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SOIL MICROMORPOHLOGY:

STUDIES IN MANAGEMENT AND GENESIS

Edited by

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Darwinian zircons as provenance tracers of dust-size exotic components in laterites: mass balance and SHRIMP ion microprobe results

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ABSTRACT

Brimhall, G.H., Compston,W., Williams, I.S., Reinfrank, R.F. and Lewis, C.J., 1994. Darwinian zircons as provenance tracers of dust-size exotic components in laterites: mass balance and SHRIMP ion microprobe results. In: A.J. Ringrose-Voase and G.S. Humphreys (Editors), Soil Micromorphology: Studies in Management and Genesis. Proc. IX Int. Working Meeting on Soil Micromorphology, Townsville, Australia, July 1992. Developments in Soil Science 22, Elsevier, Amsterdam, pp. 65-81.

At the lateritic bauxite deposit at Jarrahdale, Western Australia we quantify micromorphological evidence of an excess cumulative detrital soil component and relate its presence and accommodation in the subsurface to the combined effects of long-term, eolian deposition and progressive, dilational mixing induced by biological activity. The subsurface entry mechanism involves a repeated sequence of void space creation through root decay, detrital translocation, pore infilling, and renewed root growth. This process is evident as a multitude of oriented, geopetal, microsedimentary pore deposits cross-cutting still older in-filled voids along arcuate, concave-up unconformities observed in ultra-thin (5-micron) sections. Tubular root voids controlling invasive translocation penetrate even the most indurated of duricrusts and hence provide effective pathways for detritus to descend from the surface down to the top of saprolite. In comparison to this detrital transport, we show that *in situ* residual enrichment, viewed conventionally as the principal mechanism of bauxitization, dominates only the lowest, most primitive part of the soil above bedrock where tubular voids are uncommon. The horizontal interface separating detrital (plus minor residual) and purely residual components below is critical to mapping and understanding the exposure level of laterite profiles. This two-part soil package, previously referred to by Ollier and Galloway (1990) as detrital ferricrete overlying saprolite, was interpreted by them as being subdivided by a sedimentary unconformity. However, we conclude that the Jarrahdale lateritic bauxite has no unconformity but instead is differentiated *internally* into a composite but *continuous* biomechanical system with two distinct compartments defined by the penetration depth of exotic detritus mixed into the subsurface by pedoturbation and bioturbation. While the upper bio-active part is contaminated by surficial detritus and biochemically-cycled components like carbon and sulfur, the lower cell receives only organic acid decay products. We integrate these micromorphologic features of the soil profile with their broader geological context by application of SHRIMP ion microprobe zircon geochronology which is a new, preferred

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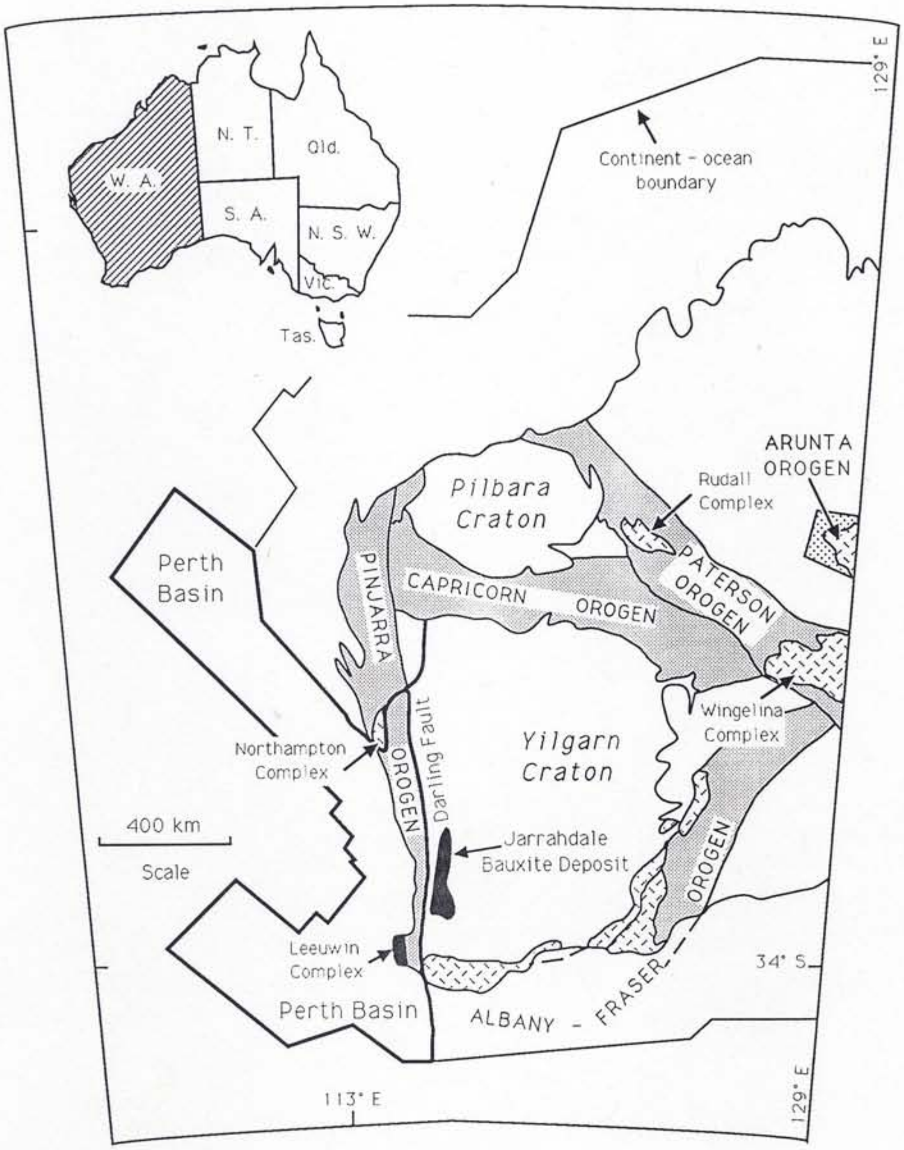

Fig. 1. Location map of Jarrahdale lateritic bauxite deposit in Western Australia in the Darling Ranges near Perth at the western edge of the late Archean Yilgarn Craton. Ancient, now eroded, Pinjarra, Albany-Fraser, Patterson and Arunta orogen mountain belts are shown modified from Myers (1990) and Trendall (1990) in relation to the Perth sedimentary Basin (Trendall and Cockbain, 1990). The Leeuwin Complex, interpreted here as the principal source of rounded exotic zircons in the Jarrahdale bauxite, is shown on the southwest corner of Australia within the Pinjarra orogen.

technique in provenance studies. This proved the exotic character of detrital zircons and also established preliminary age constraints on their ultimate provenance. From comparison of ages of rounded zircons in bauxite with dated in-place zircons in bedrocks exposed regionally, we infer the detrital source regions to be disrupted kaolinitic-laterite mantles developed earlier on eroded paleo-orogenic mountain belts surrounding the Yilgarn and/or younger sedimentary basins containing kaolinitic erosional detritus.

INTRODUCTION

The purpose of this paper is to interpret micromorphological evidence of exotic cumulative soil components in lateritic bauxite deposits which is inconsistent with the prevailing view of a simple *in situ* residual origin. Rather than fuel continued debate over merits of conflicting models of residual versus transported detrital origin, we set out here instead to apply definitive new analytical methods to determine where, how and why either or both of these contrasting enrichment mechanisms occur. The techniques we employ to resolve these issues involve both elemental and isotopic mass analysis and in combination afford unique capabilities of first discerning and then quantifying the effects of these discrete processes. We measure the mass contribution of the detrital laterite component by elemental mass balance and constrain its provenance using isotopic tracers. These new techniques make it possible to unequivocally differentiate detrital additions (aeolian, colluvial and alluvial) from residual components. Thus we can begin to integrate complex small-scale microscopic soil features with the broader long-term geological context of surficial transport processes in cratons. Here, processes occurring at ground level uniquely reflect subdued peneplained landscapes where erosion is minimal and the biota inevitably plays an important role in development of a composite weathering mantle by complex internal ordering at the interface of the biosphere with the geosphere.

ANALYTICAL STRATEGY AND FIELD SITE SELECTION

We have applied elemental mass balance and isotopic methods to the Jarrahdale lateritic bauxite deposit in the Darling Range of Western Australia (Fig. 1). This deposit has been studied by Sadleir and Gilkes (1976), Smurthwaite (1990) and Anand *et al.*, (1991) and besides excellent mineralogical profile descriptions, offers the potential advantage of having developed locally over a late Archean (2.6 Ga) granitic parent material making it possible to eliminate its variability as a cause of diversity in soil profile characteristics or a significant factor in its pedogenic evolution. Although a lingering controversy persists as to the igneous or sedimentary character of the parent material (Grubb, 1971) this issue is resolved here in a later section.

Analytical sequence

Using fresh granitic gneiss parent material exposed in a deep rail cutting as the state of comparison, we proceed through a sequence of analytical steps in a well-proven mass balance strategy (Brimhall and Dietrich, 1987; Brimhall *et al.*, 1988, 1991, 1992). First, volume change induced by weathering and pedogenesis is determined directly rather than assuming an isovolumetric process. Second, using the calculated volume changes or strains, we determine the absolute chemical gains and losses of elements in individual samples of the

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porous medium. From these true *transported* mass profiles we evaluate each zone of mass accumulation. For those with a related zone of depletion, local profile-scale migration is inferred. Zones of accumulation lacking internal source regions require influx from external sources. Thirdly, we evaluate the total enrichment factor of each element in terms of component enrichment mechanisms: residual accumulation, deformation and transport. Finally, SHRIMP (sensitive high-resolution ion microprobe) (Compston *et al.*, 1984) zircon dating is used to verify the identity of the parent material, establish its upward continuity and to constrain the provenance of dateable exotic detrital minerals associated with aluminous and ferruginous detritus shown by mass balance to have been derived from sources external to the profile.

Incompleteness of the in situ residual and detrital origin models

Basically three laterite genesis models have been advanced that differ principally in the mode of accumulation of aluminous and ferruginous minerals and in the interpretation of the relevant parent material. These models can be categorized as (1) *in situ* residual enrichment of granitic gneiss parent material, (2) detrital transport and (3) weathering of sedimentary parent material rather than granitic gneiss. Each of these models, while making important advances in understanding bauxite genesis, are incomplete and leave essential features of the profiles unexplained. The prevailing *in situ* residual model of the genesis of the Jarrahdale bauxite deposit (Sadleir and Gilkes, 1976; Davy, 1979, Smurthwaite, 1990; and Anand *et al.*, 1991) cites the similarity between chemical, mineralogical and physical characteristics of bauxite including textures and structures with specific underlying igneous rocks (generally late Archean granites or more rarely younger dolerite dikes of the Yilgarn Craton). Ollier and Galloway (1990), addressing laterite genesis in general, prefer a strict detrital origin of ferricrete occurring above saprolite and interpret the contact as being a depositional sedimentary unconformity of presumably-transported material overlying an indigenous substrate.

An alternative and controversial weathering model invoking an arkosic fluviatile sedimentary parent material instead of local granitic gneisses, was proposed by Grubb (1971) to explain the presence of a rounded abraded suite of heavy accessory minerals (zircon, rutile, ilmenite, monazite and tourmaline) in the uppermost zones of certain bauxites, including Jarrahdale. This interpretation of Grubb's "mineralogical anomalies" was refuted by Baker (1972), Sadleir and Gilkes (1976) and also Davy (1979). Davy (1979), who while also favoring a residual weathering mechanism, pointed out that the origin of the exotic accessory minerals and the means of their incorporation into the "caprock" had not been clearly identified. Davy also pointed out that windblown materials would be expected over the expanses of the Yilgarn under desert conditions inferred earlier by Killigrew and Glassford (1976).

MASS BALANCE STUDIES

By making the first application of mass balance techniques fully-integrating chemical composition with physical properties and volume change (Brimhall *et al.*, 1985; Brimhall and Dietrich, 1987) to the Jarrahdale bauxites, Brimhall *et al.* (1988) were able to use chemical elements as geochemical tracers which reveal their own history of transport. Thus, effective discrimination between residual accumulation and transport was made possible. This study of

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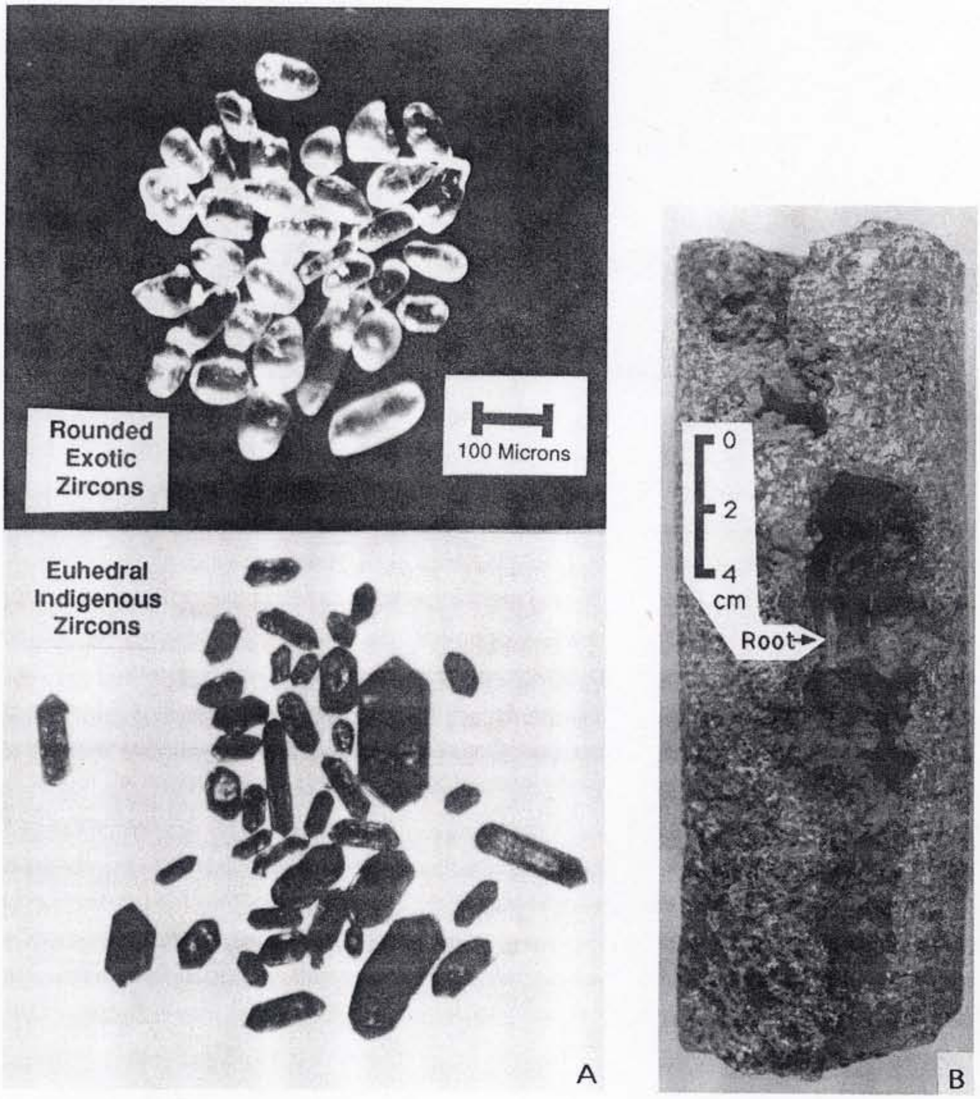


Fig. 2. (A) Comparison of clear rounded exotic Darwinian zircons (top) with cloudy euhedral indigenous zircons (bottom) from the Jarrahdale bauxite. (B) Example of a modern root occupying an older void in which detrital translocation occurs.

Jarrahdale reconciled several features of the previously contradictory interpretations and showed that the widespread but vertically-localized surficial detrital suite of accessory minerals, including rounded zircon (Fig. 2A), was in fact introduced from the top of the profile possibly after eolian transport responsible for grain abrasion. The decreasing abundance of the detrital suite with depth does not support Grubb's contention that it is derived from a fluviatile

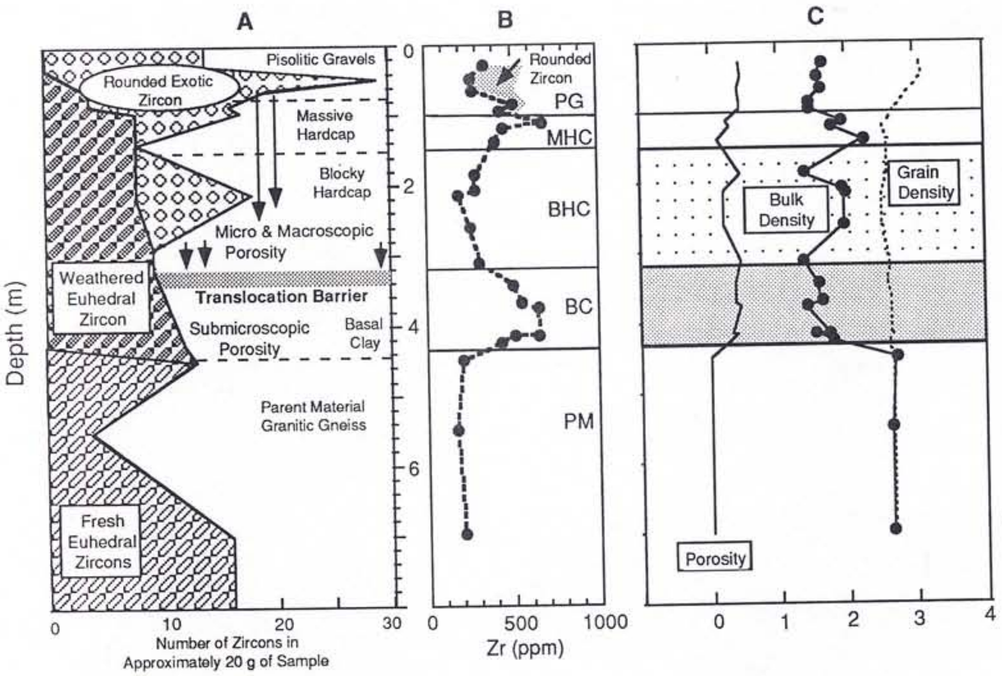
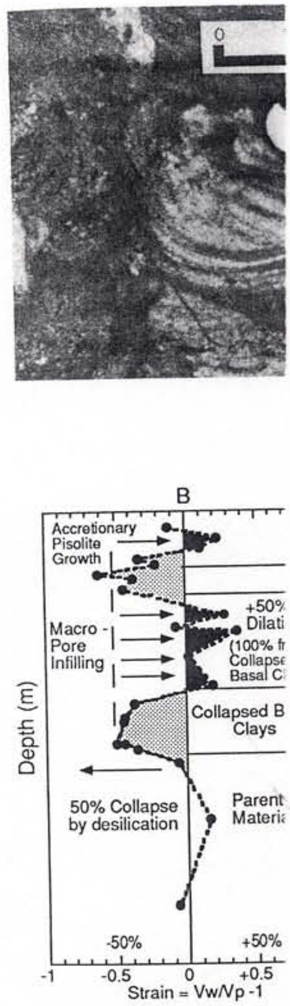


Fig. 3. **A)** Vertical distribution of zircon types in relation to laterite zones showing number of grains in each type recovered from about 20 g samples using heavy liquid separation methods. **B)** Zirconium concentration profile based on XRF analysis of pressed pills showing influence of exotic zircons. **C)** Dry bulk density (g/cm^3), porosity and grain density profiles (g/cm^3).

deposit. Instead, Brimhall *et al.* (1988) showed that size sorting of grains through pores of decreasing size with depth lent additional support to the exotic contamination hypothesis. The mechanism whereby foreign material made its way into and through soil columns was shown further to be controlled by translocation through tubules provided by decayed roots (Fig. 2B) (Brimhall *et al*, 1991 and 1992). Hence, exotic detritus is excluded from entering the submicroscopic pore system of the basal clay after passage through the pisolitic gravel, massive hardcap and blocky hardcap zones (Fig. 3A). With this interpretation, debate over *in situ* versus detrital origin became unnecessary as both processes were proven to occur but to dominate differentially with depth within the same profile for reasons governed by complex interfacial activity of biological and geological systems perturbed by major additions of detrital material.

Volumetrics of weathering

Explicit mass balance composition/density/volume relations were applied to chemical and physical data on Jarrahdale (Figs 3B and 3C). The central goal was to characterize the transport, deposition and deformation processes responsible for the formation of a multitude of oriented, geopetal, microsedimentary pore deposits cross-cutting a sequence of still older



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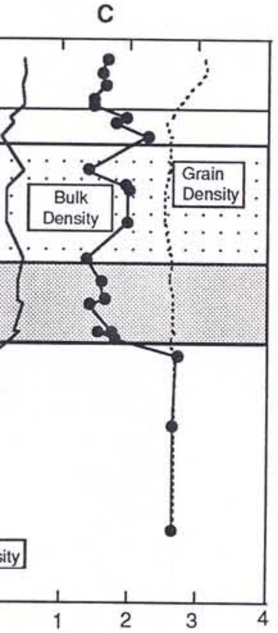

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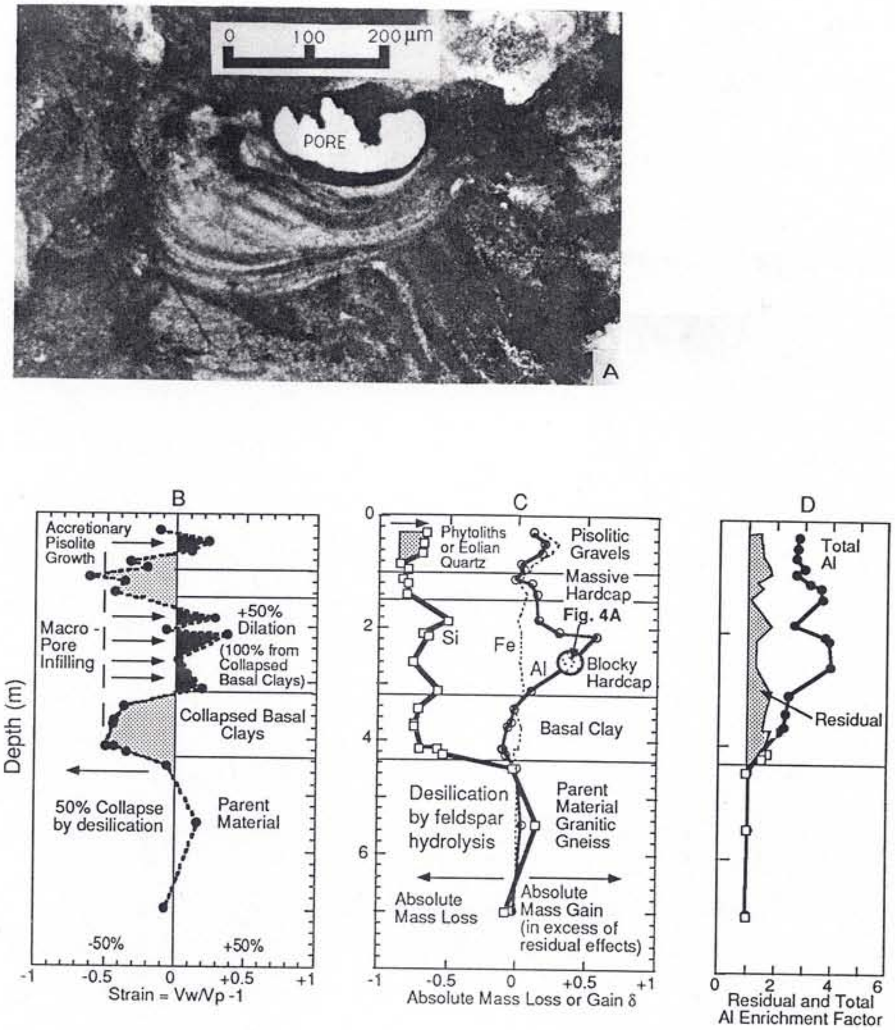

Fig. 4. **A)** Oriented ultra-thin section 5 µm thick showing in-filled pore with clay skins in blocky hardcap beneath open pore lined with chemical precipitates. **B)** Strain profile computed using zirconium concentrations corrected for the presence of rounded zircons (3B). Initial volume change is collapse related to desilication as feldpars weathered at the bedrock/saprolite interface. Expansion from this collapsed state occurs in the blocky hardcap and pisolitic gravels by macro-pore infilling and accretionary growth respectively. **C)** Absolute transported mass gains and losses for Si, Fe and Al. Note the accumulation of Al within the blocky hardcap for the same sample shown in Fig. 4A. Minor Si accumulation is evident at very top of profile, perhaps related to eolian quartz or phytoliths. Si analysis is by XRF of fused glass plate and Fe and Al are by AAS. **D)** Residual enrichment factor compared with overall enrichment factor showing residual effects account for only one-third of total Al enrichment.

in-filled voids along arcuate concave-up unconformities that were observed in ultra thin (5 μ) sections (Fig. 4A).

A *Zr* mass balance-based strainometer was used for the most basic component in the analytical strategy. Volume change during weathering, $\varepsilon_{Zr,w}$ (Fig. 4B) was computed using:

$$\varepsilon_{Zr,w} = \frac{V_w - V_p}{V_p} = \frac{V_w}{V_p} - 1 = \frac{\rho_p}{\rho_w}\frac{C_{Zr,p}}{C^*_{Zr,w}} - 1 \tag{1}$$

This method uses *Zr* as an immobile reference element after correcting its total concentration for introduced morphologically-distinct rounded zircon to yield $C^*_{Zr,w}$. Symbols V and ρ refer to volume and bulk dry density, and subscripts p and w refer to parent material and weathered samples respectively. Our technique has similarities to other approaches as reviewed recently by Moran *et al.*, (1988) which use zircon as an index of volume change. However, unlike these other studies we are not limited by the assumption of no loss of zircon and through SEM morphology and quantitative modal analysis, the movement of zircon into the soil profile is evaluated. Furthermore, after heavy liquid separation is used to concentrate zircons quantitatively, we measure modes of morphological groups of zircon using a computer-assisted line integration counting method which is statistically more accurate than point counting (Brimhall and Rivers, 1985).

Mass gains and losses

After determining volume changes, evaluation of absolute mass gains and losses during weathering, $\delta_{j,w}$ for an element, j, are computed using Eq. 2 where $m_{j,flux}/V_p$ is the overall difference in mass of element j between a modern sample in the deformed weathered state and its parent material per cm^3(Brimhall *et al.*, 1992).

$$\delta_{j,w} = \frac{m_{j,flux}}{V_p} = \frac{V_w \rho_w C_{j,w}}{V_{p100}} - \frac{\rho_p C_{j,p}}{100} = \left(\varepsilon_{Zr,w} + 1\right)\frac{\rho_w C_{j,w}}{100} - \frac{\rho_p C_{j,p}}{100} \tag{2}$$

In Fig. 4C showing results for Si, Fe and Al, a value of $\delta_{j,w}$ equal to 0 signifies no transport and indicates that only residual and deformational effects have occurred while a positive value proves accumulation by transport. A negative value shows the amount of removal. Notice that there are no source regions internal to the weathering profile for the excess transported Al and Fe evident in the blocky hardcap and pisolitc gravels. Both these elements were introduced from above the present soil profile. The in-filled pore, rich in gibbsite from the blocky hardcap shown in Fig. 4A, is depicted again by a large rounded symbol on the Al profile line in Fig. 4C to demonstrate the correspondence of micro-structure with dilation and Al accumulation by transport.

Correlated mass accumulation and inflation

The basal clay unit, developed by incongruent dissolution and desilication of feldspars (Fig. 4C), is in a highly collapsed state representing the primitive condition of *in situ* weathering from which all the upper zones have evolved. In contrast, the pisolitic gravels and blocky

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hardcap zones have experienced volumetric expansion related to the excess mineral volume of introduced detrital Al and Fe species by pore infilling and accretionary growth mechanisms respectively. The entire weathering column is however developed from a single continuous permeable medium which is differentiated internally by migration through the variably-permeable porous medium.

Contribution of residual in situ processes to ore-grade Al enrichment

The individual contributions of *in situ* residual and transported Al to the total concentration are distinguished by use of the enrichment factor which is the ratio of the Al concentration in a weathered sample divided by the concentration in the parent material (Eq. 3).

(1) Closed System (2) Open System

$$\frac{C_{Al,w}}{C_{Al,p}} = \frac{\rho_p}{\rho_w}\frac{V_p}{V_w}\left(1+\frac{100\delta_{Al,w}}{C_{Al,p}\rho_p}\right) = \frac{\rho_p}{\rho_w}\frac{1}{\left(\varepsilon_{Zr,w}+1\right)}\left(1+\frac{100\delta_{Al,w}}{C_{Al,p}\rho_p}\right) \qquad (3)$$

Terms 1 and 2 in Eq. 3 represent these two distinct contributions to the enrichment factor and are referred to here as the "closed" and "open" system parts. Term 1 describes the enrichment of Al as an immobile element. It is a product of ρ_p/ρ_w the pure residual enrichment factor multiplied by a second factor, $1/(\varepsilon_{Zr,w}+1)$ which is the same as the volume ratio, V_p/V_w. Residual enrichment results from simple removal of mobile elements with a corresponding reduction in bulk density and a corresponding increase in porosity (Brimhall and Dietrich, 1987) with volume change expressed by a separate factor. Term 2 gives the *transported* part of the enrichment factor. Notice in Eq. 3 that the residual factor affects even the transported component. An important conclusion of this analysis at Jarrahdale is that *in situ* residual concentration of Al given as ρ_p/ρ_w accounts for only one-third of the total enrichment with the remaining two-thirds being due to transport (Fig. 4D).

Inferred composition of exotic detritus

It is evident from Fig. 4C that the detrital contaminant enriching the bauxite to several times residual levels is a chemically-mature, previously weathered suite rich in aluminum and to a lesser extent iron, but is surprisingly quartz deficient. A likely source of such fine-grained argillaceous material is older deeply weathered terrains disrupted by uplift, erosion and ablation. More than 60 km east of the Darling Scarp, the lateritic cover has been partially stripped exposing the lower kaolinite-rich zone referred to as a semi-stripped etchplain by Finkl (1979) and Hocking and Cockbain (1990). These source regions are probably similar to regions described in South Australia by Milnes *et al.* (1985) supplying highly kaolinitic clastic material in the Eromanga Basin. This erosion and sedimentation history is interpreted as involving repeated exhumation and re-burial processes. The morphodynamic pattern is referred to as the "cratonic regime" by Fairbridge and Finkl (1980) where poly-cyclic topographic inversion results from escarpment retreat.

Profile evolution above and below the midprofile boundary

We have shown that under the influence of surficial deposition, the bauxite profile has evolved as a unit and has become differentiated into two principal parts comprising a composite but continuous system with an internal boundary. The lower part of the weathering system was shown to be a primitive basal residual clay regime developed *in situ* from weathering of bedrock. The contaminated system near surface slowly transforms the primitive basal saprolite or clay zone system by bioactivation, a process involving translocation of indigenous and foreign detritus through open and connected root tubules (Brimhall *et al.*, 1991 and 1992). The base of the upper system is defined essentially by the average depth of root penetration which limits the depth of translocation and hence bioactivation. Since root tubules penetrate even the most indurated of hardcaps and can be maintained in an open state by roots, this subsurface evolution proceeds even within and beneath duricrusts.

The subsurface acquisition mechanism proceeds by repeated cycles of void space creation by root decay and pore infilling, followed by renewed root growth evident in the numerous oriented, geopetal, microsedimentary pore deposits. Spatial accommodation of this excess volume of exotic detritus is through deformation developed by episodic root growth stresses causing an incremental dilational mixing which progressively inflates the soil (Brimhall *et al.*, 1991, 1992). We infer that this dilational mixing mechanism defines and is an integral part of the upper portions of lateritic weathering systems developed on rocks exposed on tectonically-stable cratons where low erosion rates ensure local retention of the clay and iron oxide products of weathering.

With these conclusions, we interpret the mid profile boundary of lateritic bauxites at Jarrahdale not as an unconformity separating two distinct materials, the overlying one having been deposited on top of the other by superposition as described by Ollier and Galloway (1990) for laterites elsewhere, but rather as simply being the internal boundary recognized here separating the basal clay system from the superadjacent zone of bioturbation and dilational mixing. Instead of stratigraphic superposition (Finkl, 1980) and aggradation above the exposed surface, we interpret the detrital deposition to occur *within* a continuum by migration down into and *through* the laterite rather than accumulate on top of it. We do not refute that unconformities do exist in laterites, but show that at least in the profile studied here, the rate of deposition of detritus must not have exceeded the capacity of bioturbation to accommodate the excess mass in the subsurface. Unquestionably, more rapid deposition of eolian detritus can literally bury laterites as in the migration of sand dunes.

Additional evidence against the midprofile boundary being an unconformity at Jarrahdale is that parent materials, differing greatly in composition and mineral assemblages, can survive and impart their character throughout the laterite profile even into surficial pisolites with little lateral dispersion (Sadleir and Gilkes, 1976). This occurs even with intense contamination, physical mixing and deformation within the upper soil system. Vivid examples of these effects are: the higher abundance of quartz in pisolites over granites in contrast to those over dolerites (Smurthwaite, 1990), lateritic enrichment of gold over primary mineralization (Davy and El-Ansary, 1986; Brimhall *et al.*, 1991), and geological mapping of inferred bedrock contacts on the basis of laterite features (Smurthwaite, 1990).

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SHRIMP ION MICROPROBE ZIRCON STUDIES

While mass balance results allow unique inferences to be made about the involvement of pedogenic material from sources internal or external to the existing weathering profile, one of its limitations is that it does not discriminate between parautochthonous material translocated downward by regolith reduction into the existing soil column and truly allocthonous material of external derivation. The mineral zircon serves as a tracer useful in resolving this dilemma and has been used elsewhere in provenance studies in sedimentary rocks with unparalleled success. The utility of zircon stems from the fact that it is not only a chemically resistant mineral surviving pedogenesis but it is also dateable. Upon formation, its crystal structure accepts uranium substituting in small quantities (generally less than several thousand ppm) for zirconium. The uranium undergoes decay to radiogenic lead. An additional advantage is that during its original growth, zircon tends to exclude common (mostly non-radiogenic lead) thereby facilitating accurate U-Pb dating and minimizing the magnitude of the necessary corrections.

Ireland (1992) showed that not only can individual zircon age components be dated, but the relative proportions of age components of crustal sources may be determined. Previously, zircon occurring in Jamaican bauxites was studied successfully using fission track ages to demonstrate that bauxite formed by lateritic weathering of volcanic ash (Comer *et al.*, 1980). Our SHRIMP dating of zircons here, however, is focused on verification of the proposed exotic character of the rounded zircons and associated aluminous material.

To resolve this issue, we apply the SHRIMP to (1) check the continuity of the granitic gneiss parent material, (2) verify the foreign character of the abraded mineral suite by using zircon as a datable pathfinder mineral, and (3) provide some constraints on the provenance of the complete exotic suite including its aluminous components.

SHRIMP capabilities and analytical conditions

Using the SHRIMP it is possible to determine Pb-U and Pb/Pb ages as well as elemental concentrations of U and Pb rapidly on individual zircons as small as 50 μm in diameter and to do so on sufficiently large numbers of grains as to generate population statistics useful in provenance analysis. Efficiency was improved in this study by automatic peak centering of the ^{204}Pb peak on Zr_2O, and ^{207}Pb and ^{208}Pb on ^{206}Pb. This helped to reduce analysis times while U, UO and ThO peaks were centered independently. We performed five scan sets on rounded zircons and seven scan sets on euhedral zircons using the following counting times: UO^+ for 2 seconds; $^{238}U^+$ for 5 seconds; ^{204}Pb, ^{206}Pb, ^{208}Pb and background for 10 seconds; and ^{207}Pb for 40 seconds. A secondary beam current of 3 nanoamps was normal. A 572 Ma gem-quality zircon from Sri Lanka analyzed conventionally with solid source mass spectrometry was used as a standard. Standards have been ^{208}Pb corrected and unknowns ^{204}Pb corrected using Broken Hill composition lead.

Continuity of the granitic gneiss parent material

We first established the age of the granitic gneiss parent material by probing 33 fresh untransported euhedral zircons (Fig. 5A). Although generally discordant, their age is clearly late Archean near 2650 Ma (Fig. 6A). In comparison, analysis of 44 weathered

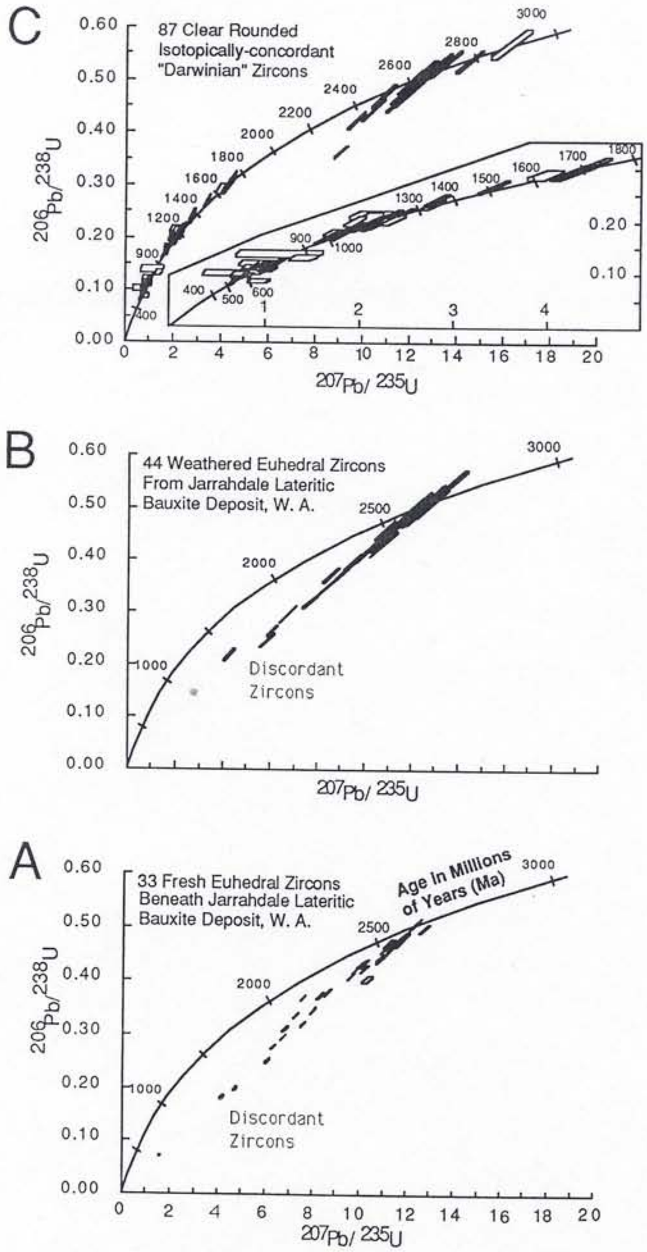

Fig. 5. SHRIMP data showing "Concordia" plot of **A)** 33 fresh unweathered euhedral zircon grains occurring at depth in the gneissic granite parent material. **B)** 44 weathered euhedral zircons in the bauxite. **C)** 87 rounded abraded exotic Darwinian zircons falling on or near "Concordia" indicating closed ^{238}U-^{206}Pb and ^{235}U-^{207}Pb systems. Ages fall into several groups between 500 to 2900 million years (Ma).

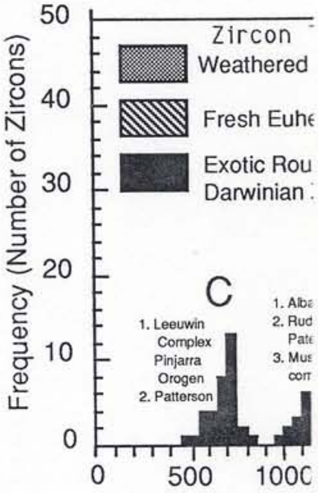

Fig. 6. **A)** ^{207}Pb/^{206}Pb age
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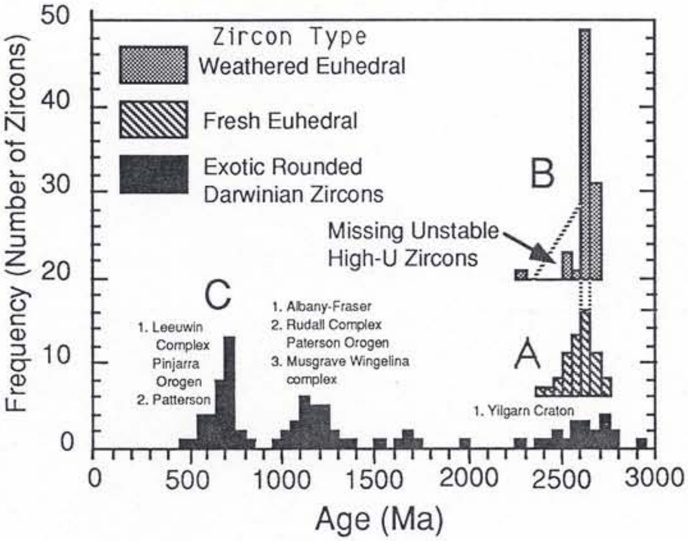

Fig. 6. **A)** $^{207}Pb/^{206}Pb$ age histogram of fresh euhedral zircons and **B)** weathered euhedral zircons. $^{207}Pb/^{206}Pb$ ages approach the ages of zircons unaffected by Pb loss as they do not rely on either Pb or U concentrations and instead use only Pb isotope ratios. Unstable high U and Th zircons with alpha track damage of the crystal structure appear to be missing in the weathered zircon population (B). **C)** ^{238}U-^{206}Pb age histograms of rounded exotic Darwinian zircon grains showing four age populations.

zircons, spanning the bauxite profile from immediately above the fresh gneiss to within a few centimeters of the surface, have a similar age and a discordancy pattern indicative of either recent lead loss or uranium gain without fractionation of isotopes (Figs 5B and 6B) as do the fresh unweathered zircons of the bedrock (Figs 5A and 6A). These two features strongly suggest upward continuity of Archean bedrock granitic gneiss parent material through what is now the bauxite profile and establish continuity of the gneiss parent material.

The age histogram for the weathered euhedral zircons (Fig. 6B) appears skewed towards older ages. We interpret this to be due to an absence of grains younger than 2600 Ma (a few grains do occur and have high U) having become more susceptible to breakdown because of their more metamict (alpha decay)-damaged character. We conclude that this is evidence of *in situ* selection of low U rounded grains and their preservation even within the weathering profile.

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Exotic character and provenance of rounded zircons

Our main objective of dating rounded zircons in the bauxite was to test the hypothesis advanced by Brimhall *et al.*, (1988) that the abraded mineral suite was exotic. The secondary objective was to constrain possible source regions. Eighty seven clear rounded (abraded) zircons contained in the upper 2.2 meters of bauxite were analyzed (Fig. 5C). From the surface downward, these rounded zircons decrease in abundance in relation to weathered euhedral zircons which increase (Fig. 3A). Within the hardcap (duricrusts), rounded zircons are subequal in number to local weathered euhedral (unabraded) zircon but below, in the saprolite, they are essentially absent. Beneath the saprolite only fresh euhedral zircons occur in the granitic bedrock.

Our SHRIMP data show that in contrast to euhedral zircons, rounded zircons are distinctly concordant (Fig. 5C). Their low uranium content indicates that survival of only the most robust, unmetamict grains are left since they are relatively undamaged by alpha particle radiation effects. As observed with the euhedral grains (Fig. 6B), this selection process may actually begin in the subsurface in the source region but undoubtedly occurs during eolian grain impact and abrasion during eolian transport episodes. Because of the remarkable survival of this robust mineral fraction during weathering, erosion, transport and redeposition, we refer to these isotopically-concordant rounded grains as "Darwinian zircons" in deference to Darwin's recognition in 1846 of the importance of atmospheric transport of land-derived dust to long-term offshore sedimentation.

An age histogram (Fig. 6C) reveals four well-defined age groups with modes near 700, 1150, 1700, and 2600 to 2750 Ma contributing 39%, 30%, 6% and 24% each to the total number of rounded zircons. Hence, the youngest age group, 700 Ma is by far the dominant contaminant of the lateritic bauxites followed by the 1150 and 2600-2750 Ma age groups.

Constraints on possible source regions of these detrital zircons are made using published compendia of major Australian Precambrian orogenic provinces (Page *et al.*, 1984) but principally from more recent published and unpublished mapping in Australia and Antarctica where age assignments have been based upon reliable conventional solid source (U/Pb and Rb/Sr) mass spectrometry or SHRIMP (U/Pb and Pb/Pb) geochronlogy (Shaw *et al.*, 1984; Nelson *et al.*, 1989; Wilde and Murphy, 1990; McNaughton and Goellnicht, 1990; Goellnicht *et al.*, 1991; Young and Black, 1991; Sheraton *et al.*, in press).

We have interpreted the provenance of the 700 Ma zircons as shown in Fig. 6C as having come principally from the Leeuwin complex southwest of the Jarrahdale bauxites (Fig. 1). The Darling Fault separates the Pinjarra Orogen containing the Leeuwin Complex from the Yilgarn Craton to the east and formed the eastern margin of a major rift zone by which Greater India was split from Australia and the western margin of Australia was defined (Veevers and Cotterill, 1978; Myers, 1990). Most of the rocks formed in collisional tectonic regimes and were accreted to the Yilgarn craton with the most recent collisional episode inferred to be near 0.75-0.65 Ga old. Leeuwin Complex rocks are intensely-deformed and consist of granite metamorphosed to granulite facies grade and include granulite, granite gneiss, and lesser anorthosite occurring as remnants of anorthosite-gabbro intrusions. The Pinjarra Orogen, while appearing as only a small potential source region, is a small fragment of a much larger plate (Wilde and Murphy, 1990).

The subordinate source regions are interpreted as being the orogens surrounding the Yilgarn Craton on its southern, eastern and northern, and/or sedimentary sequences of intermediate age containing detritus derived from them. The 1150 Ma group is interpreted as having a principal source in the Albany-Fraser Orogen in Australia and Bunger Hills of East Antarctica as is the minor 1700 Ma age component. The 2600-2750 Ma age group we assign to transport of material derived directly from the local surrounding Yilgarn block of granites and granitic gneisses.

CONCLUSIONS

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ACKNOWLEDGMENTS

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CONCLUSIONS

In cratons, because of long-term tectonic quiescence over periods on the order of billions of years, uplifted regions are levelled and erosion eventually becomes sufficiently slow that the products of weathering accumulate in deep soil columns. Continued weathering produces a nearly indestructible, chemically-mature, eclectic continental residuum composed of (1) local *in situ* residual products of weathering and stable accessory minerals, (2) local detritus accessed by regolith reduction from above a present exposure by escarpment retreat and topographic inversion, and (3) admixed exotic minerals derived from several distant weathered source regions elsewhere.

The regional topographic levelling process may be dominated by redistribution of this eclectic mixture in contrast to earlier mass removal in outflowing rivers when topographic gradients may have been higher. During the cratonal stage of soil evolution, deposition of a previously minor dust component may become a significant contributor to mass accumulation in the evolving continental residuum. It can serve to dilute indigenous elemental abundances although metal anomalies in the parent material still persist into the regolith and may even be concentrated by regolith reduction. While lateritic terrains may appear static in comparison to landscapes with greater relief and dust deposition may seem an inconsequential process, slow transmigration by escarpment retreat, colluviation, topographic inversion and regolith reduction (Ollier and Galloway, 1990; Brimhall, *et al.*, 1991) eventually desegregates even the most indurated duricrusts. By these mechanisms thorough mixing of both local and exotic detrital components occurs through repeated exposure to the rigors of the surficial environment.

Repeated re-introduction of this eclectic, chemically-mature suite back into the porous subsurface occurs through pathways open for translocation provided by connected pore networks in the loose pisolitic gravels and the tubular cavities below exploited and maintained by roots. Faunal burrows, transport and dissaggregation of termite mounds provide further mixing processes. *In situ* residual weathering is only the first step in this evolution. Sources and mechanisms of accommodation of this indigestible excess mass directly influence the fabric of cratonal soils and reflect complex interfacial activity of biological and geological systems perturbed by major additions of exotic material.

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