Valley floor kaolinitic regolith in SW Australia that has been modified by groundwater under the present semi-arid climate

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Abstract
The valley floor of the WA wheatbelt commonly consists of a diverse array of materials including alluvium, colluvium and residual lateritic regolith. The mineralogy is dominated by primary quartz and kaolinite; the ubiquitous product of intense weathering. Various amounts of iron oxides (goethite and hematite) and carbonates (calcite and dolomite) are also present. Scanning electron microscopy (SEM) was used to determine elemental distribution and thus identify processes such as impregnation, replacement and cementation. SEM elemental data explained elemental affinity groups and identified less common minerals such as cerium phosphate.

Key Words
Regolith, scanning electron microscopy, pit profiles, carbonate

Introduction
Much of the Wheatbelt of Western Australia is characterised by an ancient deeply weathered landscape of low relief formed under humid conditions and which is now experiencing a semiarid climate. The area is predominantly underlain by Archaean granitic and gneissic rocks that have been altered to lateritic profiles up to 30 metres or more deep (Johnston 1987). The complete laterite profile consists of saprolite overlying the fresh rock, overlain by the kaolinitic pallid zone, mottled zone, iron oxide rich duricrust and sandy topsoil (McArthur 1991). The main weathering products are kaolinite and iron oxides with primary quartz also being abundant. However carbonates, gypsum and many other evaporite minerals are now present, having accumulated in valley floor regolith under current semi-arid conditions. Figure 1 illustrates the stratigraphic organization of materials and some of the processes that have taken place in this complex landscape. Valley floor materials consist of diverse arrangements of alluvium, colluvium and residual lateritic regolith with all materials showing evidence of alteration by solute-rich groundwater under the semiarid conditions that have existed in the region within the past million years.
The focus of this paper is to develop an improved understanding of the materials present and the alteration processes that have occurred in this region.

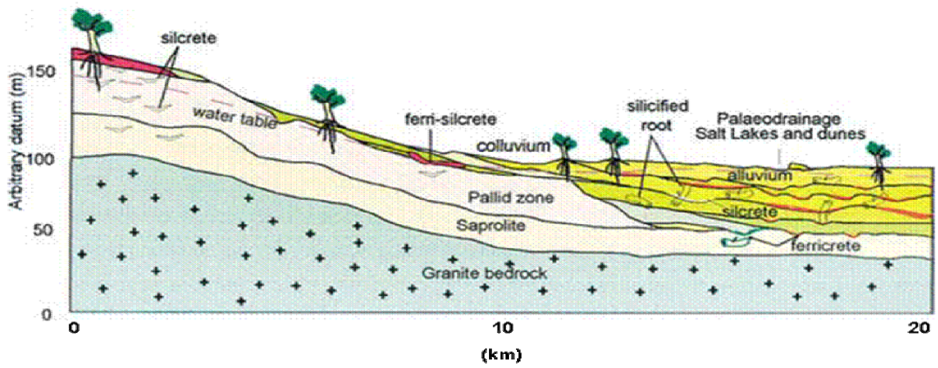

Figure 1. Illustration showing the materials present in valleys in SW Australia. From Gilkes *et al.* (2003).

Methods
Sample location and sampling method
Six sites in the WA wheatbelt were sampled. Pit profiles were taken every 200 metres along deep drains and at least 10 replicates of each morphologically distinct material type were taken.

Analytical methods
Samples were air-dried and discrete morphological components (matrix, mottles, and coarse fragments) separated. All samples were ground manually using an agate mortar and pestle. Soil minerals were

identified using powder x-ray diffraction (XRD). Traces 5.0.5 (Diffraction Technology 1999) and XPAS version 3.0 (Singh and Gilkes 1999) were used for mineral identification and data manipulation and Brindley and Brown (1980) for mineral identification.

Elemental composition was determined using a combination of x-ray fluorescence (XRF) of glass fusion beads (Norrish and Hutton 1969) and inductively coupled plasma mass spectrometry (ICP-MS) of diluted HNO_3-digested glass fusion beads

Polished thin sections were prepared by impregnating undisturbed soil with resin and kerosene was used as a lubricant in order to preserve soluble salts. Optical microscopy was used to describe fabric following criteria and nomenclature of Bullock *et al* (1985) and Stoops (2003). Scanning electron microscopy was used for imaging, microprobe analysis and element mapping.

Results

Field Morphology

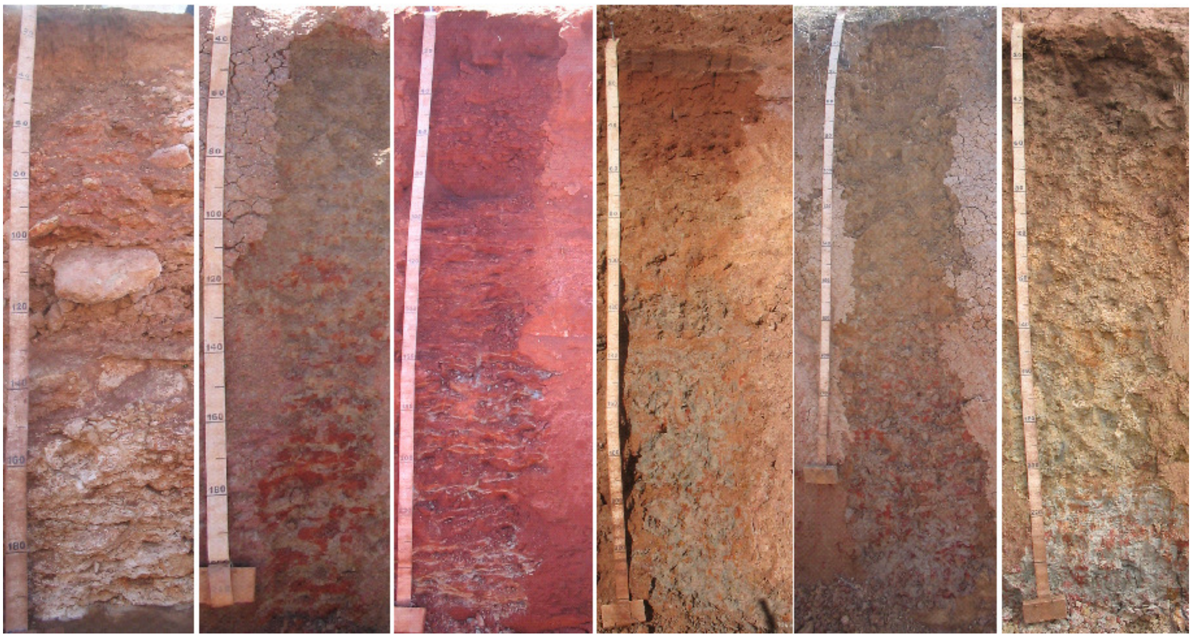

Figure 2. Representative soil profiles from the six sites sampled (from left to right); Three Springs, Pithara Morowa, Mongers 55, Dumbleyung and Wallatin Creek.

Pit photographs were taken at positions along drains. Information such as texture, structure, colour, strength, water status and the type and percentage of coarse fragments was recorded in the field with further morphological information collected in the laboratory. The six profiles included in Figure 2 are not only representative of each site; they collectively represent the materials encountered throughout the region. Three Springs was dominated by platey coarse material with as much as 80% present in some horizons. Sandy clay loam and clay loam were present above approximately 50cm.Fine material between the platey layers is light and silty light clay and consists predominantly of calcite and dolomite with very little actual clay present. Profile three (Morowa) was similar in structure to the first consisting mainly of platey red/brown hardpan through the centre of the profile and sandy loams near the surface. The photograph also shows horizontal veins of a non-cemented material. Profiles two, four, five and six (Pithara, Mongers 55, Dumbleyung and Wallatin Creek) show the mottling that is characteristic of the laterite profile. At all these sites loams in the top of the profiles tended to clay by 60cm. In general the percentage of mottles increased with depth and the distinction in colour between matrix and mottles became clearer. By the time the water table was reached up to 50% of mottles were cemented (by iron oxides) and were therefore classed as coarse fragments.

Mineralogy

The average mineralogical composition for each site is given in table 1. For all sites other than Three Springs materials were mostly comprised of quartz and kaolinite sometimes with feldspar and lesser amounts

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of other minerals. Very little kaolinite was present in the Three Springs samples, these soils often containing smectite or illite instead together with substantial amounts of carbonates. The dominance of dolerite and calcite at Three Springs may reflect the different geology at this location where a variety of metamorphic rocks occur which is in contrast to the dominantly granitic setting for the other sites (McArthur 1991). However there are broad regional patterns in soil mineralogy in SW Australia with calcareous soils and sediments becoming more abundant north of the so called Menzies Line. The Menzies Line (ML) defines the boundary between two climatic regimes. The presence of calcareous soils is one of several features including differences in rainfall, geology, regolith mineralogy and ground and surface waters that separate the two zones. The boundary follows the 30°S parallel and runs roughly east-west before heading further north towards Shark Bay at the western boundary. This is however more a transitional zone dividing two overlapping areas than a sharp distinction (Butt *et al.* 1977).

Table 1. Summary table of the average mineralogy at each site.

site	quartz (%)	kaolinite (%)	feldspar (%)	calcite (%)	dolomite (%)
DU	56.7	26.9	2.4	2.4	4.8
MG	63.9	23.7	1.6	1.5	0.8
MW	46.9	36.7	3.8	4.8	0.0
PT	54.2	25.2	2.9	1.9	0.9
TS	20.0	5.3	0.3	10.5	50.9
WC	59.9	22.2	6.8	5.9	0.8
	halite (%)	**goethite (%)**	**hematite (%)**	**palygorskite (%)**	**smectite/illite (%)**
DU	0.1	1.4	4.5	0.0	0.9
MG	0.1	4.9	2.9	0.0	0.8
MW	0.6	0.0	0.4	0.0	7.2
PT	0.3	7.2	3.2	0.0	4.3
TS	1.5	0.0	0.0	2.8	8.7
WC	0.0	2.6	1.8	0.0	0.0

X-ray diffraction was used to determine the mineralogical composition of the samples represented by the two thin sections presented below (Figures 2 and 3). The sample shown in Figure 2 was dominated by dolomite and calcite with trace amounts of quartz and illite. The sample in Figure 3 contained a large amount of quartz, significant amount of feldspar and kaolinite.

Chemistry

Three hundred samples were analysed for 55 elements. Freeware R 2.7.2 (The R Foundation for Statistical Computing 2008) was used to summarise and draw out relationships in the data. Principle component analysis identified relationships between elements and established associations with minerals. Three components were considered, the first two components explained 47% of variability with component three explaining a further 7.7%; highlighting the diverse nature of the materials. Few clear element affinity groups occur; some elements (e.g. La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm Yb and Lu) are tightly clustered as is commonly the case for the lanthanides and this cluster also contains Ni, Co, Mn and Cu. Mineralogical-chemical relationships include Ca, Mg and Sr being associated with calcite and dolomite and Fe, Cr Al and V being associated with goethite and hematite.

Microscopy

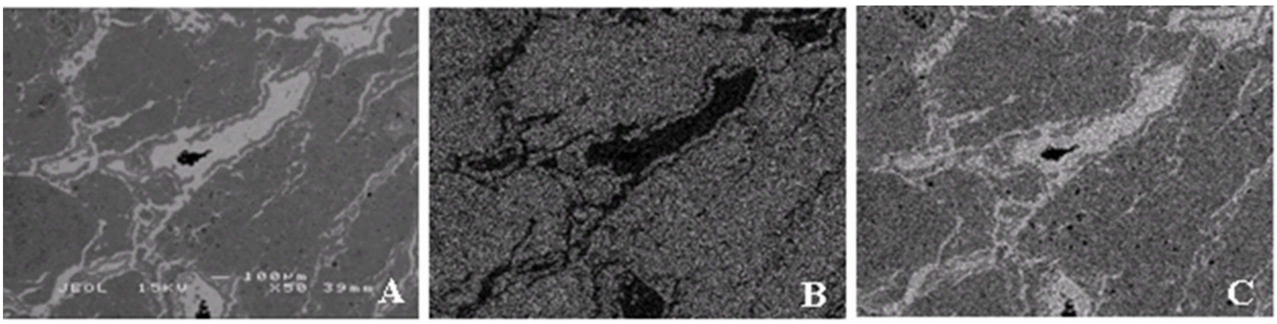

Figure 3. Scanning electron micrograph (A) of a carbonate dominated sample and the associated magnesium (B) and calcium (C) maps. The material contains little silicon and aluminium.

Scanning electron micrograph images in Figure 3 of a sample from Three Springs illustrate the dominance of Ca/Mg carbonates in this regolith. The sample contains little aluminium [clay minerals] or quartz as is also indicated by mineralogical and chemical analysis. It is therefore likely that any clay matrix was replaced, as opposed to being impregnated by authigenic calcite and dolomite that have crystallised from groundwater.

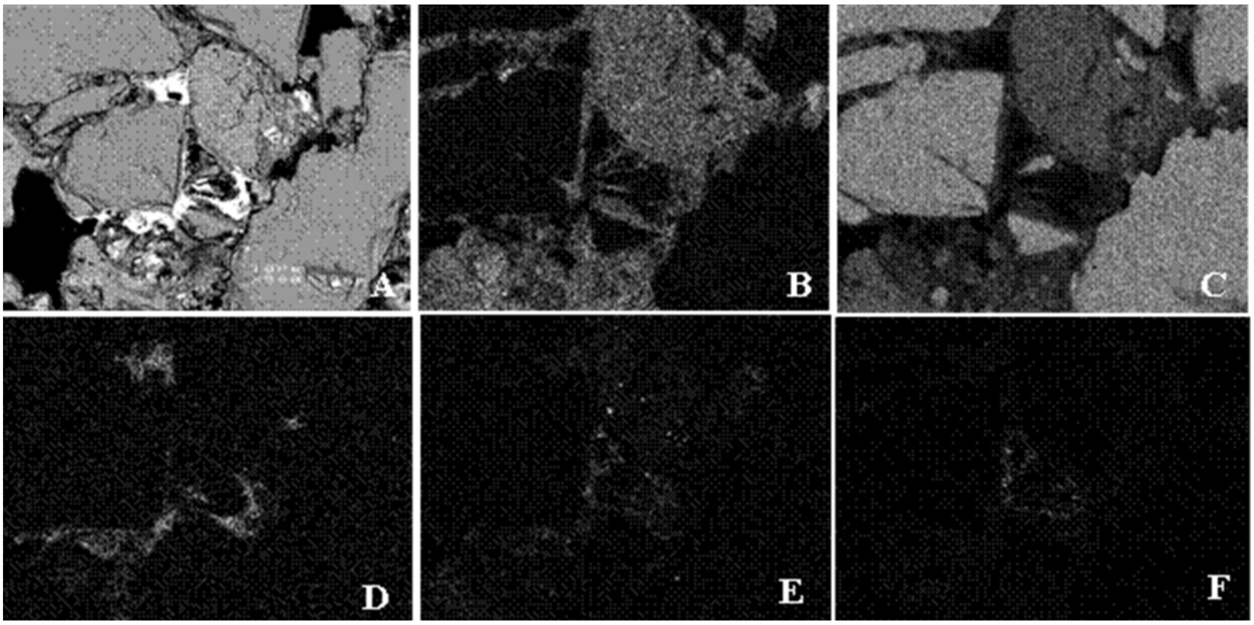

Figure 4. Back scattered electron image (A) of a matrix support sample and associated element maps for aluminium (B), silicon (C), cerium (D), calcium (E) and iron (F).

Figure 4 is of a relatively clay rich, matrix support sample, dominated by kaolinitic clay and angular quartz, both typical of the local saprolite derived from granite. The saprolite has formed *in situ* then subsequently invaded by groundwater from which diverse precipitates including iron oxides and cerium phosphate have formed.

Conclusions
Valley floor regolith in the wheatbelt of SW Australia exhibits complex variations in composition and morphology that reflect its long history of weathering and modification by ground water.

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