosted by pedogenic carbonates as well as ferruginous pisoliths and nodules (*e.g.,* Mt. Percy, Mt. Gibson; both *this volume*). The distributions of associated base metals are similar to those observed over base metal deposits; for example, at Boddington, severe leaching has resulted in mean Cu contents of 20-70 ppm in lateritic residuum even though primary and supergene mineralization contain over 1% Cu.

Deeper in the profile, where the groundwater has remained non-saline, there has been little depletion of Au and no significant supergene enrichment. Residual Au retains its primary (Ag-rich) composition and is present throughout the saprolite. In contrast, where groundwater is saline, Au is severely leached from the upper saprolite but may be concentrated at depth, as Ag-poor secondary particles. The sub-horizontal zones of supergene enrichment represent a broad exploration target, but their lateral extent is little greater than that of the primary mineralization and the alteration zone. The principal pathfinder elements (*e.g.,* As, Sb, Bi, Mo, W) appear to be little affected by leaching by saline groundwaters and, if present, remain at anomalous concentrations through the Au depleted zone.

The dispersion model (Figure 15) has the following characteristics: -

In all environments:

- *Lateritic residuum:* commonly pisolitic or nodular, cemented with depth. Widespread (500-1500 m) multi-element anomalies, in Au and pathfinder elements (As, Sb, Bi, Mo, W). Mean Au concentrations commonly exceed 1 ppm above primary mineralization. At surface, dispersion of all elements is dominantly clastic, in resistant minerals and Fe oxides, during past and present weathering episodes. Hydromorphic dispersion of Au and As at the base of lateritic residuum is mainly related to deep weathering events. Copper and Zn are strongly leached.

- *Saprolite:* pathfinder element abundances remain anomalous throughout, with some homogenization of distribution but with little lateral dispersion. Resistant alteration minerals (*e.g.,* muscovite, and W- and Sb-bearing rutile; Scott and Radford, 2005) retained throughout saprolite; muscovite may give detectable radiometric and spectroscopic signatures. Target in saprolite is narrow compared to that in soil and lateritic residuum.

In humid regions:

- Gold may be leached from soil and surface horizons of lateritic residuum, but pathfinder elements give widespread anomalies.

In arid regions, with non-saline groundwater:

- *Residual soil or upper lateritic residuum:* widespread multi-element anomalies, in Au and pathfinder elements (As, Sb, Bi, Mo, W) at surface .

- *Saprolite:* Au remains at similar concentrations to that in the primary mineralization and alteration zone, with no depletion or supergene enrichment.

In arid regions, with saline groundwater:

- *Soil or upper 1-2 m of lateritic residuum:* pedogenic carbonate may host 50% of total Au.

- *Plasmic zone-upper saprolite:* strong depletion of Au (<100 ppb) over primary mineralization, to 15->50 m depth, with sharp rise to ore-grade in supergene enrichment zones. The depth of depletion and degree of enrichment are greater with increasing salinity.

Pre-existing profile partly truncated (B-type models)

This regime typically occurs in areas of low to moderate relief where the uppermost horizon of the profile is saprolite (B-type models), locally eroded to fresh rock (C-type models). In arid areas, the soil is generally poorly developed and may be strewn with ferruginous lag where less deeply truncated. Truly residual soils are probably restricted in extent, especially where the relief is low; sheetwash and aeolian input result in the addition of exotic material to give semi-residual soils or a thin cover of essentially transported material even in erosional landscapes. Where there has been little erosion of the profile, multi-element anomalies in ferruginous lag may extend for 300-500 m across erosional plains (*e.g.,* Bottle Creek, Redeemer and Cox-Crusader, Yilgarn Craton; all *this volume*). In areas of higher relief, with greater erosion and a connected drainage network, multi-element anomalies are detectable for 1-3 km; examples are the Cu-Au deposits (discussed below) in the dry savannas of the Drummond Basin, Queensland, such as Mt. Leyshon, Pajingo and Yandan (all *this volume*). In these areas, and wherever groundwater is non-saline, Au in the saprolite appears to have been little affected by weathering. Gold grains are etched and rounded but of primary (Ag-rich) composition and there is no significant lateral dispersion, so that mineralization presents a small target. Even where supergene depletion of base metals has occurred, the Au distribution is unaffected (*e.g.,* Mt. Leyshon). Because soils are developed from saprolite, anomalies tend to be restricted in size, but are of high contrast. Both coarse (>500 μm) and fine (<75 μm) fractions are effective, emphasizing Fe oxide and clay components, respectively, but reducing much of the aeolian input. Pathfinder elements are retained through the saprolite (*e.g.,* As and Sb may concentrate in Fe oxides in highly leached saprolite on felsic rocks at Parkinson (WA), *this volume*). Rutile may stabilize elements like W and Sb (Scott and Radford, 2005). Gold may, however, be leached from gossans over sulphide-rich mineralization (*e.g.,* Calista (WA), *this volume*). Groundwaters have low abundances of all elements; their value as a sample medium requires further testing.

By comparison, in areas with saline groundwaters in southern Australia, mobility of Au has led to depletion from the upper saprolite and enrichment in the lower saprolite. Much of the Au is secondary and may show evidence of several episodes of solution and redeposition. Despite the strong leaching, however, mineralization may have a surface expression in residual soils, due to the concentration of Au in pedogenic carbonates – with many examples in the Yilgarn and Gawler Cratons (Aphrodite, Bounty, Birthday, Challenger, Junction, Panglo, all *this volume*), and potentially in parts of New South Wales and Victoria. Because of the high solubility of Au in carbonates, there can be broad, low level Au anomalies (>3-5 ppb) that extend for 300-1000 m from mineralized systems (*e.g.,* Challenger, Junction). In the Gawler Craton, in particular, such dispersion was targeted by regional calcrete surveys, sampling on 500-1500 m centres. Within such broad regional anomalies, drill targets may be defined by higher contrast local anomalies (threshold 20-25 ppb Au, maxima >200 ppb Au) that may extend only 50 m from the subcrop of mineralization, and which require detailed sampling for follow-up. In places, however, the dispersion due to the high mobility may obscure such a focus. Conversely, carbonate is a diluent to other soil components, hence pathfinder element concentrations are suppressed. Groundwaters may have anomalous Au abundances (0.01-3.0 ppb) within 1-2 km of mineralization, but pathfinder elements are generally below detection (*e.g.,* Junction, Panglo).

As in regions where the profile is preserved, follow-up sampling of the saprolite must account for the lack of secondary dispersion and, where there are saline groundwaters, for the probable near-surface depletion of Au.

In areas with carbonate-free residual soils and non-saline groundwater (Figure 16):

- *Stream sediments:* multi-element (Au ± As, Sb, W, Mo, Bi) drainage trains up to 3-5 km in dissected terrain.
- *Ferruginous lag:* multi-element anomalies extending 300-500 m across erosional plains.

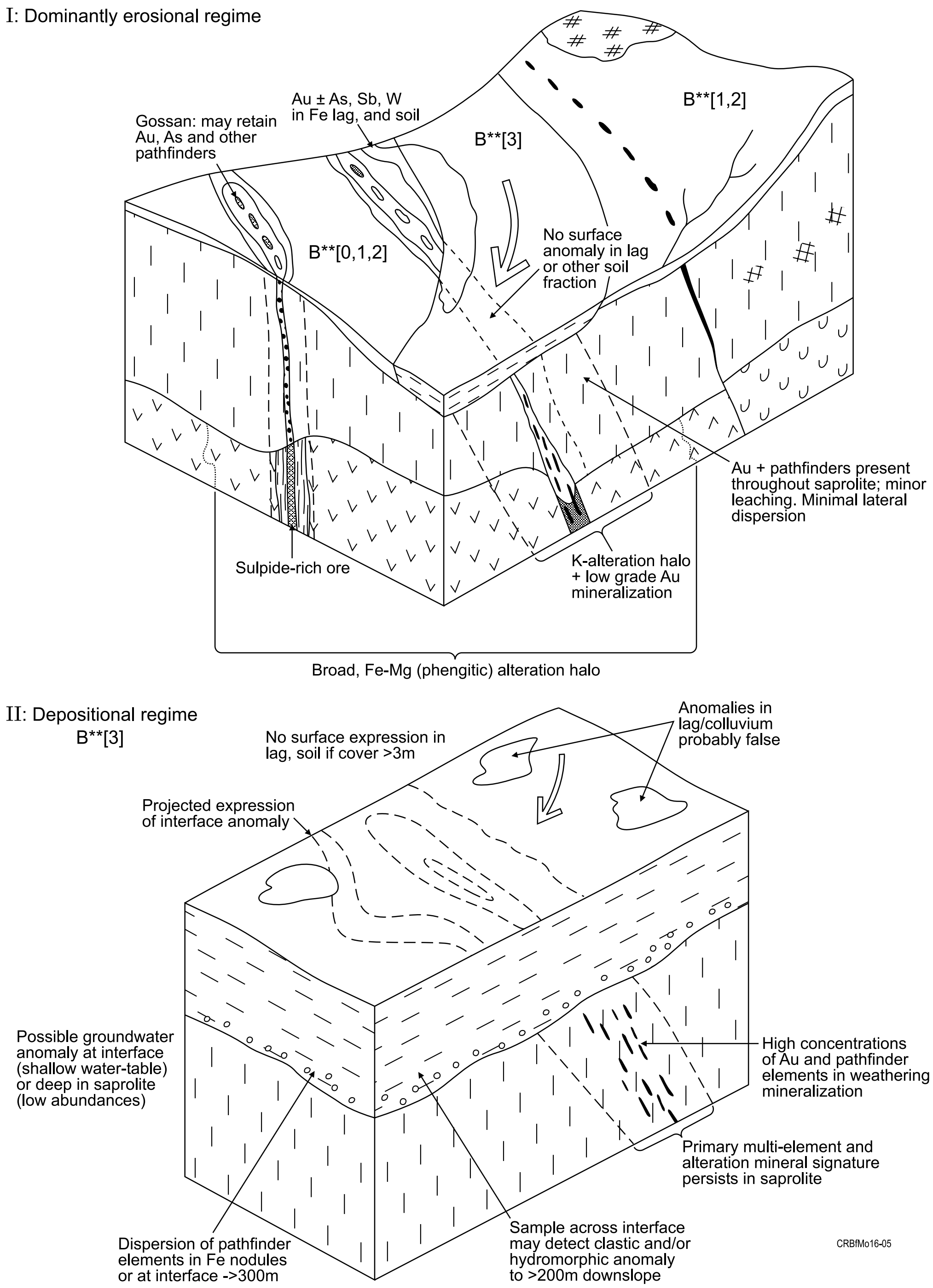


Figure 16. Dispersion model for gold deposits, Type B; carbonate-free soil; non-saline groundwater. I: Erosional and depositional terrains, low to moderate relief; incomplete or truncated profile, with saprolite outcropping, beneath residual soil or shallow transported overburden. II: Depositional regime, shallow alluvium/colluvium overlying saprolite. (For legend: see Figure 7).

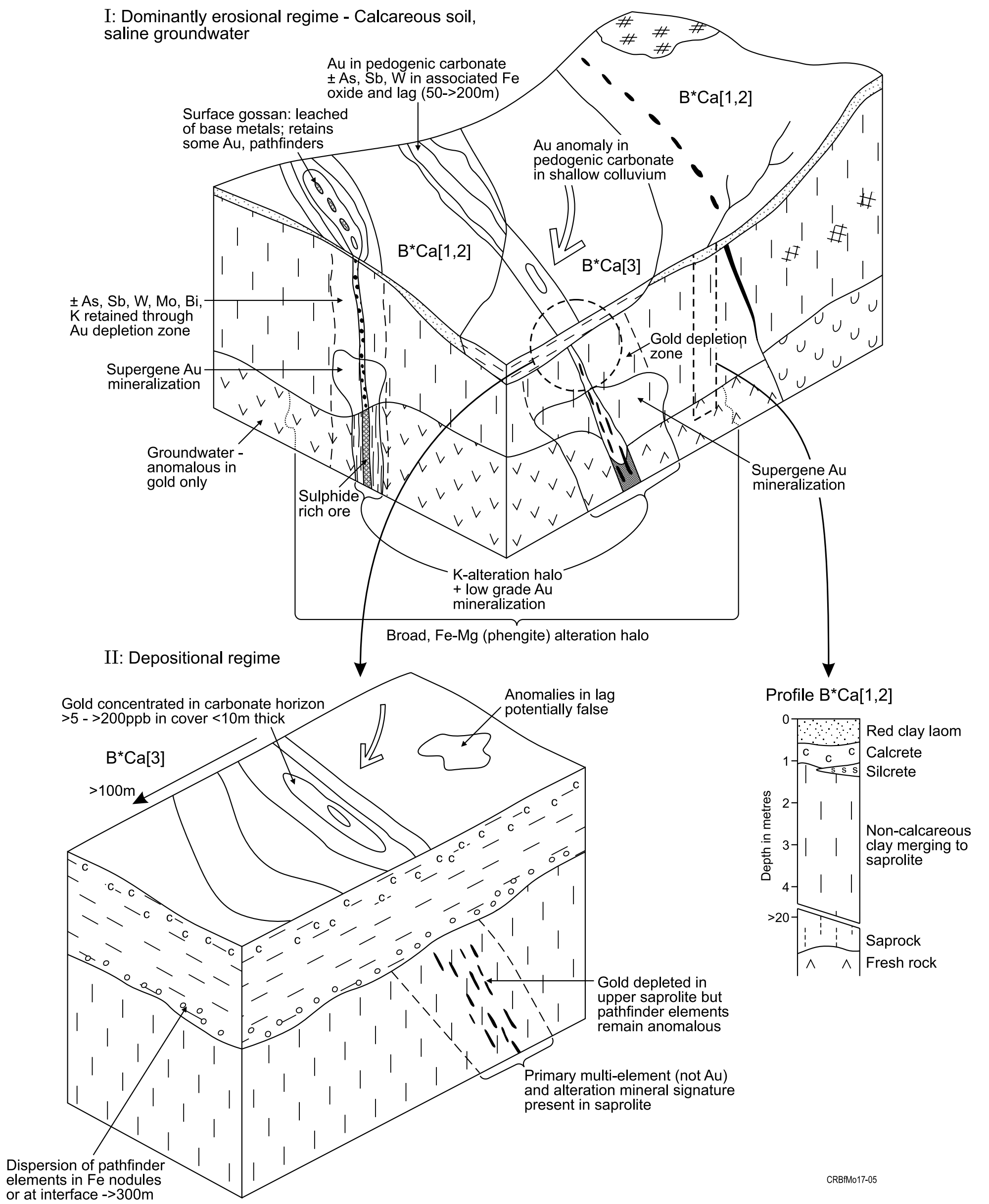


Figure 17. Dispersion model for gold deposits, Type B; calcareous soil, saline groundwater. I: Erosional and depositional terrains, low to moderate relief; incomplete or truncated profile, with saprolite outcropping, beneath residual soil or shallow transported overburden. II: Depositional regime, shallow alluvium/ colluvium overlying saprolite. (For legend: see Figure 7).

- *Soil:* high contrast, multi-element anomalies in coarse and fine fractions, generally with minimal dispersion.
- *Saprolite:* Au and pathfinder elements retained throughout profile, minimal depletion, supergene enrichment or lateral dispersion. Potassic alteration minerals (*e.g.,* K-muscovite) preserved through most of the profile; broader Fe-Mg (phengitic) alteration detectable in lower saprolite and saprock.
- *Groundwater:* low order, multi-element anomalies.

In areas with calcareous residual soils and saline groundwater (Figure 17):

- *Stream sediment and ferruginous lag:* as above.
- *Vegetation:* anomalous responses not always evident.
- *Soil:* Au concentrated in carbonate horizons, generally top 1-2 m, with minimal lateral dispersion at 25 ppb threshold to provide drill targets. High chemical mobility appears to give broad anomalies (>3 ppb Au). Pathfinder element abundances diluted; mainly confined to ferruginous fractions.
- *Saprolite:* severe Au depletion common in upper 10->40 m, with ore-grade enrichment below; effect is greatest with higher salinity, low in the landscape. Pathfinder elements retained throughout profile – possibly only in Fe oxide segregations. Minimal lateral dispersion, but Au enrichment enhances response of low abundances in alteration zone. Potassic alteration minerals (*e.g.,* K-muscovite) preserved through most of the profile; broader Fe-Mg (phengitic) alteration detectable in lower saprolite and saprock.
- *Groundwater:* may give extensive Au anomalies, but no pathfinder response.

Erosional regime - pre-existing profile eroded or not developed (C-type models)

Apart from small, localized areas of outcrop in mostly deeply weathered erosional terrain, sites where there is no significant preservation of a pre-existing regolith occur in areas of moderate to high relief. In hills and mountains in semi-arid areas, due to the slow rate of chemical weathering, dispersion in soils and stream sediments is dominantly mechanical, mainly of Au particles, with other ore-related elements hosted by gossan fragments and resistant minerals (see Winnecke (NT), *this volume*). In more humid areas, hydromorphic dispersion of Au (and pathfinder elements) is suggested by associations of Au with organic matter (*e.g.,* Timbarra (NSW), *this volume*), redistribution in soil profiles (Lefroy-Beaconsfield, *this volume*) and response to partial extraction analyses by BLEG and MMI. The characteristics of the dispersion model are broadly similar to those depicted in Figure 11 for base metals: -

- *Outcropping/subcropping mineralization*: potentially revealed by loaming or prospecting. Any gossans are immature, little leached, with high metal contents, possibly with secondary oxidate minerals (*e.g.,* malachite) and remnant sulphides.

- *Soils*: high contrast, multi-element anomalies, in all size fractions, with dominantly clastic dispersion 200 m or more downslope. Recommended intervals 40 x 400 m, closing to 20 x 100 m. Total analysis preferred.

- *Stream sediments:* anomalies in first and second order streams, all size fractions. Sampling density 3-5 per km^2, from hydraulically consistent sites, with <63 µm fraction to reduce nugget effect. Contamination by old workings potentially significant in many areas. Total multi-element analysis preferred, although BLEG (Au only) is also generally effective.

Depositional regimes - pre-existing profiles preserved, partly truncated or absent

Buried lateritic profile complete (A-type model)

Deposits in this environment have residual profiles with characteristics generally similar to those described for relict environments. The principal examples are Bronzewing, Calista and, in part, Harmony, Fender and Mt. Gibson (all WA, *this volume*), where laterally extensive lateritic residuum occurs beneath colluvium and alluvium, at depths of 2 m to >30 m). There is no evidence for significant hydromorphic dispersion of Au or pathfinder elements into the cover sequence. Anomalous concentrations of these elements within 2 or 3 m of the unconformity appear to be mechanical. A seemingly hydromorphic, multi-element surface anomaly (without Au) directly overlying mineralization at Curara Well (Kirkalocka), WA (*Gray, 1996*), evident in both total and partial extraction analyses, is attributed to co-precipitation with secondary Mn oxides in a modern drainage that overlies the deposit. Hydrogeochemical surveys, however, offer promise (*e.g.,* at Harmony). The relevant dispersion model is illustrated in Figure 15, with the following characteristics specific to depositional regimes: -

Soil: no response to underlying mineralization (neither total nor partial extraction analysis) unless transported overburden is less than two metres thick and bioturbation or other mechanisms have introduced anomalous regolith components such as lag. A possible exception is where soils contain pedogenic carbonates, which may be anomalous in Au if the sediment is <10 m thick.

- *Colluvium, alluvium and other sediments:* no response to underlying mineralization.

- *Basal sediments:* may contain laterally dispersed lateritic gravel, giving broad multi-element response; basal gravels may merge with lateritic residuum.

- *Lateritic residuum:* similar to relict regimes if well developed. Preferred sample medium if available, with Au or pathfinder responses extending up to 500 m downslope, allowing wide spaced sampling but also requiring an understanding of the palaeotopography.

Buried lateritic profile truncated or absent (B- and C- type models)

The presence of transported overburden generally greatly reduces or eliminates the surface geochemical expression of mineralization. Possible dispersion mechanisms include clastic dispersion at the old landsurface prior to sedimentation, and later mixing by bioturbation, biogeochemical cycling by vegetation, and hydromorphic dispersion by shallow groundwaters along the unconformity or into the sediments. However, rarely have these been shown to yield significant anomalies in surface media if the cover is greater than about 2-3 m thick, unless the soil is calcareous.

Where soils are non-calcareous and groundwaters generally non-saline, such as at Fender and Golden Delicious (semi-arid WA), Pajingo and, possibly, Brahman (dry savanna, Qld) (all *this volume*), clastic dispersion during sedimentation has led to Au±As±Sb±W anomalies extending >300 m downslope, mainly in basal sediments. Elsewhere, anomalies are generally confined to the interface, giving low contrast anomalies with little lateral spread (*e.g.,* 150-300 m downslope at Quasar and Chatterbox; *this volume*); any anomalies higher in the overburden tend to be random and derived from a distal source. At Quasar, the colluvium itself has a background abundance of 50 ppb Au. Even in temperate, more humid regions, there does not appear to be any dispersion into sediments, even following detailed studies using different size fractions and partial analyses (*e.g.,* Goornong South and Wyoming: both *this volume*). Conversely, orientation studies at Penny West, WA and Police Creek, Qld (both *this volume*) indicate that post-depositional dispersion can lead to anomalies in overlying soil, but these appear to be exceptions and the mechanisms are not understood.

In areas with calcareous soils and saline groundwaters, in contrast, there can be surface expression of Au mineralization through as much as 5-8 m of transported overburden, based on specific sampling of pedogenic carbonate. There are many examples from the Yilgarn and Gawler Cratons (Aphrodite, Kanowna Belle, Safari, Taurus, Challenger – *this volume*; see also Lintern, 2002). The intensity of the anomalies may vary according to the thickness of the cover, raising difficulties with prioritization. No pathfinder elements contribute to the anomalies, unless the cover is thin (<3 m) and ferruginous granules are collected, either separately or as part of a total soil sample (*e.g.,* Kanowna Belle, *this volume*). Gold is probably derived from particles in the upper saprolite, some possibly translocated upwards by bioturbation, then dissolved and recycled by plants. Beneath this surface enrichment, significant Au depletion is probable in the mid to upper saprolite, similar to erosional areas. Where the cover is >10 m, surface sampling generally gives no response, although at Junction (*this volume*), soil Au in upper channel sediments introduced during sedimentation gives rise to a soil anomaly.

Similar leaching of Au from saprolite occurs in playas and playa margins. However, although the sediments may be thin, they are rich in gypsum rather than there is no pedogenic carbonate and no soil anomaly (model code B*Gy[3], *e.g.*, Hannan South, WA: Lawrance, 2001). Even in highly saline environments such as this, however, pathfinder elements such as As, Sb and W remain anomalous through the saprolite.

The dispersion models relevant to truncated residual regolith in depositional terrains are summarized in Figures 16 and 17

Where soils are non-calcareous and groundwater is non-saline:

- *Vegetation and litter:* Au and multi-element responses possible, but rarely reported.

- *Soil and lag:* response unlikely unless part of the mineralized sequence is concealed by less than about 2 m of transported overburden. Partial extraction analysis does not appear to convey advantage.

- *Overburden:* possible dispersion haloes (>300 m) of Au and pathfinder elements in basal sediments, especially in detrital Fe oxide fragments.

- *Interface:* mechanical dispersion before and during sedimentation, and hydromorphic dispersion at or above the interface/unconformity potentially provide optimal sampling target. Mostly weak, multi-element anomalies, extending 200-400 m from subcrop.

- *Saprolite:* Au and pathfinder elements retained throughout profile, minimal depletion, supergene enrichment or lateral dispersion. Potassic alteration minerals (*e.g.,* K muscovite) preserved through most of the profile; broader Fe-Mg (phengitic) alteration detectable in lower saprolite to saprock.

- *Groundwater:* low order, multi-element anomalies.

Where soils are calcareous and groundwater is saline:

- *Vegetation and litter:* Au and multi-element responses possible, but rarely reported.

- *Soil:* Au concentrated in carbonate horizons, generally top 1-2 m, with minimal lateral dispersion. Local threshold for defining anomalies and drill targets probably <25 ppb Au, decreasing with increased thickness of cover. Pathfinder elements are not mobilized or included in carbonates, and are only present in ferruginous fractions if cover <3 m. There is no response if overburden >8-10 m. Gold anomalies in soil carbonates developed on thicker sediments are probably derived from distally-sourced detrital Au grains.

- *Overburden:* possible dispersion haloes (>300 m) of Au and pathfinder elements in basal sediments, especially in detrital Fe oxide fragments, and at interface.
- *Interface:* mechanical dispersion before and during sedimentation, and hydromorphic dispersion at or above the interface/unconformity potentially provide optimal sampling target. Mostly weak, multi-element anomalies, extending 200-400 m from subcrop.
- *Saprolite:* as for erosional areas, with severe Au depletion common in upper 10->40 m but retention of pathfinder elements retained throughout profile. Minimal lateral dispersion, but Au enrichment enhances response of primary alteration zone.
- *Groundwater:* potential for Au anomalies 10-50 ppt extending >2 km.

Palaeochannel environments

Geological setting

Palaeochannels (inset-valleys) are widespread across Australia. Many, but certainly not all, are within the broad valleys of present drainage and playa systems. The oldest sediments commonly date from the late Eocene or earlier, and hence have been deposited prior to the final phases of deep weathering. This situation is not readily defined in terms of the simple classification of geochemical models given in Table 1. However, here they are regarded as situations in which the original (pre-depositional) deep weathering profile has been truncated and overlain by transported overburden *i.e.,* model B**[3]. The palaeochannels represent a considerable hindrance to mineral exploration due to (i) the area they cover, especially when considered in association with the present drainage systems, (ii) their depth, which may exceed 50 m in the centres of large channels, and (iii) the wide variety of sediments (*e.g.,* unconsolidated sand and gravel, estuarine and lacustrine clay, dolomite beds, lignite, ferruginous gravel and duricrust), which not only represent great differences in physical and chemical environment but also give complex access and drilling conditions. Conversely, they also provide opportunities, because the sediments may host placer and supergene Au deposits (see Ore Deposits, *this volume*) . Historically, deposits in palaeochannels ("deep leads") have been a significant source of Au, including nugget Au. In Victoria, the majority are probably true placers, with the Au being of detrital origin (see Liversidge, 1893). In WA, particularly in the Kalgoorlie region, the origin is less clear. Numerous deposits have been mined, both in the past (*e.g.,* Gibb Maitland, 1919), and in the last 20 years. The deposits are generally subhorizontal and occur in the sediments. However, where palaeochannels with acid, saline groundwaters pass over or close to sub-cropping Au mineralization, they may occur in saprolite beneath or adjacent to the channels. The deposits may be in oxidizing or reducing environments. Although some Au in the sediments may be detrital, most particles are of high fineness and appear to be secondary; many of the oxidized deposits, in particular, resemble supergene enrichments in residual regolith in the same region.

Palaeochannels with fresh to weakly saline groundwater

In WA, palaeochannels occur over parts of the Bronzewing and Harmony deposits, and S of Quasar (all *this volume*). At Bronzewing, a large 40 m-deep channel passes over the Central Zone deposit, but other than enrichment of the basal gravels associated with lateritic residuum, there is no evidence for any significant dispersion into overlying sediments or soil. In contrast, at Harmony, there are two channels that originate close to the deposit. Their sediments have Au, As and W anomalies that may be reflecting mineralization at the district scale or the Harmony deposit itself. No supergene Au enrichments are known in either the sediments or the underlying saprolite in channels where the present groundwaters are fresh to weakly saline, with mostly neutral pH. Similarly, at Northparkes (NSW) (*this volume*), the palaeochannel sediments have zones of patchy Au enrichment towards the base, but there is no supergene enrichment in the saprolite. The relationship between weak As-Pb anomalies in the sediments and the underlying mineralization is uncertain.

Palaeochannels with saline groundwaters

Supergene Au deposits in, or associated with, palaeochannels have been an exploration target in their own right, but may also be indicators of significant primary mineralization. Numerous deposits are known in the Eastern Goldfields region (WA), both in dominantly reduced environments and currently oxidizing environments (although in the past, these sediments too were probably reducing). There have been a number of reports that such deposits have a surface expression. In the southern part of the Panglo deposit (*this volume*), for example, it is possible that a Au anomaly in pedogenic carbonates is reflecting ore-grade supergene mineralization at 40 m depth. The channel sediments, however, are 10 m thick, and there is some minor enrichment at the unconformity and in near-by subcrop. At Baseline, E of Panglo, calcareous soils containing over 50 ppb Au (background 20 ppb Au; maxima >150 ppb Au) are reported to indicate mineralization in saprolite at 20-25 m depth, beneath about 18 m of barren sediments (R. Howard, Pancontinental Mining Ltd., personal communication, 1992). Regional soil sampling also led to the identification of the potential of the Mt. Pleasant and Higginsville districts (*this volume*), but the relationship between any soil anomalies and individual palaeochannel deposits was indirect or absent. Conversely, at Steinway (*this volume*), a soil anomaly (>24 ppb Au, maximum 150 ppb) apparently delineates supergene mineralization in saprolite at 30-40 m depth, beneath about 20 m of sediments. However, soils over the adjacent, shallower, Greenback deposit, which has now been mined, were not anomalous. The relationship between the anomaly and mineralization at Steinway is probably coincidental, with Au derived from another source, such as the outcropping Penfold deposit, 1 km S. Other studies in this region have similarly concluded that these deposits do not have a surface expression, and that any surface anomaly is likely to be derived laterally from nearby outcropping mineralization (Butt *et al.,* 1997). The origin of the Baseline anomaly is uncertain, but similar, adjacent mineralization has no surface expression. These situations are represented by the model depicted in Figure 18.

Although dispersion through thick sedimentary cover in palaeochannels to the surface is not reliably observed, syngenetic and/or epigenetic dispersion into sediments has been recorded at several locations. There are extensive anomalies in sediments in channels entering Lake Carey from Red October and Sunrise Dam-Cleo (both *this volume*). At Red October, Au dispersion (150-200 m) appears to be mechanical, hosted by ferruginous gravel, whereas chemical mechanisms have dispersed Cu, As, Zn and W as cations in saprolite and along the unconformity, and Sb, Mo, Bi, Co and Pb as oxyanions into shallower, more ferruginous sediments. At Cleo, mainly chemical dispersion of Au (20->100 ppb) extends for over 500 m in a 10-15 m thick unit above the unconformity. This dispersion is within currently oxidized sediments but, at the nearby Sunrise deposit, Au enrichment in redox fronts immediately overlying reduced sulphidic sediments indicates a complex sequence of physical and chemical dispersion events (Lawrance, 2005), similar to those in the lignitic sediments at Mulga Rock palaeochannel (*this volume*). Reduced sediments and saprolite also occur at Swordfish, WA, and Portia, NSW (*this volume*); these have multi-element anomalies associated with sub-cropping mineralization. Detrital Au occurs at the unconformity, preserved from mobilization by the reducing conditions. In none of these sites is there any detectable anomaly at surface, in any element.

EXPLORATION MODELS FOR COPPER-GOLD DEPOSITS

Occurrence and weathering

Copper-gold deposits, particularly Cu-Au-Mo porphyries, have some specific geochemical characteristics as well as features similar to those of base metal sulphide deposits and Au deposits, especially those associated with disseminated sulphides. Most porphyries occur in the Phanerozoic fold belts of eastern Australia, but the Archaean Boddington deposit (WA) (*this volume*) is similar. A significant feature of several deposits is the extreme leaching of Cu from the upper regolith and its enrichment at depth, as oxidate minerals (sulphates, carbonates, native

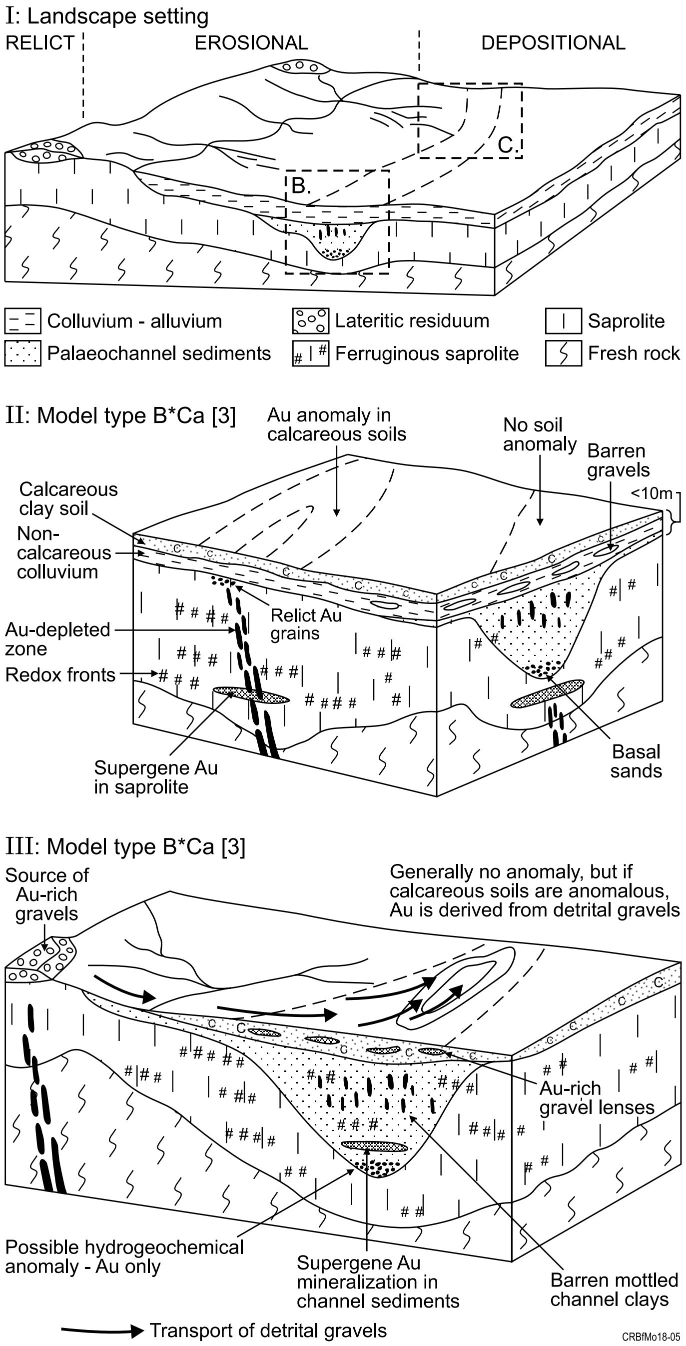


Figure 18. Model for gold dispersion in depositional areas with buried palaeochannels, calcareous soil, saline groundwater. I: Generalized landscape; II: Development of Au anomaly in pedogenic carbonate from relict Au grains in area of shallow (<10 m) overburden. III: Spurious anomaly over palaeochannel mineralization, developed from Au grains in detrital gravels.

metal), supergene sulphides (*e.g.,* chalcocite) and native Cu. Such enrichment, of course, is characteristic of porphyry Cu deposits worldwide, in all climatic environments. In comparison, Au distribution varies according to the weathering history of the regolith, as described in the previous section. In humid environments, leaching of Au mainly occurs from the soil and upper horizon of the lateritic residuum, to be concentrated in the lower horizons (especially duricrust) of the laterite, as at Boddington. Below this, there is little loss throughout the upper saprolite even though Cu is strongly depleted, and shows little or no enrichment with supergene Cu. In more arid environments, leaching of Au from soil is less, and high concentrations are maintained throughout the lateritic residuum. Gold is thus an effective pathfinder for Cu mineralization where Cu has been leached during weathering. Gold redistribution in saprolite would only be anticipated where groundwaters are saline; this has not been reported specifically from porphyry Cu-Au deposits.

Relict landform regime – pre-existing profile preserved (A-type models)

This regime generally typifies upland areas of an undulating landscape in which the complete weathered profile is preserved. Boddington, WA (*this volume*) is the only example of a deposit in this landscape environment. The surface exposure consists of lateritic residuum, including pisolitic and nodular gravels and lateritic duricrusts, or a semi-residual soil overlying these materials. As described above, residual accumulation and lateral dispersion have resulted in widespread geochemical patterns in soil, lateritic residuum and mottled zone of Au and associated pathfinder elements (*e.g.,* As, Mo, Sb, W), but Cu contents are very low (means 20-70 ppm). Because of leaching under present humid conditions, the pathfinder elements give a stronger and more extensive anomaly than Au in lateritic gravels and lag. Dispersion halos in stream sediments extend up to 5 km (Au) and 12 km (As). In saprolite, Au and pathfinder element abundances remain similar to those in bedrock mineralization; variations in the regolith described previously to be due to supergene depletion and enrichment (Davy and El-Ansary, 1986) are now thought to reflect primary controls (Symons *et al.,* 1990). Copper, however, is strongly leached from the upper saprolite, but is concentrated (>1% Cu) at the base of saprolite in a zoned assemblage of malachite, cuprite, native Cu and chalcocite, with some native Ag and Au (Symons *et al.,* 1990), similar to supergene zones typical of porphyry deposits elsewhere. The dispersion model is essentially that depicted in Figure 15, with the specific variation related to the Cu distribution.

Erosional landform regime - pre-existing profile partly truncated (B-type models)

Many of the epithermal and porphyry Cu-Au deposits in the Tasman Fold Belt occur in areas of moderate to high relief, in climates ranging from savanna to temperate. They have fairly prominent surface expressions in outcropping saprolite, soil and stream sediments, commonly with supergene Cu enrichment deep in the profile. At Mt Leyshon (*this volume*), a multi-element anomaly in saprolite is dispersed 100-300 m downslope in residual and colluvial soil. There is also a strong Au response, with Cu-Pb-Zn, extending for 3 km in stream sediments by BLEG and total analyses. Gold distribution in the regolith is typical of dry savanna environments, with little depletion or enrichment. Copper Cu is leached from the upper saprolite, but there is 2-20 m of supergene Cu mineralization (1-2% Cu in chalcocite, digenite, bornite and covellite) is present deeper in the regolith. Pajingo and Yandan (both *this volume*), in the same region as Mt. Leyshon, have similar surface responses, but little or no supergene mineralization.

Similar surface responses and supergene enrichment occur in more humid savanna areas, *e.g.,* Mt. Cannindah (Fletcher, 1980) and Ajax (Large, 1980), and in temperate regions further S (Thursdays gossan and Copper Hill (NSW); Dogwood (Vic); all *this volume*). In each case, Cu contents in surface media are commonly strongly leached compared to supergene and primary mineralization, but Au, Mo, Pb and/or As are retained. In many deposits, stable alteration minerals (e.g. K-muscovite) are evident in saprolite and may remain to surface, potentially detectable hyperspectrally at scales ranging from airborne surveys to sample logging. Radiometric response to such minerals are reported at the Ajax Cu-Zn-Ag prospect (Large, 1980), Copper Hill and Northparkes (Dickson and Scott, 1997) and Hill 800 (*this volume*), implying that such an approach would be successful. The dispersion model is illustrated in Figure 19.

- *Stream sediment:* multi-element anomalies (Au, BLEG Au, Cu, Pb, Zn) extending 2-4 km.
- *Gossan, rock chip and soil:* strong multi-element anomalies (*e.g.,* Au, Pb, As, Mo), with Cu strongly leached relative to primary concentrations. Clastic anomalies for 100->300 m occur downslope, with hydromorphic seepage anomalies (Cu, Zn) in humid regions. Resistant potassic alteration minerals may give surface hyperspectral or radiometric response.
- *Saprolite:* Cu intensely leached from upper saprolite (<500 ppm), but concentrated in secondary oxidate minerals and supergene sul-

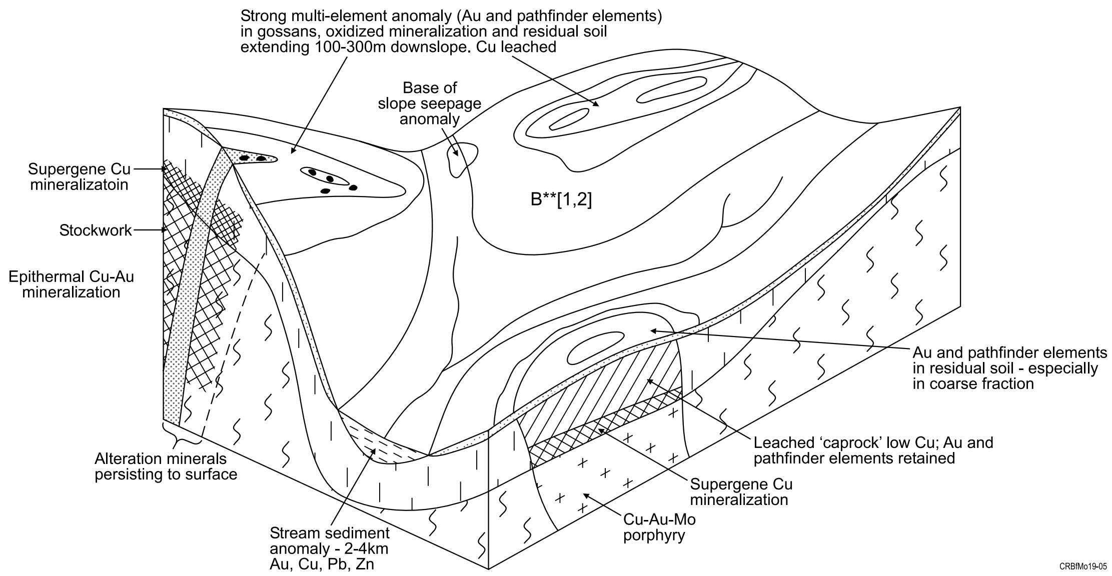


Figure 19. Dispersion model for porphyry Cu-Au-Mo deposits. Type B, erosional terrain, moderate relief; incomplete or truncated profile, with saprolite outcropping or beneath residual soil.

phides in lower saprolite and saprock. Gold distribution largely unaffected by weathering.

Depositional regimes - pre-existing profiles partly truncated

As in other Au- and Cu-bearing base metal deposits, there is little evidence for any metal dispersion into or through transported overburden. At Yandan (*this volume*), for example, surface anomalies terminate where alluvium occurs. At Pajingo (*this volume*), the Tertiary Southern Cross Beds have higher background Au contents close to the deposits, with local syngenetic clastic anomalies (100-300 m) near subcropping mineralization. However, there is no apparent hydromorphic dispersion within or through these sediments, and partial extraction analytical responses reflect the composition of the overburden itself, rather than underlying mineralization. At Northparkes (*this volume*), there is little indication of mineralization in colluvial/alluvial soils over saprolite. The palaeochannel sediments have zones of patchy Au enrichment towards the base, but low Cu contents; although the sediments contain weak As-Pb anomalies, their relationship with the mineralization is unclear. Like other porphyry deposits, the mid-upper saprolite, here present immediately below the unconformity, has anomalous Au contents. Copper appears to be depleted (<2000-5000 ppm), but shows supergene enrichment in saprock, at the base of the regolith, which is suggested as the optimum sample medium.

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