JARRAHDALE DISTRICT, WESTERN AUSTRALIA

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INTRODUCTION

The Jarrahdale bauxite deposits, held by ALCOA of Australia Limited, are located 45 km southeast of Perth in the Darling Range at about 32°50'S and 116°5'E (Figure 1). Economic bauxite mineralisation is confined to the lateritic upland geomorphological division of the Darling Plateau (Figure 1) and extends approximately 30 km east from the Darling Scarp and 150 km south from Perth's eastern suburbs to the Harris River area, north of Collie. The grade of bauxite decreases progressively in an easterly direction along with the present-day rainfall so that, at the 600 mm isohyet, the bauxite is below the level of commercial exploitation.

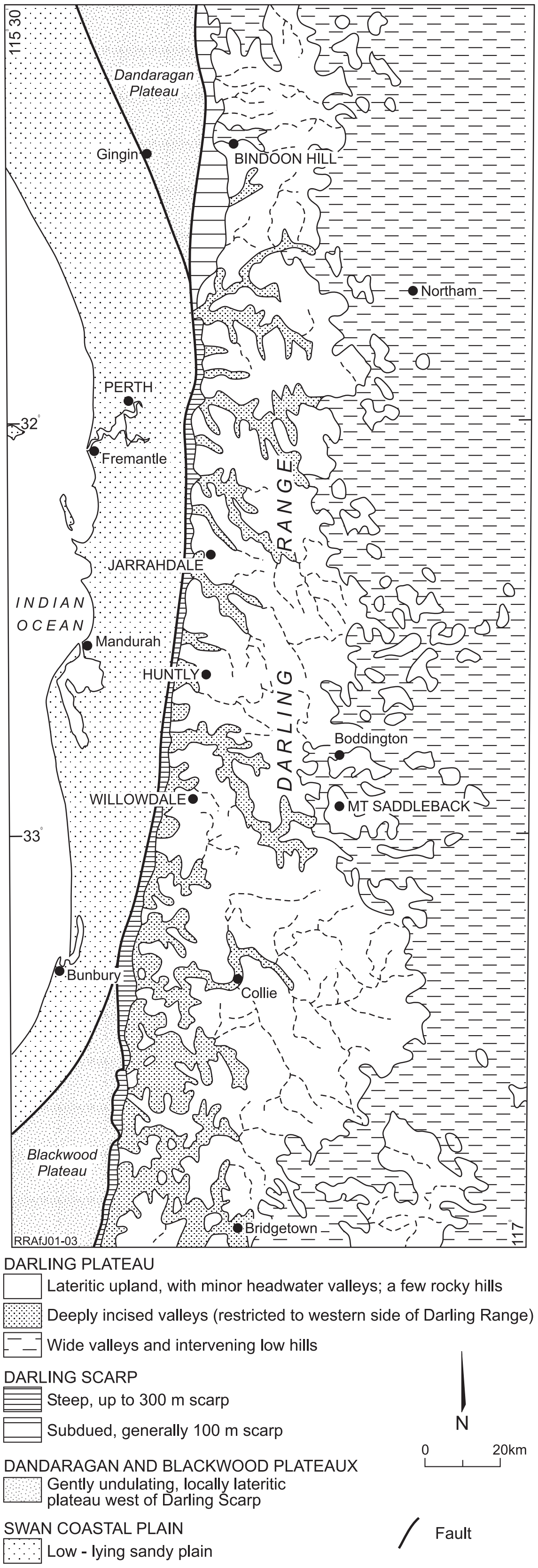

Figure 1. Geomorphological divisions of the Darling Range and adjacent areas. (after Hickman *et al*., 1992)

PHYSICAL SETTING

Geology

The Darling Range is underlain by Archaean crystalline rocks of the Yilgarn Craton. In the Jarrahdale area, the bedrock consists principally of porphyritic granite with lesser migmatite gneiss in the northwest part of the area. Numerous north–west trending dolerite dykes have intruded the predominantly granitic rocks, and commonly constitute over 10% of bedrock. These dykes are typically 5–50 m wide and can reach lengths of up to 100 km (Hickman *et al*., 1992).

Geomorphology

The western boundary of the Darling Plateau is the Darling Scarp, rising abruptly 100 to 300 m above the low lying subdued topography of the Swan Coastal Plain. The Jarrahdale area has a broadly undulating surface with crests ranging in altitude from 260 to 370 m above mean sea-level and swampy valley floors set some 50 to 100 m below the crests. Over much of the area, the plateau is dissected by rectilinear drainage. The valleys are characterised by flat swampy valley floors that are in the order of 200 m wide and are flanked by smooth slopes of less than 5^{o}.

Climate and vegetation

The Jarrahdale area has a Mediterranean climate with mild wet winters, warm dry summers and a mean maximum temperature ranging between 12 and 28°C. The total annual rainfall is approximately 1200 mm. The dominant vegetation is scherophyll forest. Varying proportions of *Eucalyptus marginata* and *Eucalyptus calophylla* form the upper storey on the ridge crest and slopes. *Banksia grandis, Persoonia longifolia and Xanthorrhoea preisii* and *Macrozomia riedlei* dominate the middle and lower storey. *Eucalyptus calophylla* and *Melaleuca preissianan* dominate the upper storey of the valley floors, where the lower storey contains *Xanthorrhoea preisii*, *Kingia australis* and *Hypocalymma angustifolium.*

REGOLITH–LANDFORM RELATIONSHIPS

The Darling Plateau is extensively mantled with deep weathering profiles that have developed on all rocks. Bauxite and bauxitic duricrust are extensive and best developed on hill slopes rather than crests or valley floors (Figure 2). The duricrust occupies gently sloping to horizontal upland areas with an average elevation of 280 to 300 m. Steeper slopes may have a thin cover of transported gravels but, in general, bedrock is generally near-surface. There is little duricrust below 200 m. Blocks of duricrust, released by headward erosion of streams, degrade to ferruginous gravel on the lower slopes of valleys. On a local scale, the topography of the weathering front is much more irregular than that of the top of the duricrust (Figure 2).

On the Darling Plateau, in undissected terrain (lateritic upland in Figure 1) with shallow valleys and gentle slopes, the soil thickness increases with distance from the crests towards the valley floor. Sandy gravel is predominant on the slopes and crests whereas sandy soil increases in thickness towards the valley floor. Figure 3 typifies these relationships from the Jarrahdale area. Uplands show a toposequence of very gravelly soils (sandy gravel) and lateritic duricrust on the crests to mid slopes. The crest of the ridge may be occupied by large dolerite dykes represented by outcrops of fresh rock enclosed in an aureole of lateritic duricrust. The sandy gravel increases in thickness to more than 1 m on mid slope and lower slope positions where it overlies various forms of lateritic duricrust on bauxite zone. On lower slopes, the gravel merges with sand and is interlayered with sand. Orange earths dominate the valley floor but in some situations yellow–brown sand may extend on to them. Podzolic soils and cracking clays also dominate some valley floors. Here, lateritic duricrust is absent and the soils overlie saprolite. Pockets of goethite-rich duricrust ('bog iron'), formed by chemical or biochemical precipitation of hydromorphically transported Fe, may occur in valley floors. Outcrops of fresh rocks are rare.

On long steep slopes in dissected terrain, the soil pattern is complex. Rock outcrops are common, and slump features and infilled valley-side depressions indicate a prior geomorphic environment more dynamic than at present on the Darling Plateau. Orange earths dominate the surface with saprolite an important substrate, although fresh rock is common. Local convexities are associated with greater thickness of soil.

Local variations in duricrust morphologies occur within a catena. The mid slope positions are dominated by pisolitic duricrust which can underlain by fragmental duricrust. By contrast, only fragmental duricrust occurs on crests and upslope positions where pisolitic duricrust is generally absent. The absence of pisolitic duricrust suggests removal by erosion and its detritus now occur on the lower slopes.

REGOLITH CHARACTERISATION

A typical weathering profile on granite (Figure 4) averages about 20 m in thickness and consists of gravelly soil, lateritic duricrust, bauxite zone, saprolite and saprock. However, in detail, profiles are extremely variable. The presence of deep shears has resulted in differential weathering to produce localised areas of deep kaolinitic clay. The soil forming the upper part of the profile consists of lateritic gravel in a clayey sand matrix and overlies lateritic duricrust. Soil averages about 0.5 m thick. Lateritic duricrust over granite reaches thickness of 1–2 m. Pinnacles of bedrock, and isolated corestones can occur high in the profile, lessening the thickness of duricrust.

Lateritic duricrust may be either essentially residual, or locally transported and cemented. Over dolerite dykes, the duricrust is red–brown and contains very little quartz. Over granitoids, the duricrust is light brown, with abundant visible quartz. Fragmental duricrust preserve the original fabric of the granitoid including original quartz grains and feldspar laths now pseudomorphed by gibbsite. Outcrops with relict bedrock textures are common. Pisolitic duricrust overlies fragmental duricrust and contains black to red simple or compound nodules and pisoliths cemented by gibbsite and goethite. They have a greater variety of fabrics and a more complex mineralogy than the underlying fragmental

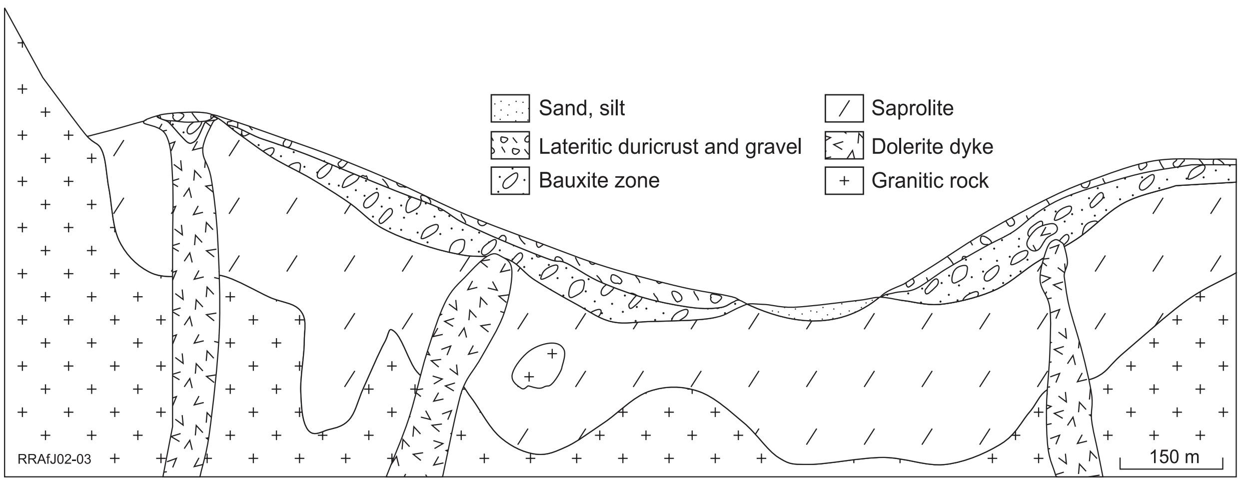

Figure 2. Schematic cross section showing the general relationship between landforms and regolith, Darling Range.

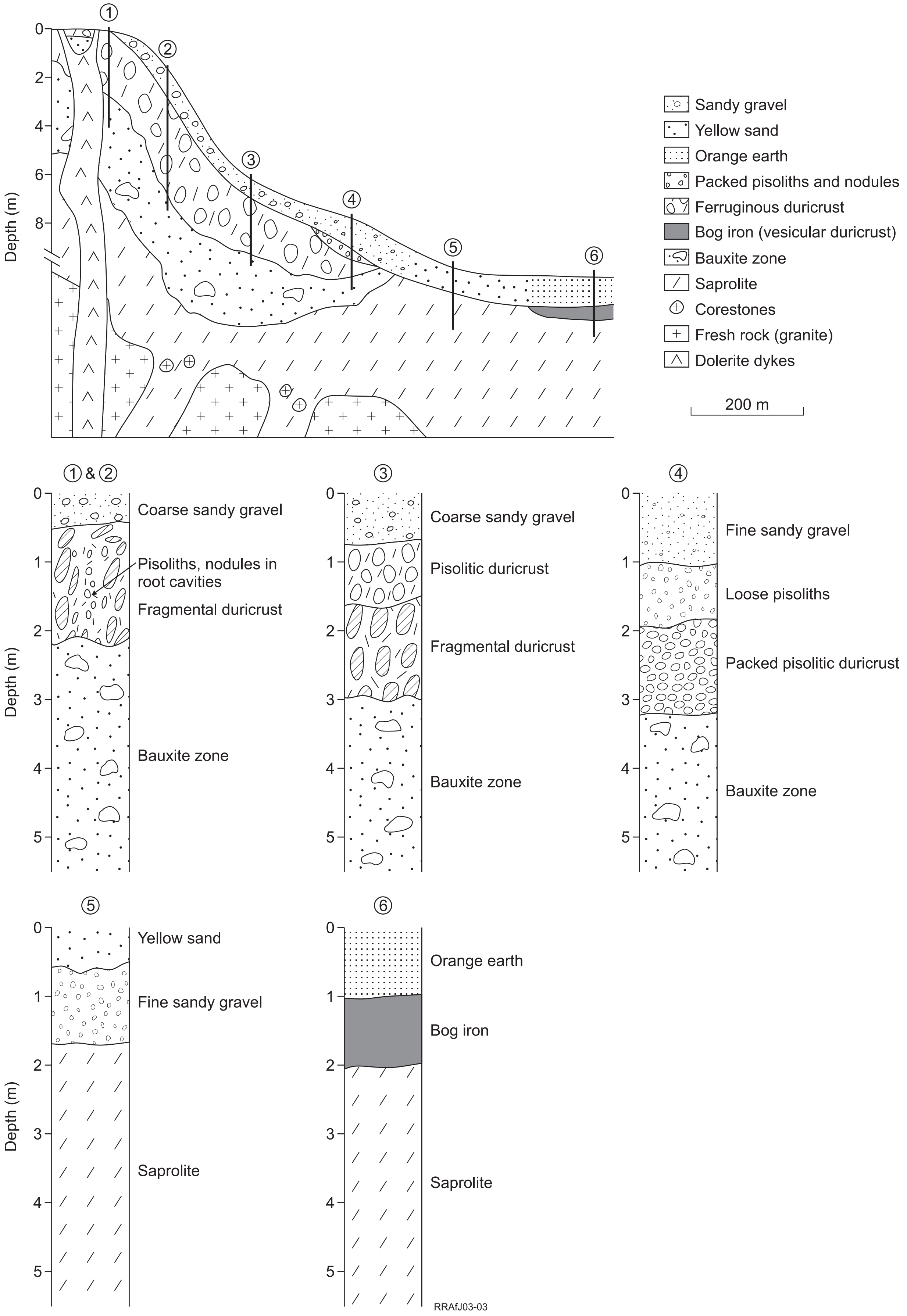

Figure 3. Schematic cross section and profiles showing trends in soil and ferruginous duricrust morphology following a sequence from crest to valley floor at Jarrahdale. Sandy gravels and ferruginous duricrust on crest and mid slope giving way to yellow sandy soils on the lower slopes and orange earths in valleys. The gravels become thicker and finer downslope.

duricrust, suggesting individual pisoliths in pisolitic duricrust have formed under different weathering environments. Pisolitic duricrusts with concentric pisoliths are common and have a variety of cores. Pisolith nuclei comprise either: (a) a mixture of χ-alumina, hematite, maghemite and gibbsite; (b) hematite and gibbsite; or a few with (c) lithic fragments.

The friable bauxite zone immediately underlies the duricrust. This zone is yellowish to reddish brown, generally about 3 m thick, but can be up to 10 m thick in mid slope positions on large ridges. The bauxite zone contains round to angular nodules and saprolitic fragments in a fine grained, loose, earthy or sandy matrix. The coarser material ranges from 2 mm to over 100 mm. Feldspar pseudomorphs are common in gibbsite nodules and are often 1-2 mm in size.

The contact between the friable bauxite zone and saprolite is commonly abrupt. The upper part of the saprolite may be mottled, but the clay becomes increasingly bleached with depth. Saprolite is generally 10–15 m thick. The saprolite consists of vermicular kaolinite pseudomorphs after primary grains of mica, an isotropic groundmass of kaolinite after feldspar, coarse quartz and abundant large voids. Thus, the saprolite has a much lower bulk density and higher porosity than the parent rock. Over mafic rocks it ranges from pure white to multicoloured kaolinitic clay with mottles, commonly overprinted by liesegang rings. Saprolite passes downwards into saprock, before fresh bedrock is reached. Where saprolite overlies dolerite, its basal contact is commonly very sharp, and may occur over a few centimetres. Over granites the contact between fresh rock and saprolite is generally gradational over 2–3 m.

Iron oxides and gibbsite are the dominant minerals in the bauxite zone and lateritic duricrust. Goethite is present in larger amounts in the bauxite zone and duricrust overlying dolerite (20 and 19%, respectively) than over granite (8 and 11%, respectively), owing to higher iron and lower quartz contents of the dolerite. Similarly, hematite has an average abundance of 3 and 4% for granitic derived bauxite and duricrust materials respectively, and 15% for both doleritic derived bauxite and its duricrust. Aluminium substitution in goethite ranges from 22 to 35 mole % (Anand and Gilkes, 1987a). Anand and Gilkes (1987a) found no significant differences in level of Al substitution in goethite between lateritic duricrust on granite and dolerite. The two parent materials provide quite different amounts of Fe, Al and other ions, but these differences had no effect on Al substitution which must therefore reflect pedochemical conditions rather than the gross abundance of ions.

Maghemite is present in near surface pisolitic duricrust and in loose pisoliths where it is commonly associated with corundum. Formation of maghemite due to heating of the soil by fires is a major mechanism and this origin is supported by the association between corundum and maghemite (Anand and Gilkes, 1987b).

Gibbsite reaches maximum concentrations in the duricrust and bauxite zone. However, it decreases appreciably in surface pisolitic lag gravels where poorly crystalline alumina (χ-alumina) becomes the major Al mineral. Boehmite was not detected in the bauxite zone but was present in significant amounts in loose pisoliths and pisolitic duricrust. Small amounts of relict muscovite occur in granitic duricrust. Deeper in the profile, the major change from bauxite to saprolite is marked by the absence of gibbsite; only small amounts of this mineral occur in the saprolite. Halloysite and/or kaolinite are most abundant in the saprolite.

The major chemical components in bauxitic duricrusts are Al, Si and Fe; whereas Ti, V, Cr and Zr are minor but important constituents. The concentrations of these various elements are a function of bedrock geology and the modifying influences of weathering. Each element has a particular pattern of enrichment or depletion through the profile. The main geochemical characteristics of the weathering profiles are summarised below:

- The proportion of residual quartz, together with absolute values for Fe, Ti, K, Mn, V and Zr in the duricrust may be used to discriminate granite-derived from dolerite-derived duricrust.
- There is almost complete leaching of Na, Ca and Mg, together with partial leaching of K and a considerable loss of Si. Relative to the bedrock there is an absolute gain of water and an important increase in Al, Fe, Ti, Cr and V in duricrust.
- Zirconium, Ga, Sn, Nb and Th are generally concentrated in the upper parts of the profiles. Barium, Sr and Zn are generally lost, whilst the abundances of Cu, Co, Ni and Pb vary.

REGOLITH EVOLUTION

The mineralogical and chemical composition and distribution of bauxitic profiles result from the interaction of parent rock, topography, climate, vegetation, drainage and erosion. Weathering has residually enriched Al and Fe in relation to the combined effects of Si depletion and the almost total loss of Mg, Ca, Na and K. These changes are consistent with dissolution of feldspars, amphiboles, biotite, pyroxene and chlorite. Relatively immobile elements (Cr, V, Ga, Ti and Zr) are concentrated in the upper profile. Boundaries of dykes and quartz pegamatite veins continue without alteration of dip or strike as they pass from bedrock to saprolite zone (Sadleir and Gilkes, 1976; Davy, 1979). This together with relict fabrics in the saprolite lead to the conclusion that changes from bedrock to saprolite have been nearly isovolumetric.

The characteristics of duricrusts suggest two modes of formation — in saprock and soil. Fragmental duricrust has resulted from direct gibbsitisation of saprock without forming a kaolinite-rich deep saprolite. Subsequent ferruginisation has helped to protect the rock fabric, except in extreme ferruginisation where rock fabric is progressively destroyed. However, pisolitic duricrusts with the greatest mineralogical diversity have a far more complex history than mineralogically simple fragmental duricrust. Here,

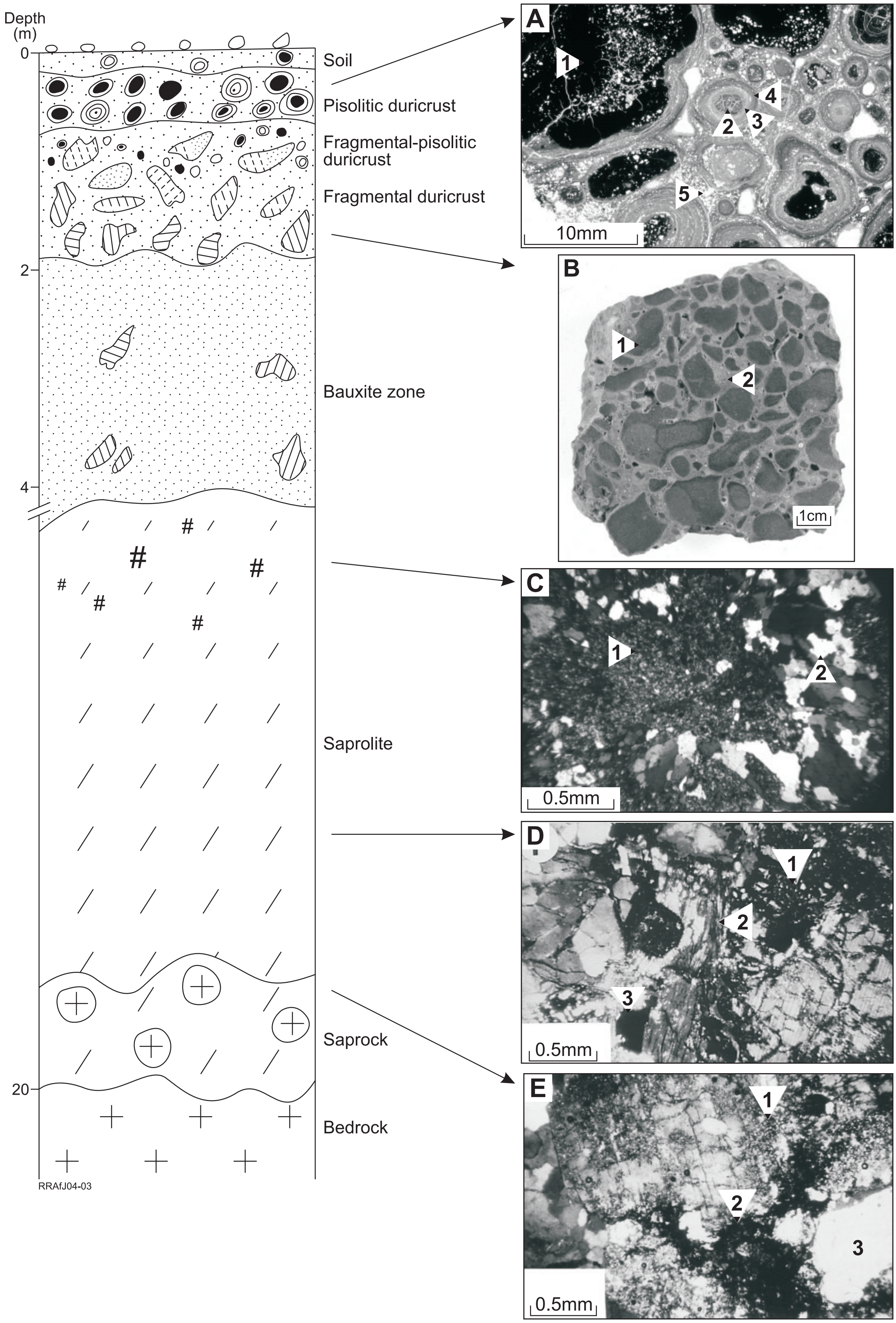

Figure 4. Typical bauxitic weathering profile. Photomicrographs of fabrics from various horizons of a weathering profile developed over granite at Jarrahdale. (A) Optical micrograph of a polished section of pisolitic duricrust showing hematite-maghemite-rich (1) and hematite-rich pisoliths (2) surrounded by lighter (3) and darker (4) cutans in a quartz-gibbsite-rich matrix (5). (B) Fragmental duricrust showing angular to sub angular hematite-gibbsite-rich fragments (1) in a gibbsite-quartz-rich matrix (2). (C) Optical micrograph of upper saprolite showing feldspars completely replaced by kaolinite (1) set in a close packed relict quartz (2). (D) Optical micrograph of middle saprolite showing the alteration of feldspar to a mixture of halloysite and kaolinite (1), highly altered biotite which has exfoliated and goethite and/or clay minerals between the cleavage plains (2) and opaque mineral (3). (E) Optical micrograph of lower saprolite showing early stages of alteration of feldspar to a mixture of halloysite and kaolinite (1) and partly altered biotite showing a mixture of Fe oxide and clay minerals (2) and quartz (3).

pisoliths are formed by replacement or cementation of soil or colluvium by leaching, migration and accumulation of Fe oxides in the gibbsite matrix or in voids. This is not a single event, but involves multiple leachings and precipitations. It contains varibale amounts of aeolian material, but the source of this material is uncertain, and it is generally difficult to distinguish exotic aeolian constituents from more locally-derived colluvial or alluvial materials. Pisoliths with well developed multiple cutans have a complex, cyclic history and have formed by both accretionary and concretionary processes. Disconformable contacts between cutans, some including thin layers of quartz, indicate that the cutans formed by accretion. Formation of concentric pisoliths by progressive inward hydration to goethite of a pre-existing hematite-rich nucleus, as proposed by Tardy and Nahon (1985), is suggested by irregular dissolution of edges and scattered remnants of the original nucleus within a pisolith. However, the latter situation is uncommon.

The χ-alumina suggests mobilisation, migration and accumulation of aluminium. χ-alumina is considered to have formed by the dehydroxylation of hydroxides and oxyhydroxides (Misra, 1986). The solubility of $Al(OH)_3$ around pH 4 is fairly high (Misra, 1986) so that significant amounts of Al may occur in the strongly desilicated acid soil solution that exists in the near-surface horizons of bauxitic profiles. In drier seasons, Al may concentrate in soil solution by evaporation and evapo-transpiration, and precipitate as a hydrous amorphous gel in the soil matrix due to increases in pH and concentration (Hsu, 1989).

Lateritic duricrusts contain more Fe than the underlying saprolite. Some workers have explained the extra amounts of Fe in relation to the underlying saprolite by general landscape lowering (e.g., Trendall, 1962). There appears to little or no lowering of land surface during the formation of fragmental duricrust as indicated by preservation of rock fabrics. Furthermore, Sadleir and Gilkes (1976) and Davy (1979) considered that pegmatite veins outcropping in the railway cutting at Jarrahdale can be followed from fresh rock into the duricrust. The duricrust over the pegmatite is represented by gibbsite containing extremly coarse, angular quartz. In neither case is there a flattening of the dip of the contact between the dyke and host rock, which would be expected if the duricrust were part of a condensed profile.

Deep weathering profiles at Jarrahdale yield late Tertiary palaeomagnetic ages (Dr B. Pillans, ANU, written communication, July 2002). In contrast, deep weathering profiles in the eastern Yilgarn yield both early and late Tertiary palaeomagnetic ages (Table 16 in Anand and Paine, 2002). The absence of older weathering imprints in the western Yilgarn may well be a consequence of denudation during and since the Mesozoic.

There has been a great deal of discussion regarding the role of topography on the formation of bauxitic weathering profiles. The topography of the bauxitic deposits is controlled by the nature of the bedrock; faults define stream courses, thicker dolerites underlie ridges (Hickman *et al*., 1992). If the bauxite formed in the past on a peneplain, which was then uplifted and subsequently eroded, the thickest bauxite would not now lie on the mid slopes. However, if they formed in the past on topography similar to that of today, it follows that all the erosion that presumably followed the rejuvenation of the streams did not modify the established bauxite-topography relationships. It appears that the bauxites in the Darling Range are forming today. This is consistent with the decrease in bauxitic grade with the present rainfall.

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