AGSO Journal of Australian Geology & Geophysics, 16 (3), 231–241

Towards distinguishing transported and *in situ* ferricretes: data from southern Australia

R.P. Bourman[1]

Controversy has arisen in the past decade concerning ferricrete genesis by relative (*in situ*) or absolute (lateral) concentration of iron and aluminium oxides. Some regard 'laterite' profiles as stratigraphic sequences, with crusts being remnants of iron-impregnated valley sediments. In contrast, the traditional notion of 'laterite' formation invokes vertical translocation of minerals under humid tropical conditions on peneplains close to ultimate base level, with incomplete profiles reflecting variable degrees of erosion. Criteria to discriminate the dominant mode of ferricrete origin include topographic and stratigraphic relationships. A transported origin is favoured by unconformable contacts between truncated bedrock structures or quartz veins, overlain by ferruginised materials, whereas preservation of bedrock structures through the complete profile indicates formation in place. Ferricrete macromorphology can also be useful in determining whether iron oxides have moved into an area.

Petrological studies suggest that pisoliths with angular irregular shapes and diffuse external borders, and those with similar framework grains within pisoliths and matrix materials, appear to have formed *in situ*. Formation by physical break up of ferruginised materials, transport and modification is favoured by broken surface coatings, different-sized grains in pisoliths and their matrix materials, different-sized grains in adjacent pisoliths, multiple laminar goethite rinds on pisoliths, abraded compound nodules cemented together by ferruginous, concretionary material, and complex pisolith-within-pisolith structures. Monomineralogy may suggest *in situ* pisolith formation, whereas transport is favoured by polymineralogical pisoliths resting on materials that could not have provided the elements for their formation. In pisolitic ferricrete, significantly different matrix composition from that of the pisoliths favours interpretation of pisoliths as clastic components incorporated within different materials. Furthermore, maghemitic pisoliths at depth suggest transport and burial, and scattering of palaeomagnetic data from individual pisoliths indicates physical disturbance since their formation.

Introduction

The view that 'laterite' formed on peneplains close to sea level under the influence of humid but seasonally dry tropical climates, which caused fluctuating water tables that facilitated vertical translocations of minerals, thereby concentrating iron and aluminium oxides in surface crusts, has dominated early theories of 'lateritisation' in southern Australia (see reviews in Hunt et al. 1977; Hunt 1985; Bourman 1989 1993b; Ollier 1994). However, in contrast to this interpretation, particularly in the decade since the publication of the paper by Milnes et al. (1985), there has been greater emphasis on the role of lateral transport in explanations of ferricrete genesis. Milnes et al. (1985) interpreted 'laterite' profiles in southern South Australia largely as sedimentary sequences; the iron-rich crust was thought to be a unit younger than the underlying bleached and mottled zones, with which it formed an unconformable contact, having been deposited in a former valley. Lateral transport and relief inversion have come to be regarded by some workers as the dominant processes in ferricrete formation (e.g. Ollier & Galloway 1990; Ollier 1991; Ollier 1994).

'Ferricrete' has been adopted by some workers to replace the term 'laterite', which has been applied to a wide range of weathered materials (e.g. Ollier & Galloway 1990). The term 'ferricrete' was originally used by Lamplugh (1902) to describe a ferruginous conglomerate, but subsequently it has been extended to include all iron-cemented and indurated surface crusts and sub-surface horizons (e.g. Bourman 1993b).

Consideration of the discrimination between the *in situ* or transported nature of 'lateritic' materials needs to be put into perspective.

- Some weathering has obviously occurred in place, as evidenced by the preservation of bedrock structures such as bedding and joints; such weathering may be regarded as isovoluminous.
- Almost all ferricretes display some elements of lateral transport of iron and/or aluminium oxides, either physically or in solution; but even clearly transported ferricretes have been subsequently affected by weathering.
- There is abundant evidence of lateral movement of iron in solution and physical movement of pisoliths in present-day landscapes.

Thus, the formation of ferricretes appears to be a continuum between those clearly transported and those formed by weathering in place, and it is important that a set of criteria be established which will allow the delineation of the whole range of ferruginous duricrusts, particularly those that are hard to categorise. It may be difficult to distinguish between ferricretes resulting from landscape lowering that involves elements of lateral transport and ferricretes related to longer distance lateral transport, especially where rounded materials are involved.

In this paper, the term *in situ* is reserved for isovoluminous weathering in which original bedrock structures can be seen either microscopically or in hand specimen. If something is *in situ* it should be in the precise position of original formation. Conversely, ferricretes formed by landscape down wasting are considered to be residual or sedentary in nature.

In investigating the origins of ferricretes, it is important that regolith materials be carefully studied in the field to establish their topographic, geomorphic, stratigraphic and age relationships, and to search for critical bedrock and sedimentary structures. It is imperative that the field relationships be well established before proceeding with detailed laboratory work; data from both must be complementary.

Field observations of ferricretes

Topographic relationships

The relationships of ferricretes to present-day topography are significant in establishing their origins. If ferricrete occurs in a modern valley floor or a relatively lowland position, the nature of physical and/or chemical transportation, and potential former sources of iron oxides upslope or up-valley, must be considered.

Subdued relief is usually assumed for 'laterite' development. However, some ferricretes in the Darling Ranges occur on slopes of 5–20° and completely mantle valleys wider than one kilometre with a relief amplitude of 100 m (Fig. 1) (e.g. Mulcahy 1960). The valleys are clearly of considerable antiquity and it is difficult to envisage ferricrete development on them without contributions by both physical and chemical transportation. At least five hypotheses can be proposed:

1. Uplift and physical dissection of the landscape followed by deep chemical weathering accompanied by duricrusting; i.e. formation of the valley before duricrusting.

[1] School of Human and Environmental Sciences, University of South Australia, Holbrooks Road, Underdale SA 5032.

2. Deep chemical weathering and duricrusting during valley incision.
3. Duricrusted valley development dependent upon the original depth of weathering; i.e. development of a duricrusted valley during incision of a previously deeply weathered landscape.
4. Duricrusting of valley sides by transport and redeposition of eroded pre-existing duricrust during ongoing weathering.
5. Tectonic dislocation by warping of the duricrusted surface. This hypothesis may account for some sloping duricrusted surfaces, but it is difficult to envisage development of a duricrusted valley by this process.

At the present time, in parts of the Darling Ranges, there is clear evidence of physical transport of pisoliths on slopes of less than 10°. On the toe slopes of catenas and near the bases of valleys, there are loosely packed beds of currently uncemented pisoliths up to 1 m thick. Older generations of underlying pisoliths, now cemented, occur in exposures up to several metres thick and incorporate boulders of earlier pisolitic ferricretes, the surfaces of which are glazed with a thin goethite patina (Fig. 2).

Fragmental duricrust, which underlies pisolitic duricrust over much of the Darling Ranges, is considered residual, as bedrock structures are preserved and its chemical composition shows affinities to the underlying bedrock (Anand 1994). Its mineralogy is dominated by hematite and gibbsite and, in contrast to the overlying pisolitic duricrust, maghemite is typically absent (Anand 1994). Consequently, the surface pisolitic duricrust is likely to contain transported elements.

Figure 1. View across valley in the Darling Range of Western Australia. The valley is approximately 1.5 km wide, with a relief amplitude of some 120 m, yet it is mantled with pisolitic ferricrete both across and down valley. Maximum slopes in the valley are 20°.

Examples of landscape inversion occur in the Mount Lofty Ranges, where former ferricreted valley floors now form high points in the landscape, indicating increasing relief amplitude rather than complete landscape inversion. It is possible, in some circumstances, to reconstruct landscapes by examining remnants of former valley floors, which can reveal palaeodrainage lines. These remnants are usually sloping, which may indicate former water flow in the region, but tectonic disruption should not be discounted.

At Mount Talbot in the Darling Range, ferricrete occurs on a granite bedrock interfluve, displaying only minor weathering, at the highest point in the landscape. In this and similar cases without higher present or former sources of iron enrichment and insufficient time for major landscape inversion there are some problems faced by the relief inversion hypothesis (Conacher 1990). Such situations are highly suggestive of duricrust formation by residual weathering and landscape downwasting over very long periods, with only a thin weathering horizon remaining. Furthermore, in other situations, weathering of transported materials will occur after deposition, highlighting the need to distinguish transported and *in situ* elements of the same duricrusts.

Stratigraphic relationships

An origin involving transport is favoured by the existence of clear-cut unconformable contacts between underlying weathered zones with preserved bedrock structures and/or quartz veins, which are truncated and overlain by duricrusted stratified sediments (Fig. 3) or transported ferricrete materials. Conversely, the preservation of bedrock structures through the complete profile would indicate formation in place (Hickman et al. 1992, p. 14). At times, micromorphological observations may be required to identify bedrock structures if they are not obvious in hand specimen. Dolerite dyke positions have been established by chemical analysis of the overlying 'laterite' in the Darling Range, suggesting minimal lateral transport in duricrust formation in these locations.

Channel fill materials overlying bleached and kaolinised saprolite (Fig. 4) comprise a variety of sediments (sands, gravels, clays, pisoliths, and other ferruginous clasts) deposited in former stream channels. Ferricretes are not always associated with these channel fills and iron oxides may be either concentrated into megamottles (Ollier et al. 1988), such as at the Kanowna deposits (Anand 1993), or spread diffusely throughout the fill material. Where a ferricrete is developed in younger sediments, it may be difficult to determine if the underlying older rocks were weathered and kaolinised before

Figure 2. Iron-cemented pisoliths and nodules incorporating large clasts of transported ferricrete (e.g. near sharp end of pick) covered with patina of goethite. Jarrahdale area, Darling Range, Western Australia. Pick handle 40 cm long.

Figure 3. Road cut exposure in Esperance area, illustrating iron-cemented sediments overlying weathered steeply dipping rocks with a marked unconformity. Note the truncated quartz veins and the black maghemitic pisoliths at the surface. Notebook measures 10 x 7 cm.

Figure 4. Road cut on Eyre Peninsula, South Australia, revealing underlying steeply dipping Precambrian rocks that have been weathered, differentially bleached and mottled. They are overlain by younger, horizontal palaeochannel deposits that have, in turn, been weathered and ferruginised in the top 2 m of the section. Note that the large mottles in the basal part of the section do not extend into the younger palaeochannel. Section is 7 m high.

deposition and ferruginisation of the younger sediments or if they were weathered simultaneously. Different hydrological characteristics in the two units may have favoured iron precipitation within the more porous overlying sands and gravels.

It is not always possible to resolve this problem, but some evidence from the Adelaide area favours separate phases of kaolinisation and ferruginisation. Here, where kaolinised bedrock with overlying ferruginised sediments is common, there is some stratigraphic evidence that kaolinisation preceded ferruginisation. Furthermore, a drill core from north of Adelaide shows plant roots in growth position, in pallid, kaolinised bedrock overlain by fossiliferous Tertiary carbonaceous sediments (Benbow et al. 1995). This suggests that the older bedrock had been weathered, kaolinised, and eroded, and was supporting plant life when it was buried in the Tertiary. Magnetostratigraphy and stable oxygen isotope analyses from either side of an unconformity may assist in resolving the question of whether weathering imprints are contemporaneous or related to different or ongoing weathering phases.

Iron impregnation of pre-existing sediments, particularly where they directly overlie unweathered bedrock, can be interpreted as lateral transport of iron oxides in solution. For example, coastal beach/dune sediments in the Bremer and Myponga valleys, related to Tertiary shorelines in the uplifted Mount Lofty Ranges, are now cemented by iron oxides (e.g. 'Lucernbrae' ferricrete resting on slightly weathered bedrock in Figure 5). The ferricreted sediments are more accurate palaeogeographical indicators of the former shoreline position than are the associated but lower limestones, which were deposited considerably below the water level. Consequently, the relationship between such ferricretes and former shorelines may be an important indicator of their transported mode of origin.

Where no obvious unconformity exists between ferruginous duricrusts and underlying bleached, kaolinised and mottled bedrock, palaeontological data may identify different ages of units in which separate parts of the weathering profiles have developed. For example, in the western Otway Basin of Victoria, weathering and ferruginisation affect a wide variety of rock types and sediments of different ages in various topographic situations (Gibbons & Gill 1964; Gibbons & Downes 1964; Kenley 1971; Kenley 1975; Abele et al. 1976; Bourman 1989). Gibbons & Downes (1964) noted that the undissected surfaces of the Dundas Tableland and the Brim Brim Plateau are remarkably flat, capped by 'laterite' described as massive ironstone zones underlain by mottled and leached (pallid) sub-zones, up to 10 m thick, and regarded as 'classic examples of peneplains' capped by 'standard laterite profiles' (Kenley 1975).

The Late Miocene to Early Pliocene Dorodong Sands comprise basal quartz sands, gravels, clays and ironstones. They are strongly ferruginised in outcrop, and are transported ferricretes formed in deposits younger than the underlying weathered and mottled fine-grained Lower Cretaceous Otway Group sediments. The topography and the discontinuous nature of the duricrust suggest preferential formation in a relatively low topographic area where iron oxides could accumulate from lateral sources, leading to the replacement of previously existing sediments by iron oxides without marked volumetric alteration. In the Casterton area, Kenley (personal communication) discerned an unconformity between the Dorodong Sand and the underlying Heytesbury Group, and inferred its presence in other places on the basis of 'laterite' lithology and stratigraphic position, and in some localities on the basis of Tertiary microfossils incorporated into pisoliths.

In situ ferricretes

The formation of ferricrete by weathering *in situ* is described by Bourman et al. (1995) in the Triassic Telford Basin of South Australia. In this case, weathering of sideritic siltstone produced voidal concretions as significant components of ferricretes, in which siderite was transformed to alternating

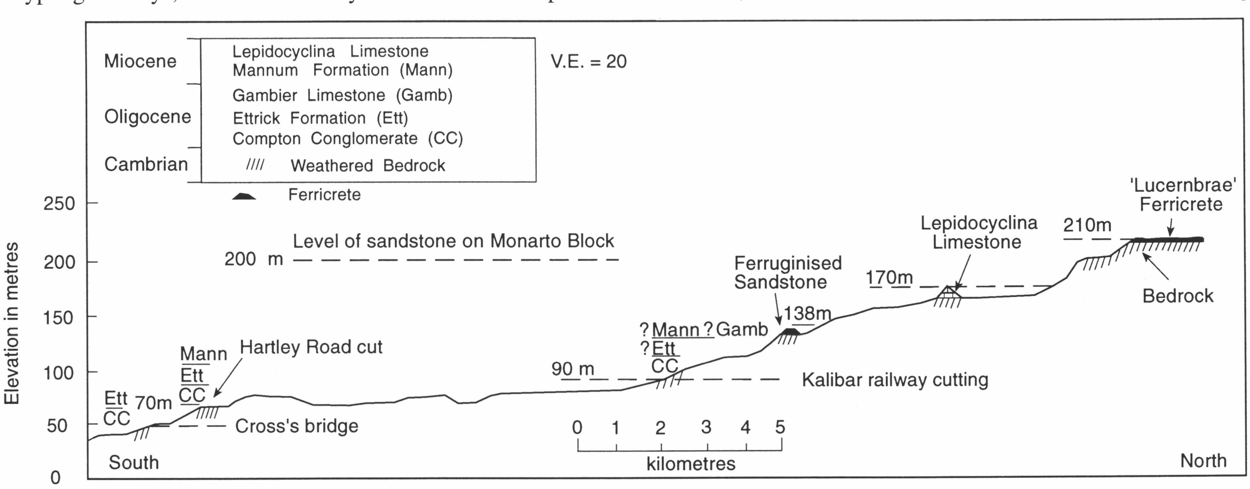

Figure 5. Section extending up valley in the Bremer Valley of the eastern Mount Lofty Ranges of South Australia. Note the relationship of the Lucernbrae ferricrete to the *Lepidocyclina* limestone. The ferricrete is interpreted as ferruginised beach and dune sand deposited at the level of the Tertiary (16 Ma) shoreline, and rests on slightly weathered Cambrian bedrock.

layers of hematite, goethite and lepidocrocite by weathering in place. Thin sections show similar silt-sized framework grains in the weathered ferricrete as in the original sideritic siltstone. Individual concretions may, however, be transported after formation by erosion. If ferricretes are *in situ* they should be formed in the same materials as the underlying materials and in such cases the absence of pisoliths may indicate *in situ* formation.

In the Casterton area many different rocks, sediments and materials have been weathered and ferruginised to different degrees (Kenley 1975). Some limestones contain iron-rich minerals, such as glauconite, siderite and chamosite, which have been weathered to produce secondary iron oxides. Most of the ferruginised limestone sediments (e.g. Compton Conglomerate) have a mono-iron mineralogy (goethite), which suggests simple impregnation by transformation of pre-existing iron-rich minerals. Retention of CaO and P_2O_5 in these sediments also argues against them being strongly influenced by terrestrial leaching environments.

Residual or sedentary deposits

Detritus derived from downwasting of mottled saprolite, involving little transport, should have close affinities to the underlying bedrock materials and show little effect of rounding. Thin sections should show similar structures in the detrital clasts as in the underlying bedrock. The clastic nature of the upper sections of many profiles suggests that previously weathered materials have been eroded, transported and deposited, largely as colluvium, and were probably associated with landscape downwasting. The clastic nature of the deposit may be apparent at many scales, from large disoriented boulders of iron-impregnated sediments to macroscopic and microscopic clasts that rest unconformably on underlying weathered bedrock.

In hand specimen, the detrital origin of some material becomes apparent, as angular to sub-rounded clasts of iron oxides, varying through mixtures of hematite, goethite and maghemite, together with fragments of hematitic bedrock, some with yellow rinds, are set in matrices of kaolinite and gibbsite. Some of the pisolitic crusts are similarly complex.

One of the arguments presented against ferricrete formation by downwasting of the landscape is that inordinate amounts of crustal rocks need to be weathered to produce the required concentrations of iron oxides (Ollier 1994). Ollier (1994) quoted the work of Nahon & Tardy (1992), who calculated that, in parts of Africa, the landscape must have been lowered between one and three kilometres since the Cretaceous. However, if ferricrete does not form uniformly over the landscape, but accumulates only sporadically in favoured locations, sufficient iron may be provided without excessive landscape lowering. Consequently, this argument does not negate the reality of landscape downwasting, but more work needs to be done to establish the amount of downwasting involved in landsurface development and ferricrete formation.

Transported ferricretes

A transported origin for ferricrete is favoured by the presence of components in the crust, including large fragments of reworked crusts, that are different from the underlying materials. For example, in the Sydney area, at Terrey Hills, there are clear unconformable relationships between ferruginous crusts and the underlying Hawkesbury Sandstone. Detritus such as that in Sydney area indicates residual weathering and downwasting that incorporates lateral transportation. Aeolian input to 'lateritic' materials may also be significant (Brimhall et al. 1988; 1991).

Investigations of weathering profiles should involve the search for evidence of lateral transport of physical particles or chemical precipitates derived from lateral sources. The interpretation of a weathered profile as a stratigraphic sequence is well illustrated at Peeralilla Hill in the Mount Lofty Ranges. Drilling through a thick surface ferruginous crust has revealed underlying sandy sediments, which in turn rest on weathered Cambrian metasediments (Fig. 6). An excavation through the crust has exposed white and green calcareous clays, which contain barite and calcite. The presence of calcite and barite may argue against leaching and the operation of intensive weathering processes in the formation of the ferricrete crust, although they may have precipitated out of groundwaters after the ferricrete developed. Nevertheless, the high total Fe_2O_3 content of approximately 70 per cent suggests iron oxide influx from lateral sources into a former depression. Thus, the sequence at Peeralilla Hill is interpreted as resulting from the deposition of iron oxides in a depression on an ancient landscape.

Macromorphology of ferricretes

The formation of ferricretes by lateral transportation is suggested by their macromorphology, especially if they contain ferricreted clastic sediments, ferricreted bedrock, pisolitic, slabby and vesicular to massive ferricretes (Bourman 1993a). On the other hand, vermiform ferricrete, some nodular types, and ferricretes with voidal concretions are considered to have formed essentially in place. Ollier (1994) considered that iron

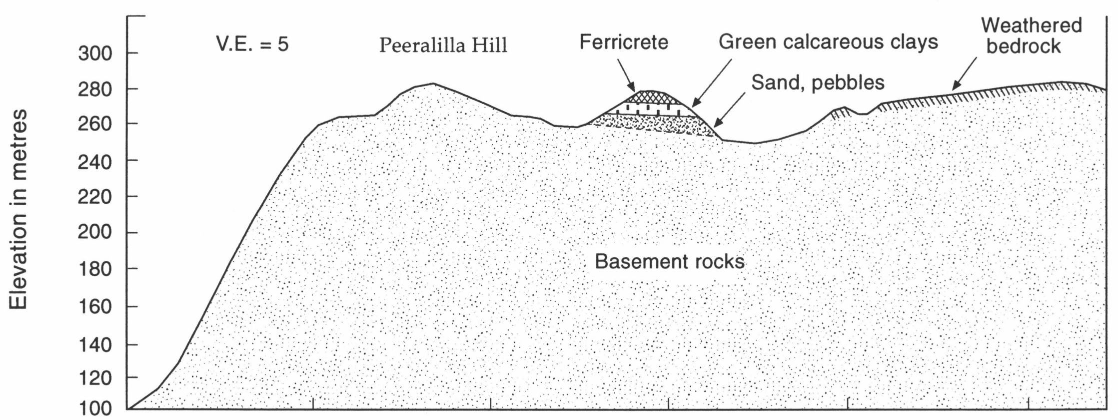

Figure 6. Cross section through Peeralilla Hill in the South Mount Lofty Ranges of South Australia. A thick vesicular ferricrete successively overlies green, calcareous clays, sands and pebbles and weathered Cambrian metasediments. It occupies a relatively low-lying position in the landscape and was a former peat swamp that acted as a sink for iron oxides brought in in solution, forming bog-iron ore as the iron oxides replaced organic material.

oxides precipitated above and below unconformities have different appearances with the 'resorted earth' above being pisolitic or nodular and that below being vesicular, vermiform, or tubular in character. Further investigation of ferricrete macromorphology, in a wide variety of situations, may yield valuable results with respect to identifying the origin of the ferricrete.

Pisolith formation

Investigations of pisolith formation are important, because pisoliths are significant components of many ferricretes. Much controversy exists concerning the origins of pisoliths. Some believe that pisoliths form *in situ* and that their development can be observed progressively through subsurface zones to the surface. Others interpret pisoliths as a result of physical disintegration of ferruginous material, followed by rounding and the acquisition of rinds during physical transport and modification in the soil environment. In resolving this issue it is necessary to examine localities where pisoliths are clearly transported and to examine their detailed characteristics.

Field evidence

In several locations pisoliths occur on sedimentary deposits which could not have provided the parent materials for pisolith formation. For example, in the mid-north of South Australia a ferruginous pisolith lag is underlain by calcareous material resting on a presumed Early Tertiary to pre-Tertiary erosion surface (Horwitz 1961). A similar situation occurs on the Blue Range of Eyre Peninsula, where bleached Precambrian metasediments are overlain successively by up to 2 m of calcareous fine earth and a sandy grey soil containing fragments of ferruginised sandstone bedrock and glazed pisoliths (Bourman 1989). The pisoliths are extremely magnetic, well sorted and glazed, which suggests modification in a near-surface environment.

Clearly the pisoliths have been transported: the formation of ferruginous clasts within calcareous parent material is most unlikely. The pisolith lag may have been transported laterally from higher parts of the landscape or have been concentrated at the surface by biological processes. Alternatively, it is possible that the calcium carbonate was blown into the area after mottling of the underlying material and pisolith formation, and the pisoliths progressively migrated upward as calcium carbonate loess accreted in the fashion described by Jessup (1960) and Chartres (1983) to account for the formation of stony tableland soils. In both these examples the present land surfaces are probably quite young, having been engulfed or overwhelmed by wind-blown calcium carbonate, probably during the Pleistocene.

Another example is provided near Kingscote on Kangaroo Island, where a road cutting reveals a base of iron-mottled clayey sands succeeded by a calcareous-rich horizon up to 1 m thick (Fig. 7). Overlying the calcium carbonate-rich layer is a yellow duplex soil, which contains ferruginous pisoliths both in the A-horizon and at the surface. Quartz, hematite, and maghemite dominate the mineralogy of the pisoliths; minor minerals include felspar, kaolinite, mica, gibbsite, smectite, and anatase. The chemical and mineralogical compositions of the pisoliths reflect a long history of transport in the environment. They may have been derived from older Tertiary ferricretes, especially as they contain gibbsite, which is common on nearby older, more severely weathered parts of the landscape. The fact that the soil and its pisoliths drape the valley where the carbonate layer has been eroded suggests that the pisoliths were emplaced after dissection of the carbonate layer. The complex internal structures of the pisoliths, their high iron contents, and the mineralogical and chemical incompatibilities of the pisoliths with the underlying materials suggest derivation from a lateral source. The pisoliths mantle the soil over a variety of relief, attesting to the physical mobility of pisoliths, which are widespread over much of the Kangaroo Island landscape. Lateral physical translocation of individual pisoliths, especially after fire or other vegetation degradation, appears to be extremely significant in explaining the present distribution of many ferruginous pisoliths.

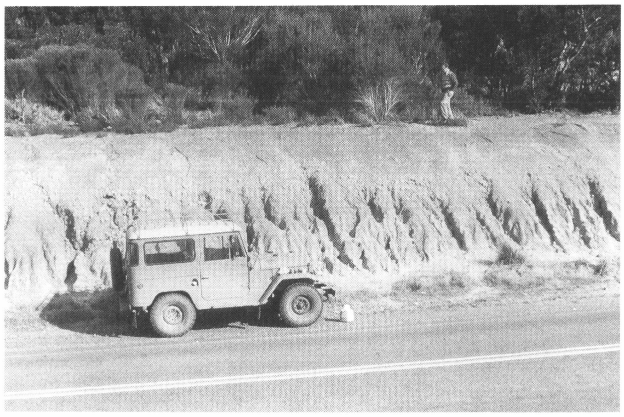

Figure 7. Road cutting 4 m deep on the Kingscote–Penneshaw road, Kangaroo Island, South Australia. Mottled Pleistocene sandy sediments at the base of the section are overlain by a lighter coloured carbonate-rich horizon on which the modern soil with complex maghemitic pisoliths rests.

In some cases, it is possible to demonstrate transport of pisoliths into sediments and former valleys, where the underlying materials could have provided an appropriate parent material for pisolith formation. For example, within iron-mottled Pleistocene sediments at Redbanks, Kangaroo Island, reworked pisoliths have been buried along with quartz clasts and grits. In many instances, transported pisoliths are often associated with stone lines that might indicate transport and reworking. Thin sections show the pisoliths to be complex with variable core materials, such as metamorphic rock fragments and clasts of clay and iron oxides. The cores are rimmed with several laminae of iron oxides (hematite, maghemite, and goethite) and fine quartz grains. The presence of multiple rinds and maghemite suggests some antiquity in the pisoliths and that they occupied a surface or near-surface position before transport and burial.

A further example occurs near Mount Desert on Fleurieu Peninsula, where a road cut at about 250 m a.s.l. has exposed former channels cut into kaolinised and iron-mottled metasedimentary rocks of the Cambrian Kanmantoo Group, and infilled with detritus, including fragments of bedrock mottles and pisoliths with multiple rinds, particularly near the base of the channel. Pisoliths at the base of the channel are identical in all respects to pisoliths that occur to the west of this site and at a higher elevation on the summit surface, where they form a one metre thick deposit in conjunction with bedrock fragments and other detrital materials. The individual pisoliths have characteristic goethitic surface rinds. Undisturbed resin-impregnated samples taken across the contact of the channel base and its infill do not reveal any indication of incipient pisolith development in the weathered bedrock below the channel. The occurrence of maghemite-rich pisoliths at about 6 m below the present ground surface is interpreted as evidence for transport from a higher section of the summit surface and subsequent burial near the base of a former channel.

Micromorphology

Microscopic studies reveal that pisoliths often have hematitic cores with kaolinite and gibbsite in the matrix. Matrix voids and fractures are coated by subsequent generations of hematite. Pelletal structures and ooliths of gibbsite also occur in the matrix. Such pisoliths do not appear to have formed *in situ*. In places, virtually pure gibbsite occurs on the margins of pisoliths, suggesting either that iron has been leached from the rind or that aluminium-rich gels have crystallised as gibbsite. Where individual quartz grains do not appear to be well rounded, extensive transport may not have occurred and this observation favours the view of pisolith accumulation consequent upon landscape downwasting.

Bourman et al. (1987) described a series of depositional multiple laminar goethite rinds on pisoliths, with occasional gibbsite, incorporating individual quartz grains or lenses between them, as evidence of their accretionary origin. They suggested that deposition of the laminae and incorporation of the quartz occurred in a succession of pedogenic environments, consistent with a long history of exposure, transportation and weathering. Some pisoliths reveal complex multi-cored structures, with closely packed quartz in the centres of the pisoliths, whereas the rinds contain very little quartz and are composed of virtually pure hematite. The lack of quartz in the rinds is of significance to the origin of the pisoliths, as the preservation of quartz would be expected. The composition of pisolith cores is variable; some are composed largely of gibbsite and others, hematite. The thickness and complexity of the rinds suggest long and complicated histories of development with layering occurring by accretion in different environments. Some smaller pisoliths display less complex structures and were probably incorporated into the ferricrete at a later stage. Thus, there appear to be pisoliths of different ages within the pisolitic crusts.

Coventry et al. (1983) described micromorphological features indicative of *in situ* and inherited, transported origins. For example, pisoliths with irregular shapes and diffuse external borders appear to have formed *in situ*, particularly as they display none of the evidence for transportation. Other evidence, which may indicate *in situ* formation, includes pisoliths without rinds, pisoliths that are angular, and those with the same framework grains within pisoliths as in the matrix materials. However, during development the angular pisoliths may be rounded by dissolution of irregularly shaped edges, and rinds may form in place, so that the above criteria may not always be reliable.

According to Coventry et al. (1983), the formation of pisoliths involving transportation is favoured by:

- incomplete or broken surface coatings on pisoliths;
- different particle-size distributions of sand and silt grains in pisoliths and their matrix materials;
- different particle-size distributions of sand and silt grains in adjacent pisoliths;
- laminae of silt-sized quartz grains inside some pisoliths that are not continuous outside of the pisoliths; and
- compound nodules cemented together by ferruginous, concretionary material whose structure has been truncated by abrasion.

Other possible transport indicators include multiple laminar goethite rinds on pisoliths, incorporating individual quartz grains or lenses between them, and the presence of complex combinations of pisolith-within-pisolith structures. The deposition of the laminae and incorporation of the quartz may have occurred in a succession of pedogenic environments, which would be consistent with a long history of exposure, transportation and weathering.

Mineralogy of pisoliths

Once at the surface or in the near-surface soil environment, pisoliths appear to undergo transformations that lead to higher total iron contents and transformations in iron mineralogy from goethite to dominantly hematite and maghemite. The simple monomineralogy of pisoliths appears to favour *in situ* formation. Transported pisoliths commonly have different chemical and mineralogical compositions to surrounding matrix materials, and display multiple rinds.

A site on the northern margin of the Waitpinga Creek drainage basin (near Victor Harbor, 80 km south of Adelaide), at 100 m a.s.l., appears to contain both *in situ* and transported pisoliths. The transported surface pisoliths have very different characteristics to the *in situ* pisoliths at a depth of about one metre. The surface pisoliths comprise 44.9% Fe_2O_3, 41.7% SiO_2 and 7.96% Al_2O_3 with an ignition loss of 3.85%. Their iron oxide mineralogy is dominated by hematite and maghemite, and kaolinite, smectite and mixed layer clays are present in small amounts. The surface pisoliths have multiple compound rims.

The pisoliths at depth have developed in a well-sorted silty sandstone, consisting of rounded and sub-rounded grains in a ferruginous clay-rich matrix. They are composed of material identical to that in the bulk of the deposit, which contains some grains of tourmaline, felspar, andalusite and polymozaic quartz grains of metamorphic origin. At higher magnifications, the iron oxides show a colloform fabric that indicates multiple influxes of iron oxides into pores. Some quartz grains have hematite coatings and laminated goethite and clay occur in the voids. Some fractures in the clay matrix are filled with hematite, which suggests various phases of hematite formation. In contrast to the surface pisoliths, those at depth contain only 5.35% Fe_2O_3, with 75.5% SiO_2 and 9.1% Al_2O_3; the iron oxide mineralogy is principally goethite, with a trace of hematite.

Pisolitic ferricretes

In many pisolitic ferricretes, the mineralogy and chemistry of the inter-pisolith matrix are significantly different to those of the pisoliths. For example, gibbsite, hematite, maghemite, kaolinite, and goethite have been identified in pisoliths, whereas the surrounding matrix has contained only goethite and kaolinite (Bourman 1989). In such cases, the pisoliths may be interpreted as clastic components different from the materials in which they are found. Pisoliths in southern Australia commonly display high total-iron content and an iron oxide mineralogy dominated by hematite and maghemite. Maghemite may occur both in the body of the pisolith and in outer concentric layers. In some localities in Western Australia, hematite is a significant portion of the matrix material (Anand & Gilkes 1987a).

The occurrence of jarosite, alunite, and smectite in ferricrete overlying unconsolidated sand in a clay pan bottom, 10 km northwest of Pinjarra Dam, South Australia, within the Corrobinnie Depression, is compatible with the accumulation of iron from groundwater in a lacustrine environment. Reddish-purple sandy clay with yellow streaks, recovered from below the level of the above ferricrete, also contained minerals such as natrojarosite, alunite and barite(?), compatible with a lacustrine origin for the iron accumulation. It appears very likely that in the Corrobinnie Depression the presence of lakes and sluggish drainage of former Tertiary palaeochannels favoured the accumulation of iron oxides, and this, rather than differential erosion of more or less continuous ferricrete crusts, could account for the sporadic distribution of ferricretes in the area.

Analyses of other samples of pisolitic ferricrete collected from near the surface and resting on or incorporated within sediments of the presumed Garford Formation (Benbow & Pitt 1978) of the Corrobinnie Depression revealed similar compositions. Furthermore, in all samples, the pisoliths displayed different mineralogical compositions and iron and titanium contents to those of the surrounding matrix materials (Bourman 1989). For example, pisoliths contained hematite, kaolinite, maghemite and anatase, with an iron and titanium contents of 30.26% and 1.24%, respectively, whereas iron-rich matrices were composed dominantly of goethite with minor hematite, kaolinite, smectite, felspar and anatase, and no maghemite. The iron content of the matrix is considerably less at 19.94%, as is TiO_2 at 0.68%. In all cases, the pisoliths contain more iron, dominated by hematite and maghemite, whereas the main iron mineral detected in the iron-rich matrix was goethite. Where maghemitic pisoliths are found at depth, it is likely they have been incorporated into the matrix material after being at the surface. The evidence presented above suggests that, regardless of where the pisoliths originally formed, they spent some time at the surface, undergoing modification, before being reincorporated into younger sediments.

Palaeomagnetism

According to Ollier (1994), palaeomagnetic dating demonstrates that crusts have formed in the past and are not undergoing modification. He argues that if ferricretes were formed by a process continuing to the present, they should be constantly remagnetised and have zero palaeomagnetic age, whereas many have been dated to the Tertiary and Cretaceous.

However, there is confusion over whether palaeomagnetic dates refer to ferricretes or to underlying weathered zones (c.f. Schmidt & Ollier 1988). Moreover, in some localities, even mottled zones show weathering transformations, with hematite converting to goethite.

Palaeomagnetism appears to provide reasonably acceptable data in respect of the geomagnetic reversal time scale and mottled zones through which original sedimentary structures are preserved (Pillans & Bourman 1995). These investigations demonstrate both variability in the development of a single mottled zone as well as similar timing of formation for both mottles and adjoining bleached zones.

On the other hand, pisolitic ferricretes are almost impossible to date and, if pisolitic ferricrete had formed *in situ*, there should be coincidence in the palaeomagnetic signatures preserved in the individual pisoliths. Hunt (1985) established that the scattering of remanent magnetism in individual pisoliths in the Sydney area indicated physical disturbance since their formation, implying transportation. However, Brimhall (personal communication 1993) prefers to explain this observation simply in terms of disorientation by volumetric change following *in situ* formation.

In situ or transported?—a case study from Sydney

Many workers before Hunt et al. (1977) regarded 'laterite' profiles in the Sydney area as fossil soils formed under tropical climatic conditions during the Miocene on a 'peneplain' close to sea level, with the present sporadic distribution of 'laterite' resulting from dissection after uplift (e.g. Faniran 1969). In contrast, Hunt et al. (1977) interpreted the 'laterite profiles' as reflecting contemporary near-surface alteration of iron-rich Hawkesbury Sandstone units, including the mobilisation of iron minerals as crystalline solids. Evidence used to support this view included:

- the coincidence of structures in the 'lateritic profiles', especially at Terrey Hills, with structures in the Hawkesbury Sandstone;
- the overlap of iron concentrations in the 'lateritic profiles' with those contained in iron-rich sequences in the Hawkesbury Sandstone;
- the lack of evidence for iron-enrichment in indurated zones and impoverishment in mottled zones;
- the absence of variations in aluminium and silica down profiles;
- the recognition of original sandstone fabrics in nodular, indurated zones;
- the *in situ* formation of maghemitic nodules within the profiles.

Consequently, they saw no need for external sources of iron or for long-distance lateral iron oxide transport. Hunt et al. (1977) regarded the surface on which the 'laterite' occurs, not as a peneplain, but as a dip slope coincident with the upper surface of the Hawkesbury Sandstone.

An alternative explanation by Bourman (1989) reported a clear unconformable contact between weathered Hawkesbury Sandstone and overlying fine-grained sediments that contained clasts of dense magnetic material and pebbles of coarse-grained hematitic sandstone, similar to those occurring in the Terrey Hills site. The contacts were observed in a cutting on the nearby Mona Vale Road and in the former Belrose quarry (Fig. 8). Subsequently, Bourman (1989) interpreted the indurated materials as weathered and iron-indurated clastic deposits of colluvial, detrital origin rather than weathered Hawkesbury Sandstone structures.

Differential desilicification of the Hawkesbury Sandstone along susceptible beds is common, such as at Beacon Hill, where essentially unweathered bedrock occurs near the summit, but is underlain by considerable thicknesses of weathered and iron-depleted sandstone. Thus, sections of the sandstone may be coherent, whereas, elsewhere, beds have been preferentially removed to cause collapse of overlying strata. In several road cuttings along West Head Road, sandstone depressions thus formed have been infilled with colluvial material derived from upslope. The colluvial material includes fragments of hematitic sandstone and fine-grained strongly magnetic clasts, both of which occur at the surface over many areas of the plateau in the Kur-ring-gai Chase National Park. These materials resemble those occurring in the clastic deposits that constitute most of the indurated zone at Terrey Hills. Thus, while the structures present in the indurated material may not be directly inherited from original sandstone structures, deposition of the clastic sediments may have been influenced by them, so that the clastic structures could mimic those of the original sandstone.

The occurrence of maghemite at depth throughout the weathered zones throws some light on the origin of the duricrusts. Faniran (1970) reported that maghemite in the Sydney 'laterites' occurs mainly in the cores of pisoliths and decreases rapidly with depth in the profiles, being mainly confined to upper indurated zones. However, clasts composed of maghemite, hematite and small amounts of quartz and mica have been identified throughout the weathered zones above the Hawkesbury Sandstone in a variety of ferricrete types, such as pisolitic, nodular, vermiform and iron-impregnated sandstone (Bourman 1989). The distribution of maghemitic flakes throughout the weathered profiles may suggest a derivation from iron-rich solutions permeating through weathered material, in the fashion described by Schwertmann & Taylor (1987). However, there is ample evidence that many of the maghemitic clasts have formed elsewhere, and been transported and deposited within finer grained sediments above the sandstone bedrock.

For example, maghemite is visible in thin sections of cores of pisoliths from deep locations within profiles, and other pisoliths have maghemitic rinds that almost certainly developed through the transformation of goethite by surface burning. Another indicator of surface or near-surface modification may be the presence of corundum in some maghemitic surface pisoliths. The corundum could have formed by the heating transformation of gibbsite or aluminium-substituted goethite (cf. Anand & Gilkes 1987b). Other possible sources of maghemitic clasts in the Sydney duricrusts include magnetite from within the Hawkesbury Sandstone and siderite from the Wianamatta Shales or from basic igneous rocks (Faniran 1970). Whatever the source of maghemite, it is clear that the clasts have been transported to their present positions.

Ferricretes in the Sydney area appear to result from a long complex history involving weathering, erosion, transport, and deposition. This is exemplified by complex profiles (Fig. 9) and a series of mixed facies of ferricretes (pisolitic, nodular, clastic, vermiform, and vesicular) as well as soft and hard mottles. These may be related to different environments. For

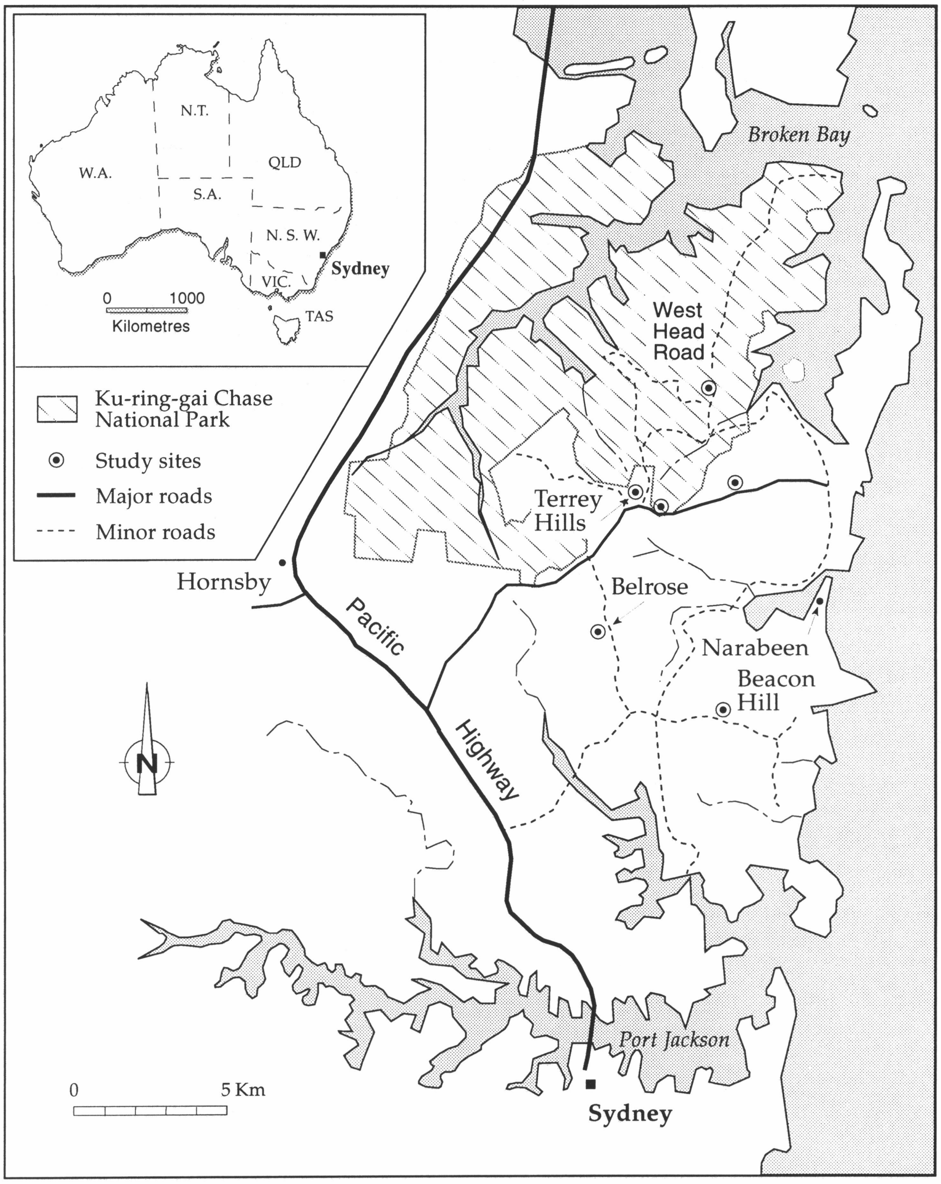

Figure 8. Location map of the Terrey Hills area and study sites, Sydney, NSW.

example, vesicular ferricrete, which is composed dominantly of goethite with small amounts of kaolinite, hematite, quartz, and gibbsite, appears to be a chemical deposit, suggesting that the area has acted as a sink for iron oxides transported in solution at some time in the past, impregnating pre-existing bioturbated fine soils or organic matter. Pisolitic crusts may relate to former soils, and, in places at Terrey Hills, there appears to be a succession of superimposed and hardened fossil soils, displaying biogenic structures and burrows similar to the modern soil. Clastic ferricrete material has formed by the iron-impregnation of colluvium, and vermiform structures may reflect biogenic influences or the passage of soil or groundwater through the deposit, leading to its dissolution. Hardened and soft mottles may relate to exposure and variations in seasonal water tables. These various ferruginous materials occur in a colluvial mantle, which comprises the indurated zone at the Terrey Hills site, where Hunt et al. (1977) argued that clear *in situ* bedrock structures occur.

Evidence of protracted weathering is provided by the abundance of gibbsite in the mottled and indurated zones and it probably developed through the incongruent dissolution of kaolinite. There is an inverse relationship between the relative abundances of kaolinite and gibbsite (Bourman, 1989). Hunt et al. (1977) reported gibbsite in the Hawkesbury Sandstone, but Standard (1967) did not indicate any significant gibbsite in it. Although some of the kaolinite may be detrital (Standard 1967), its abundance suggests long periods of weathering, as the greatest amounts of gibbsite and kaolinite occur within detrital material above the weathered and kaolinised Hawkesbury Sandstone. These minerals may have been derived both from the weathering of the immediately underlying sandstone and from the Wianamatta Shale.

Variations in the mineralogy and chemistry of pisoliths in pisolitic ferricrete and their surrounding matrix materials suggest formation in different environments. Maghemite enclosed in pisoliths suggests a near-surface formation and subsequent burial or incorporation into soils. The encapsulation of maghemite within pisoliths negates the significance of contemporary flushing of maghemite through the profile to concentrate it as discrete nodules.

Biogenic structures, including burrows, trails and plant roots, suggest that some of the clastic materials were unconsolidated soils and weathered zones, subsequently iron-impregnated and hardened. Coating of the biogenic structures with subsequent deposits of iron oxides suggests further complexities in the development of the indurated zones.

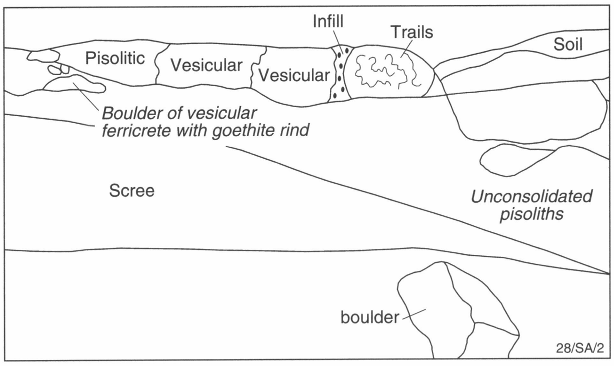

Figure 9. Variable and complex duricrust at Terrey Hills, Sydney, NSW. Duricrust of pisolitic (cemented pisoliths), vesicular (bog-iron ore) and vermiform (trail-like features) types, and soil overlie unconsolidated pisoliths. An isolated boulder of pisolitic crust occurs in the foreground.

Some workers (e.g. Faniran 1970) have considered that the Hawkesbury Sandstone has insufficient iron for the formation of iron-cemented duricrusts and preferred iron sources from the Wianamatta Shale and the basic rocks of the area. After examining detrital quartz from weathered Hawkesbury Sandstone and Wianamatta Shale, Burgess & Beadle (1952) and Beadle & Burgess (1953) concluded that in most cases 'laterite' had formed from shales overlying or interbedded within the Hawkesbury Sandstone. They argued that the origin of 'laterite' from shales could account for both the source of iron, as the Wianamatta Shale has a Fe_2O_3 content of 510 per cent, and the abundance of kaolinite in profiles. Their analytical work suggested that extra iron was added to the profiles from weathering of shales and basalt flows.

On the other hand, Hunt et al. (1977) considered that the weathered profiles showed no evidence of iron-enrichment in the indurated zones nor depletion in the mottled zones, and claimed that, as there were overlaps in the iron content of zones of the Hawkesbury Sandstone and iron-rich crusts, there was no need to invoke external sources of iron. However, many of the iron-rich zones within the Hawkesbury Sandstone are quite thin and may be inadequate to produce the total amount of iron within the 'laterite' profiles. It appears that the iron bands in the Hawkesbury Sandstone have been incorporated into the profiles, but dominantly as clasts rather than as the tiny flakes suggested by Hunt et al. (1977). Chemical analysis of the Hawkesbury Sandstone gives a low total iron content, 0.32–1.41 per cent (Bourman 1989). An iron-rich crust, a few centimetres thick, within the Hawkesbury Sandstone had an Fe_2O_3 content of 19.97 per cent, dominantly in the form of goethite with only a small amount of hematite. The iron oxides could have been deposited with the bulk of the rock or introduced at a later stage during weathering processes, with the latter possibility being favoured.

Standard (1967) reported subsurface siderite, at up to 4 per cent, as the main iron mineral present in the Hawkesbury Sandstone. This mineral was not identified in the outcrops sampled, which suggests transformation to other iron oxides, which it will do rapidly in oxidising environments (Bourman 1989). It does appear, however, that the local zones of iron enrichment require influxes of iron oxides from outside the immediate area, and may have been derived from a variety of sources. If the view is followed that there was not a uniform blanket of ferricrete across a former 'peneplain' surface, but a landsurface of some relief, with only localised colluvial and chemical concentrations of iron developing in favourable environments as the landscape suffered weathering and downwasting, then there is no requirement for vast amounts of iron.

Contrary to the view of Hunt et al. (1977), there is evidence of profile differentiation in the section at Terrey Hills. There is a fairly uniform iron content down the indurated zone of the Terrey Hills profile, ranging from 20 to 40 per cent with a slight increase towards the surface. However, at the base of the most northerly outcrop there is a rapid drop in total iron content to only a few per cent. Moreover, the depletion of bases and silica within the profile indicates the influence of considerable leaching.

There is certainly ample evidence of ferrihydrite formation in the modern environment, where it forms a sludge or gel following precipitation from iron-rich waters along roadside drainage channels. The transformation of ferrihydrite to hematite and/or goethite may better account for some of the observations of Hunt et al. (1977), rather than invoking the eluviation of tiny crystalline flakes of hematite and maghemite through the profiles. The fact that much maghemite is locked up in the cores of pisoliths suggests that those maghemite-rich pisoliths at depth are not currently forming.

Conclusion

The formation of ferruginous duricrusts by relative (*in situ*) and absolute (lateral) accumulation of iron and aluminium oxides has been well documented (e.g. d'Hoore 1954), but not all workers have agreed on the significance of these processes and their recognition in the final weathering product. An attempt has been made to develop a first approximation for establishing criteria that might be useful in distinguishing the *in situ* and transported components of ferricretes.

In assessing the origin of a particular ferricrete, it is necessary to combine all types of evidence. For example, in the Sydney area, evidence from field relationships, chemistry, mineralogy, macro-structures and micro-morphology suggests a long and complex history of erosion, deposition and weathering, including the formation and hardening of soils on a landscape subaerially exposed and undergoing downwasting and erosion for a long time, which led to the accumulation of iron and aluminium oxides in favourable environments.

Acknowledgments

The paper has benefited by the comments of Ravi Anand and Johnathon Clarke. David Brittain prepared the figures.

References

Anand, R.R., 1993. The regolith and its exploration and economic significance. In: Williams, P.R. & Haldane, J.R. (editors), An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields—excursion guidebook. Australian Geological Survey Organisation Record 1993/53, 75–100.

Anand, R.R., 1994. Regolith–landform evolution and geochemical dispersion from the Boddington gold deposits, W.A. CSIRO Division of Exploration and Mining Report 24R, 149 pp.

Anand, R.R. & Gilkes, R.J., 1987a. Variations in the properties of iron oxides within individual specimens of lateritic duricrust, Western Australia. Australian Journal of Soil Research, 25, 287–302.

Anand, R.R. & Gilkes, R.J., 1987b. The association of maghemite and corundum in Darling Range laterites, Western Australia. Australian Journal of Soil Research, 35, 303–311.

Anand, R.R., Churchward, H.M., Smith, R.E. & Grunsky, E.C. 1991. Regolith landform development and consequences on the characteristics of regolith units, Lawlers District, Western Australia. CSIRO/AMIRA Laterite Geochemistry Project P240. 160 pp.

Abele, C., Kenley, P.R., Holdgate, G. & Ripper, D., 1976. Otway Basin. In: Douglas, J. G. & Ferguson, J. A. (editors). Geology of Victoria. Geological Society of Australia, Special Publication No. 5, 528 pp.

Beadle, N.C.W. & Burgess, A, 1953. A further note on laterites. Australian Journal of Science, 15, 170–171.

Benbow, M.C. & Pitt, G.M., 1978. The Garford Formation. Quarterly Geological Notes, Geological Survey of South Australia, 68, 8–15.

Benbow, M., Callen, R.A., Bourman, R.P. & Alley, N.F., 1995. Deep weathering, ferricrete and silcrete. In: Drexel, J. (editor), The Geology of South Australia. S.A. Department of Mines and Energy. Bulletin 54, Chapter 10.

Bourman, R.P., 1989. Investigations of ferricretes and weathered zones in parts of southern and southeastern Australia—a reassessment of the 'laterite' concept. Ph.D. thesis, University of Adelaide. 495 pp. (unpublished).

Bourman, R.P., 1993a. Modes of ferricrete genesis: evidence from southeastern Australia. Zeitschrift für Geomorphologie, 37(1), 77–101.

Bourman, R.P., 1993b. Perennial problems in the study of 'laterite'—a review. Australian Journal of Earth Sciences, 40, 387–401.

Bourman, R.P., Milnes, A.R. & Oades, J.M., 1987. Investigations of ferricretes and related surficial ferruginous materials in parts of southern and eastern Australia. Zeitschrift für Geomorphologie. N.F. Suppl.-Bd., 64, 1–24.

Bourman, R.P., Fitzpatrick, R.W. and Self, P.G., 1995: Character and origin of ferruginous voidal concretions in weathered Triassic sediments of the Telford Basin, South Australia. 10th International Clays Conference, Adelaide, 1993, Proceedings, 344–352.

Brimhall, G.H., Lewis, C.J., Ague, J.J., Dietrich, J.H., Teague, T. & Rix, P., 1988. Metal enrichment in bauxites by deposition of chemically mature aeolian dust. Nature, 333, 819–824.

Brimhall, G.H., Lewis, C.J., Ford, C., Bratt, J., Taylor, G. & Warin, O., 1991. Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion and eolian influx in lateritization. Geoderma, 51, 51–91.

Burgess, A. & Beadle, N.C.W., 1952. The laterites of the Sydney District. Australian Journal of Science, 14, 161–162.

Chartres, C.J., 1983. The pedogenesis of desert loam soils in the Barrier Range, western New South Wales. ii—weathering and soil formation. Australian Journal of Soil Research, 21, 1–13.

Conacher, A.J., 1991. Lateritic duricrust and relief inversion in Australia. Ollier, C.D. & Galloway, R.W., The laterite profile, ferricrete and unconformity—a discussion. Catena, 18, 585–588.

Coventry, R.J., Taylor, R.M. & Fitzpatrick, R.W., 1983. Pedological significance of the gravels in some red and grey earths of central north Queensland. Australian Journal of Soil Research, 21, 219–240.

Faniran, A. 1969 A deeply-weathered surface and its destruction: a geomorphological study of duricrusts in the Northern Sydney District. Ph.D. thesis, University of Sydney, 464 pp. (unpublished).

Faniran, A., 1970. Maghemite in the Sydney duricrusts. American Mineralogist, 55, 925–933.

Gibbons, F.R. & Downes, R.G., 1964. A study of the land in southwestern Victoria. Soil Conservation Authority, Victoria. 269 pp.

Gibbons, F.R. & Gill, E.D., 1964. Terrains and soils of the basaltic plains of far-western Victoria. Proceedings of the Royal Society of Victoria, 77, 387–395.

Hickman, A.H., Smurthwaite, A.J., Brown, I.M. & Davy, R., 1992. Bauxite mineralisation in the Darling Range, Western Australia. Geological Survey of Western Australia. Report, 33, 82 pp.

d'Hoore, J., 1954. Essai de classification des zones d'accumulation de sesquioxydes libres sur de bases genetiques. Sols Africains, 3, 66–80.

Horwitz, R.C., 1961. The geology of the Wakefield Military Sheet. Report of Investigations, Geological Survey of South Australia, 18, 1–32.

Hunt, P.A., 1985. The mobility of silicon and iron in the near-surface zone; A re-evaluation of the concept of duricrust in central and eastern New South Wales. Ph.D. thesis, Macquarie University, 343 pp.(unpublished).

Hunt, P.A., Mitchell, P.B. & Paton, T.R., 1977. "Laterite profiles" and "lateritic ironstones" on the Hawkesbury Sandstone, Australia. Geoderma, 19, 105–121.

Jessup, R.W., 1960. The stony tableland soils of the southeastern portion of the Australian arid zone and their evolutionary history. Journal of Soil Science, 11, 188–197.

Kenley, P.R., 1971. Cainozoic geology of the eastern part of the Gambier Embayment, southwestern Victoria. Otway Basin. In: Douglas, J.G. & Ferguson, J.A. (editors), Geology of Victoria. Geological Society of Australia, Special Publication No. 5, 89–153.

Kenley, P.R., 1975. Geology and geomorphology of southwestern Victoria. A.I.H.S. symposium, Horsham. Geological Survey of Victoria.

Lamplugh, G.W., 1902. Calcrete. Geological Magazine, 9, 575.

Milnes, A.R., Bourman, R.P. & Northcote, K.H., 1985. Field relationships of ferricretes and weathered zones in southern South Australia: a contribution to 'laterite' studies in Australia. Australian Journal of Soil Research, 23, 441–465.

Mulcahy, M.J. 1960. Laterites and lateritic soil in southwestern Australia. Journal of Soil Science, 11, 206–225.

Nahon, D. & Tardy, Y., 1992. The ferruginous laterites. In: Butt, C.R. & Zeegers, H. (editors), Regolith exploration geochemistry in tropical and subtropical terrains. Handbook of Exploration Geochemistry, 4, 40–55, Elsevier, Amsterdam.

Ollier, C.D., Chan, R.A., Craig, M.A. & Gibson, D.L., 1988. Aspects of landscape history and regolith in the Kalgoorlie region, Western Australia. BMR Journal of Australian Geology & Geophysics, 10, 309–321.

Ollier C.D., 1991. Laterite profiles, ferricrete and landscape evolution. Zeitschrift für Geomorphologie, 35, 165–173.

Ollier C.D., 1994. Exploration concepts in laterite terrains. The Australasian Institute of Mining and Metallurgy, Bulletin, 3, 22–27.

Ollier C.D. & Galloway, R.W., 1990. The laterite profile, ferricrete and unconformity. Catena, 17, 97–109.

Pillans, B. & Bourman, R.P., 1995. The Bruhnes/Matuyama Polarity Transition (0.78 Ma) as a chronstratigraphic marker in Australian regolith studies. AGSO Journal of Australian Geology & Geophysics (this issue).

Schmidt, P.W. & Ollier, C.D., 1988. Palaeomagnetic dating of Late Cretaceous to Early Tertiary weathering in New England, NSW, Australia. Earth Science Reviews, 25, 363–371.

Schwertmann, U. & Taylor, R.M., 1987. Iron oxides. In:

Dixon, J.B. & Weed, S.B. (editors), Minerals in soil environments. Soil Science Society of America, Madison, Wisconsin.

Standard, J.C., 1969. Hawkesbury Sandstone. In: Sydney Basin. Geology of New South Wales. Journal of the Geological Society of Australia, *16, 406–415.*