LADY BOUNTIFUL EXTENDED GOLD DEPOSIT, WESTERN AUSTRALIA

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INTRODUCTION

The Lady Bountiful Extended (LBE) gold deposit is situated about 37 northwest of Kalgoorlie, at 30°30'S, 121°13'E, in the east of the KALGOORLIE 1:250 000 (SH51-9) map sheet area (Figure 1). Major nearby mining developments, now largely inactive, include the Lady Bountiful, Golden Kilometre, Quarters, Rose Dam, Bluegum, Black Flag and Racetrack mines.

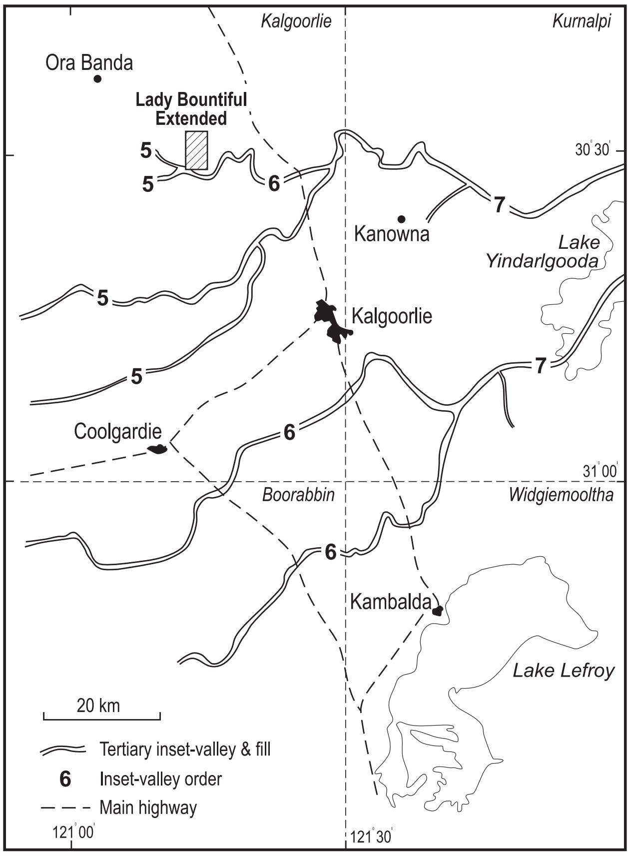

Figure 1. Distribution of inset-valleys in the upper reaches of the Roe drainage basin. 1:250,000 map sheet names, order of inset-valleys and location of the small, fourth-order Lady Bountiful Extended drainage basin also shown.

At LBE, gold is hosted by the clastic sedimentary fill of a well-integrated network of Tertiary palaeovalleys, now buried beneath a veneer of Quaternary sediments and therefore having little or no surface expression. Traditionally known as 'deep leads' and 'palaeochannels', the palaeovalleys were termed 'inset-valleys' by de Broekert (2002) in order to emphasise their subordinate and entrenched position within the bedrock surface of a much broader and older system of 'primary valleys'. The inset-valleys and their fills are widespread throughout the Eastern Goldfields, but have been studied in greatest detail at LBE (Dusci, 1994; de Broekert, 2002) on account of the excellent exposures provided by an extensive system of open-cuts used to extract the gold-mineralised fill. Other mining centres in the Eastern Goldfields where the inset-valley fills have been widely mined for gold include Kanowna to the northeast of Kalgoorlie and Higginsville situated along to western margin of Lake Cowan, south of Lake Lefroy (Figure 1).

PHYSICAL SETTING

Precambrian geology

The mineralised inset-valley fills constituting the Lady Bountiful Extended gold deposit occur within the western part of the Liberty Granodiorite — a small (~30 km^2), tear-shaped, post-tectonic Archaean pluton intruded into greenstone rocks forming the western limb of the Goongarrie–Mt Pleasant Anticline (Swager *et al*., 1995). Along the western and eastern margins of the Liberty Granodiorite lie differentiated mafic intrusive rocks (mostly gabbros) of the Mount Pleasant and Mount Ellis sills, whereas the northern margin of the pluton is bounded by ultramafic flows of the Siberia Komatiite (Figure 2). Quartz veins are common within the Liberty Granodiorite and are thought to have been the ultimate source for most of the gold hosted within the upper part of the bedrock saprolite and basal part of the inset-valley fill. A 50–100 m wide Proterozoic dolerite dyke traverses the northern part of the Liberty Granodiorite in an east–west direction creating a bedrock high in the base of those buried inset-valleys which cross it.

Geomorphic setting

Preferential weathering and erosion of the Liberty Granodiorite has resulted in the formation of a small amphitheatre-like drainage basin enclosed on all sides, except to the south, by strike ridges of mafic–ultramafic rocks. The modern drainage locally breaches the greenstone strike ridges in its headwaters to the north (Figure 2), and discharges into Black Flag Lake (playa) some 6 km to the southeast of the LBE mining area. The buried inset-valley network forms a similar dendritic drainage pattern to the modern drainage, but is closer to the west of the granodiorite's margin. Most of the weathered granite- and sediment-floored drainage basin lies between 360 and 390 mAHD and the highest point in the surrounding greenstone ridges is about 440 mAHD. The modern landsurface is therefore subdued and provides little indication of the much greater relief that exists along the Precambrian bedrock–Cenozoic sediment unconformity.

Climate and vegetation

A semi-arid climate, with hot, dry summers and cool, wet winters characterises the region. The mean annual rainfall for the city of Kalgoorlie is about 270 mm, which is distributed fairly evenly throughout the year except for a small peak in May to July. Most winter rain comes from eastward moving cold fronts, whereas most summer rain comes from thunderstorms and the remnants of southerly moving tropical cyclones. Eucalyptus spp., saltbush and bluebush dominate vegetation in the LBE area. *Acacia* spp. are prominent in areas of outcropping mafic and ultramafic bedrock (Dusci, 1994).

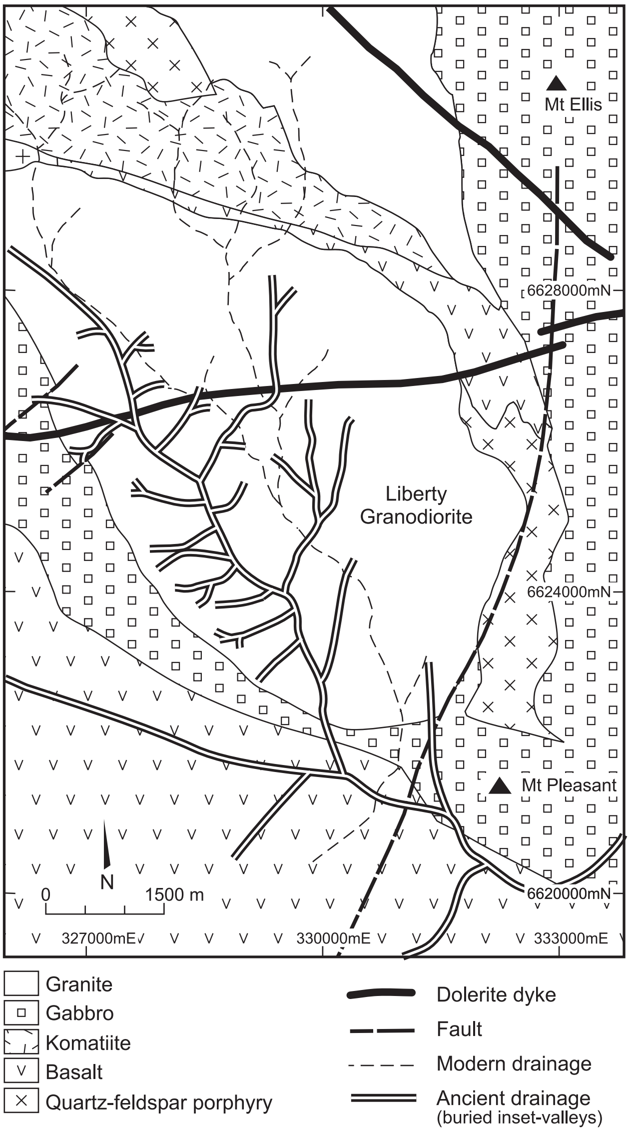

Figure 2. Bedrock geology of the Lady Bountiful Extended gold deposit area with distribution of the buried inset-valley network.

GEOMORPHOLOGY OF THE INSET-VALLEYS

The spatial distribution of the buried inset-valleys at LBE is shown in Figure 2. Four orders of tributaries (*sensu* Strahler, 1952) are present, with the fourth-order inset-valley leading from the drainage basin reaching a maximum width and depth of about 600 m and 40 m, respectively. Thalweg gradients vary from 0.8% for the major fourth-order inset-valley to 3.0% for first-order tributaries incised along the flank of the greenstone strike ridge forming the western margin of the drainage basin. The inset-valleys narrow markedly where crossing the dolerite dyke in the north of study area (Figure 2). Most of the inset-valleys have an open V-shaped transverse-sectional form, locally interrupted by small benches developed in their lower side-walls. Owing to the narrowness of the open-cuts, complete flank-to-flank exposures of the inset-valleys are rare.

The four orders of inset-valleys exposed by mining within the Lady Bountiful Extended drainage basin contribute to a much larger network of inset-valleys, which ultimately join to form an eight-order inset-valley that drains in an easterly direction beneath Lake Roe toward the western margin of the Eucla Basin. The inset-valley network that LBE forms a small headwater drainage basin of is therefore termed the Roe 'palaeodrainage' system (Kern and Commander, 1993).

REGOLITH CHARACTERISATION

Weathered Precambrian bedrock

Weathering of the Liberty Granodiorite has produced a thick zone of saprolite, comprising white, poorly indurated, matrix-supported medium quartz sandy kaolin clay. Red to brown iron oxide mottles are abundant, particularly along the western margin of the pluton where the granodiorite abuts gabbroic rocks and is rich in biotite and hornblende. Quartz veins are locally common, and ultramafic xenoliths are inferred to be present on the basis of chromite within the saprolite's heavy mineral fraction (de Broekert, 2002). The depth to which the Liberty Granodiorite has been weathered varies greatly, reaching a maximum of about 50 m in the western part of the drainage basin. Smaller thicknesses of saprolite occur beneath the inset-valley floors indicating that the granodiorite was mostly weathered before incision of the inset-valleys and to a lesser degree thereafter.

Weathering of the mafic–ultramafic rocks surrounding the Liberty Granodiorite has produced a variety of ferruginous nodular to pisolitic duricrusts underlain by ferruginous saprolite (Dusci, 1994). Exposures of fresh bedrock at Mt Pleasant indicate that the depth of weathering in the greenstone rocks is highly variable and generally less than that of the granodiorite.

Inset-valley fills

Completely filling and then overlying (burying) the inset-valleys set within the weathered Liberty Granodiorite is a distinctive sequence of Cenozoic terrigenous sediments, reaching up to ~40 m in thickness. Composite stratigraphic sections for these are shown in Figures 3 and 4. On the basis of three unconformities, the lowermost of which is the inset-valley form, the Cenozoic sedimentary succession can be subdivided into two alloformations and an overlying unit of 'primary-valley' fill, which is distributed widely throughout the landscape and did not contribute significantly to filling of the inset-valleys at LBE. Open-cut exposures and exploration drilling for gold, uranium and groundwater in the Kalgoorlie region (e.g., Commander *et al*., 1992) indicate that the unconformities are of regional significance, extending throughout the remainder of the Roe inset-valley network (Figure 1) and adjoining drainage basins.

<u>Alloformation 1</u>

The basal alloformation (AF1) of the inset-valley fill (essentially the allostratigraphic equivalent of the Wollubar Sandstone defined by Kern and Commander, 1993) varies in composition according to type of bedrock into which the inset-valleys have been incised

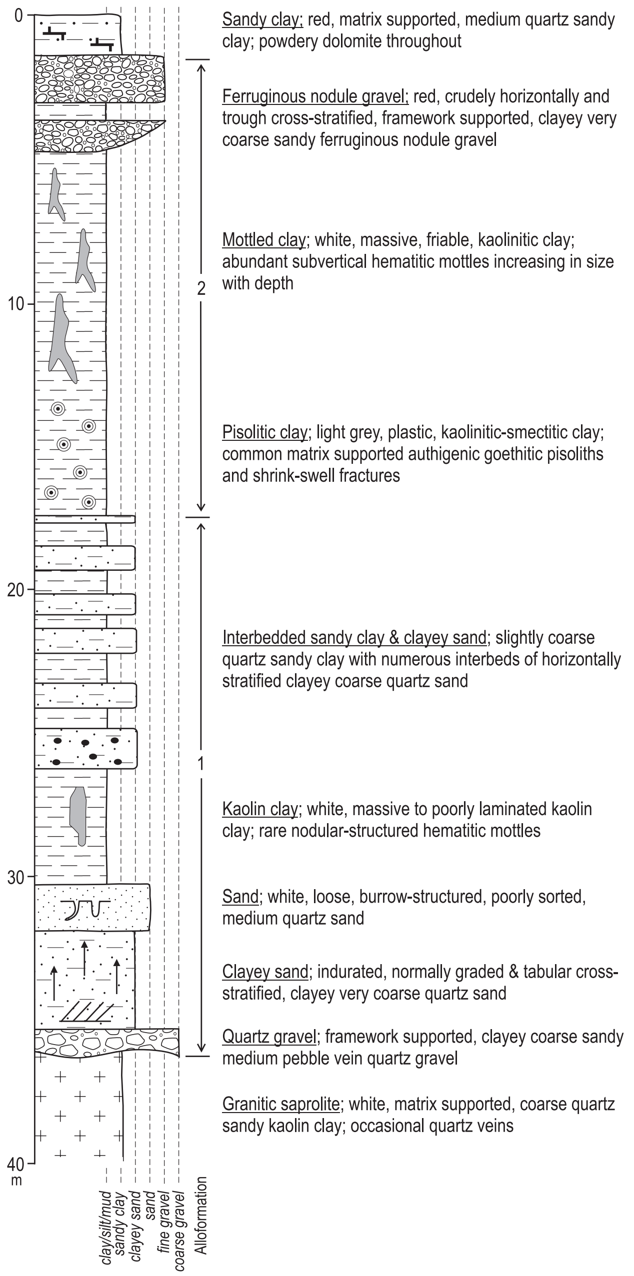

Figure 3. Composite lithostratigraphic column for the fills of inset-valleys sourced from weathered granite, as occurs in the centre of the LBE drainage basin.

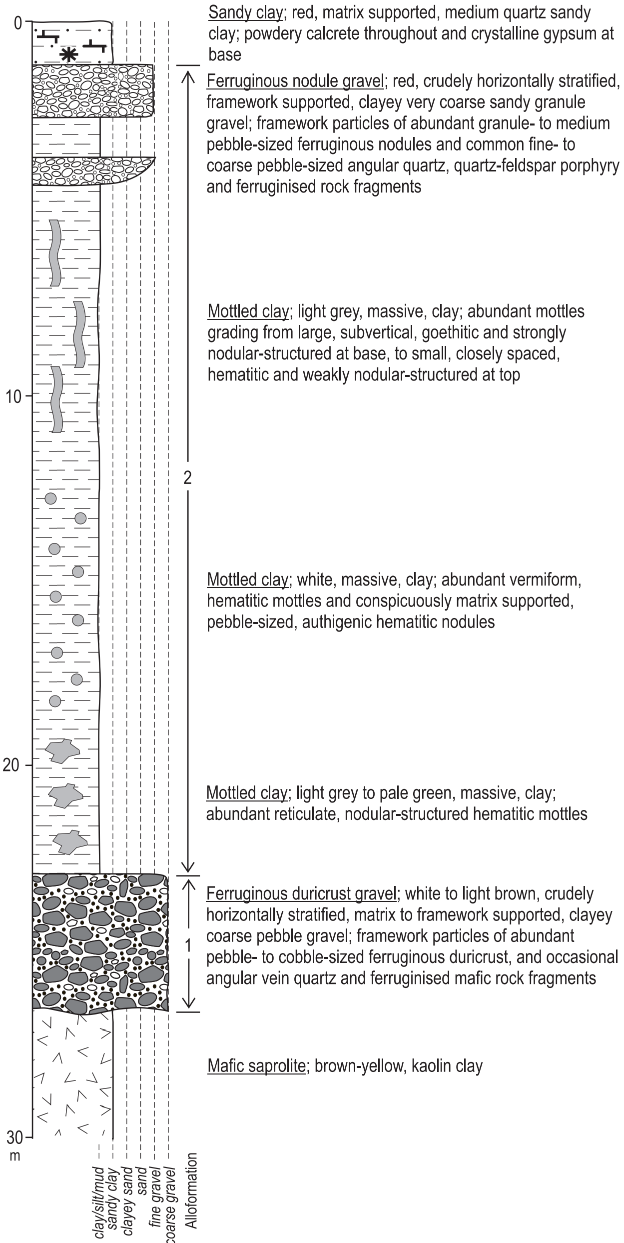

Figure 4. Composite lithostratigraphic column for the fills of inset-valleys sourced from weathered greenstone, as occurs along the western margin of the LBE drainage basin.

and from which the sediments have been sourced. At LBE, two major varieties or 'fill-styles' of AF1 can be recognised — one primarily developed over and sourced from weathered granite and the other primarily developed over and sourced from weathered mafic/ultramafic rocks.

The more widespread, 'granitic' fill-style (Figure 3) has at its base a thin matrix to framework supported sandy quartz gravel resulting from the fluvial concentration of vein quartz from the underlying granitic saprolite. A small proportion of well rounded quartz pebbles in this and overlying sandy lithofacies suggests contributions from a former texturally mature fluvial sediment. Overlying the basal vein quartz gravel is a moderately thick unit of grey, moderately indurated, clayey coarse quartz sand, characterized by abundant cycles of coarse-tail graded bedding and lesser sets and cosets of planar cross strata. These structures, together with 'outsized' clast of vein quartz embedded within the base of the unit, are suggestive of rapidly waning current velocities under conditions of high sediment supply. Within the indurated clayey coarse sand are lenses of loose, medium quartz sand, probably formed by the eluviation of matrix clay in the groundwater. Forming the uppermost lithofacies of AF1 over weathered granite at LBE is a thick unit of interstratified kaolinitic clay and clayey medium quartz sand. The kaolin clay interbeds range from massive to finely laminated to burrow-structured, whereas the clayey sand strata are typically horizontally stratified. Interlayering of the clay and sand strata occurs at a variety of scales and is suggestive of a strongly cyclic discharge.

The less common variety of AF1 with a dominantly weathered mafic/ultramafic bedrock provenance is considerably simpler than the 'granitic' fill-style, essentially comprising a thick sequence of framework to matrix supported ferruginous duricrust rock fragment gravel accompanied by less numerous clasts of vein quartz and weathered mafic saprolite (Figure 4). Weak interstratification with finer-grained sediment is once again suggestive of a strongly episodic fluvial discharge.

Alloformation 2

Unconformably overlying AF1 with a sharp to gradational (bioturbated) contact lies an assemblage of dominantly fine-grained lithofacies forming alloformation 2 (the allostratigraphic equivalent of the Perkolilli Shale as defined by Kern and Commander, 1993). The dominant depositional lithofacies of AF2 is a thick unit of light grey kaolinitic-smectitic clay, characterized by yellow goethitic mottles and matrix supported goethitic pisoliths (Figures 5). The pisoliths typically have well-developed cortical laminae which extend to the centre of the pisolith (Figure 5a) or encase a nucleus commonly composed of fossilized wood, medium quartz sandy clay, or older pisolith fragments. Substitution of aluminium for iron in the goethite crystal lattice is low (~10 mole %) indicating that the pisoliths formed in a hydromorphic environment, such as would occur in the case of bog iron ore. Most probably, the pisoliths were formed along with the matrix clay in a hydrologically fluctuating wetland environment. Rare lenses of cross-stratified goethitic pisolith gravel in the base of the kaolinitic-smectitic clay indicate that the goethitic pisoliths are syndepositional and were not formed by post-depositional weathering.

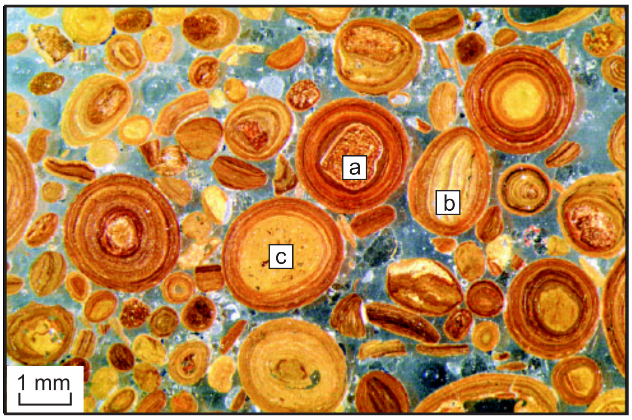

Figure 5. Thin section photomicrograph of goethitic pisoliths in kaolinitic–smectitic clays of AF2. Note variety of nuclei, including: (a) fossilized wood fragments, (b) fragments of older goethitic pisoliths, and (c) fragments of sandy clay.

Towards the landsurface, the kaolinitic-smectitic clay becomes intensely weathered, resulting in the leaching of smectite to kaolinite and the formation of large, vertically elongate hematitic mottles, probably associated with the dissolution and reprecipitation of iron around ancient tree roots (Anand and Paine, 2002). Other prominent overprint features of AF2 at LBE include large pods of micritic dolomite and lenses of breccioid- to nodular-structured opaline silica (opal A and opal CT). Lenses of cross-stratified ferruginous nodules are common, increasing in abundance toward the landsurface. Geochemical and petrographic evidence suggests that the ferruginous nodules were derived from ferruginous duricrusts developed over mafic–ultramafic rocks situated along the divides of the LBE drainage basin (Figure 2). Unlike the goethitic pisoliths, these are therefore of extraformational origin.

DATING

Palynomorphs extracted from the base of alloformation 1 in the lower reaches of the Roe inset-valley network correlate with the Middle *Nothofagidites asperus* Zone of the Gippsland Basin in southeastern Australia, indicating a late Middle to Late Eocene age for deposition of the lithosome (de Broekert, 2002).

Alloformation 2 is typically barren of palynomorphs and other microfossils, preventing an accurate estimate of depositional age. However, spores and pollens extracted from lignite bands in the middle of thick unit of clay in the upper part of Rollo's Bore, near Coolgardie, indicate that the AF2 was deposited during the Oligocene to Early Miocene (de Broekert, 2002).

DEVELOPMENTAL HISTORY

The absence of increased weathering depths beneath the inset-valley floors, their open V-shaped form and the interbedding of sand- and clay-rich strata within the inset-valley fills, indicate that the Liberty Granodiorite was deeply weathered before inset-valley incision. Clasts of ferruginous duricrust within the base of AF1 along the western margin of the drainage basin (Figures 2 and 4) further indicate that the surrounding strike ridges of greenstone were also deeply weathered and supported a thick ferruginous duricrust as occurs to the present day.

Inset-valley incision probably resulted from stream rejuvenation following epeirogenic uplift of the Yilgarn Craton during the Middle Eocene (de Broekert, 2002), although stream incision would also have been favoured by a humid climate and a thick mantle of weathered bedrock. Deposition of AF1 began shortly thereafter in a fluvial environment, with the high rates of sediment supply and the narrowness of the inset-valleys promoting channelised flow and the limited preservation of overbank fines. Discharge was strongly cyclic and water depths were shallow, though water levels did not decline to the point of desiccation. Contemporaneous marine transgressions along the southern margin of Australia invaded the lower reaches of the inset-valley networks, such as at Lakes Lefroy and Cowan (Clarke, 1994), but had very limited or no influence on deposition within the upper reaches of the inset-valley networks, such as at LBE.

Following a major phase of erosion within the inset-valleys, low sea-levels and a marked cooling of climate in the earliest Oligocene saw the development of cool, dry conditions onshore, transferring the inset-valley floors into a hydrologically fluctuating wetland environment. Deposition of AF2 commenced at a very slow rate and may have continued through to the Early Miocene (de Broekert, 2002). Lenses of ferruginous pisolith and nodule gravel, sourced from within and outside of the 'basin' of deposition respectively, reflect the episodic establishment of fluvial conditions. A further marked drying in climate in the Middle Miocene led to the development of internal drainage and deposition of various ephemeral-fluvial, alluvial fan, playa-lake and aeolian sediments, thereby burying and obscuring the inset-valleys and their fills.

Alteration of the inset-valley fills probably commenced during or shortly after their deposition, with the form and rate of alteration largely being driven by changes in climate and attendant movements in the saturated zone. The lenses of dolomite are, for example, inferred to have developed during periods of aridity when the rates of groundwater throughflow were very low, whereas the hematitic mottles are likely to have formed during more humid phases when the inset-valley would have been well vegetated and iron was readily mobilised by organic acids secreted by tree roots.

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