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REGOLITH TERRAIN ANALYSIS FOR IRON ORE EXPLORATION IN THE HAMERSLEY PROVINCE, WESTERN AUSTRALIA

FINAL REPORT

M.F. Killick, H.M. Churchward and R.R. Anand

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CSIRO Exploration and Mining Report 268R, 1996
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SUMMARY

This report presents the findings of our study of the processes responsible for the genesis, transport, deposition and preservation to the hematite-rich, low-phosphorous sediments ("lump" ore) commonly distributed throughout the study areas.

Mineralisation
A weathered mantle comprising an upper hematite-rich zone overlying a lower goethitic zone was developed throughout the region. The mineralisation process was driven by the disequilibrium between meteorically derived groundwater and substrate, in the weathering zone. Mineralisation proceeded by incongruent dissolution of BIF, with silica being removed in solution, and iron precipitating as goethite prior to dehydration to hematite. Weathering zones were also developed in bedded mineralisation, where present. BIF texture is preserved in weathered/mineralised BIF. Shales weathered to pisoliths, clays and microcrystalline goethite.

Climate
Weathering occurred in the humid climatic condition which prevailed for an extensive period of time prior to the mid-Miocene. Until this time, landscape stability was maintained by rates of weathering exceeding rates of erosion of weathered material. Change of climate from humid to arid in mid- to Late Miocene times suppressed vegetation cover and destabilised the weathered mantle.

Erosion and Deposition
The weathered mantle was eroded from the uplands, and transported to lower lying areas. Sediments were deposited at sites of gradient reduction and flow expansion, burying weathered zones in the floors and sides of valleys. Primary sediment deposits typically comprise mature lower sections of hematite-rich gravels overlain by immature mixtures of goethite, hematite and BIF, recording an inversion of the weathering stratigraphy. Some sediments have been subject to erosion and local re-distribution by valley fluvial systems.

Subcrop
The basement unconformity preserves significant elements of the Tertiary landscape, although weathered zones have been eroded from some areas. Structural and erosional lows in the resultant surface have the demonstrated capacity to retain commercial deposits of mature detritus. Alluvial fan, sheetflood and fluvial facies have been recognised in subcrop.

Preservation
Mature detritus deposits are preserved where they were cemented, or were by-passed by later, erosive systems. By-passing was controlled by factors intrinsic to sedimentation, including excess of sediment supply, choking and causing avulsion of channel systems.

Implications for Exploration
The preservation of weathered zones underlying modern rangefront spurs and re-entrants, demonstrates that the morphology of the study areas typically follows the Tertiary landscape.

Scoured sediment traps are likely to be situated at the mouths of the Tertiary drainage systems. The presence of structural traps may be inferred from outcrop expression of faults and folds. Where conditions favouring preservation apply, traps may preserve commercial deposits of mature detritus.

PREFACE

The principal objective of the project is to improve the effectiveness of exploration for mature detritus by developing a better understanding of the processes responsible for its generation, transport and deposition. The research includes: establishment of the field relationships, including regolith mapping, mineralogical and geochemical characterisation of the regolith; and 3-D modelling to illustrate the nature of the unconformities separating basement and sediments, the unconformities separating discrete packages of sediment within the detritals, and the distribution of those packages. This report presents results on these aspects based on the Brockman, Mount Sheila and Mount Margaret study areas.

The regolith and landscape of the Hamersley Province has a long and complex history. Two stages appear to have been important to the development of landscape, regolith and the patterns of detrital deposition. A hematite-rich ferruginous zone ('laterite') was developed as an blanket across undulating land surfaces at various levels, probably as a result of weathering in the warm-humid Cretaceous and Early Tertiary climate. Since the Early Tertiary, the climate has become more seasonal and arid. Erosion has outpaced weathering processes, resulting in the erosion of the whole or part of the weathering profile and its deposition as detritus.

It is concluded that the likely source of mature detritus is from a regionally extensive, hematite-rich, ferruginous horizon of a weathering profile. The ferruginous horizon is preserved throughout the study area in subcrop, beneath mature detritus, and rarely at high levels. The typical sediment profile is of mature detritus overlain by immature detritus in an 'inverted' stratigraphy caused by sequential stripping and deposition of a hematite-rich surface zone, followed by stripping and deposition of an underlying goethite-rich hydrated zone. Weathering of primary mineralised deposits also contributed to the mature detritals, but the proportion of this contribution is not known. The most prospective trap sites recognised are structural or erosional morphological depressions developed on non-BIF lithologies, and any sites where mature detritus deposits may be by-passed by later channel systems.

R.R. Anand
Project Leader

1 INTRODUCTION

1.1 Exploration problems

An understanding of the controls on the processes of mineralisation, erosion, sediment transport and trapping are fundamental necessities for discovery and development of commercially significant deposits in sedimentary systems. The purpose of this research is to examine existing theories about each of these, and where appropriate to propose new models based upon our experience and knowledge of sedimentary geology.

This work formally describes the character and disposition of the major landscape elements of the study areas. Our analysis of the inter-relationships of landscape elements has allowed us to propose a new model for landscape evolution. We believe that this model will permit identification of ancient stable landscapes. Geomorphological and geological interpretation of this information may assist identification of areas of commercial interest.

1.2 Objectives

1.2.1 Principal Objective

To improve the methods for iron exploration in the Hamersley Basin under regolith cover through better understanding of the processes of weathering, erosion and deposition that have formed, modified and concealed the deposits.

1.2.2 Specific Objectives

The specific objective of this study is to establish a regolith-landform framework for support of exploration in the selected areas of the Hamersley Province. This includes:

1) establishing the weathering processes responsible for the formation of the regolith;

2) establishing the weathering history;

3) mapping the nature, distribution and stratigraphy of the regolith components;

4) determining the petrological, mineralogical and chemical characteristics of the regolith materials, and

5) developing a series of regolith models which describe the distribution of detrital deposits.

1.3 Work Plan

The scheme of work for this research project comprised:

1) A fieldwork component for establishment of the field relationships including regolith mapping and sampling. Two periods of seven weeks total duration were spent in the field. In addition, two short follow-up visits were made to the three study areas.

2) A geochemical component to examine some aspects relevant to understanding the genesis of mature detritus.

3) A modelling component to define the size and shape of mature detritus deposits, the nature of their bounding surfaces, and the processes controlling their deposition and preservation.

This report is structured so that after presentation of the fieldwork, topics are dealt with in order of source, transport and trap. We have attempted to minimise repetition by use of internal referencing.

1.4 The Study Areas

This investigation was located in the Hamersley Iron Province of the central Pilbara region of Western Australia, between 22° 00' S and 22° 40' S and, 117° 15' E and 117° 45' E, in the northern half of the Mount Bruce 1:250 000 map sheet. Three areas were chosen for detailed study namely, Mount Margaret, Mount Sheila and Brockman (Fig. 1). The Jeerinah and the Pylon road sites, west and southwest of the Mount Sheila area, were additional point locations studied in the programme.

This region is one of marked relief with belts of ranges, gorges and scarps contrasting with adjacent low relief areas, generally of erosional and depositional plains. A broad zone of high relief across the northern half of the study area, and occupying the Hamersley Range syncline, is generally referred to as the Hamersley Range. A secondary tract of high relief, extending to the southwest, occupies the Mount Brockman syncline and will be referred to in this report as the Brockman Range. These two areas of high relief, dominated by BIF of the Hamersley Group (Fig. 2), are separated by tracts of generally low relief, largely on rocks of the Fortescue Group. This is the Nammuldi Plain, which merges with similar terrain east and south east of the Brockman Range. The summits of Mounts Brockman and Sheila are in excess of 1000 metres while the Nammuldi Plain is at about 600 metres above MSL. The general elevational differences between high and low relief areas are from 200 to 500 metres.

The Hamersley and Brockman Ranges encompass a complex array of deep valleys, generally forming a dendritic pattern. These are steep sided and have slightly inclined floors that broaden downstream into wide valleys. In contrast, a relatively simple curvilinear strike valley type occurs between the main range masses and the outlying broadly convex ridge formed by the Marra Mamba Formation. Notable is the Brockman Valley, adjacent to the Brockman Range the floor of this feature is at about 600 metres above MSL. Another such valley, along the southern flanks of the Hamersley Range, is occupied by Cave Creek. Most of the Hamersley Range drains northward to the Fortescue River while the Brockman Range drains into the Boolgeeda River system. The Nammuldi plain is drained by the Duck River system while similar terrain, south of the Brockman Range, is in the Beasley River catchment.

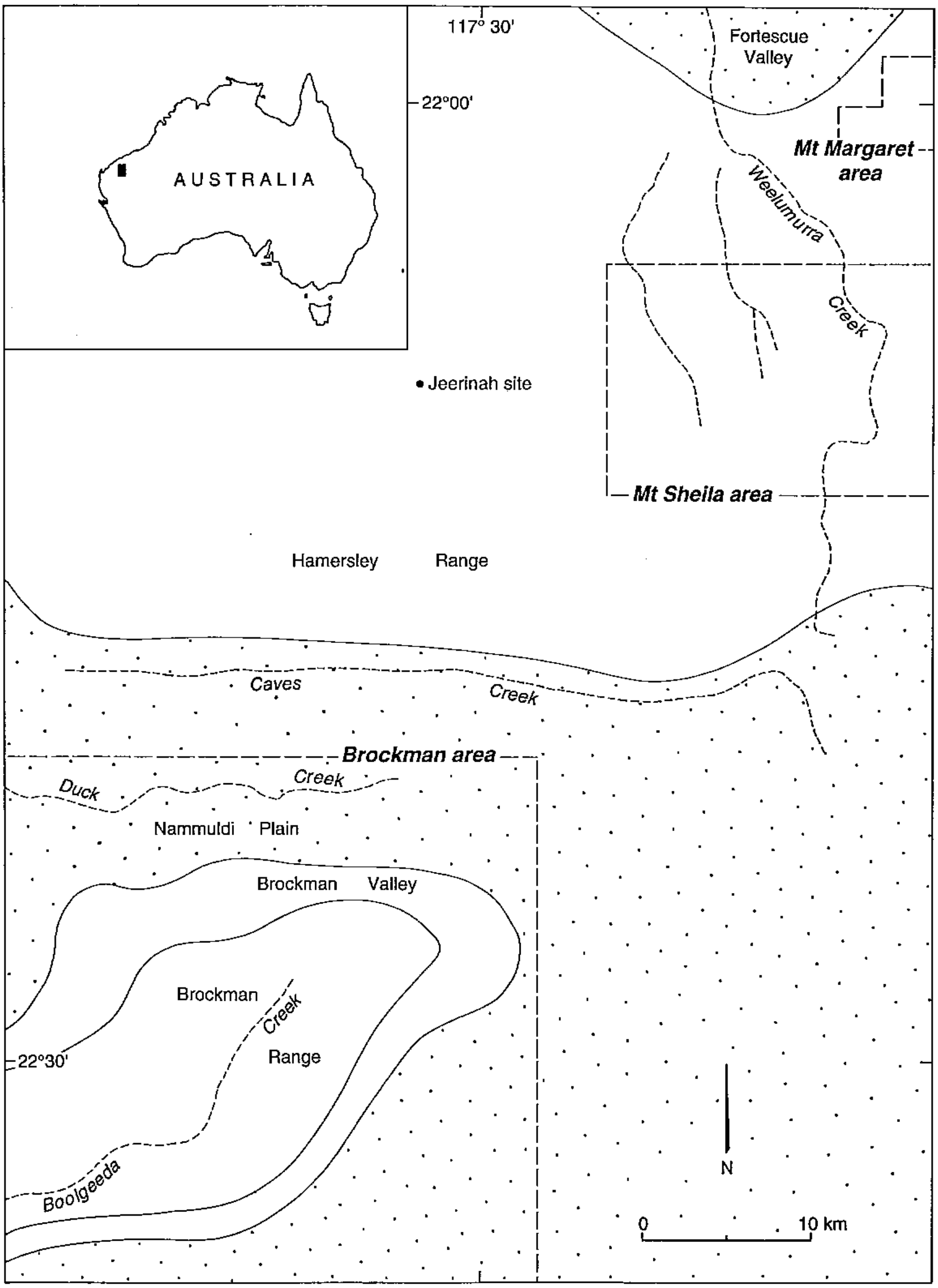


Figure 1. Location map showing study areas and geographical terms.

PROTEROZOIC	Mt. Bruce Supergroup	Hamersley Group	Ᵽhw	WOONGARRA VOLCANICS: Probably several flows. Grey to black porphyritic dacite, also devitrified glass and silicified green chloritic lava
			Ᵽhj	WEELI WOLLI FORMATION: Banded jaspilite with interbedded shale and medium-grained dolerite
			Ᵽhb	BROCKMAN IRON FORMATION: Banded jaspilite and chert with some shale dolomitic with riebeckite and crocidolite at Wittenoom Gorge. Contains *stromatolites*
			Ᵽhs	MT. McRAE SHALE: Shale, siltstone and dolomitic shale with jaspilite and chert, and MT. SYLVIA FORMATION: Three thin jaspilite beds with dolomitic shales
			Ᵽhd	WITTENOOM DOLOMITE: Grey crystalline dolomite with intercalations of chert and dolomitic shales in the upper part
			Ᵽhm	MARRA MAMBA IRON FORMATION: Chert and jaspilite with pronounced "pinch and swell" structures, small occurrences of manganese and deposits of crocidolite
		Fortescue Group	Ᵽfj	JERRINAH FORMATION: Shale, chert, jaspilite, mudstone, quartzite and dolomite. Intruded by dolerite sills
			Ᵽfb	MT. JOPE VOLCANICS: Dark green vesicular and amygdaloidal basalt, pyroclastics and pillow lavas
			Ᵽfbu	Bunjinah Pillow Lava Member - Well formed pillows, aphitic and vesicular basalt

Figure 2. Stratigraphic column for the upper Fortescue Group and lower Hamersley Group.

1.5 Locations, Definitions, Terminology

Geographical locations (*e.g.* Nammuldi Plain, Brockman Valley *etc.*) are given in the location map (Fig. 1). Locations given as AMG use the Australian Geodetic Datum (1966). Geological terms used in this report are defined here. Terms are taken from the American Geological Institute Glossary of Geology (3rd Edition). Other terms specific to local geology are referenced. Sediment is used as a synonym for detritus for reasons of style. Detritus is used in place of detrital in this report because the adjective cannot stand alone.

base level: (of deposition): The highest level to which a sedimentary deposit can be built.

bedded mineralisation: *In situ* rock, principally altered BIF, which has been de-silicified and is enriched in iron. This includes all mineralisation which has occurred by other than surface processes.

BIF: Banded Iron Formation.

canga: A Brazilian term for a well-consolidated rock comprising clasts derived from itabirite, hematite or other ferruginous material in a limonite matrix (varying from 5-95% of the total rock mass). Park (1959, in Morris 1994, p2.3) defined canga as "a rock formed by the cementation by hematite of rubble ore into a hard ironstone conglomerate". Hamersley Iron have applied the term to the deposits of "hematite/goethite clasts in a strong goethitic cement" which are common in the Pilbara.

CID: Channel Iron Deposits. The iron-rich horizons of (inferred) palaeo-channels, including both the Robe Formation and Poondano Formation

(Morris 1994). CIDs are included in the units mapped as "Tp" (Tertiary Pisolite) by the GSWA, but are not synonymous.

clast: An individual constituent, grain or fragment of a sediment or rock, produced by the mechanical weathering (disintegration) of a larger rock mass.

detrital: adjective. Pertaining to, or formed from detritus; said especially of rocks, minerals and sediments.

detritus: *noun.* A collective term for loose rock and mineral material that is worn off or removed by mechanical means as by disintegration or abrasion. Derived from other rocks and moved from its place of origin.

doline: A circular depression in a karst area, commonly funnel shaped. Its drainage is subterranean.

ferricrete: A conglomerate consisting of surficial sand and gravel cemented into a hard mass by iron oxide derived from the oxidation of percolating solutions of iron salts.

ferruginous duricrust: A conglomerate consisting of surficial sand and gravel cemented into a hard mass by iron oxide derived from the oxidation of iron from percolating solutions.

hydrated: Where water has been incorporated into the structure of a mineral.

immature detritus: (DI). Mineralogically immature sediment. Poorly sorted with angular to sub-rounded clasts. High LOI, >3:1 SiO_2/Al_2O_3, moderate P and high BIF/chert component.

intraclasts: A general term for a component of a rock representing a torn-up and re-worked fragment of pene-contemporaneous sediment, usually weakly consolidated.

laterite: A family of materials derived from ferruginisation and residual accumulation of Fe. The original rock texture may be partly preserved or completely destroyed.

mature detritus: (DM). Mineralogically mature sediment. Well-sorted with a high proportion of sub-rounded to rounded clasts (predominantly hematite). Moderate LOI, <3:1 SiO_2/Al_2O_3, moderate P (<0.08%) and very minor BIF/chert component.

metasomatic: (replacement). Replacement of one rock or mineral type with another without significant alteration of the volume, fabric or structure of the original material.

MSL: Mean sea level.

neomorphic: Replacement of one mineral or crystal phase by another without recognisable retention of the original crystal fabric.

pisolith: A small rounded or ellipsoidal body in a sedimentary rock, resembling a pea in size and shape. Larger and less rounded than an oolith, though sharing the same concentric and radial internal structure.

pseudomorphic: Replacement of one mineral or crystal phase by another while retaining the original crystal fabric.

saprolite: A soft, earthy typically clay-rich thoroughly decomposed rock, formed in place by chemical weathering of igneous, metamorphic or sedimentary rocks. Characterised by structures which were present in the unweathered rock.

scree: A term commonly used as a loose equivalent for talus.

sediment: Solid fragmental material that originates from weathering of rocks and is transported or deposited by air, water or ice, or that accumulates by other natural agents such as chemical precipitation. Forms layers on the Earth's surface at ordinary temperatures in a loose, unconsolidated form.

Superband: Contraction of "superimposed band" of Tertiary sediments(?) related to karst development in the Wittenoom Dolomite Formation in the area of the Brockman syncline.

supergene: Said of a mineral deposit or enrichment formed near the surface, commonly by descending solutions.

talus: Rock fragments of any shape or size lying at the base of a cliff or steep rocky slope. Deposited chiefly by gravitational falling, rolling or sliding.

Tp: Tertiary (Robe) pisolite. Pisolitic limonite with fossil wood fragments, occurs along old river channels (GSWA).

weathering: The destructive process or group of processes by which earthy or rocky materials on exposure to atmospheric agents at or near the Earth's surface are changed in colour, texture, composition, firmness, or form, with little or no transport of the loosened or altered material. Most weathering occurs at the surface, but it may take place at considerable depths, as in well jointed rocks that permit easy penetration of oxygen and circulating surface waters (*c.f.* supergene).

2 THE REGION: SITES, GEOLOGY AND GEOMORPHOLOGY

2.1 Introduction

2.1.1 Geology

On a regional scale, the Hamersley Group metasediments can be most simply described as relatively flat-lying along the northern margin of outcrop, becoming more complexly folded to the south. In the northern study areas (Mount Sheila and Mount Margaret), outcrop is limited exclusively to rocks of the Hamersley Group. Passing south, the Hamersley Group once formed a regional anticline, then dipped down into the syncline which now comprises outcrop of the Brockman study area (Fig. 1). Hamersley Group rocks have been eroded from the anticline, leaving the underlying Fortescue Group rocks exposed on the Nammuldi Plain. This structural variation has a significant influence on the local style of iron mineralisation and its preservation *in situ* or as sediment.

2.1.2 Geomorphology

Descriptions of the landscape of the Hamersley Range have been published by several authors (*e.g.* Twidale *et al.*, 1985, Morris *et al.*, 1992). From a distance, the regional landscape is characterised by uplands of smoothly rounded hills and high valleys, separated from low broad river valleys and abbreviated by steep scarp slopes, incisions and gorges. The high-level and low-level elements of this landscape can rarely be seen to be connected by relict smooth slopes which bridge the present day scarps (Fig. 3). The generation of the smooth elements and broad valleys had been attributed by these authors to the development and subsequent stripping of one or a number of weathered zones, the "Hamersley Surface(s)".

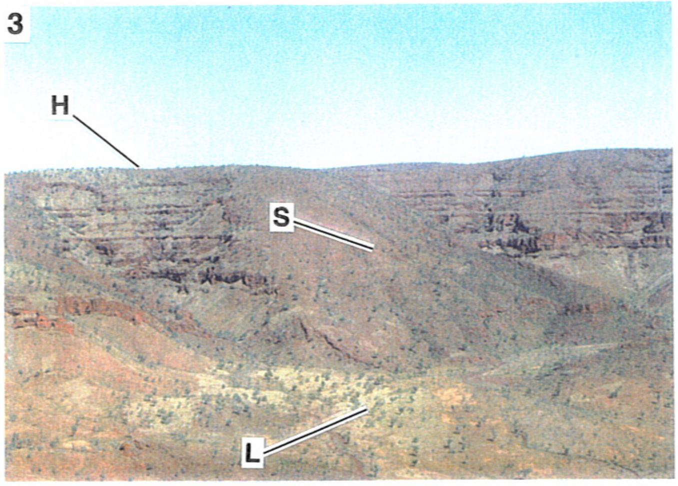
2.2 Brockman Area

2.2.1 Geology

In general terms, the Brockman Iron Formation dips towards the centre of the Brockman Range, forming a syncline which plunges to the WSW. Detailed examination of the Brockman Iron Formation range front shows that outcrop has been subject to complex folding on a local scale.

The spurs along the northern edge of the Brockman Range front (*e.g.* Location AMG 546000:7520400, Fig. 4) commonly comprise Dales Gorge Member BIF dipping to the north, in contrast to the dominant southerly dip. These spurs are interpreted as relics of the northern limb of a parasitic antiform which was developed along the northern edge of the Brockman outcrop, and oriented sub-parallel with the regional structure. This dipping limb also preserves approximately orthogonally oriented (N-S) minor (~100 metre scale) folding.

The range front is also cut by a series of high angle dextral strike-slip faults trending NW-SE (*e.g.* AMG 531620:7518100; Figs. 5, 6 & 7). Typically, BIF units directly NE of these faults are folded into minor synforms and have been mineralised, while those same lithologies to the SW of the faults are undisturbed and un-mineralised (Fig. 8). The size of these mineralised pods varies from a few cubic metres to in excess of hundreds of cubic metres over the width and depth of outcrop . Similar structures have been developed on the south-eastern margin of the Brockman area, but are less well preserved.



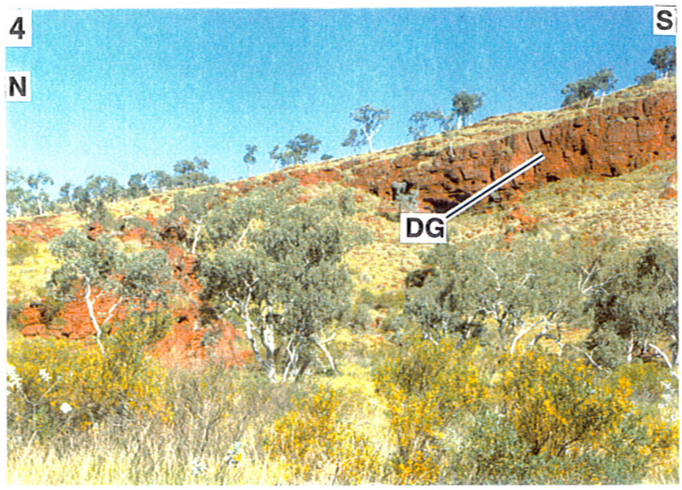


Figure 3. Smooth slope (S) bridging scarp and joining high-level (H) and low-level (L) elements of the landscape.

Figure 4. Dales Gorge Member BIF (DG) dipping north into the Brockman valley, in contrast to the regional trend.

Figure 5. Dextral strike-slip fault illustrated by displacement of dolomite bed in McRae Shale (arrowed). Note Dales Gorge Member (DG) dipping NE towards Brockman Valley is not displaced by movement interpreted to have occurred along plane oriented in the direction of photograph.

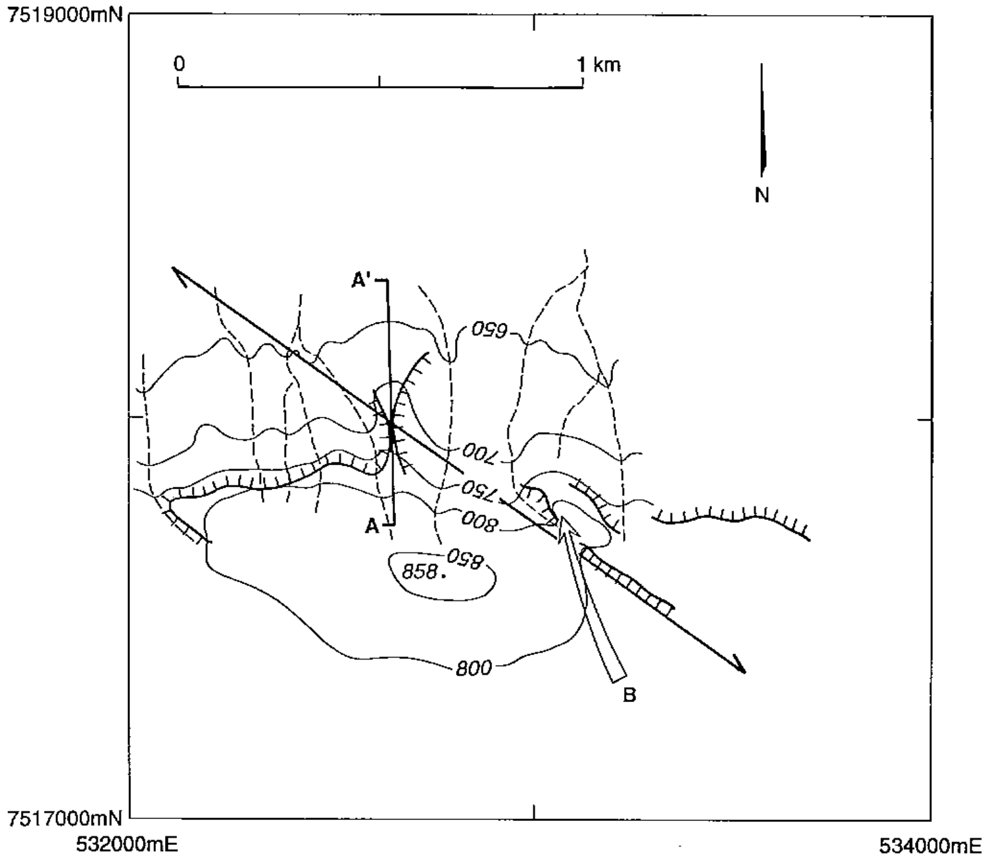


Figure 6. Topographic map showing location of a dextral strike-slip fault in the Brockman range front. Mineralisation is confined to the area of BIF outcrop located immediately NE of the fault (*e.g.* location **B**).

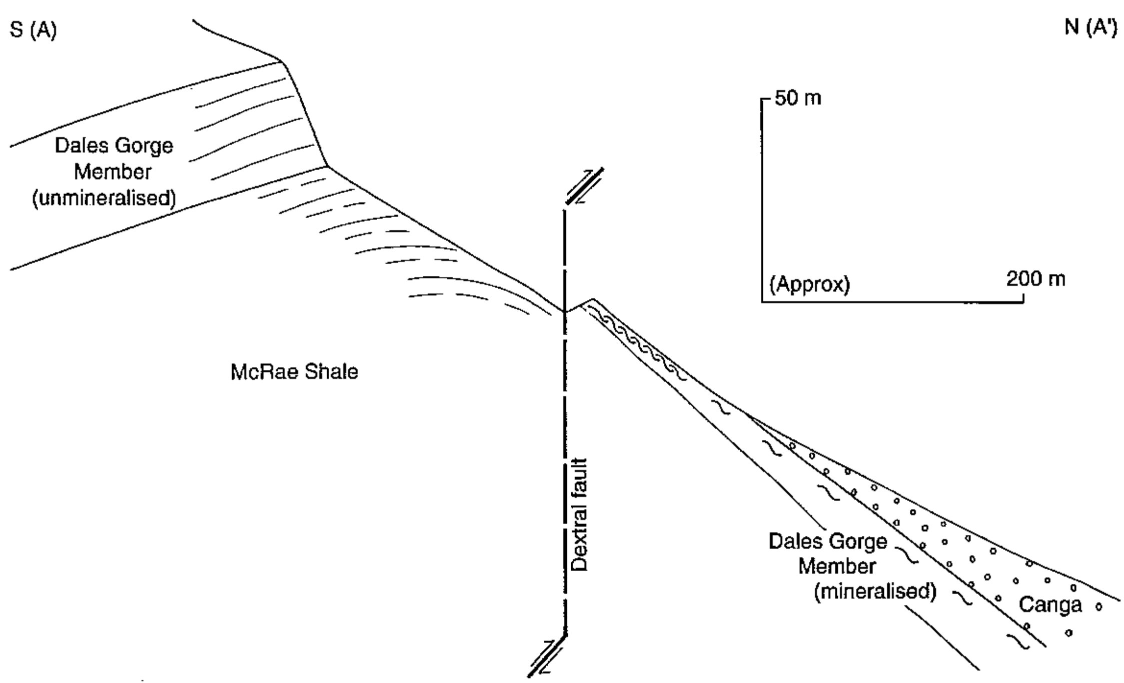


Figure 7. Section A-A' (see Fig. 2) showing schematic distribution of mineralisation relative to the fault, and Dales Gorge Member folded steeply down to the north.

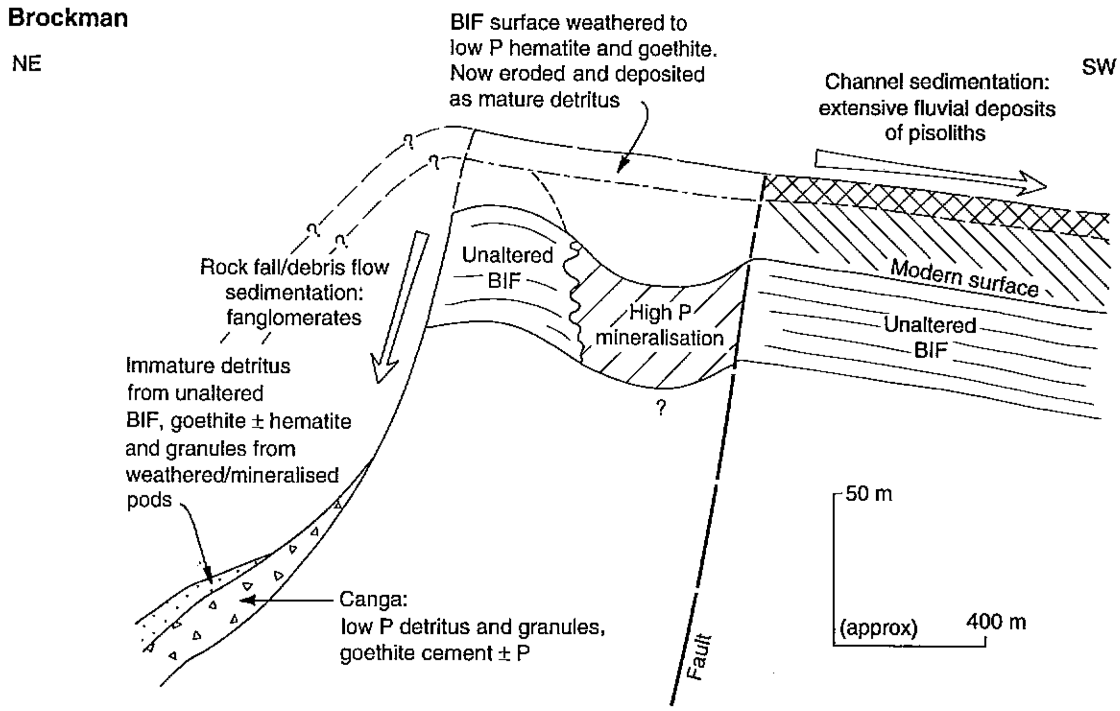


Figure 8. Schematic cross section of the northern range front at Brockman. Mineralised BIF is located NE of strike-slip fault, grading into unaltered BIF. Unaltered BIF is also located immediately SW of faults.

Where NW-SE oriented faults cut the north dipping anticline limbs, the mineralisation is locally silica-enriched. In these zones, the Fe-silicates are botryoidal and have conchoidal fracture (Fig. 9).

A corollary of the preservation of the northern limb of the Dales Gorge Member parasitic antiform dipping under the sediment cover of the Brockman Valley requires (at least part of) that Member to be preserved as a synform in valley subcrop (Fig. 7). Where the Dales Gorge Member is preserved dipping down to the base of outcrop, it is commonly mineralised.

Where the range front has been incised by gullies, fresh BIF is generally exposed by the incision, although outer and lower margins of the re-entrants may expose sections of weathered *in situ* material (*e.g.* Locations AMG 545350:7519300, 528600:7512800).

2.2.2 Geomorphology

The modern drainage systems run axially along the strike valleys developed over the Wittenoom Dolomite, then cut radially outwards via gorges through the ridge formed by the Marra Mamba Formation. This ridge has been breached along planes of weakness created by faults in the BIF (Fig. 10). Rivers have encroached from the surrounding plains, and captured the internal drainage of the Brockman Valley.

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Figure 9. Silica-enriched mineralised BIF from fault zone. Silica enrichment is recognisable by rounded/botryoidal appearance (arrow) and conchoidal fracture.

Figure 10. A tributary of the Beasley River breaching Marra Mamba Formation BIF (middle distance) along fault plane. It thus has captured the internal drainage of part of the Brockman strike valley.

Close to these gorges, incision into the valley sediments has led to the development of a complex of linear ridges separated by V-shaped gulleys (Fig. 11). These immature detritus ridges consist of goethitic and clay rich fines with an admixture of BIF clasts. Headward incision has not yet gone to completion, leaving areas such as Silvergrass Plains at what was probably the local balanced base level.

2.2.3 Valley Deposits

The valleys surrounding the Brockman Range are filled with a variety of immature and mature detritus. The surface expression of these sediments is variable. Close to incisions and gorges where drainage passes out through the ridge formed by the Marra Mamba Formation, the detritus is deeply incised (Fig. 11). Away from these drainage outlets, headward stream incision has not progressed far enough upstream to erode some areas (*e.g.* Silvergrass Plains).

Mature detritus may be exposed at surface, but most commonly are covered by mixed and immature detritus. Close to the range front, immature detritus typically comprise pebble- to boulder BIF clasts in a silty goethite/soil matrix (Fig. 12). Clast size decreases away from scarp slopes towards the Marra Mamba Formation dip slopes, and the proportion of matrix increases. The most distal deposits typically comprise a silty goethite-rich matrix supporting lenses and layers of BIF pebbles and cobbles (Fig. 13). The silty matrix is commonly partly indurated with ferruginous cement. In the southern exposures, immature detritus coarsens upwards from silty sands with moderately well rounded pebbles, to cobbly sands with angular to very angular BIF clasts.

Where the immature detritus has been incised, erosion has rarely exposed the underlying mature detritus. Crystalline goethite cemented hard-pans containing immature and mature clasts are commonly exposed in creek beds. Calcretes are also developed in the immature detritus.

2.2.4 Canga

The spurs running north from the Brockman range front are commonly veneered with variable thicknesses of mineralised clasts. These veneers vary from loose sediment filling irregularities in the surface to goethite cemented wedges of canga which increase in thickness down slope until they pass under immature valley fill sediments. Where cangas overlie the Dales Gorge Member, the BIF has typically been mineralised and is hematitic in composition. Where the substrate comprises the aluminous Mount Sylvia and McRae Shale units, it is goethitic in nature. In some cases, relict weathered zones developed on the ends of spurs have been preserved against erosion by canga crusts, while the connection with the range front has been eroded, leaving outliers standing free from the range front (Location AMG 538550:7519550; Fig. 14).

Minor pockets of loose and mature cemented detritus overlying weathered *in situ* basement are also rarely preserved in saddles and depression of the Brockman Range (AMG 537450:7518350). However, most high-level outcrop in this area comprises relatively fresh rock.

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Figure 11. A fan of immature detritus incised by vee-shaped gulley, leaving linear ridge.

Figure 12. Coarse immature detritus with angular BIF clasts and rounded canga boulder and cobble intraclasts overlying weathered (bleached) McRaė Shale near (proximal to) range front.

Figure 13. Angular pebble and cobble clasts of immature detritus supported by goethite matrix, distal from range front

Figure 14. Small hill (arrowed) is weathered Dales Gorge Member overlain by canga crust. This hill records the base of the Tertiary range front, about 400 metres out from the modern range front, and indicates the maximum degree of range front retreat in the Brockman area. From middle to far distance behind small hill are the Brockman Strike Valley, Marra Mamba ridge and Hamersley Range, respectively.

2.3 Mount Sheila Area

2.3.1 Geology

Outcrop in the Mount Sheila area is stratigraphically higher than in the Brockman area. The relatively flat-lying BIF units of the Dales Gorge Member outcrop close to valley floor level. Therefore, the valleys are typically floored with the Dales Gorge Member, McRae Shale or Mount Sylvia Formation (Fig. 15). The Mount Sheila area is dissected by long and sinuous valleys which form a dendritic drainage system, in contrast with the curvi-linear strike valley of the Brockman range front.

Brockman Iron Formation BIFs are locally folded and faulted, but Brockman style *in situ* mineralisation has not been identified. Weathered zones are generally absent in outcrop, except where they have been preserved underneath canga deposits.

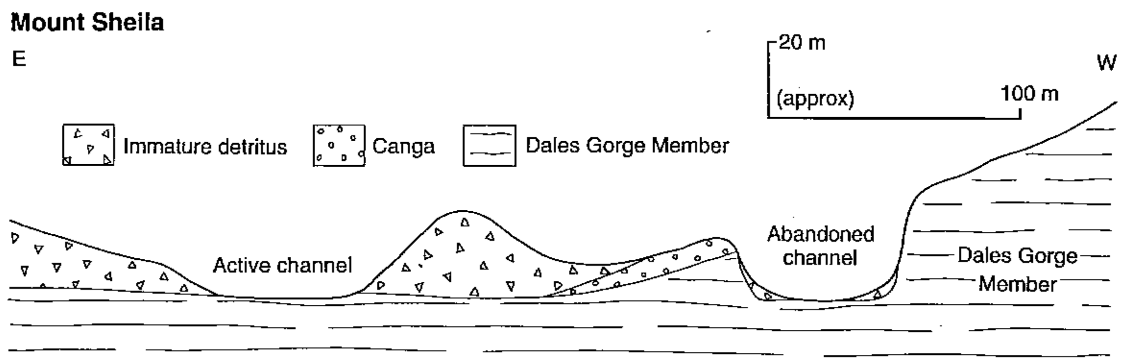


Figure 15. Schematic cross-section in Mount Sheila area. Canga overlies margin of valley incised into Dales Gorge Member. Valley has subsequently been filled with immature detritus. An abandoned incised channel separates the canga and some immature detritus from steep valley slopes. The currently active channel has cut through immature detritus to expose un-mineralised Dales Gorge Member BIF in the channel base.

2.3.2 Geomorphology

In the Mount Sheila area, headward incision by channels has progressed to the ends of the drainage systems. In the broader valleys, the typical local expression of this process is the linear ridge and gulley morphology, where ridges comprise relict deposits of aluminous and goethitic fines mixed with BIF clasts. These ridges are separated by straight- to sinuous gulleys containing the down-cutting channels (Fig. 16).

In the narrower tributary channels, headward incision has resulted in the removal of exposed high grade detritus (typically cangas) from virtually all slopes except those in the highest parts of the drainage system, at the heads of valleys. Where canga deposits are preserved, channels have cut precipitous gulleys through them and down to fresh bedrock (Fig. 17).

At present, some of the sediments being liberated from the upper- and middle reaches of the tributary system are undergoing temporary storage in Weelumurra Creek, but they are being removed from the area on reaching the Fortescue river system.

Figure 16. Incised fans of BIF clasts mixed with aluminous and goethitic fines (immature detritus). Note linear ridge and gulley morphology, where ridges are separated by straight- to sinuous vee-shaped gulleys incised by the down-cutting channels.

Figure 17. Canga (arrowed) excised by headward incision of channel system. Canga rises smoothly to link valley floor with rounded hill tops.

Figure 18. Canga overlying siliceous but weathered and goethitic BIF.

2.3.3 Valley Deposits
Sediments exposed on valley floors and in sections incised by gullies comprise immature detritus. Where channels have been constrained by valley sides, landforms are erosional. Where channels exit the range (*e.g.* Weelumurra Creek), flow expansion has led to deposition of sediment, and landforms are aggradational.

2.3.4 Canga
Canga deposits are very well developed and preserved in the Mount Sheila area. They are typically located near the heads of valleys, where they form smoothly curved crusts which pass down from upper- and mid level slopes to valley floors (Fig. 17). Cangas are developed across the Dales Gorge Member as well as the Whaleback and McRae Shale Members.

Canga outcrops may be greater than 10 metres thick and extend for more than 1 kilometre (*e.g.* AMG 563000:7547700). Fracture patterns in these deposits align with the regional fault patterns, indicating that slight movement has occurred along these lines of weakness since the Tertiary. Deposits are bedded on a decimetre- to metre scale, and can rarely be seen to contain cross bedding structures. These indicate that the clasts have been transported by an aqueous medium and deposited as bedload. Depressions on the tops of beds may contain crystalline goethite, interpreted as an alteration product of fines ponded on the tops of flows.

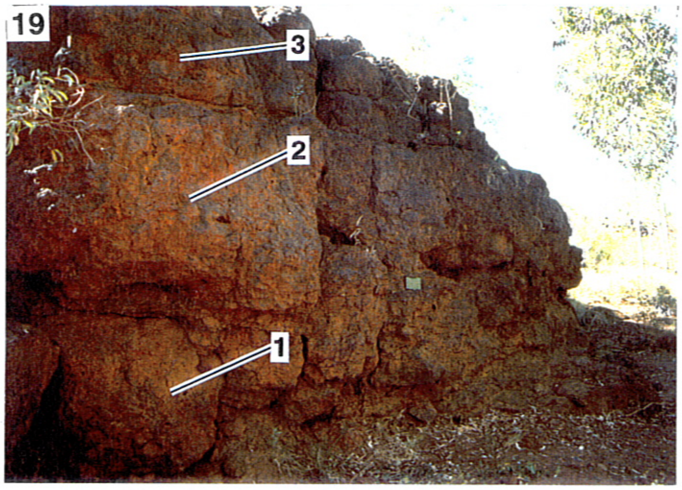
The *in situ* substrate on which the cangas are preserved is commonly heavily weathered. As at Brockman, underlying shale units are goethitic in composition. Weathered BIF units are typically hematite enriched, but still goethitic and siliceous (Fig. 18).

2.3.5 Mount Lois Site
Two sections have been visited to the north and west of Mount Lois, in the Weelumurra valley.

The western section is exposed in a railway cutting (AMG 572751:7556330) adjacent to the eastern bank of Weelumurra Creek. It comprises about 4 metres thickness of gravelly conglomerate. It can be sub-divided into three units each of about 1-1.5 metres thickness and separated by clay-rich layers (Fig. 19). The units extend over the length (hundreds of metres) of exposure.

Individual beds within each unit comprise amalgamated and laterally discontinuous lenses of conglomeratic and pisolitic hematite gravel. Some fossilised plant fragments are recognisable in hand specimen. Some large scale cross-stratification is preserved in lenses of the more pisolitic clasts. The basal unit is more fractured and goethitic than the overlying two units.

The other site, at the base of the north slope of Mount Lois (AMG 575600:7557100), comprises a tongue of relict ferruginous crust surrounded on three sides by breakaways. The profile of the top surface of this crust rises smoothly to connect with the sloping flanks of Mount Lois, indicating the form of the Tertiary landscape (Fig. 20).



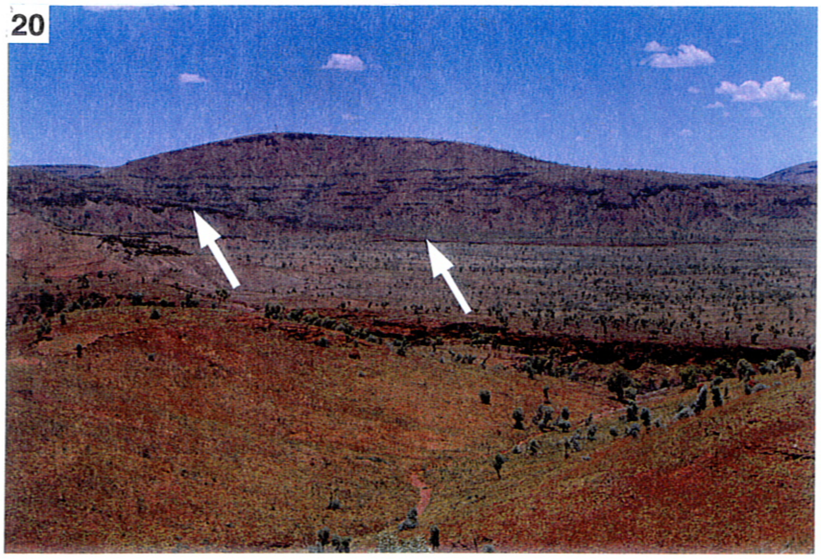


Figure 19. Gravelly conglomerate containing fossilised plant fragments at Mount Lois. Conglomerate can be sub-divided into three units each of about 1-1.5 metres thickness and separated by clay-rich layers. The units are laterally extensive over the length (100's of metres) of exposure.

Figure 20. Ferruginous crust (arrows) rising smoothly SE (left) to connect with the sloping flanks of Mount Lois, indicating the form of the Tertiary landscape.

The top of the rise is capped with about 2 metres thickness of transported material comprising pisoliths, detrital fragments and fossilised wood in a goethite matrix. This crust overlies weathered McRae Shale(?).

2.4 Mount Margaret Area

2.4.1 Geology

Brockman Iron Formation rocks in the Mount Margaret area, like those of the Mount Sheila area, are not systematically folded. The open valleys within this area are typically floored at an elevation of about 600 metres by weathered basal Dales Gorge Member or McRae Shale. Substantial scarps have been developed to the north and west, which has resulted in the area being preserved as a high plateau with hills of remnant BIF. The scarps are incised by a number of gorges (*e.g.* at Hugh Bluff and Roy Parsons Gorge) which have been eroded from the level of the high plateau directly to the base level of Weelumurra Creek and the Fortescue valley. In comparison, approaches to the Mount Sheila area are mantled with sediments, and the ground rises gently to meet the hills.

Two different types of weathered surfaces are exposed here. The first is seen at the Mount Margaret drilling site, which comprises a narrow and confined valley set in a synclinal fold in the Joffre(?) Member (Fig. 21). On each side of the valley, spurs of weathered BIF are preserved under canga caps. Along the margins of gullies separating the spurs, reasonably complete sections are exposed. These sections show a weathering profile passing down from fully mineralised BIF to relatively unweathered/un-mineralised BIF over vertical sections of about a few metres. Canga is patchily preserved over the spurs.

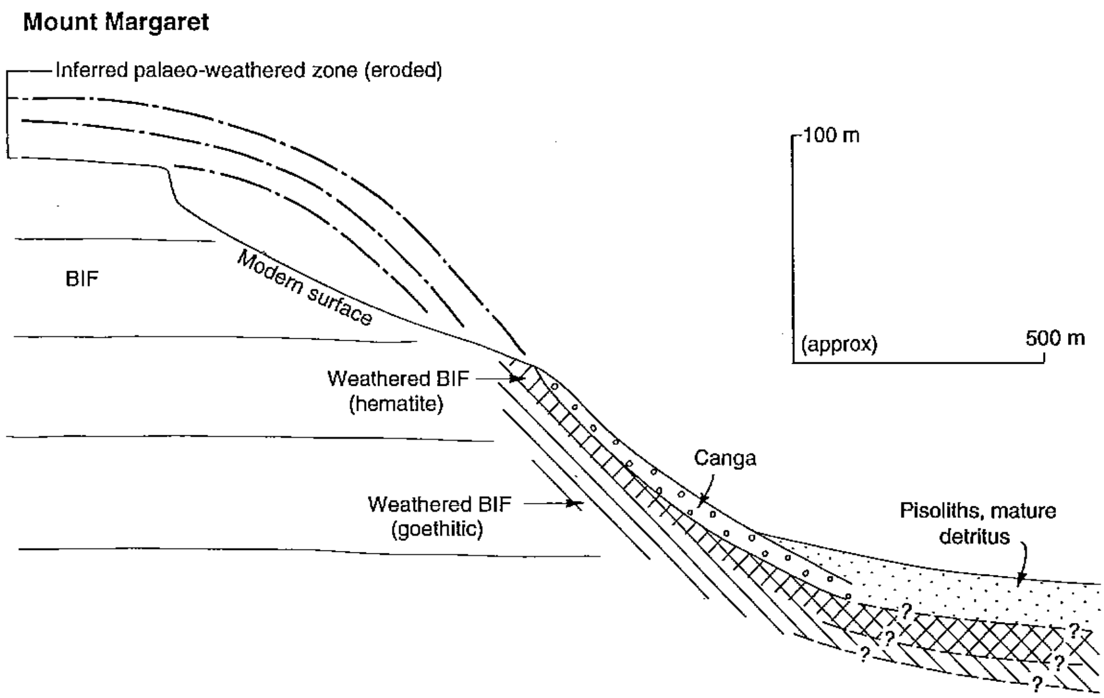


Figure 21. Schematic cross-section from Mount Margaret drilling site. Canga overlies weathered BIF. The weathering profile passes down from fully mineralised BIF (hematite) to relatively unweathered/un-mineralised BIF over vertical sections of a few metres.

The second type is seen at Hugh Bluff and Roy Parsons Gorge, where the lowest parts of the Dales Gorge Member and the top of the McRae Shale are exposed in the valley floors (Figs. 22 & 23). These outcrops are heavily weathered and support a thin and patchy cover of sediment. These sites offer the most extensive probable analogues of Tertiary weathered terrain. The sides of these valleys and their surrounding hills have been stripped of weathered cover, leaving relatively fresh BIF exposed.

2.4.2 Hugh Bluff Site

At Hugh Bluff, the base of the Dales Gorge Member is exposed in the floor of a broad valley which is inclined gently down to the south and east, sub-parallel with the underlying bedding. Hugh Bluff is truncated to the west by a scarp slope which has been penetrated by gorges (Fig. 24).

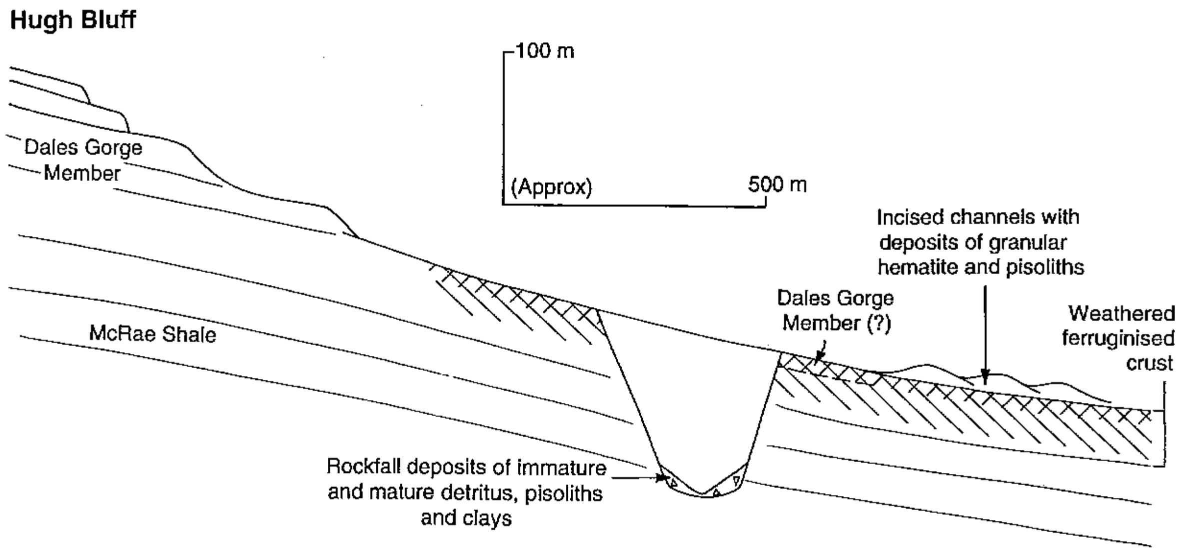


Figure 22. Schematic cross-section from Hugh Bluff showing gorge incised through weathered base of Dales Gorge Member and topmost McRae Shale.

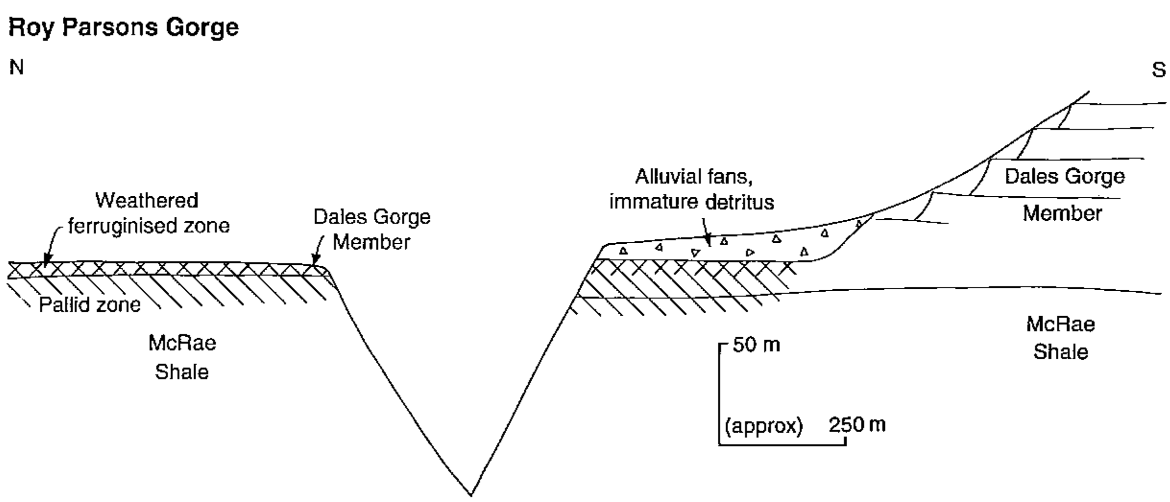


Figure 23. Schematic cross-section from Roy Parsons Gorge where incision cuts through weathered base of Dales Gorge Member and topmost McRae Shale.

Figure 24. At Hugh Bluff, Dales Gorge Member exposed in the base of a broad valley dipping gently to the south and east, sub-parallel with the underlying bedding. Here, valley is truncated to the west by a scarp which has been penetrated by a gorge (mid distance).

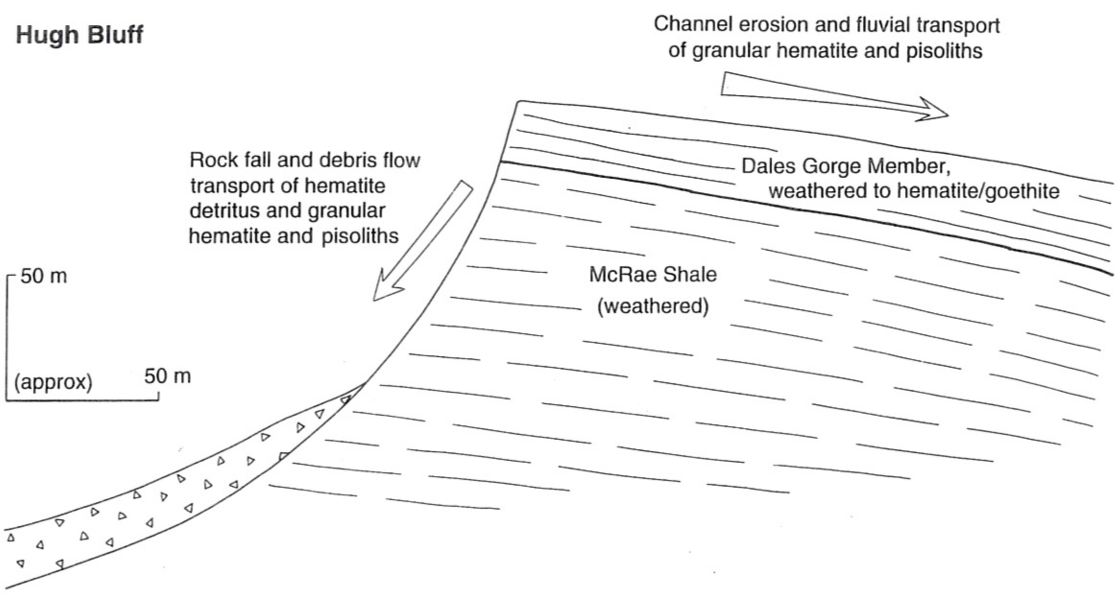


Figure 25 Schematic cross-section of outcrop at Hugh Bluff. Pisolitic sediments are being transported SE in channels, and a mixture of pisoliths and coarser fanglomerates (proto-canga) is accumulating at the base of the scarp slope.

The Dales Gorge Member is heavily weathered to hematite and goethite, but some BIF texture is preserved *in situ*, and in some clasts liberated from the surface. Most surface clasts have multiple goethite skins, and can be categorised as pisoliths, regardless of whether or not the cores are of recognisable origin. The valley floor has been incised by numerous shallow channels and rills draining to the SE. Sediments in these channels are dominantly pisolitic (Fig. 25).

2.4.3 Roy Parsons Gorge Site

At Roy Parsons Gorge, a slightly undulating tract comprising the floor of a high level valley overlies Dales Gorge Member and McRae Shale. The valley slopes gently down to the NE from a low divide which separates it from the neighbouring Hugh Bluff area. This subdued topography preserves an extensive goethitic crust of weathered material. The valley is rimmed to the NW and SE by Dales Gorge Member outcrop. The valley centre has been deeply incised by the southward advance of Roy Parsons Gorge from the Fortescue valley. The floor of this valley is comparatively flat lying and the surface is deeply weathered to goethite and clay.

The floor of the SE margin of the valley is overlain by a series of alluvial fans prograding NW from the Dales Gorge Member. Some of these fans have been truncated by the gorge. The fans consist of immature detritus in a goethitic/silty soil matrix (Fig. 26).

2.4.4 Geomorphology

The step down from the high level valleys of the Mount Margaret area studied here, to the Fortescue and neighbouring valleys causes the local fluvial systems to be essentially "open" at their downstream ends. Local sediment storage is therefore controlled by the competence of the fluvial systems to transport it, rather than by "damming" at base level. This has resulted in little sediment storage in the majority of the area. This is demonstrated in the broad valleys above Roy Parsons Gorge and east of Hugh Bluff, where the modern land surface is interpreted to be co-incident with the Tertiary weathered surface, and where there is no significant build-up of sediments.

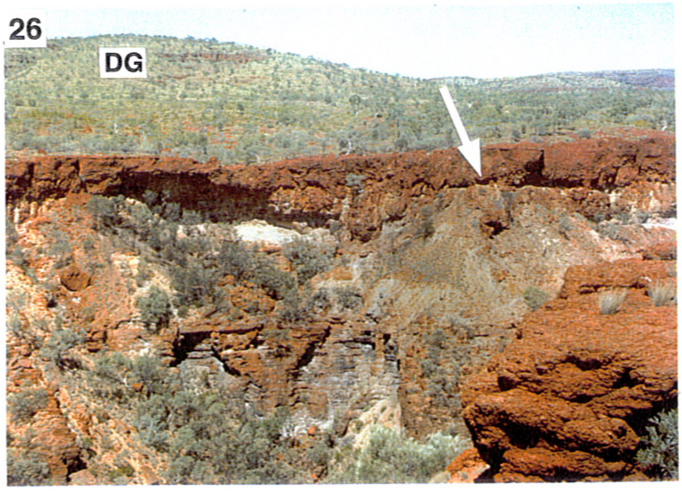
An exception to this general rule is seen in the confined valley of the Mount Margaret drill site, where a significant volume of sediment is stored. This storage may be a function of the inability of the local streams to generate sufficient volumes of water from a restricted catchment to move the available sediment. If so, this does conform to the competence requirement outlined above.

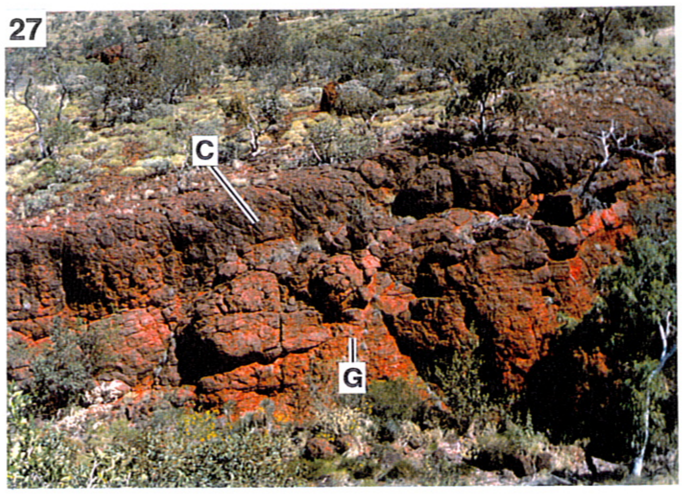
2.5 Other Sites

In addition to areas specified by Hamersley Iron for this project, additional sites of interest visited by CSIRO during the course of research are described below.

2.5.1 Pylon Road

This location is situated where the road running north from the Caves Creek road enters the Hamersley Range, immediately west of the power transmission line (AMG 547600: 7537200). Stream capture where the range front has been penetrated by a tributary of Caves Creek has resulted in incision and exposure of a weathered section through the base of the Dales Gorge Member and the upper part of the McRae Shale.





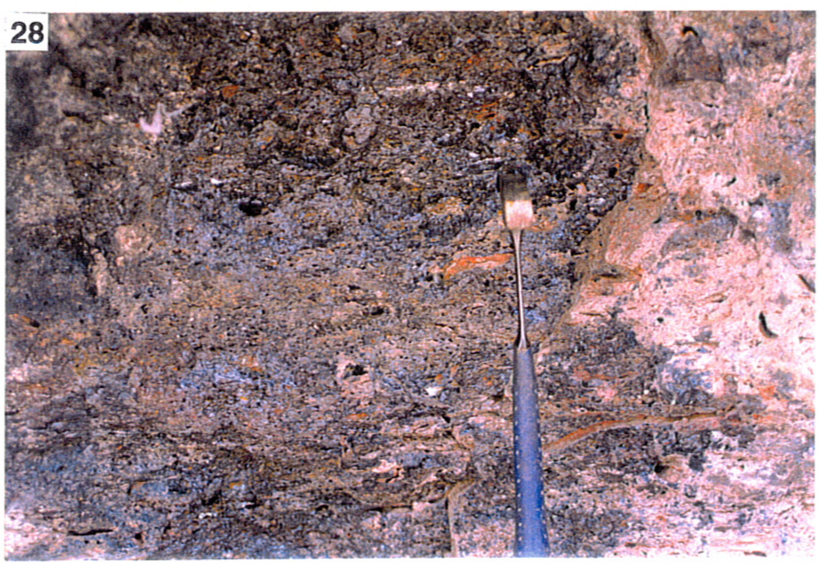


Figure 26. Weathered (bleached) floor of SW margin of the valley at Roy Parsons Gorge overlain by truncated alluvial fans (arrow) prograding NW from the Dales Gorge Member (DG). The fans consist of immature detritus.

Figure 27. Base of valley at Pylon Road excised by stream capture through range front. A weathered zone of hematitic BIF and goethitic shale (G) is patchily overlain by canga (C).

Figure 28. BIF altered to crystalline goethite. Although fractured and slightly brecciated, it retains recognisable BIF microstructure and bedding.

Figure 29. Brecciated and goethite-cemented hematite-rich crust interpreted as being of eluvial origin, having probably been formed by *in situ* deflation of a dissolving mass as BIF was mineralised.

Figure 30. Exposed BIF surface comprising a fully mineralised (hematite) BIF.

In the base of the valley, a weathered zone of hematitic BIF and goethitic shale is preserved. This is overlain in places by canga (Fig. 27). Some minor faulting is present, with massive silica cementation of fault breccias. A veneer of immature sediment patchily covers the local outcrop.

2.5.2 Jeerinah

The Jeerinah site (AMG 545635:7550614) is situated in a similar geographic setting to the Mount Sheila sites. At the head of a dendritic valley incised into the Dales Gorge Member, relatively fresh BIF grades upwards into a zone of weathered BIF. The weathered material is mainly goethitic. Although fractured and slightly brecciated, it retains recognisable BIF structure and bedding (Fig. 28). The top 1-2 metres of this outcrop comprises highly disrupted detrital hematite with the appearance of canga (Fig. 29). This enigmatic crust is interpreted as being of eluvial origin, having probably been formed by collapse and re-cementation of a dissolving mass.

Up-slope of this section, *in situ* BIF has been partly- to fully mineralised. Where fully mineralised, outcrop comprises predominantly hematite (Fig. 30).

2.6 Tertiary Pisolite

Locations situated north and south of Brockman, on the Nammuldi Plain and Beasley River catchment were visited. Outcrops typically comprise 2-5 metres of ferruginous crust overlying Fortescue Group basement with an angular unconformity. Fortescue Group outcrop is saprolite. Sections are typically whitened at base of exposure passing up through a ferruginous mottled zone to the unconformity.

Ferruginous crusts are zoned from bottom to top. At their bases (defined as a clastic zone), poorly preserved bedding structures may be visible. Individual beds of decimetre scale thickness are amalgamated into laterally extensive units of 0.5-1 metres thickness (Fig. 31). Clasts include mineralised BIF and pisoliths, and range from silt to pebble size. Some of this material has been eroded and re-deposited as intraclasts up to about 70 centimetres diameter (Fig. 32).

Central zones comprise cemented ferruginous material without recognisable clasts but having a blocky cleavage/fracture. These zones are overlain by topmost zones of pisoliths. Pisoliths may be of indeterminate origin or contain mineralised BIF or plant fragments.

Tertiary Pisolite deposits on the Nammuldi Plain are present as the caps on mesas. They are commonly flat lying at an altitude of about 600 metres above MSL, but at the southern margin of the Nammuldi Plain, the ferruginous cap rises smoothly to blend into the upper slopes of Marra Mamba Formation ridge. As the crust rises, its' thickness decreases and the lower clastic zone thins and pinches out.

Tertiary Pisolites situated south east of the Brockman Range are similar in nature to those north of Brockman, but at about 570 above MSL metres are situated topographically lower.

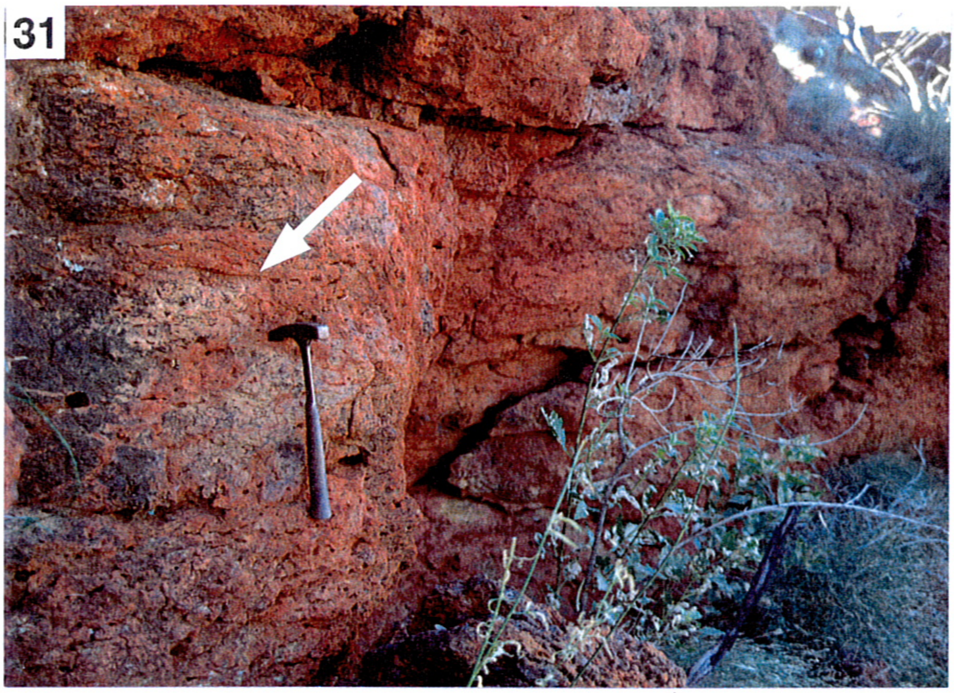


Figure 31. Ferruginous CID crust, zoned from bottom to top. At the base, poorly preserved bedding structures are visible (arrow). Individual beds of decimetre scale thickness are amalgamated into laterally extensive units of 0.5-1m thickness. Apparent thin beds in upper part of section may be artefact of weathering.

Figure 32. CI deposits of poorly sorted conglomerate ranging from silt to boulder intraclasts of up to about 70 cm diameter.

3 THE REGOLITH

3.1 Introduction

The high grade mineralised detritus mined at Brockman form part of a complex array of regolith materials throughout the study areas. An appreciation of these materials provides a context in which to investigate the detrital ores.

The regolith is a product of geomorphic processes and weathering in a range of geological settings. Bedrock is the prime source of materials, although both are often considerably modified by weathering. Bedrock lithology also influences topography and patterns of weathering. Topography, in turn, constrains weathering processes, the retention of the products of weathering, their removal and subsequent deposition. Crusts produced by weathering may control the stripping of the regolith. The role of past and present climates, though recognised, cannot be assessed with any certainty. Thus geological and topographic factors provide the prime basis for defining and classifying the regolith.

3.2 Regolith Maps

Maps of the three study areas were produced at a scale of 1:50 000 (Appendix 1) using stereo interpretation of colour photos (approximate scale of 1:40 000) and field checking. Contour information, at 10 metres interval, was also an aid.

The study areas are dominated by rocks of the Hamersley Group. Each area has geological and topographic features which are sufficiently different to affect the regolith and so warrant individual attention. Thus, in the Mount Margaret area, a significant part of the upper regolith comprises laterite profiles with duricrusts. These materials are generally poorly developed or exposed on Hamersley Group rocks elsewhere. The Mount Sheila area has the same general suite of landforms associated with rocks of the Hamersley Group elsewhere, but with valley deposits which have been subjected to partial stripping, transport and deposition. The Weelumurra Creek drainage system is active here. The Brockman area has regolith-landform associations which are poorly represented in the other areas, including the suite of regolith materials associated with Fortescue Group rocks.

The mapping units recognised are presented in Table 1. The primary division is made on the basis of associated geological province, *i.e.* Fortescue Group or Hamersley Group. Subdivision of these groups was effected according to the associated geomorphic environments, whether it be:

1) relict (representing areas with extensive deep weathered mantle, frequently developed *in situ* on the underlying rocks),
2) erosional (*i.e.* areas of little or no highly weathered material, and often with extensive rock outcrop) or,
3) depositional (*i.e.* areas dominated by several metres thickness of transported debris).

The nature of the regolith materials and some topographic features were used in further classification of the units.

	General nature of the regolith	Soil	Lag	Topography
fRg	Laterite profiles and goethitic crusts extensive. Pallid saprolite, mainly out of shaley rocks, a common substrate.	Shallow, gravelly ,brown sandy clay loam. Goethitic crust is close to the surface.	Brown, goethitic gravels.	Gently undulating planar tracts: some as caps of mesas.
fEs	Saprolite, as outcrop/subcrop, mainly from shaly rocks. Some fresh rock outcrop.	Duplex profiles: compact sodic B horizon.	Quartz, shale and Fe-coated gravels.	Slightly undulating plains with minor drainage floors.
fEr	Rock outcrop extensive: mainly of shales and cherts, some volcanics.	Very thin profiles of red stony, clay loam.	Cobble and gravels of cherts, shales and volcanics.	Rises, low hills and low strike ridges.
fDg	Deposits: probably over discontinuous goethitic crusts.	Gravelly, light clay.	Goethitic gravels with some Fe- stained shales and cherts	Gently inclined plains merging, in places, with unit fRg.
fDhg	Deposits: hematite granule, now as crusts with goethitic matrix. Goethitic crusts a common substrate.	Very shallow gravelly, sandy clay loam.	Hematitic granules extensive.	Very gently inclined planar tracts: usually as caps of mesas.
fDrp	Deposits: gravel of chert and shale.	Very gravelly, red clay loam and light clay.	Gravels of chert and shale: some hematitic and goethitic granules.	Flat plain.
fDrac	Deposits: gravels of chert and shales.	No soil developed.	Gravels of chert and shale: some hematitic and goethitic granules.	Broad, anastomotic, active, stream channels.
hsRg	Laterite profiles: goethitic crusts extensive. Pallid saprolite from McRae shale, a common substrate.	Shallow gravelly, brown, acid sandy clay loam.	Goethitic gravels and granules: hematitic granules uncommon.	Broadly undulating tracts: usually deeply incised at the margins.
HbRh (not mappable)	Laterite profiles: hematitic crusts extensive, merging at depth to goethitic crusts.	Shallow gravelly, red brown, acid sandy clay loam.	Hematitic gravels and granules.	Local, gently inclined slopes.

Table 1: Mapping units for the Mt Margaret, the Mt Sheila and Brockman regolith maps.

	General nature of the regolith	Soil	Lag	Topography
hbErc	Rock outcrop extensive: mainly banded-iron and chert.	Rare patches of shallow stony red clay.	Cobbles of banded-iron and chert.	Complex of smooth, undulating convex crests and slopes.
hbErm	Rock outcrop extensive: mainly banded-iron and chert.	Rare patches of shallow stony red clay.	Cobbles of banded-iron and chert.	Complex of smooth, broadly convex crests and slopes and, locally steep, irregular slopes and ravines.
hbErv	Rock outcrop extensive: mainly banded-iron and chert.	Very rare patches of shallow stony red clay.	Cobbles of banded-iron and chert.	Complex of smooth crests and steep, irregular slopes and ravines.
hm Er	Rock outcrop extensive: mainly banded-iron and chert.	Rare patches of shallow stony, red clay.	Cobbles of banded-iron and chert.	Crests and slopes of broad ridges.
hDrac	Channel deposits: cobble and gravel of banded-iron and chert.	No soil.	Cobbles and gravels of banded-iron and chert.	Broad, active, anastomotic channels of major streams.
hDrhgf	Deposits: cobble and gravel of banded-iron and chert, both hematitic and lithic. Hematitic granule sequence as a thick substrate; commonly some clayey deposits, also. Goethitic crusts common at depth.	Very stony, red clay.	Cobbles and gravels of banded-iron and chert: some hematitic granules.	Piedmont tracts, often as gently inclined, fan-like features. Complex of broad shallow drainage floors.
hDrhgif	As above.	As above.	As above.	As above but complexly incised and, in part, fragmented by later phases of erosion.
hDrhgap	As above, but crusts less common.	As above.	As above.	Fluvially active, aggradational plains. Complex array of broad shallow channels and low banks.

Table 1: (continued). Mapping units for the Mt Margaret, the Mt Sheila and Brockman regolith maps.

	General nature of the regolith	Soil	Lag	Topography
hDchg	Deposits: clays, some lenses of banded-iron and chert, gravel. Thick sequences of hematitic granule at depth: some goethitic crusts also.	Friable red clay: some profiles more gravelly than others.	Sporadic patches of hematitic granules.	Stable plains at the toe of piedmont slopes.
hDhg	Deposits of hematitic gravels and granules, as crusts with goethitic matrix: goethitic crust substrate.	Very shallow stony, red clay loam.	Hematitic granules and gravels: some goethitic gravels.	Crests of mesas: usually planar and, slightly to moderately inclined. In dissected ends of tributary valleys.
k	Calcrete-capped rock outcrop (rocks usually shaley).	Shallow stony calcareous earths.	Scattered fragments of calcrete and shale.	Broadly convex, slightly undulating tracts.

INDEX TO MAP UNIT SYMBOLS

Geological		Regolithic		Topographic			
f	Fortescue Group	s	saprolite	R	Relict terrain	if	incised fans
h	Hamersley Group	c	clayey deposits	E	Erosional terrain	ac	active channels
m	Marra Mamba	r	lithic fragments	D	Depositional terrain	c	crests
s	McRae shale	h	hematitic fragments and/or crusts	p	plains	v	ravines, steep slopes.
b	Brockman Formation	g	goethitic crusts	ap	active plains	m	complex of crests and ravines.
		k	calcrete	f	fans		

Table 1: (continued). Mapping units for the Mt Margaret, the Mt Sheila and Brockman regolith maps.

The regolith landform unit codes used for these maps convey some of this information. Thus the first element of a particular unit symbol will be either **f** or **h**, referring to the respective rock Group (Fortescue or Hamersley) over which it occurs. A second element is sometimes used to refer to a particular piece of geological information, such as **b**, for BIF or **s**, for McRae Shale, with which the unit is associated. Then **R** (relict), **E** (erosional) or **D** (depositional) refer to the broad geomorphic environment relevant to the particular unit. Subsequent elements of any one unit symbol can refer to salient aspects of regolith material and landform, the nature of these symbols being indicated in the legend.

3.3 Regolith Mapping Units

3.3.1 Units of Relict Terrain

Mapping units associated with relict terrain are dominated by deep weathered mantles, commonly with goethitic upper crusts, developed *in situ* and occurring as outcrop or subcrop. They occupy areas of low internal relief and are commonly slightly undulating.

The unit **fRg**, developed on rocks of the Fortescue Group, typically occurs as mesas flanked by erosional scarps (breakaways), and are distributed across the north-central parts of the Nammuldi Plain. In contrast, areas of relict terrain with deep weathered mantles and crusts developed *in situ* as a surface and subsurface feature, are uncommon on rocks of the Hamersley Group. However, one such area (mapped as unit **hsRg**) on the Mount Margaret map, is developed on McRae Shale. It occupies a slightly undulating plain on a plateau surface between two gorges. Elsewhere, *e.g.* Jeerinah, limited areas of intensively weathered BIF with a surface crust (unit **hbRh**), are present at the heads of valleys and on low. These are not mappable at the scale used.

The morphological features of deeply weathered sections on the shaly rocks of the Fortescue Group and the McRae Shale have much in common. Typically, an indurated ferruginous upper horizon will merge at depth with more friable argillaceous materials with coarse brown, red brown and yellow brown mottles in a pale kaolinitic clay mass. Pale clays dominate the sections where they merge with unweathered rock at depth (Fig. 26). Complete weathered sections developed on BIF comprise indurated black metallic hematitic upper horizons that have the general laminated and bedded textures of BIF (Fig. 28). These evolve, at depth to indurated goethitic horizons which retain little BIF texture. However these textures become more apparent as the weathered sections merge with the underlying BIF.

3.3.2 Units of Erosional Terrain

Eroded Fortescue Group terrain is represented by two mapping units: **fEs**; erosional plains, and **fEr**; low hill belts. The regolith of the erosional plains largely comprises saprolite derived from shaly rocks. This is partially mantled by thin, discontinuous sandy colluvium. Rock outcrops extensively on the low hills of unit **fEr**, with saprolite common on the narrow intervening pediments.

In Hamersley Group erosional terrain, the Marra Mamba Formation is represented by only one unit, **hmEr**, a low stony ridge set out from the main mass of the Brockman Range. Erosional tracts associated with the Brockman Formation are represented by three units. Of these, unit **hbErc** typically comprises broadly convex crests of major ridges and spurs. The generally smooth appearance of these areas contrasts with the irregular nature of adjacent unit, **hbErv**, which consists of steep irregular scarps and ravines. Unit **hbErm** is a complex of the two previous units. Unweathered rock is extensively exposed in all three units. On the mid- to lower crests of where spurs of unit **hbErc** extend to valley floors, small areas retain weathered sections. These are commonly partly truncated and buried by colluvium, and cemented to form canga.

3.3.3 Units of Depositional Terrain

The regolith of depositional terrains generally comprises an upper transported member of variable thickness overlying fresh rock or variably weathered substrates. Transported materials are dominated by granule to cobble-size lithic or mineralised fragments. They may be indurated by ferruginous cements. Siliceous and calcareous cements are more rarely developed.

On Fortescue Group rocks, the unit **fDg** fringes elements of the laterite-capped weathered surface, unit **fRg**. These gently inclined slopes are mantled by colluvium containing a high proportion of goethitic nodules and pisoliths. The most extensive depositional unit of this group, **fDrp**, features an upper transported element containing clasts, apparently derived from both Fortescue Group and Hamersley Group (probably Marra Mamba Formation) rocks. The flat to very gently inclined surface expression of this unit is extensively developed on the Nammuldi Plain, extending eastwards across the low divide between the Duck Creek and Fortescue drainages. To the west (down drainage), this depositional unit gives way to areas of erosional terrain. Active stream channels on areas of Fortescue Group rocks are represented by the unit **fDrac**.

Several mesas, capped by crust of transported granules, and surrounded by erosional tracts in rocks of the Fortescue Group, have been mapped as unit **fDhg**. The upper crust of granules and fossil wood is relatively more hematitic than the underlying goethitic crust developed from weathering of shaly rocks. Many of the granules have well developed goethitic cutans. Fine fragments of hematite or BIF form the cores of some granules but many cores are of an indeterminate nature. These crusts can be greater than 10 metres thick. They have been mapped as **Tp** (*i.e.* Tertiary Pisolite, de la Hunty 1965) and are most extensive on the western parts of the Nammuldi Plain and on similar erosional terrains south of the Brockman Range. This unit often comprises irregular but elongate mesas with crests slightly inclined towards, but clearly separated from the present drainage by scarps. Thus these might be seen as relicts of a once more extensive depositional plain now largely destroyed by erosion, following widespread drainage incision.

The most extensive depositional unit associated with the Hamersley Group is **hDrhgf**, and the closely associated units, **hDrhgif** and **hDrhgap**. These comprise clastic sediment deposited as fans and valley plains along the Brockman Valley and the valleys within the Hamersley and Brockman Ranges. When deeply incised, areas of this sediment are delineated as unit **hDrhgif**. Isolated areas of this unit are surrounded by fluvially more active tracts of the valley floors represented by unit **hDrhgap**. The unit **hDrac** comprises broad, flat-floored channels of major active streams such as Weelumurra Creek.

Where the valley floor is unaffected by drainage incision, the gravelly fan deposits merge to more argillaceous facies in positions distal from range and hill fronts. One example of this unit **hDchg**, is located at the foot of the eastern extremity of the Brockman Range. This tract, (Silvergrass Plains), comprises the unit **hDchg**. It occupies a divide between two drainage systems that share the limits of this valley. This feature had a broadly concave profile which makes it a lake after significant rains.

The degree of erosional modification of these valley deposits appears to depend on the nature of the drainage system. Within the main body of the Brockman and Hamersley Ranges where drainage systems are complex and tributaries common, valley floors have been considerably modified by stream incision and partial sediment removal. Here, large areas of fan, designated on the maps as **hDrhgf** or **hDrhgif**, have been replaced by fluvially more active tracts *i.e.* unit **hDrhgap**. In the Brockman Valley, by contrast, fluvially active floors (unit **hDrhgap**) are more limited in extent, leaving more of the fans intact, though in parts they are deeply incised. This reflects a relatively more stable fluvial environment on the floor of the Brockman Valley than along the complex valley systems within the range masses. This situation might in part, be related to the lack of tributaries and the effect of this on stream dynamics. Much of the more recent fluvial action along the Brockman Valley is related to the development of neighbouring drainages. Thus, where the Duck Creek system to the north has encroached upon the Brockman Valley by breaching the ridge of Marra Mamba Formation rocks, there is a zone of marked drainage incision represented by the unit **hDrhgif**. Elements of the Beasley River system have had a similar effect along this valley south of the Brockman Range.

Sediment modification by fluvial processes (units **hDrhgf, hDrhgif** and **hDrhgap**), has apparently affected no more than about the upper 10 metres of the sediments. Thus there are similarities in vertical sections for all valley floors in terrain dominated by the Hamersley Group rocks, whether they are within the range or along the Brockman-type valleys peripheral to the ranges. Sections passing up from *in situ* goethitic materials through mature detritus and into immature detritus are commonly preserved in these valleys.

Some units associated with the Hamersley Group rocks have thick crusts developed in clastic materials, which rarely have sedimentary structures. They are shown on the map as unit **hDhg**. Such crusts may be as much as 10 metres thick. Upper parts of crusts are dominated by granule to coarse gravel sized BIF clasts which show a moderate to high degree of hematisation (canga). The upper clastic parts of these canga crusts are underlain by material intensively weathered from underlying rocks. More commonly, these are goethitic, but some are more hematitic and may have BIF-like textures.

The more striking examples of unit **hDhg** occur as low mesas in the upper reaches of the valley systems within the Hamersley and Brockman Ranges where there has been local stream incision. These features rise with low- to moderate gradients from valley floors to mid-slopes. Their smooth upper slopes contrast with the irregular nature of steeply inclined flanking terrain. Areas of this unit are also common on the lower crests of spurs flanking the Brockman Valley, and on rises and low hills set out from the range front which in such situations can have steep irregular slopes, *i.e.* unit **hdErv**. The unit **hDhg** therefore often appears to reflect a prior condition of the range front or valley side.

3.4 Regolith Pattern Development

The regional regolith patterns owe many of their characteristics to an ancient stable landscape and its modification by landform processes. Maps of this area show scattered remnants of the deep mantle, such as in unit **fRg**, commonly flanked by erosional terrain and occupying the less elevated parts of the landscape such as the Nammuldi Plain. In contrast, on the slopes of the range fronts and valleys within the ranges, remnants of the deep mantle extend up from valley floors to mid-slope positions along smooth gently concave slope elements. These are typically protected by canga developed in colluvium, and form substrates to unit **hDhg**. The patchy distribution of these materials, and their juxtaposition with erosional terrain is interpreted as being indicative of the previous great extent of the mantle.

It is argued in this report that debris, generated by dismemberment of the weathered surface on the Hamersley Group BIFs, contributed significantly to the detritus in the adjacent valley floors: the mature detritus was sourced largely from hematised upper parts of the weathered zone; after this zone was removed, exposed BIF has contributed to the immature detritus. These materials form the bulk beneath the unit **hDrhgf** as well as units **hDrhgif** and **hDrhgap**, these last two being relatively surficially modified variations of the first. This late sedimentary modification of these deposits suggests greater fluvial action on the valley floor, possibly the consequence of climatic fluctuation through its effect on fluvial dynamics. Although this may be the case for the complex open systems within the ranges, for the more protected environments of such as the Brockman Valley, incision and surficial modification is dependent also on the development of neighbouring catchments breaching the Marra Mamba ridge and accessing part of the Brockman Valley drainage. An adequate assessment of the role of climate in the evolution of the deposits is not possible here, but it is clear that consideration must be given to the effect of other factors such as geomorphology (*Section 7.4.1*).

Depositional systems developed on the Fortescue Group rocks are represented by two major mapping units. Unit **fDhg** comprises scattered mesas with crests of weathered indurated crusts overlying truncated laterite weathering profiles. These have been interpreted as being relics of a once more extensive depositional plain and are currently being replaced by extensive erosional tracts. Unit **fDra** comprises extensive plains in the eastern part of the Nammuldi Plain. This unit appears to be younger than unit **fDhg**, in that it is set slightly lower in the landscape. Nevertheless, both units have been subject to erosion since this process became more dominant over deposition.

It is clear that there has been some considerable modification of the original landscape along the range front and steep valley sides, where unit **hDhg** occurs as canga-encrusted low hills set-out from zones of active erosion. There has also been widespread modification of regolith on the Fortescue Group, notwithstanding the relatively low relief. Whereas in areas of the Hamersley Group, much of the debris has been deposited close to the erosion scars, over the Fortescue Group much of the sediment released by erosion has been removed by a complex system of channels. This might in part be related to lithological differences between the two groups, with argillaceous rocks of the Fortescue Group yielding relatively more mobile fine-grained sediments in comparison with the coarse-grained debris from the BIFs of the Hamersley Group.

4 MINERALISATION: PROCESS AND GEOLOGICAL SETTING

4.1 Introduction

This section presents the results of the petrographic and chemical analyses. The texture, mineralogy and chemical composition of samples of all classes is summarised, and the variety and order of mineral transformations has been interpreted from this evidence.

This interpretation is then examined in conjunction with the field evidence of the distribution and location of mineralised material, and a model for the geological setting of mineralisation is proposed.

4.1.1 Sample Analysis

Forty hand specimens have been sectioned and described, and analysed by XRD and XRF. Petrographic descriptions and photomicrographs of each sample are presented in Appendix 2. Analytical results, including hand specimen classification, mineralogy and major and selected minor and trace element concentrations, are presented in Table 2. This table is given in a form which has been sorted on Al concentration.

Four samples have been analysed by electron microprobe for variations in the distribution of Fe, Al and P. Typical results from the transects are presented below (Fig. 33). One sample was mapped for Fe, Si, Al, P, Zr, Ti and Y distribution (Fig. 34).

4.2 Petrography

Samples have been examined in polished section. They are classified on the basis of their geomorphological and geological setting, and their composition and texture (Appendix 2). Comparative study of the illustrations allows a number of generalisations to be made about the evolution of the samples. Where relevant, specific samples are identified and given App. 2 page numbers (*e.g.* Sample 21/8/95/3, A2.3).

4.2.1 In Situ *Material*

Part mineralised BIF typically comprises interlaminated hematitic and siliceous layers (21/8/95/3, A2.5). Hematite crystals are rich in goethite inclusions. Siliceous material is partly ferruginised, and may vary from translucent masses to finely crystalline material separated by goethite partings (29/8/95/4A, A2.3), depending on degree of alteration.

Mineralised BIF comprises interlaminated hematite and goethite. Some samples have a similar appearance to part mineralised BIF, but the XRF analyses reveal a reduction in Si concentrations from >45% to 1-3%, indicating that the siliceous laminae have been altered to goethite. Removal of Si has reduced *in situ* rock density, resulting in the development of a variety of solution fabrics. These include vugs, internal sediment, faults, differential collapse structures and stylolites.

Vugs are commonly lined with goethite fringe cements (15/8/95/2, A2.18) and may be filled with chert. Internal sediment, derived from collapse of unsupported material into underlying pores, may be identified by disruption and dislocation of laminae (15/8/95/11, A2.21). This sample also has poorly developed stylolites. Faults and fractures in the BIF

Sample number	Location	Material	Clasts	Matrix	XRD Whole Rock Mineralogy	XRD Resistate Mineralogy	Fe2O3	SiO2	Al2O3	P2O5	TiO2	Zr	OXIDES	TotalTr	loi	Si:Al
							%	%	%	%	%	ppm	%	ppm	1050	
21/8/95/3	Sheila	BIF (altered)			q, h, g		51.84	46.77	0.27	0.015	0.02	0.1	99	405	1.88	173.22
14/8/95/2	B2Bdd	Mnlsd BIF			h, g		94.41	0.63	0.33	0.223	0.02	9	95.7	109	2.73	1.90
15/8/95/3	BR NE	Mnlsd BIF			h, g		92.64	1.30	0.53	0.454	0.01	19	95.1	608	4.44	2.47
8/6/95/1	BR NE	Mnlsd BIF			h, g		91.75	1.75	0.60	0.149	0.03	15	94.4	318	5.05	2.90
29/8/95/4	Hugh Bluff	Imm detrit	BIF	goeth csf	q, h, tr g		51.65	47.28	0.66	0.034	0.02	9	99.7	141	1.28	71.64
14/8/95/4	B2Bdd	Mnlsd BIF			g, h		90.54	1.11	0.68	0.133	0.01	3	92.6	1179	6.41	1.64
16/8/95/4	BR ext	Mnlsd BIF (fault)			g/h		90.20	1.43	0.68	0.273	0.02	12	92.7	123	6.45	2.10
ACC276	R P Gorge	Mnlsd BIF			h, g		94.26	1.12	0.71	0.111	0.03	0.1	96.4	286	2.49	1.58
15/8/95/4	BR NE	Mnlsd BIF			h/g		91.95	1.48	0.72	0.206	0.03	18	94.5	483	4.33	2.05
14/6/95/3	BR NE	Mnlsd BIF			g, h		86.42	2.52	0.79	0.271	0.04	29	90.2	1098	9.67	3.19
15/8/95/12	BR NW	Mnlsd BIF			h, g, tr smec(?)		91.17	2.50	0.80	0.224	0.02	21	94.8	281	4.51	3.14
16/8/95/11	BR SE	Mnlsd BIF			h, g, tr smec(?)		90.79	1.66	0.80	0.180	0.02	13	93.5	358	4.71	2.07
14/8/95/5	B2Bdd	Mnlsd BIF			h, g		91.16	1.81	0.91	0.082	0.11	17	94.2	681	5.27	1.99
15/8/95/10	BR NW	Canga	Mnlsd BIF, pis	goeth	h, g		89.91	2.04	1.00	0.085	0.03	9	93.2	663	5.70	2.05
21/6/95/1	BR NE	Mnlsd BIF			g, h		87.84	2.06	1.08	0.171	0.01	35	91.2	722	8.22	1.92
24/11/95/3	Jeerinah	Mnlsd BIF (?)	Mnlsd BIF, pis, oth	goeth	g, h, tr q, parag(?)		87.56	2.35	1.08	0.353	0.64	61	92.2	1302	6.48	2.18
15/8/95/11	BR NW	Mnlsd BIF			h, tr clay (smec?)		91.21	5.08	1.23	0.145	0.03	11	97.8	968	1.42	4.14
16/8/95/6	BR ext	Mnlsd BIF (?)		goeth	g, h		86.81	0.73	1.34	0.195	0.08	14	89.3	1189	9.50	0.55
15/8/95/2	BR NE	Mnlsd BIF			h, g		86.58	4.06	1.42	0.114	0.01	21	92.6	3747	6.44	2.86
7/6/95/4	BS2D	Mat detrit	Pis, Mnlsd BIF		h, tr g		95.39	0.63	1.49	0.142	0.34	43	98.1	426	1.87	0.42
9/6/95/2	BR SE	Canga	Mnlsd BIF, others	goeth	h, g	rutile anatase	91.03	1.50	1.53	0.147	1.28	129	95.5	1124	4.19	0.98
24/8/95/4	Pylon rd	Mnlsd BIF			g, tr h, q		80.39	4.22	1.71	0.657	0.19	13	87.4	1076		2.47
16/8/95/5	BR ext	Canga	Mnlsd BIF, other	goeth	g, tr smec(?)		92.35	2.20	1.72	0.461	0.52	26	97.5	672	1.39	1.28
16/8/95/10	BR SE	Mnlsd BIF			h,g		88.03	1.58	1.81	0.321	0.33	104	92.1	1053		0.87
24/11/95/4	Jeerinah	Mnlsd BIF			h, g, parag(?)		88.52	2.91	1.9	0.257	0.11	32	93.8	506	5.43	1.53
15/8/95/13	BR NW	Canga	Other, BIF	goeth	h, g, tr q, pos smec		89.55	1.46	1.95	0.152	0.20	45	93.4	1148	6.07	0.75
3/6/95/5	BS2D	Canga+cement	Pis, Mnlsd BIF	goeth	h, g, pos smec		90.38	1.60	2.31	0.134	0.43	63	95.0	805	4.35	0.69
28/8/95/2	Sheila	Canga	Mnlsd BIF, other	goeth	h, g, tr q, pos smec		89.17	3.10	2.81	0.131	0.43	80	95.7	611	3.18	1.10
3/6/95/1	BS2D	Canga clast	Mnlsd BIF	goeth	h,g,tr q		86.27	3.08	3.44	0.066	0.32	79	93.3	669	6.24	0.90
27/8/95/3	Sheila	Mat detrit	Pis, mnlsd BIF		h, tr q, pos g		90.28	2.45	3.72	0.087	0.46	89	97.1	448	1.7	0.66
2/6/95/2	BS2D	Mat detrit	Pis, Mnlsd BIF		h, pos tr mica		88.66	4.61	3.85	0.135	0.25	72	97.8	337	1.9	1.20
24/11/95/1	R P Gorge	Canga (csf matrix)	Pis, oth, mnlsd BIF	goeth csf	g, h, q		77.42	4.09	6.43	0.126	0.79	121	89	2181	10.52	0.64
23/8/85/1	Railway	Canga (csf matrix)	Polynuc	goeth csf	g, h, pos tr mag		74.33	8.64	7.74	0.056	0.39	85	91.5	729	9.11	1.12
29/8/95/3	Hugh Bluff	Mat detrit	Mnlsd BIF, pis		h, tr q		79.42	9.83	7.78	0.059	0.51	168	97.7	760	2.53	1.26
ACC277	R P Gorge	Imm detrit	Hem, BIF	goeth csf	q, h, g, kao		44.51	39.11	9.82	0.118	0.61	166	94.9	1276	5.47	3.98
24/11/95/2	R P Gorge	Canga (csf matrix)	Pis, minlsd BIF, BIF	goeth csf	h, g, q, kao	qtz, kao, anatase, rutile, prob zircon	69.06	11.5	11.64	0.071	0.98	218	93.5	1211	6.56	0.99
9/6/95/1	BR SE	Imm detrit	BIF	goeth csf	q, h, g, kao, pos tr halloy, smec		25.39	54.3	12.34	0.083	0.57	128	94.2	1194	6.15	4.40
29/8/95/2	Hugh Bluff	Canga (csf matrix)	Mnlsd BIF, pis	goeth csf	h, g, tr pos kao or chl	anatase, kao, pos zircon	70.09	9.34	12.39	0.043	0.72	181	92.7	986	7.64	0.75
29/8/95/1	Hugh Bluff	Weath McRae Shale	Pis		h, g, tr kao	qtz, kao, anatase, prob zircon	66.54	10.54	12.71	0.051	0.92	201	90.9	1983	9.78	0.83
ACC275	Hugh Bluff	Weath McRae Shale	Pis	goeth csf	g, h, magnetite(?) maghem(?) kao		55.3	14.06	17.74	0.089	0.59	157	87.9	1277	12.53	0.79

Table 2. Analytical results from a suite of *in situ* and transported samples from the study areas. The table includes hand specimen classification, mineralogy and major and selected minor and trace element concentrations. These data have been sorted on Al concentration, which gives good differentiation between genetic and depositional types. Petrographic descriptions and photomicrographs of these samples are presented in Appendix 2.

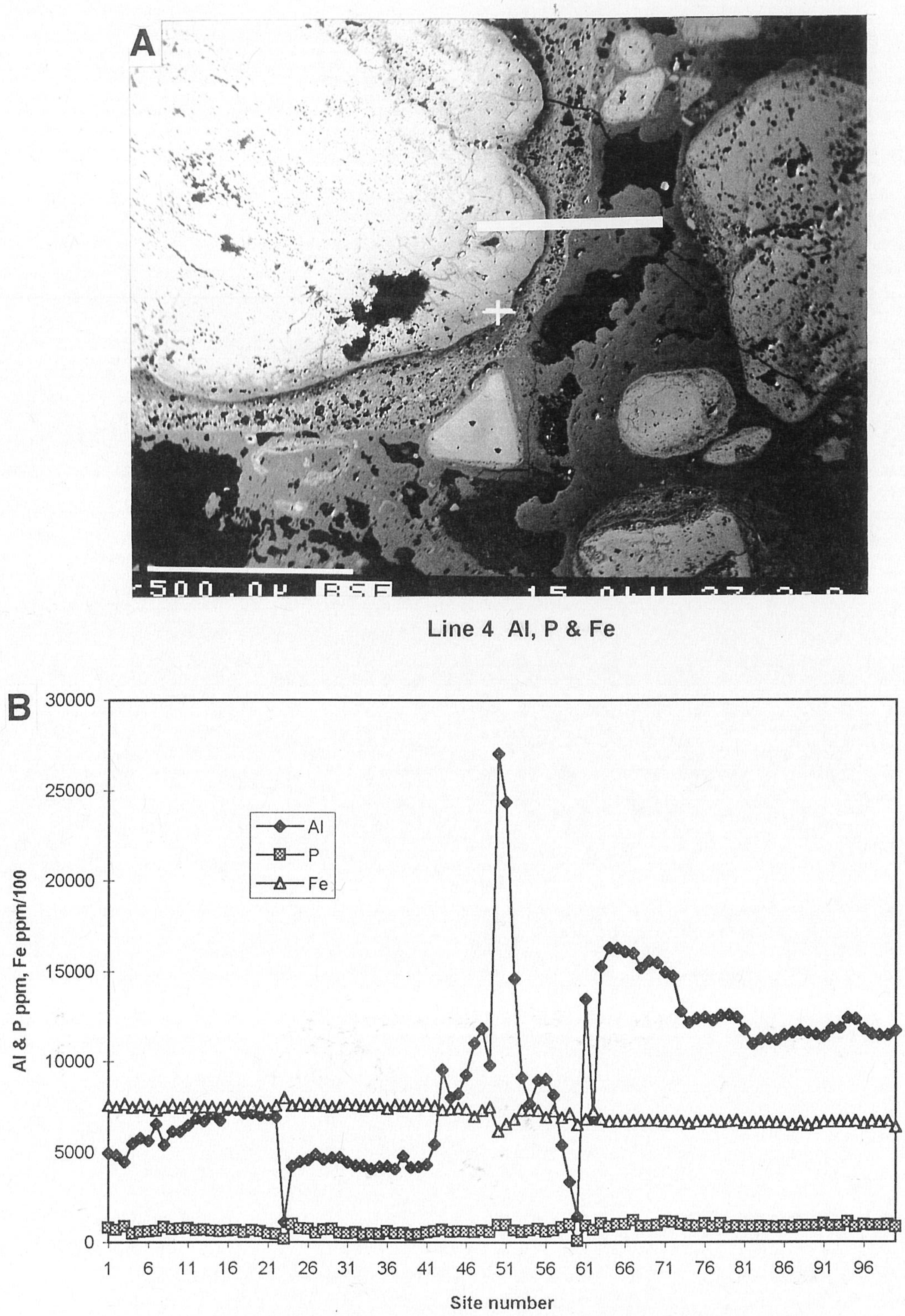


Figure 33. (A) SEM photomicrograph showing path of probe. 100 points were analysed over a distance of about 0.5 mm. The path runs from hematised BIF (left) across an accretionary layer and on to vitreous goethite cement. (B) Results from traverse showing distribution of Al, P & Fe. Al concentration is generally low in altered BIF, peaks markedly in the accretionary layer, and is relatively stable but high in the vitreous goethite cement. P concentration remains below 800 ppm in altered BIF, and most of the accretionary layer, rising to greater than 800 ppm towards the edge, and across the goethite. Fe concentration forms two relatively stable plateaux, being lower in the vitreous goethite, although an antithetic relationship with Al give minor variation. Fe concentration is divided by 100 to bring it into scale.

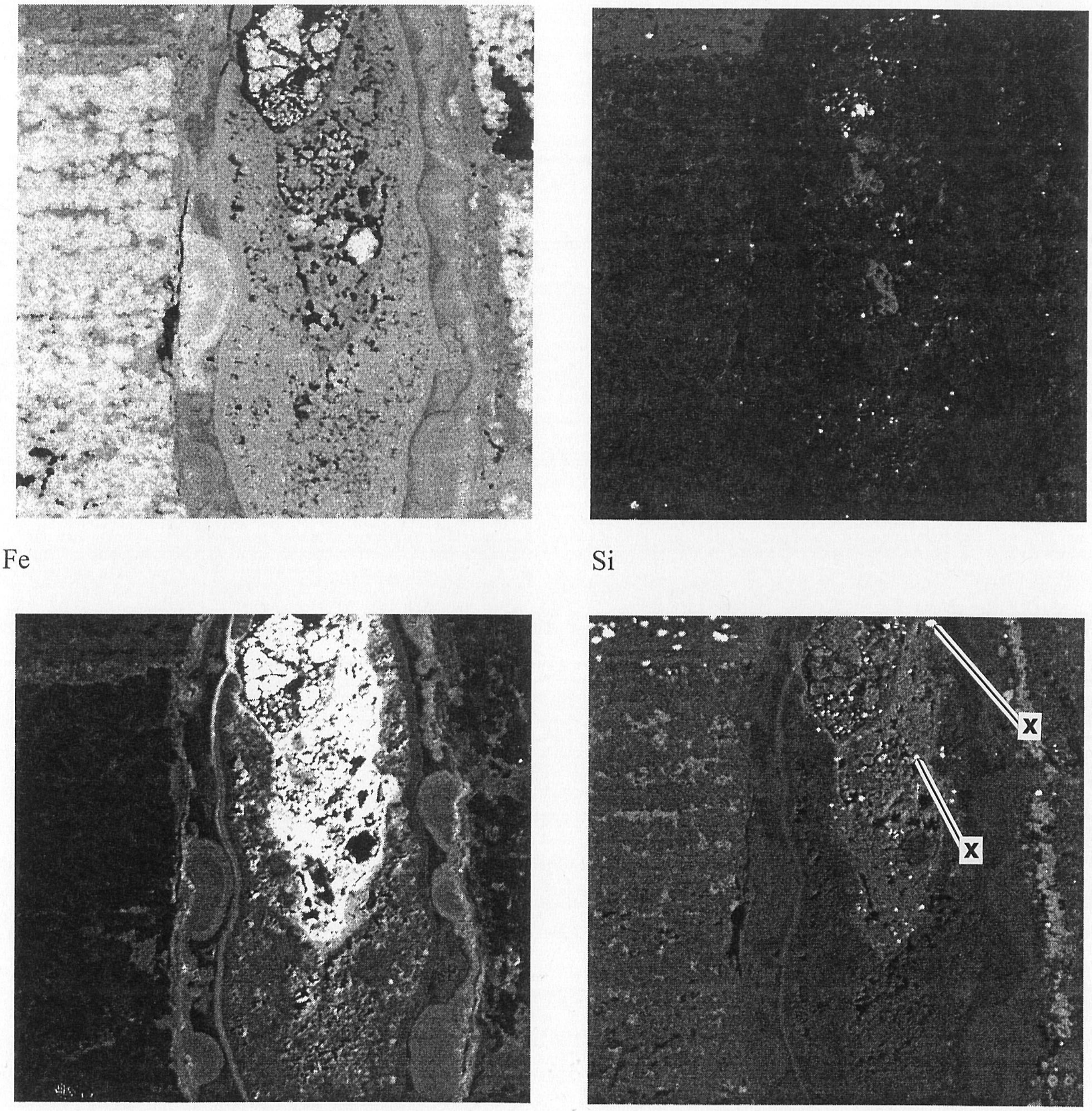


Figure 34. Maps from electron microprobe analyses of weathered/mineralised BIF, goethite cement and fracture filling sediment. Mapped elements are: Fe, Si, Al, P, Zr, Ti and Y. Brighter areas indicate relatively higher concentrations. Fe shows greatest concentration in hematite. Darker grey areas are goethite cement and sediment. Si shows as discrete silicate grains, mostly concentrated in the sediment. Diffuse silica at top left is concentrated in the upper part of a goethite lamina. Al concentration is inverse of Fe, being most concentrated in sediment, and with lowest values recorded from the hematite. P is diffusely but selectively distributed in goethite cement, and sediment. Bright areas are P-rich minerals, including xenotime (X).

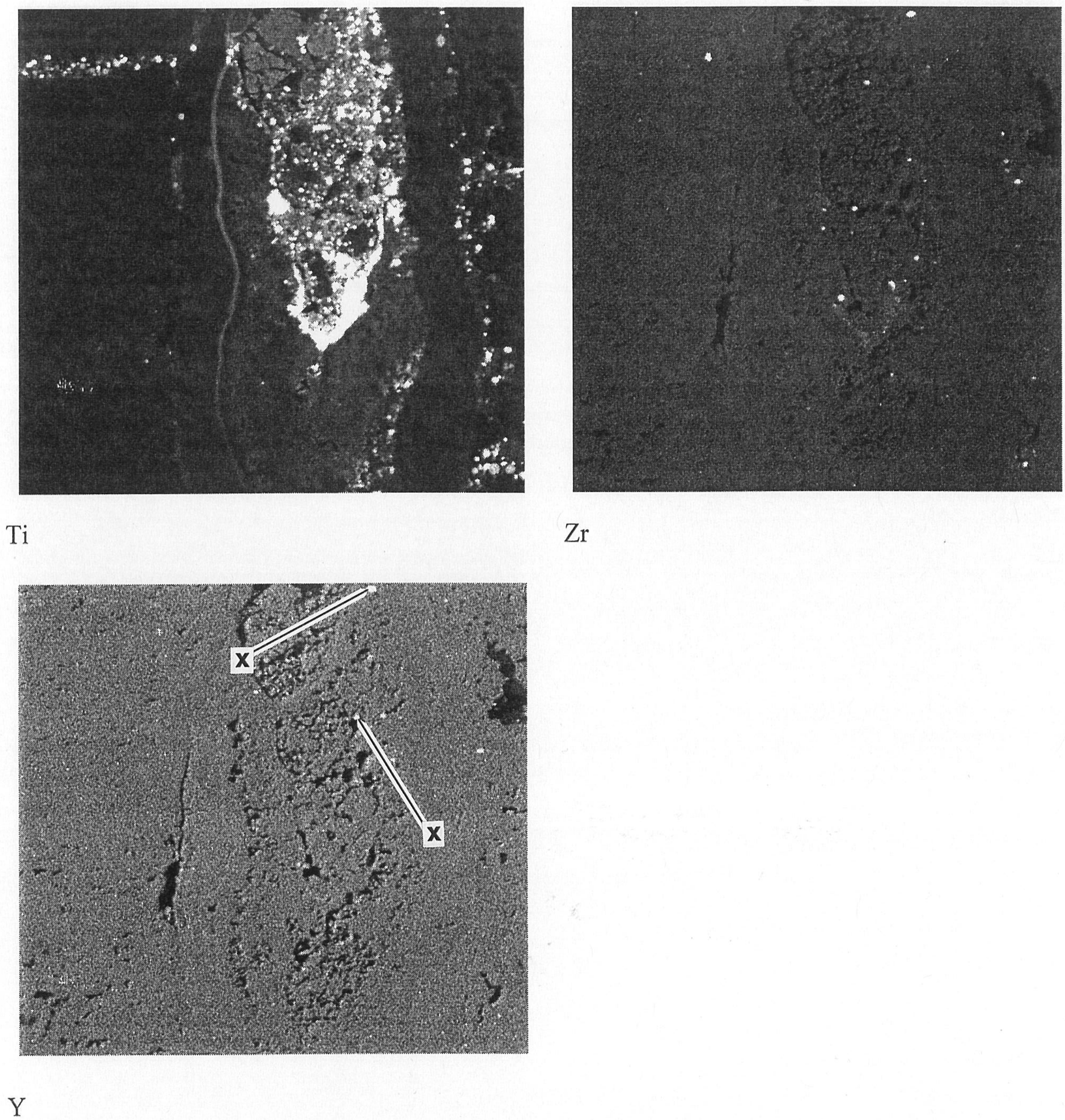


Figure 34. **(continued)** Ti shows very strong concentration in sediment and as discrete grains trapped in goethite cement. The grains are mainly rutile and ilmenite. Zr shows the distribution of discrete detrital zircon grains. Y map (measured as P background intensity) shows bright spots of probable xenotime grains, including some with no Zr response (X).

fabric are also sites for differential collapse (15/8/95/12, A2.12) and localised goethite precipitation (14/8/95/4, A2.22).

Favoured sites of hematite precipitation include the crystal boundaries where hematite laminae are in contact with goethite laminae (15/8/95/3, A2.7; 15/8/95/12, A2.11). Isolated hematite crystals supported in goethite laminae are commonly corroded (8/6/95/1, A2.19; 24/11/95/4, A2.16). With sufficient time, Si removal and re-distribution of Fe from goethite to hematite may result in total loss of both initial fabric and intermediate mineralogy (24/8/95/4, A2.26; ACC276, A2.27).

A single sample from Brockman 2 Bedded mineralisation (14/8/95/4, A2.24) contains microplaty hematite, has preferred orientation of platy clasts, and an interlocking crystal mosaic texture. This is interpreted as recording a metamorphic event.

4.2.2 Mature Detritus

Clasts in mature detritus and transported cangas are essentially similar in their range of origin and composition. Clasts may be mineralised BIF, wood fragments, of composite or of indeterminate origin. Clasts are commonly coated with hematite or goethite cements of variable thickness and preservation. In cangas, these clasts are cemented by goethite.

Mineralised clasts mostly comprise hematite, but some are goethitic. In mineralised BIF fragments, diagnostic laminae are preserved as lines of pores and/or goethite inclusions in a hematite matrix. Boundaries between clasts and overlying cements may be sharp (3/6/95/5, A2.37) or gradational (16/8/95/5, A2.42). The latter has a laminated goethitic core which merges into a structureless but desiccation-fractured hematite rim.

Wood fragments (16/8/95/5, A2.42; 23/8/95/1, A2.32) are preserved by replacement of plant tissue by iron oxide. Pores may be filled with chert or goethitic clay, or be empty. Indeterminate cores are typically fractured but otherwise featureless hematite (7/6/95/4, A2.31), similar in appearance to the desiccating goethite rim of the BIF clast in 16/8/95/5 (A2.42). Composite clasts may contain any combination of clasts and (typically) hematite cement.

4.2.3 Immature Detritus, Tertiary Pisolite, Other Ferruginous Crusts

The immature detritus samples are matrix supported pebbly conglomerates. Clasts vary in texture from angular to rounded and in composition from hematite to BIF. Matrices are dominated by clay size-fraction goethite, and clay minerals including kaolinite and smectite. Samples are mottled red/brown and are moderately indurated with ferruginous cements and chert.

Tertiary pisolite comprises poorly indurated mixtures of hematite and goethite clasts in clay size-fraction goethite cements. Clasts are typically coated, and cores include mineralised wood, indeterminate grains and probable mineralised BIF (HMC29, A2.56).

Ferruginous crusts have been also been developed on the non-BIF substrates of the Wittenoom Dolomite, McRae Shale *etc.*. These crusts commonly contain clastic components in a goethitic matrix, and are poorly to moderately goethite cemented. They differ from immature detritus by having locally well developed multiple skins on some clasts, and containing numerous mineralised clasts which have undergone several cycles of cementation and mobilisation.

4.3 XRD and XRF Analyses

Results are presented in Table 2. The XRD shows mineralogies to be dominated by hematite, goethite and quartz. Clay minerals identified include kaolinite, smectite and possible halloysite. Rutile, anatase and zircons were identified in the resistate from an Fe digestion.

The cross-plot of Si *versus* Al (Fig. 35) shows a nearly 1:1 relationship (except for the Si-rich BIF samples), indicating that Al is present in the form of clay minerals (kaolinite and smectite, Table 2). Clays may have been introduced by mixing during transport, by infiltration, or be *in situ* where samples were derived from weathered shales. The last give the highest concentrations of Al. Sorting the data with respect to Al concentration differentiates between samples which are interpreted to have been mineralised *in situ*, mature detritus and canga, and mixed detritus with microcrystalline goethite and clay matrix. This relationship is clearly demonstrated when Al concentration is plotted against Zr concentration (Fig. 36). If the Al concentration increases as a result of increase in clay content, then the positive correlation with Zr concentration indicates that detrital zircons are being introduced with the clays, and that the shales may be the source of detrital zircons.

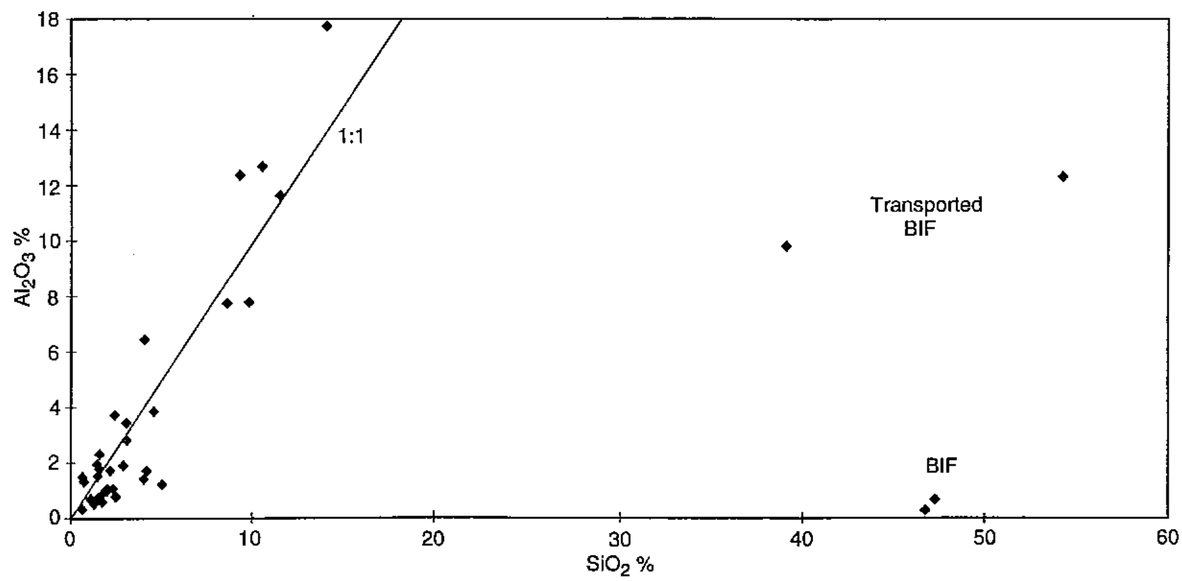


Figure 35. Cross-plot of Si *versus* Al showing a nearly 1:1 relationship, except for the Si-rich BIF samples.

The mixing trend of clays with mineralised material is illustrated in Figure 36, where *in situ* mineralised BIF (except sample 16/8/95/10) plots in the area below 50 ppm Zr. Transported material with crystalline goethite matrix (canga) plots above 50 ppm Zr and below 5% Al. Transported material with clay size-fraction goethite matrix has greater than 6% Al. These data mainly fall on the line which describes the mixing of clay with mineralised BIF.

The two samples (16/8/95/10 & 9/6/95/2) which lie above the clay-mixing line of Fig. 36 and have relatively low (around 2%) Al concentrations are mineralised BIF (**b**) and canga (**c**) from the south-eastern side of the Brockman Range (**c**). The mineralised BIF sample is discussed in greater detail below. Relative depletion in Al in the canga may be related to the pattern of cementation seen in polished section. The earlier cement generation comprises kenomagnetite, which may have formed by reduction and dehydration of goethite. If so, Al may have been expelled along with the water from the goethite.

Transported/mixed samples cannot be geochemically differentiated from weathered *in situ* samples derived from shale units (sample ACC275) or weathered BIF samples interpreted to have been subject to vertical mixing in the weathering profile (sample 29/8/95/1).

The results of XRD analysis of the resistate from sample digestions show a heavy mineral assemblage of rutile, ilmenite(?) and zircons. When Ti is plotted against Al (Fig. 37) a similar relationship to Zr:Al (Fig. 36) is seen, although the separation between *in situ* and transported material and their sub-sets are not so well illustrated. No apatite has been identified in any sample.

4.4 Microprobe Analyses

Sample 16/8/95/10 (A2.25) comprises a specimen of hematite/goethite mineralised BIF collected from *in situ* on the SE margin of the Brockman area. Fractures in the sample are lined by a series of crystalline goethite cement phases, with the remaining voids part-filled with cement and sediment Fig. 38). The area of Figure 38, including all of these phases has been geochemically mapped for Fe, Si, Al, P, Zr, Ti and Y, using the electron microprobe (Fig. 34).

The highest Fe concentrations (brightest) are seen in the hematite of the mineralised BIF (left). The darker areas are goethite seen as laminae within the altered BIF, and cement and sediment. Al concentrations are the inverse of Fe, being most highly concentrated in the sediment, present in the goethite and having lowest values in the hematite.

In general, P follows Al, being variably present in goethite and absent from hematite. Some Al-rich goethite (*e.g.* laminae in BIF and botryoidal cement) is relatively depleted in P. The goethite lamination at top left contains a diffuse occurrence of P. This lamination is chemically segregated into an upper zone of relative Si enrichment with patchy P concentrations, and a lower zone of relative Al enrichment and zircon, rutile and ilmenite concentration.

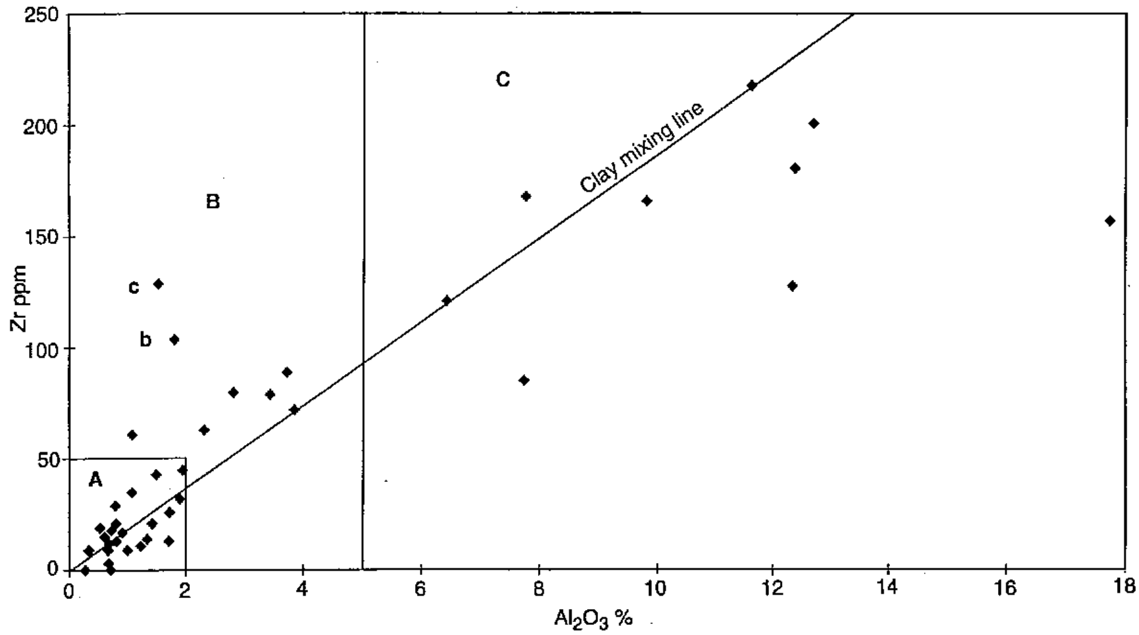


Figure 36. Cross-plot of Al *versus* Zr concentration showing the mixing trend of clays with mineralised material. *In situ* mineralised BIF plots in area A (<50ppm Zr & <2%Al). Transported material with crystalline goethite matrix (canga) plot in area B (>40ppm Zr & <5% Al). Transported material with clay size-fraction goethite matrix (area C) has >6% Al. Samples (b) and (c) are mineralised BIF and canga, respectively.

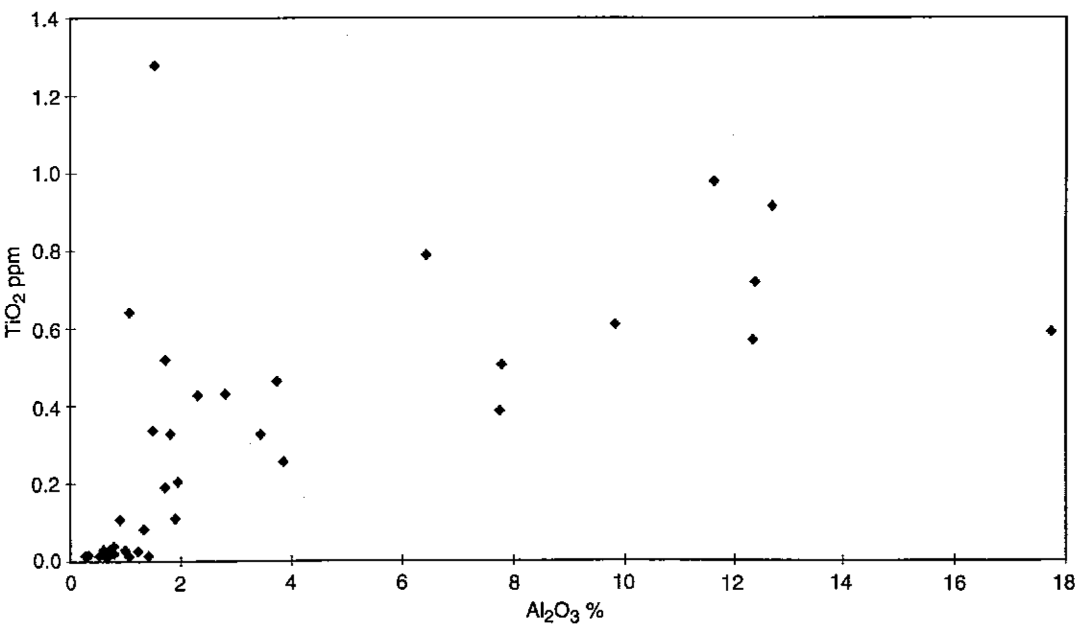


Figure 37. Cross-plot of Ti:Al showing a similar relationship to Zr:Al (Fig 46), although the separation between in situ and transported material and their sub-sets are not so well illustrated.

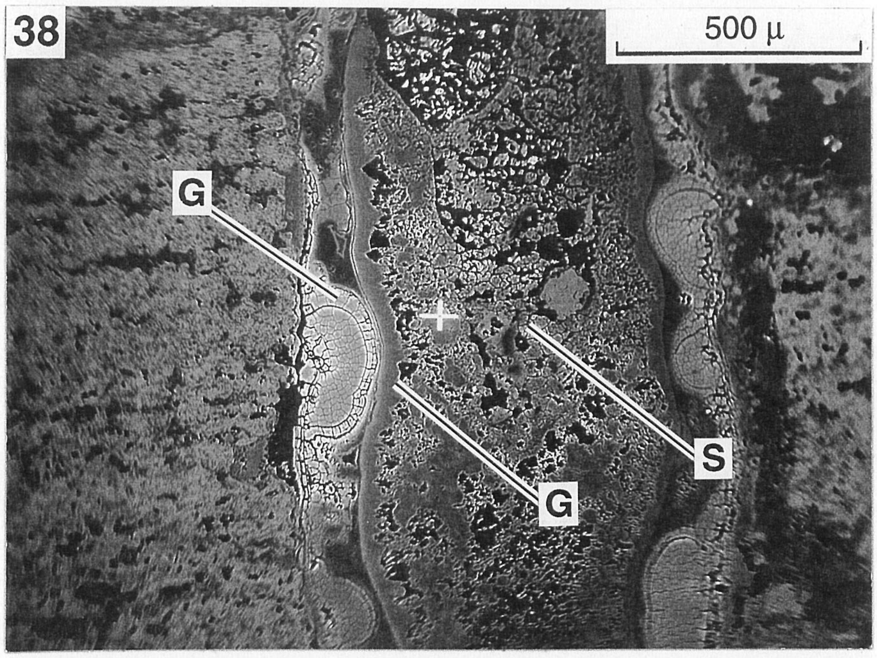


Figure 38. Scanning electron photomicrograph of the area of microprobe analysis. Image shows vertical fracture through horizontal laminae of mineralised BIF. Fracture is lined with goethite cement (G) and filled with a combination of cement and sediment (S). The bright area of goethite cement (centre) shows a fracture pattern developed during the analytical programme. Scale bar is 500µ long. Field of view about 1.5mm wide.

The bright grains in the sediment fill and in the vertical line of cement (right) comprise xenotime (YPO_4). Xenotime has an isostructural relationship with zircon, and the two minerals are commonly reported together (Deer *et al.* 1978). The xenotime grain identified here has been imaged and analysed with the microprobe (Fig. 39). The image shows a bright grain comprising a core and outer coating separated by a dark inner coat. The core and outer coat are relatively enriched in Zr and P, respectively (Fig. 39B & C). The outer coat has euhedral crystal terminations, typical of authigenic phases. On that basis, this grain is interpreted as an authigenic xenotime overgrowth developed on a detrital zircon. No apatite has been identified.

Detrital zircons, ilmenite and rutile grains are present in the fracture filling cement and sediment. Titanium is also diffused through some goethite cement phases.

Microprobe transects have been run across three other samples, all classified as canga. These transects cross detrital clasts (mineralised BIF, pisoliths and indeterminate hematite and goethite), authigenic cements and fine sediment fill (Fig. 33). The results show essentially the same distribution of elements as the maps of sample 16/8/95/10 (Fig. 34). From this it is concluded that except for zirconium, minor and trace elements from the suite analysed are generally present as diffuse components of crystalline goethite and particularly associated with detrital goethite and clays. These elements may also be present as discrete detrital grains. Zirconium has only been detected as discrete detrital zircon grains.

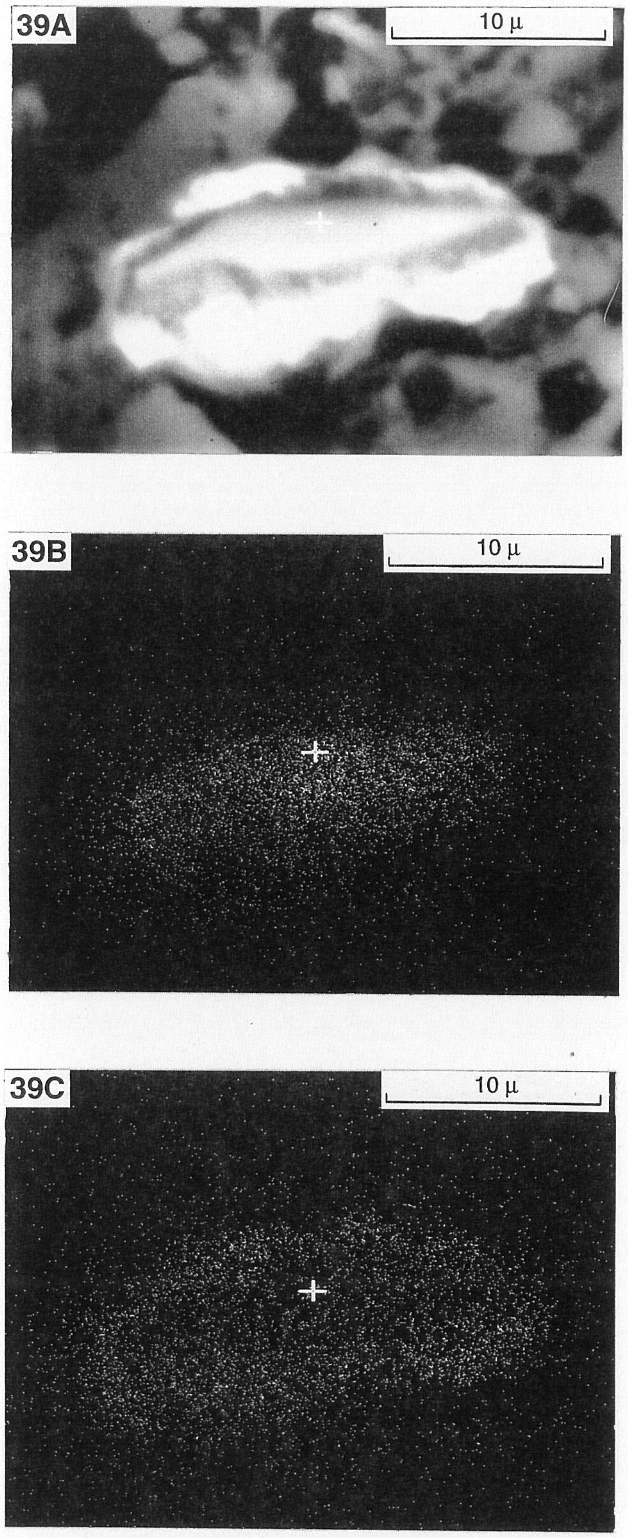


Figure 39. (A) Scanning Electron photomicrographs of detrital zircon grain comprising zircon core with dark inner coat and bright xenotime (YPO_4) outer coat. Euhedral crystal termination along top edge of grain (outgrowth) is typical of authigenic overgrowths. Scale bar is 10μ long.

(B) Microprobe map of Zr concentration showing enrichment in the area of the central grain.

(C) Microprobe map of P concentration showing enrichment in the area of the xenotime (YPO_4) overgrowth.

4.5 Mineralisation: Interpretation

The petrographic evidence and geochemical data indicate that the dominant process in mineralisation of BIF was a progressive loss of Si, leading to collapse and ultimately, a complete restructuring of the parent BIF texture. Local re-distribution of Fe is also apparent, although whether this was accompanied by a net gain from external sources is unclear.
The earliest steps in the mineralisation process included alteration of the ferruginous and carbonate components of BIF to goethite, and then to hematite, resulting in the common preservation of goethite inclusions. Alteration of the ferruginous BIF components to hematite preceded significant loss of Si from the non-ferruginous silicate components.

Alteration of the non-ferruginous silicate components appears to have proceeded by loss of Si accompanied by replacement with goethite. Goethite at the boundaries with hematite layers was subject to dissolution and re-precipitation as hematite overgrowths. Elsewhere, conversion of goethite to hematite proceeded *via* intermediate steps of crystal ordering and expulsion of exotic cations, and dehydration.

Hematite crystals (typically carbonate pseudomorphs) in non-ferruginous silicate layers may have been deposited as autochthonous sediment in pores or aggregations formed when the Si was lost and the layers deflated. Some of these hematite crystal have been subject to reversion to crystalline goethite. Acicular crystalline goethite precipitated directly in free pore space, where some areas are seen to have been subject to re-ordering to more blocky crystals, and thence by dehydration to hematite.

Mineralised BIF clasts in mature detritus and canga are closest in composition with the most fully mineralised *in situ* samples (*e.g.* 16/8/95/10, A2.25). Polynuclear clasts commonly have hematite cements, including those in goethite cemented canga. These textural and mineralogical relationships are interpreted as indicating that mineralisation has typically gone further to conclusion in mature detritus than in modern outcrops of weathered *in situ* material.

4.6 Geological Setting

The potential geological settings where mineralisation may have occurred are examined here, in relation to the setting and distribution of mineralised material in the study areas. Three possible settings for mineralisation are:

1) bedded mineralisation (and its weathering products)
2) post-erosional mineralisation,
3) mineralisation by surface weathering of BIF units.

Direct evidence for 1) is provided by the presence of the Brockman-2 bedded mineralisation, as well as numerous smaller pods of mineralised BIF in the area. The development of canga provides the best evidence for 2), post-depositional alteration of sediments. However, alteration in cangas is restricted to the precipitation of goethite cements. There is no evidence to suggest that there has been significant alteration of siliceous clasts to hematite. We argue, below that the evidence supports our thesis 3): that BIF has been altered by weathering to laminated hematite and goethite, without necessarily being subject to an intermediate bedded mineralisation/enrichment phase.

4.6.1 Bedded Mineralisation

A supergene model to account for the formation of the majority of the world's ***in situ*** BIF-derived iron mineralisation was proposed by Morris (1985). The model requires reduced Fe to be transported in solution from the surface by percolating groundwater, and its precipitation at depth by oxidation. This results in the pseudomorphous replacement of BIF by goethite prior to partial dehydration to hematite/goethite. Morris considers that mineralisation grows upwards from below as erosion cuts down, and the process becomes one of weathering when the ground surface reaches the mineralisation.

Earlier formed (pre-Phanerozoic) iron mineralised deposits required burial for their preservation, with the resultant metamorphism causing dehydration of goethite to hematite. Morris considers microplaty hematite to be a particularly characteristic metamorphic alteration product of goethite. In contrast, more recently developed (Mesozoic) supergene mineralised bodies retain their initial metasomatic mineralogy of hematite and goethite.

Regardless of the mechanism and scale of formation, pods of mineralisation exposed at the Earth's surface will undoubtedly contribute mature detritus to sedimentary systems. The scale of that contribution and the distribution of its products are uncertain.

4.6.2 Surface Weathering of Bedded Mineralisation

A three-tiered weathering profile developed on non-metamorphosed (supergene) Brockman Iron Formation mineralisation was described by Morris (1994, fig. 4.7). The lowest horizon comprises high phosphorous martite/goethite mineralisation retaining the parent BIF structures. This horizon is overlain by 3-4 metres of aluminous goethite retaining no remnant of BIF related textures. Morris reports that in some areas (*e.g.* Marillana and Koodaideri) goethitic/hydrated zones may be as much as 75 metres thick. The topmost zone ("carapace") is up to 2 metres thick, is hematite-rich and retains BIF texture.

Morris attributes the conversion of martite/goethite mineralisation to hematite in the topmost zone to slow dehydration caused by lengthy exposure in the hot arid climate. He considers that the characteristically low phosphorous content of "carapace" results from this conversion. Hematite crystals have fewer sites for the retention of phosphorous than goethite, with expelled water (possibly bacterially mediated) carrying the excess away.

Explicit requirements for this model are: a) the presence of pre-existing mineralisation, and b) exposed bedding oriented sub-vertically to facilitate the penetration of ground water.

4.6.3 Post-Erosional Mineralisation

Detrital material has been examined for evidence of post-erosional mineralisation. Detrital hematite clasts in cangas commonly retain BIF textures and surface coatings indistinguishable from un-cemented mature detritus clasts. Both groups have clasts with hematite cores which fit the mineralised end-member category of a range of alteration which runs from un-mineralised BIF. These cores have goethite and hematite coatings and cements recording multiple phases of fracturing, transport and re-cementation.

Petrographic examination shows that cemented and un-cemented mineralised detrital clasts share a similar development history with mineralised *in situ* samples. Once liberated as sediment, these clasts were variably subject to storage, cementation, erosion and transport. The essential similarity between cemented and un-cemented clasts suggests that preservation as canga is a normal, if peripheral, stage in the sedimentary cycle. The common characteristic, that mineralisation is best developed in sediments, is likely to be due to a combination of both length of time exposed to mineralising conditions (including post-erosional alteration), and physical attrition. Post-erosional alteration includes precipitation of goethite cements, and dehydration of goethite to hematite. Physical attrition results in loss of goethite when clasts cleave preferentially along weak or brittle goethite planes. Goethite is then subject to removal as fines and clay size fraction material.

4.6.4 Surface Weathering Mineralisation of BIF

Weathered/ferruginised sections are preserved in the floors and sides of valleys of all study areas (see Section 2). The most complete weathered sections preserved on BIF units comprise hematite/goethite crusts overlying goethitic zones which pass down into less altered bedrock. Shale units show a similar arrangement, with hematite/goethite and goethitic zones, passing down through bleached zones into less weathered material. Eluvial processes may cause local mixing within the topmost weathered zones.

Some weathered outcrops in the Brockman area are developed on bedded mineralisation (*e.g.* Brockman 2 bedded), but no pods of bedded mineralisation have been identified by the authors in the Mount Sheila and Mount Margaret areas. Most weathered sections are developed directly on apparently un-mineralised material, or grade into un-mineralised material via a thin (less than 10 metres) partial alteration zone.

The degree of completeness preserved in weathered sections is uncertain. Soils are typically absent from valley sides and at high levels. Weathered zones in valley floors typically have lags of gravel to cobble sized mineralised clasts overlying clay-rich goethitic crusts. In both settings, erosion or deflation has left hematite-rich material exposed at the top of the most complete sections. It is reasonable to suppose that soils may have been developed and then stripped from weathered horizons. Soils may have been the sites for late-stage dehydration of goethite and early development of skins and cements.

4.7 Discussion

A model for the source of mature detritus must reconcile the following observations.

1) No bedded mineralisation has been identified at the Mount Sheila and Mount Margaret areas.
2) That weathered zones are preserved at all study areas.
3) That weathered BIF is enriched in hematite and depleted in silica.
4) That mature detritus is distributed throughout the study areas.
5) Mature detritus contains little or no un-mineralised BIF.

Our field observations (Section 2) show that bedded mineralisation of BIF is confined to the Brockman area, where occurrences are more deeply developed and more extensively mineralised than weathered zones on BIF. In comparison, relict weathered zones developed in basement are common throughout the study areas, although generally thinly developed and variable in degree of mineralisation.

Had discrete bodies of bedded mineralisation been the source of mature detritus at Mount Sheila and Mount Margaret, then some trace should have been preserved. Their absence suggests that primary mineralisation is not the principal source of mature detritus. The wide distribution of weathered zones supports our proposal (Section 8) that a regionally developed weathered mantle was the source of mature detritus, rather than numerous (hypothetical) bodies of bedded mineralisation which have now vanished.

The petrographic work and analytical data indicate that weathered BIF samples have undergone incongruent dissolution. Si has been lost, and Fe oxides have evolved from aluminous goethite towards hematite. Sequential replacement of ferruginous and siliceous BIF components has caused mineralised material to locally inherit the BIF laminae. Removal of Si has caused significant volume reduction in the weathering zone, resulting in deflation, fracturing and ultimately, brecciation of the mineralised BIF (Fig. 40). The chemistry of this weathering process is well established (*e.g.* Thomas, 1994, Krauskopf, 1979), and is effectively driven by the dis-equilibrium between meteoric water and substrate.

Mature detritus is widely distributed throughout the study areas, and typically contains little or no siliceous detritus. Sedimentary processes typically result in dispersion and mixing of clasts, although local concentrations do occur. Therefore, if the mature detritus was sourced from areas comprising both mineralised and un-mineralised BIF (*e.g.* bedded mineralisation surrounded by BIF), then the deposits would be dominated by mixtures (immature detritus) with rare pockets of hematite-rich sediments in locally favourable sites of concentration.

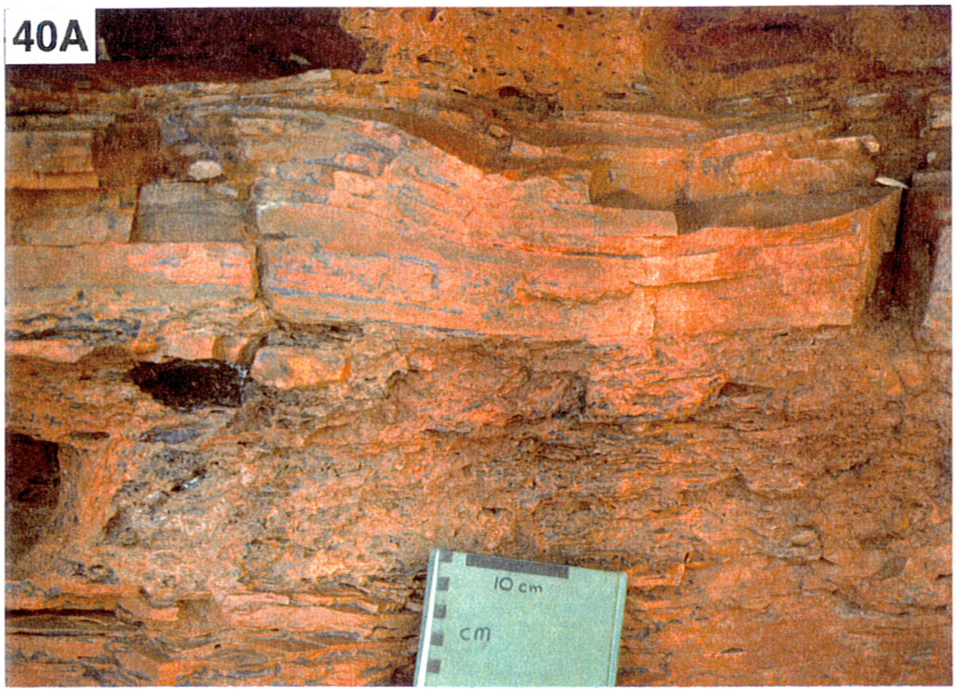
The almost total absence of siliceous material from the mature detritus indicates that BIF was not available for mobilisation in the period when the mature detritus was being deposited. In the absence of any evidence to support a major contribution from post-depositional alteration, then the primary source for mature detritus must have been geographically widespread.

4.8 Conclusions

That weathering processes were capable of converting BIF from silicate to hematite/ goethite without the need to for an intermediate stage of "bedded mineralisation" formation.

That the principal regional source of mature detritus was weathered BIF. Where catchments include bedded mineralisation, mineralised material must have been contributed from these sources.

That clasts and some cements in mature detritus are typically closer to end-member hematite mineralisation than *in situ* weathered hematite/goethite. This probably reflects a combination of residence time under mineralising conditions, and physical attrition during transport.



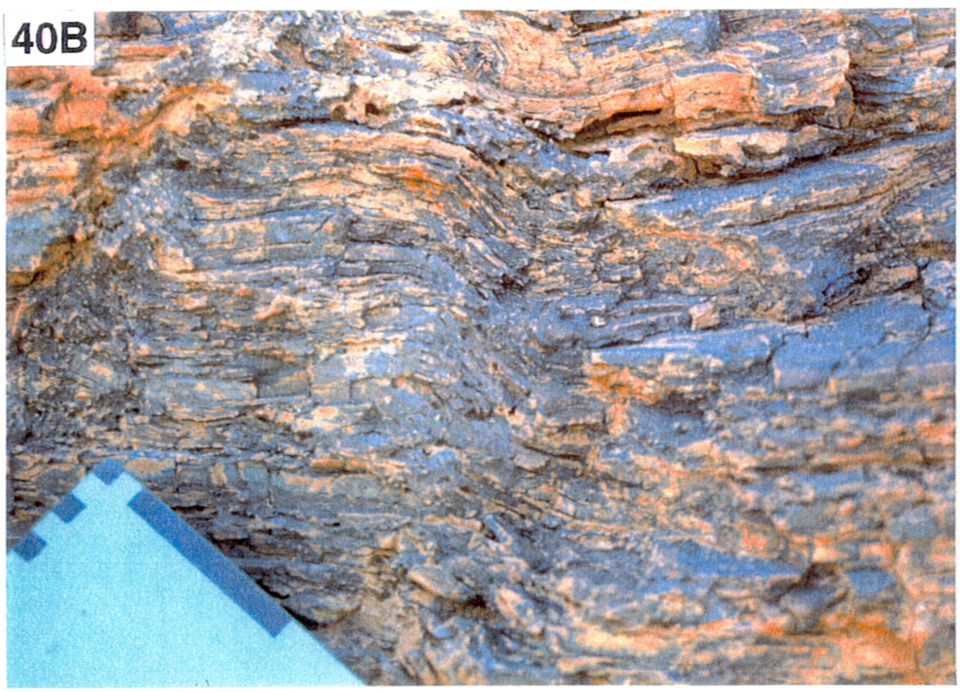


Figure 40. (A) BIF *in situ* interbedded with brecciated mineralised BIF. (B) Mineralised BIF folded and brecciated into centimetre-scale platy clasts.

5 SEDIMENTOLOGY

5.1 Introduction

Valleys in the three study areas contain variable thicknesses of sediment fill. These sediments commonly extend up the lower flanks of hills. Patches and thin veneers of sediment also fill pockets and bedrock depressions at higher levels. From a distance this tends to give a false impression of topographic smoothness to what in reality is generally rugged outcrop.

As a first approximation, valley sediments can be characterised as comprising a lower (mature) gravelly zone dominated by hematite clasts, overlain by an upper (immature) zone of fine goethite and detrital clays, mixed with clasts of hematite and BIF (Fig. 41). In detail, this pattern has been complicated by patchy deposition, mixing and partial erosion of sediments from both zones.

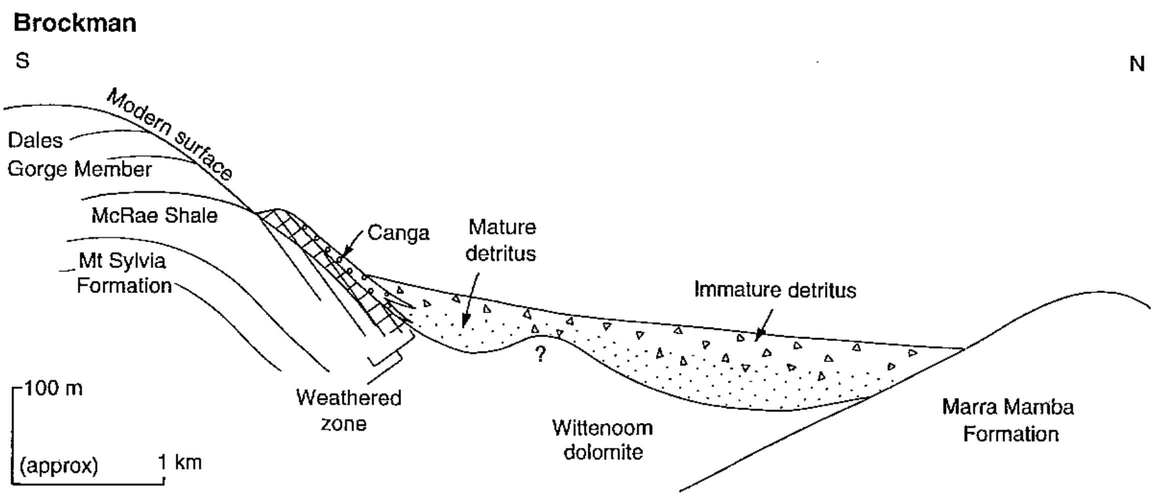


Figure 41 Schematic section showing typical distribution of mature and immature detritus, canga, weathered zones and bedrock. This section shows the basement structural high present beneath valley fill detritus north of Brockman 1 Pit.

The sediments vary in texture from unsorted boulder conglomerates to gravelly silts, and in composition from BIF and clay to hematite and goethite. Sedimentary structures are generally poorly preserved. Genuine scree-slopes are rare in the study areas, although slopes close to range fronts may be sprinkled with talus. The majority of valley margin sediments have unit morphologies and rare sedimentary structures which are typical of the deposits of mass wastage and mass flow. These deposits have been subject to post-depositional modification by fluvial processes. Braided fluvial deposits are found in the axes of valleys, interfingering with the mass flow deposits. The Tertiary Pisolites **(Tp)** which cap Fortescue rocks may be of colluvial, braided- or of meandering-fluvial origin.

Cangas are treated separately as a special case, because their textures preserve evidence that they include rocks of both eluvial and sedimentary origin. Thus they are transitional materials which must be considered collectively.

5.2 Mass Wastage Deposits

The tops of hills in the study areas are generally capped by apparently smoothly rounded BIF units. Mid- to upper slopes may be similarly rounded or comprise steep scarps of BIF outcrop linked by smoother shale units. The BIF scarps are commonly stepped where siliceous units are separated by shale partings (Fig. 3). Most outcrop consists of relatively fresh rock. Depressions within these surfaces and steps in the BIF units, and areas of relatively low slope typically retain patchy coverings of locally derived loose rock, with some fines (colluvium) and poorly developed soils. Where the parent rock is unweathered, this sediment usually consists of coarse and angular BIF clasts. Where the parent rock is mineralised or weathered, clasts comprise hematite, pisoliths and goethitic silt. This material can be regarded as being in temporary storage, and subject to down-slope creep, or wholesale expulsion during major storm events.

5.3 Alluvial Fan Deposits

Alluvial fan deposits of the region may be grouped into two classes: mature and immature. Mature fans dominantly comprise clasts of hematite ± a goethite matrix. This composition includes hematite clasts with crystalline goethite cements, in the class of cangas (Section 5.7). Weathering, alteration of detrital clasts and matrix, and precipitation of goethite cements has resulted in significant post-depositional loss of textural information from mature fans. Immature fans mostly contain fresh or moderately weathered BIF ± hematite and goethite clasts in a goethitic and aluminous silt- to clay-size fraction matrix.

5.4 Mature Deposits

5.4.1 Mature Alluvial Fan Deposits

Mature fan deposits are common at Mount Brockman, where they are preserved at the base of the range front scarps. The situation at the Mount Margaret drill site is probably analogous to Brockman, where canga deposits are preserved on the ends of small spurs, forming a series of deposits located along both sides of the valley. Mature fans in the Mount Sheila area occupy a different geomorphological setting, being preserved at the heads of valleys, and contain a different suite of sedimentary structures.

Brockman type mature fans typically overlie horizons of weathered bedrock. Weathering patterns may follow surface topography (Fig. 42). Basal contacts may be sharply defined (Fig. 18), or apparently gradational. Where gradational, the bedrock is typically mineralised and brecciated to such a degree that primary bedding structures have been obscured or lost (Fig. 40). Mineralised basement has typically undergone some degree of down-slope creep, and thus fits into the range which varies from *in situ* weathered material, through rock slides and debris flows (sediment gravity flows) to fluid gravity flows (see below).

Bedding in mature fans is usually crudely developed on a 0.1 to >2 metre scale, and may decrease in thickness upwards. Dips are conformable with the local slopes, typically dipping at 12-15°, and rarely up to about 30°. Beds are laterally discontinuous over outcrop scale, and have undulating bounding surfaces. Bed contacts are variably preserved and mostly non-erosive. Tops of some beds are uneven with projecting coarse clasts and depressions filled with fine grained sediments. Some beds may be amalgamated, which is highlighted where lenses of finer material are preserved.

Beds typically comprise clast to matrix supported unsorted or poorly sorted gravelly conglomerates. Common clasts include hematised BIF (Fig. 43) or goethite fragments and pisoliths. Some clasts may be locally derived canga intraclasts, and there may be some rare immature clasts (Fig. 44). Bedding structures are rare, but include sorting, poorly developed imbrication, fining-upwards in the top few centimetres, and very rarely, large scale cross-stratification. Beds tend to become finer-grained and better sorted upwards.

The mature fans in the Mount Sheila area are generally similar to those at Brockman, with the exception that they tend to be finer grained, better sorted, and contain a higher proportion of cross-bedding structures (Fig. 45).

Most outcrops preserve scours eroded into underlying beds. These are typically filled with lenticular gravels and conglomerates which may become better sorted and finer grained upwards.

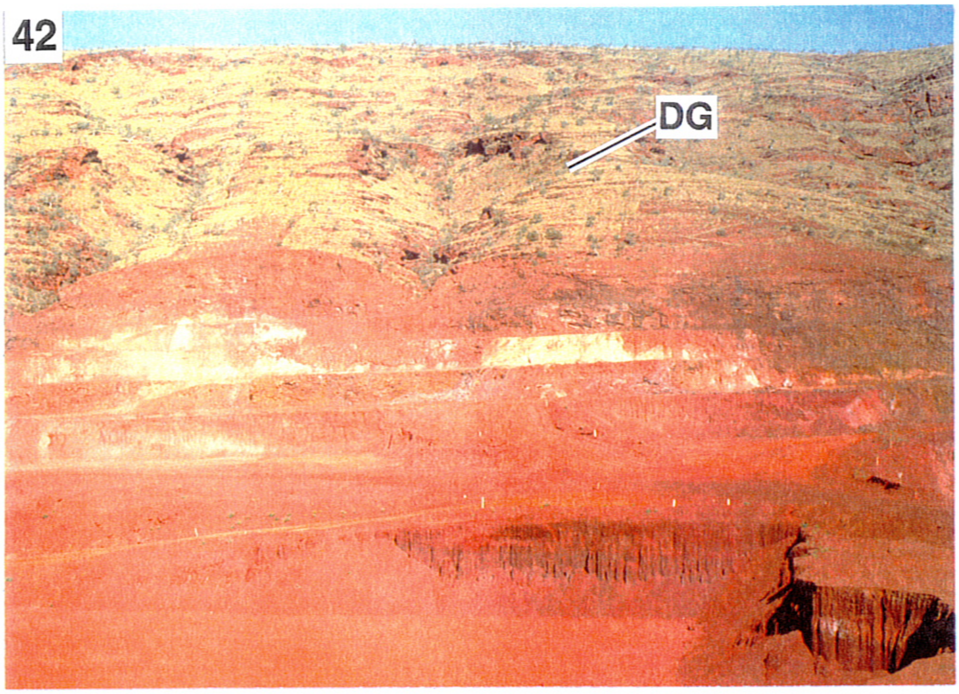
5.4.2 Interpretation

Sediment gravity flows are an end member of a process continuum which extends through turbulent fluid gravity flow to heavily sediment-laden stream flow with increasing inclusion of water (Leeder, 1982). These processes dominate the transport of sediment to sites of deposition on alluvial fans (Blair & McPherson, 1994). The different and characteristic grain support mechanisms which dominate each type of process are not limited to one type of flow.

Debris flows are a type of sediment gravity flow. They typically occur either where colluvium becomes saturated past the point of instability and the resultant slide disintegrates into a debris flow, or where fast moving water intercepts and entrains a body of unstable sediment. Debris flows are non-erosive because they move in a laminar manner. They stop when the flow becomes too thin to sustain the internal shear stress, commonly as a result of flow expansion, de-watering and decrease in gradient down-fan.

The textural evidence that is preserved, namely general lack of erosive contacts between beds, disorganised fabrics and poor sorting within beds, indicates that alluvial fan sedimentation in the region was dominated by debris flows (see Nemec & Steel, 1984; Blair & McPherson, 1994).

The presence of crude imbrication and fining-up sequences in some beds suggests that a minority of deposits were produced by fluidal sediment flows (*e.g.* sheetfloods). The cross-stratification is typical of typical of deposition in channels, some of which are preserved as the concave-up structures seen in some outcrops.



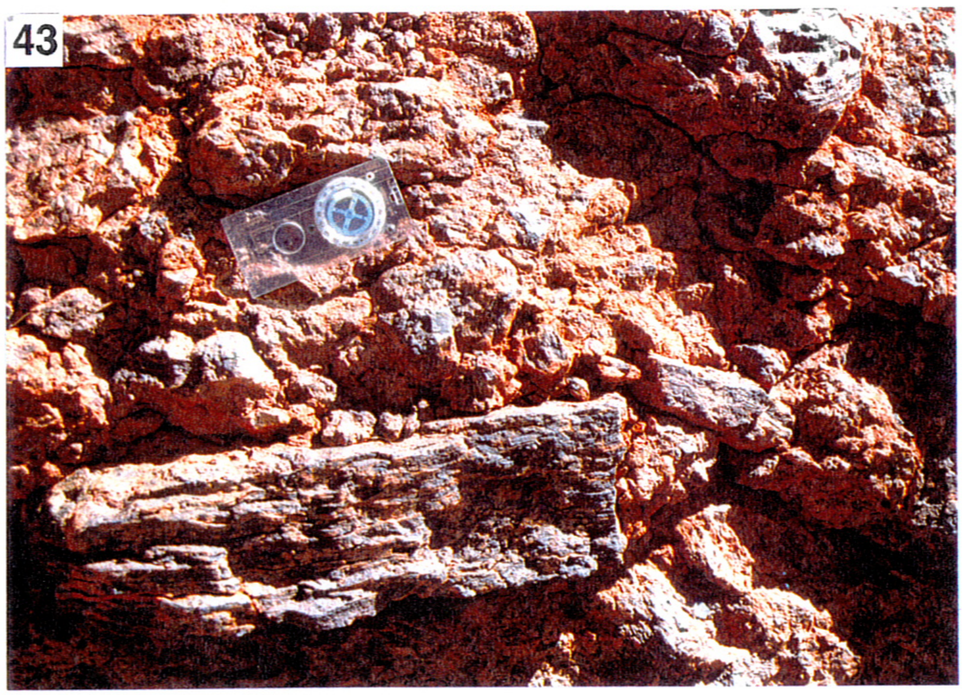


Figure 42. Range front at Brockman Pit 1 showing weathered Dales Gorge Member (DG) overlying bleached McRae Shale (white). Note that undulations in the ferruginised zone located immediately above bleached zone are followed by modern surface topography. This concordance suggests that weathering mineralisation patterns were subject to topographic control, and the modern surface closely approximates the Tertiary landscape.

Figure 43. Boulder-sized mineralised BIF clast in canga. Boulder is about 40cm long.

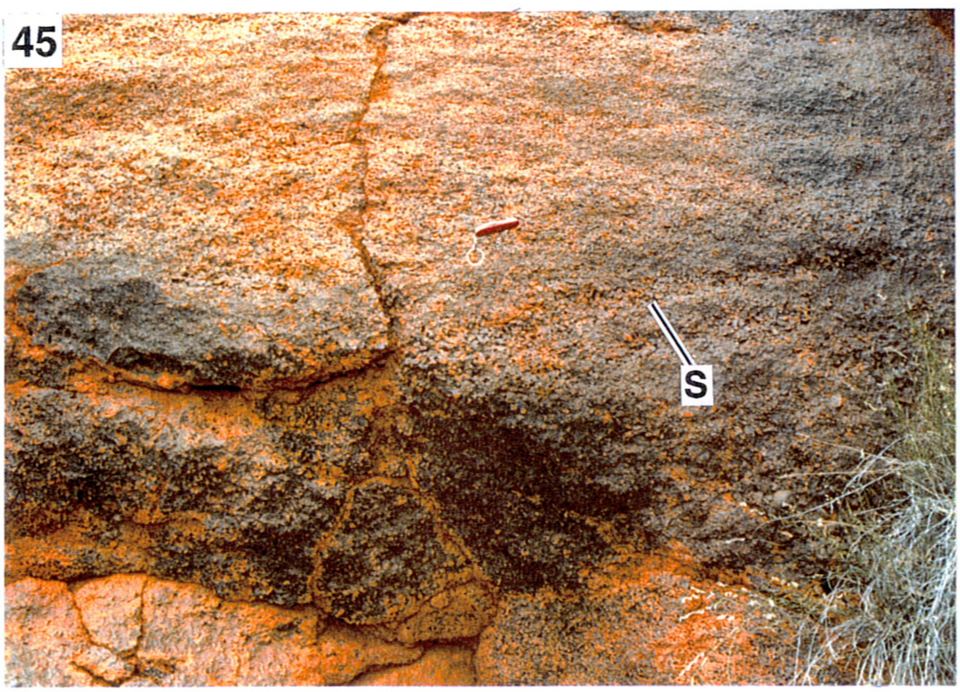


Figure 44. Line of immature cobbles (centre) generated by fracturing of a platy clast of immature (siliceous but partly goethitised) BIF.

Figure 45. Well-sorted pebbly canga from Mount Sheila area, where primary bedding structures are best displayed. Large-scale stratification (S) is identifiable by subtle variation in clast size and relative proportions of clasts and matrix.

Because alluvial fan sedimentation is typified by episodes of deposition separated by significant periods of non-deposition, fans are subject to a number of secondary (modifying) processes. These include channelling and erosion, bioturbation, soil development and cementation.

Some of the channel structures incised into alluvial fans are probably of secondary origin. Other than the presence of solution pipes, evidence for bioturbation is lacking. This is probably due in part to the pervasive textural alteration caused by goethite precipitation/ alteration. Close to the range front, mature fan deposits have undergone pervasive cementation.

Cementation takes the form of alteration of clay-size fraction goethite and soils to crystalline goethite cement, which may in turn be overlain by authigenic silica. Cementation which appears to be ubiquitous in outcrop may be seen to be patchy in subcrop. This is apparent in Brockman Pit 1 (Fig. 46), where cemented and un-cemented fan deposits are preserved as a series of interleaved sheets. This potentially unstable arrangement will encourage detachment of cemented layers, and on exposure, would leave the un-cemented horizon vulnerable to rapid erosion.

5.4.3 Mature Distal Deposits

These are best exposed in the Brockman pits. In Pit 1 they typically comprise gravelly sands, consisting of mainly pisolitic sand and granules with varying proportions of pebbles up to about 4 centimetres diameter, with a silty goethite matrix. Hematite clasts preserving BIF textures are common (*e.g.* Sample 7/6/95/4, A2.31), and rare intraclast cobbles of cemented altered BIF clast and pisoliths (canga) are seen. Individual beds of decimetre- to metre scale form a series of 2-4 metre thick sheet-like units. Beds are generally parallel sided, but with contacts undulating on an up to 20 centimetres scale. Sheets are laterally and longitudinally extensive and parallel sided. They are traceable over the 100-200 metres of outcrop and correlatable across the pit. Contacts between units of all scales tend to be sharp but conformable. Beds and sheets dip WNW at about 8-10° (Fig. 47).

Bedding structures are generally poorly displayed. They are dominated by parallel lamination, with rare cross-stratification and some scour structures. Laminae are revealed by regular variation in gravel content of beds, changing from clast- to matrix supported. Foresets of cross-stratified sediments dip at up to about 20°, generally to the north and west. Scours have up to about two metres relief and containing dipping lenses and layers of coarse and fine fill, and some steeply dipping cross-stratified sands.

Although generally friable, some vertical columns of sediment are lightly cemented by silica, and show slightly more resistance to erosion and collapse than the surrounding material. These structures typically pass down from the top of a specific bed and into those below. These columns may comprise sediment fills of voids created by oxidation of plant roots.

In sections close to the range front, un-cemented mature detritus is seen to interfinger with cemented mature detritus (canga, Fig. 46). Apart from alteration(?) of the silty goethite matrix to crystalline goethite cement, cangas differ little from un-cemented detritus in clast composition.

The mature detritus is overlain by immature detritus comprising mixed hematite and fresh BIF clasts in a goethite matrix. Contacts between mature and immature detritus vary from gradational to erosively unconformable.

5.4.4 Interpretation

The bedding structures preserved in these deposits indicate deposition as bedload or from suspension. Significant thicknesses of laterally extensive individual and amalgamated sheets of laminated and poorly sorted sediment are typical deposits of sheetfloods (*e.g.* McKee *et al.*, 1967). These are unconfined shallow flows which occur during flood events. Sheetfloods transport sediment as a poorly sorted slurry, and deposition of coarse and fine material occurs simultaneously as a result of shallowing caused by flow expansion and infiltration. Lamination is caused by surges in flow and variation in the class of sediments in train.

Cross-stratified units are generated by the downstream progression of large-scale (greater than ripple-sized) bedforms, such as longitudinal or diagonal channel bars. This process tends to sort coarser traction and saltation sediments, from finer suspended sediment. With waning flow, fines tend to be trapped and infiltrate into the coarser deposits. The scours have the morphology and contain the structured fills typical of small-scale channels and gulleys.

From the reasoning set out above, the distal mature detritus is interpreted to have been deposited on a fluvial floodplain as either channel or over-bank deposits. The deposits of meandering channel systems tend to be dominated by lateral accretion structures, not recognised here, and their architecture typically comprises coarse grained channel units surrounded by overbank fines. Braided system deposits tend to be dominated by bars and scours, and their architecture comprise stacked and laterally extensive amalgamated sheets of coarse sediment. On this basis, the channel deposits are interpreted as braided in origin.

Braiding of channel systems may have a number of different causes, but the most significant is an excess of sediment availability over the competence of the system to transport it. The resultant accumulation of sediment causes vertical accretion by growth of channel bars (rather than the lateral accretion by point bar migration in meandering systems). Excess sediment is typically available where climate inhibits sediment stabilisation by vegetation, or where high relief causes instability. The widespread preservation of (albeit poorly displayed) sedimentary structures in these deposits suggests that bioturbation was inhibited, either because of rapid accretion or because the climate did not encourage the development of significant plant cover.

5.5 Immature Deposits

The immature deposits of the region overlie the mature deposits, and are therefore better exposed. Immature deposits display similar structures and unit morphologies to those of the mature deposits and are accordingly interpreted as representing deposition from a similar suite of sedimentary systems.

Deposits of immature alluvial fans radiate from range front gullies, and gorges and feeder valleys into the main valleys of the region. The immature depositional systems evolve from (proximal) rockfall and avalanche deposits, through alluvial fans into distal alluvial plains, braided fluvial systems and ephemeral lake/clay pans with increasing distance from the range front. These depositional systems and their deposits interfinger with each other in such a manner as to render necessary their description and interpretation as a continuum. Sections through these deposits are best exposed where they are incised by gullies. This has occurred in all of the study areas.

Where sections are exposed adjacent to the range front, contacts between immature cover and underlying basement, mature fans and canga generally comprise angular unconformities or paraconformities. At Brockman and Mount Margaret, this typically occurs at the ends of spurs. Immature detritus in range front gullies typically unconformably overlies fresh bedrock or goethitic BIF from low in the weathering profile (Fig. 12).

The top surfaces of the immature fan systems typically dip less steeply than mature fans (7-10° *versus* about 12-15°, and rarely up to about 30°). At Brockman, where the immature fan systems are ponded against the Marra Mamba Formation, these slopes decline in gradient away from the range front, to the extent that they may pass into playa lakes (*e.g.* Silvergrass Plains). In the Mount Sheila and Mount Margaret areas, the dendritic feeder valleys extend further into more open areas before ponding occurs.

The proximal to distal textural relationships show a fining trend, from boulder conglomerates with goethitic silt and soil matrix to mainly sandy/silty goethite with gravel and cobble lenses. Away from the range front, the finer grained facies show a tendency to coarsen-up, from structureless fines with rounded pebble lenses to crudely bedded cobbly sands and silts. Clasts comprise mainly immature BIF but include intraclasts of canga and moderately indurated immature conglomerate. Cementation is variably developed, from moderate ferruginous induration of matrix-rich- to surface coating of matrix-poor sediments.

With rare exceptions (*e.g.* Fig. 48) bedding structures are generally poorly displayed. Matrix-rich sediments tend to be massive and fractured with most primary structures obscured by probable bioturbation. Carbonate concretions (calcretes) appear to be concentrated in topographic highs, with crystalline goethite cemented horizons being exposed in channel floors. Matrix-poor conglomerates tend to be scoured, with imbricate fills. Scours are laterally discontinuous, and correlatable over short (typically 2-5 metre) distances.

Within the study areas, immature deposits are typically undergoing incision (Fig. 16). In the Brockman Valley, the ridge formed by the Marra Mamba BIF has been breached by channels which have advanced to capture the internal drainage (Fig. 10). This lowering of base level has caused widespread incision and headward erosion of the immature sediments. Incision has not gone to completion, and at Silvergrass Plains a playa lake has been preserved.

At Mount Sheila and Mount Margaret, drainage has consistently flowed to a more open area, but incision and erosion of a significant fill of immature sediments in the feeder valleys is ubiquitous.

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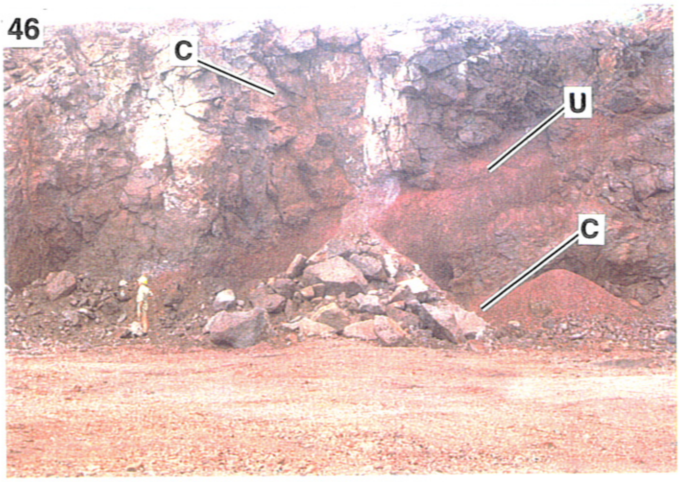

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Figure 46. Interbedded cemented- (canga, C) and un-cemented (U) mature detritus, dipping from top right to bottom left, in Brockman 1 Pit.

Figure 47. Sheets of distal mature detritus (sheetflood and channel deposits) dipping WNW at about 8-10°, Brockman Pit 1.

Figure 48. Channel cutbank showing scoured and low-angle cross-stratified immature detritus in braided fluvial deposits at Mount Sheila area.

5.5.1 Discussion

Episodic depositional events comprising debris-flow and sheet flood events have alternated with periods of non-deposition, erosion and fluvial re-working against a background of local rock-falls and avalanches. The massive deposits of fine sediment seen in Brockman Valley sections adjacent to the Marra Mamba Formation may be part lacustrine rather than pure alluvial plain deposits. The presence of a modern ephemeral lake at Silvergrass Plains suggests that unrecognised ancient lake deposits may commonly be present in the area.

The immature sediments are the fossil record of a period of primarily depositional activity. At present, the study areas are dominated by incision and erosion, with some modern sediment present as a veneer on the immature sediments, and in temporary storage or transit in modern channel systems. In the Brockman area, this net erosion may be explained by the base-level lowering described above, but no such control is apparent in Mount Margaret or Mount Sheila. Alternative explanations may include climatic variations influencing erosion, transport and deposition rates; or source area evolution. This last is attractive because it is supported by the evidence of the widespread presence of traces of relict, relatively easily mobilised, weathered materials in the source areas.

Where weathered profiles are developed over BIF, they typically comprise hematised BIF overlying a hydrated goethitic zone. Valley sediment fills preserve a stratigraphy of hematised BIF clasts overlain by a mixture of goethitic fines and BIF. This pattern is interpreted here as an inverted stratigraphy derived from sequential stripping of weathered profiles. The upper admixture of weathered intraclasts and immature BIF clasts reflects the removal of weathered zone materials, the exposure and subsequent erosion of fresh BIF.

The evolution from erosion and deposition of weathered material to erosion and deposition of BIF may also be invoked to account for the current net erosion of immature detritus in the region. The BIF units are inherently much more resistant to erosion than weathered materials, and the resultant reduction in sediment supply may have starved the area sufficiently to force sedimentation rates into deficit.

5.6 Modern Fluvial Deposits

Throughout the region, modern channels are incised into goethitic/immature sediments (Figs. 15, 48). These channels may be straight or meander slightly, but with the general exception of localised cut bank erosion, they are laterally fixed. Where channels emerge from narrow valleys on to the broad alluvial plains (*e.g.* Nammuldi Plain, Weelumurra Creek), depositional processes dominate, beds become filled with sediment and fluvial systems assume braided forms.

5.7 Canga

5.7.1 Introduction

Canga deposits vary from crusts of varying thickness on weathered valley margins at Brockman and Mount Margaret, to bedded masses greater than ten metres thick and overlying relatively fresh to weathered BIF at Mount Sheila. In all study areas, particularly Mount Sheila, cangas may be found which preserve bedding structures interpreted as being of fluvial, sheetflood or debris flow origin (*Section 5.4.2*). However, "hematite/goethite clasts in a strong goethitic cement" commonly form outcrop of more ambiguous origin.

5.7.2 Transported Canga

At Mount Sheila, the large deposits of canga preserve large-scale cross-stratification, of undoubted fluvial origin. Elsewhere, internal bedding structures of cangas are poorly preserved, and these deposits are interpreted as comprising transported clasts on the basis of crude bedding, poor or non-existent sorting and the presence of intraclasts.

In outcrop, these deposits are fully indurated, with hematite clasts in a goethite matrix. In reflected light microscopic examination of polished sections, the matrices are seen to typically comprise a combination of euhedral, and radial-fibrous crystalline goethite (*e.g.* Sample 28/8/95/2, A2.44).

5.7.3 Ambiguous "Eluvial" Canga

The proposed "surface weathering" model source for BIF mineralisation (Section 4.6) operates by a combination of silica removal and replacement by iron. Volume reduction and compaction is a corollary of the removal of silica. This settling causes fracturing, and ultimately, brecciation in brittle rocks (Fig. 40). Where settling occurs on slopes, mineralised material will tend to creep down hill. Compaction will also occur, resulting in the formation of fissures and the development of detachment planes. When fossilised, these deposits form the "cemented rock-slide" end member of the mass-flow deposit spectrum. Rock-slides vary in style and intensity from detachment and movement with very little disturbance of structure of discrete blocks along a slip plane. With increasing intensity, rock-slides grade into debris flows.

In the south wall of Brockman Pit 1 and at Brockman Extension, mineralised BIF can be seen which retains relatively undisturbed primary (BIF) bedding laminae, but which is fractured into centimetre-scale platy clasts (Fig. 40). This material can be seen to make up detached blocks in various states of disintegration. Blocks have been penetrated by Fe precipitating solutions, and crystalline goethite cements and pisoliths are common (*e.g.* Sample 16/8/95/6, A2.51). Sediment has accumulated in fissures and fractures and solution pipes. It is possible that brecciation and slumping may have been locally assisted by karst development in the underlying Wittenoom Dolomite Formation.

At Jeerinah, what is interpreted as relatively undisturbed hematite/goethite mineralised BIF (Fig. 40) overlies canga deposits comprising pisolitic and well rounded mineralised BIF clasts in a crystalline goethite matrix (Sample 24/11/95/3, A2.28). This relationship may be ascribed to transport of a detached block over previously transported material, or the deposit may be mostly *in situ*, with the texture derived from weathering/mineralisation processes.

5.7.4 Discussion

As used in the Hamersley Iron Province, the term "canga" covers a variety of mineralised materials which were goethite cemented at different stages of their evolution. The include *in situ*, cemented rock-slide, debris-flow and channel gravel deposits. The convergent evolution of different rocks and loose sediments to canga is observed in polished sections, where samples from a variety of locations and genetic settings are seen to be texturally and mineralogically similar. It is the fact of crystalline goethite cementation of hematite, rather than transport, which causes these deposits to be classified as canga.

There are a variety of alternative names which may be applied to canga, including ferruginous duricrust and ferricrete. These general terms do not differentiate between the nature of the clasts (mineralised or un-mineralised) and types of cements. The term "canga" does discriminate, being an internationally established term for mature-grade clasts strongly cemented in a ferruginous matrix. The term is also particularly useful because the definition is non-genetic. It can therefore be applied to chemically- or texturally similar deposits of sedimentary and/or purely diagenetic origin.

6 FACIES ARCHITECTURE (SUBCROP)

6.1 Introduction

The preceding sections have been concerned with the description and interpretation of surface features and outcrop in the study areas. This section uses Hamersley Iron drilling data to examine the evidence for the size and shape of mature detritus deposits, and the nature of their bounding surfaces. This information is used to develop an understanding of depositional processes and trapping mechanisms, and as an aid to the identification of exploration targets.

6.2 Data Modelling

Strands data from the strike valley north of the Brockman range front have been utilised for modelling the basal unconformity surface (Figs. 49A & 50A) and the contact between mature and immature detritus (Figs. 49B & 50B). A set of isopach maps have been generated which show the thickness distribution of mature detrital and immature detritus (Figs. 49C, D & 50C, D). In addition, a set of sections running south-north are presented (Figs. 51 & 52).

The structural arrangement of basement lithology has had a fundamental influence on the geomorphological evolution of the Mount Brockman area. The strike valleys of this area are developed on the Wittenoom Dolomite, Mount Sylvia Formation and McRae Shale, and are constrained at their margins by the barriers of the Marra Mamba Formation and Dales Gorge Member. This geometry has isolated local drainage from Duck Creek and the Beasley River. Prior to deposition of the mature detritus, base level within this system was eroded to a minimum of about 550 metres above MSL, some 45 metres below that of the Nammuldi Plain. The deep incision has locally enhanced the deposition and preservation potential of strike valley sediments. Lithological and structural constraint of the local drainage system may have overloaded (choked) it with sediment to the extent that drainage spilled over the Marra Mamba Formation hills, leading to erosion and incision of channels along planes of weakness, and causing capture of Brockman drainage.

6.3 Western Brockman Valley

6.3.1 Brockman 2

The unconformity surface (Fig. 49A) shows significant variation in basement relief. In the Brockman mine site area, a basement high forms a ridge running east-west, sub-parallel with the rangefront along about northing 7519000-7519500. The ridge tapers and pinches out to the west from a maximum of about 600 metres width and over a distance of about 2.5 kilometres, and is separated from the range front by a valley about 300-500 metres wide (Figs. 49A, 51B, 51C). The co-incidence of the valley and ridge with the local fold axes, and the connection of the ridge with the north-stepped margin of Dales Gorge Member outcrop to the east of the Brockman mine suggest a structural control on the trapping and preservation of the Brockman 2 deposit.

At its eastern end, the ridge stands a maximum of about 26 metres above the valley (Fig. 51C). This difference declines westwards to less than 10 metres over a distance of about two kilometres (Fig. 49A). This valley was of sufficient scale to control the distribution of sediments in the lower part of the Brockman 2 deposit, as is indicated by the east to west dip of pisolitic sediments in the base of Pit 1. At 580 metres above MSL, the base of Pit 1 is situated approximately 20 metres below the ridge crest.

The buried valley deepens and widens to the west, with individual scours becoming shallower, but more continuous down-slope. The valley continues parallel with the range front for about 2.5 km, then turns north, breaching the basement ridge to join the main part of the valley (Fig. 49A). An apparent tributary running from west to east along a continuation of the buried valley joins it at this point of northerly departure. Two other tributaries join this system running north directly off the range front. Both of these gulleys are associated with locally enhanced scouring adjacent to their junctions (Fig. 49A).

On the scale of the map, the main part of the Brockman Valley deepens to the NE. This may indicate the direction of flow or result from some other process such as dissolution of the Wittenoom Dolomite.

The sections (Figs. 51A-C) show a variable but systematic S-N evolution, from canga encrusting the range front to mature detritus valleys, with pisoliths tending to be best preserved in the deepest levels. These sediments were deposited at the sites of flow expansion situated closest to the gorges feeding sediment from the high-level source to the valleys. In addition, the sections show that mature detritus tends to have been deposited over hydrated basement, whereas immature detritus has been deposited on mature detritus or on "fresh" (non-hydrated) basement. From this, it can be inferred that the mature sediment was deposited by an essentially non erosive depositional system.

Deposition of the mature detritus was followed by significant erosion which either preceded or was directly associated with deposition of immature detritus. The immature detritus depocentre is situated north of the earlier deposits (Figs. 49C, 49D), and the main channel axis appears to have veered to the NNW. Northward channel migration probably led to erosion of the basement ridge which would have been a more significant topographic feature during the time of mature detrital deposition.

6.3.2 Superband

The Superband detritus was deposited in a linear strike valley incised into the Wittenoom Dolomite adjacent to the Marra Mamba Formation (Fig. 49A). The basal unconformity has been identified as extending down to about 550 metres above MSL (*e.g.* DH488, DH673; Fig. 51). This depth of incision places the floor of the valley about 20 metres below the base of the Brockman 2 deposit, and about 45 metres below the unconformity between the Fortescue Group and the Channel Iron Deposits of the Nammuldi Plain. The presence of resistant Marra Mamba Formation BIF between the Brockman Valley and the Nammuldi Plain and the difference in base level suggests that separate, unrelated drainage systems operated in each. It seems likely that the palaeodrainage from the Brockman Valley ran west/southwest along strike, and the current northward drainage pattern post-dates deposition of the Superband.

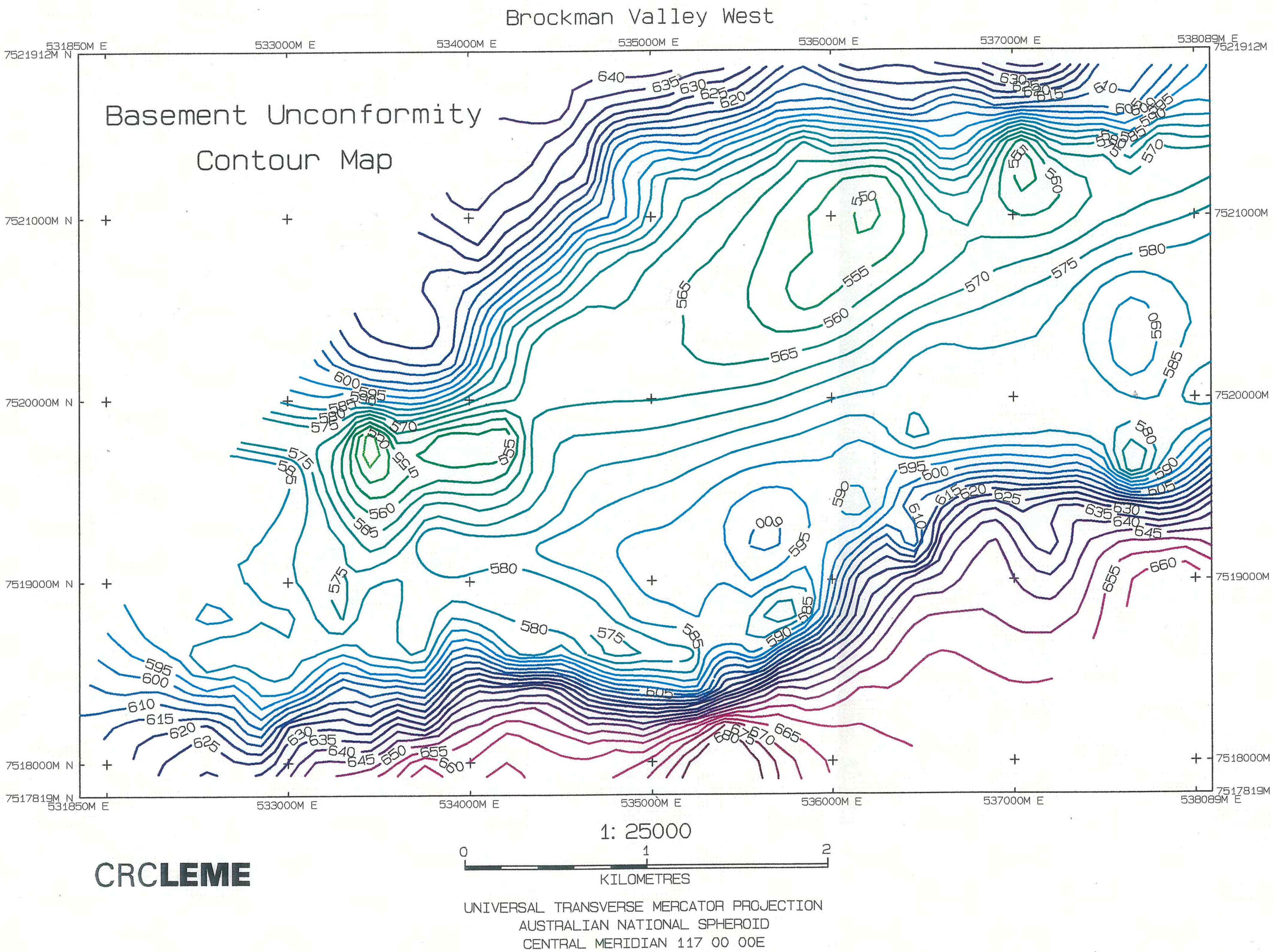

Figure 49A. Contour map of basal unconformity between basement and sediments, Brockman Valley West.

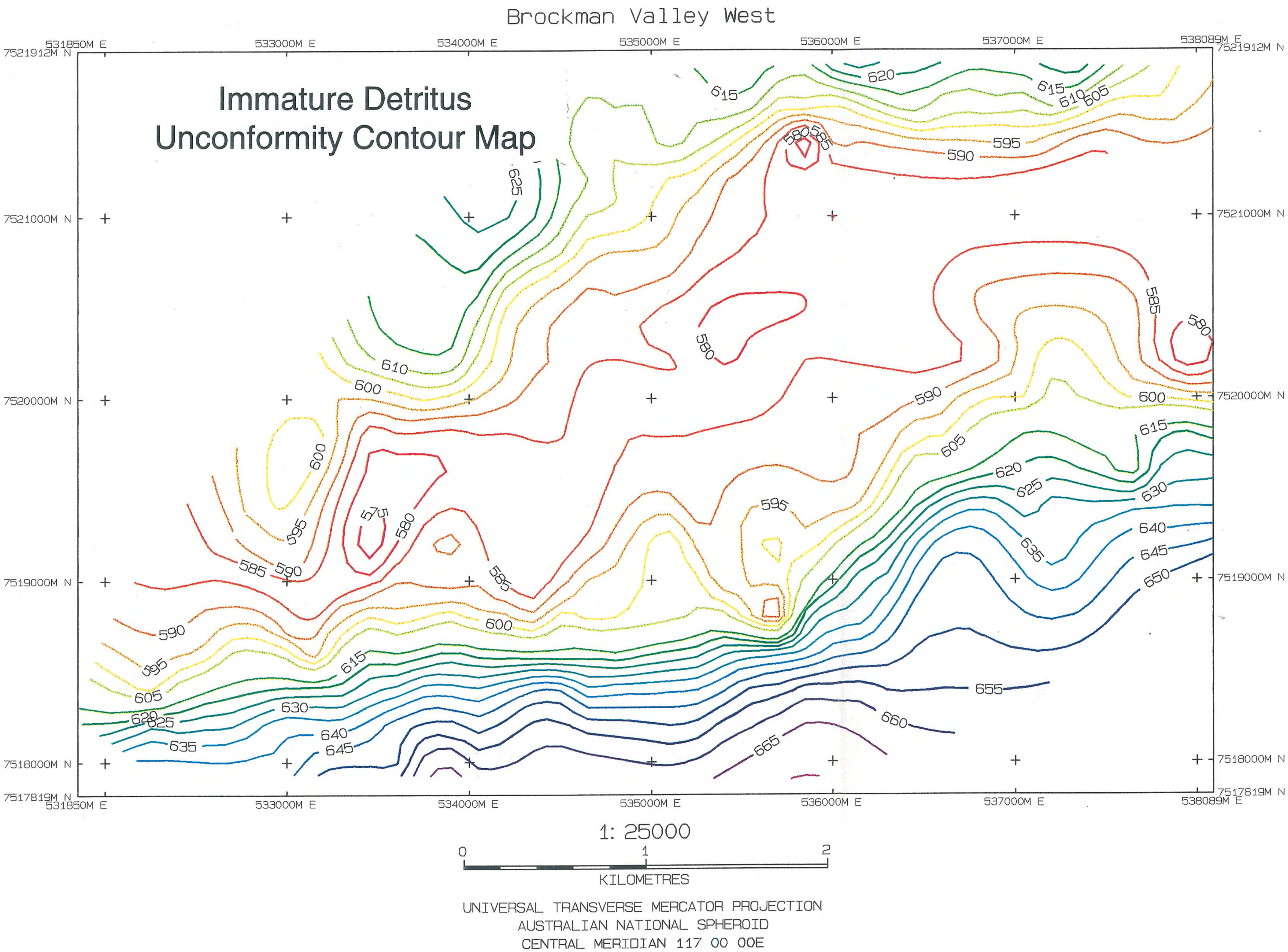

Figure 49B. Contour map of unconformity surface between immature detritus and mature detritus, Brockman Valley West.

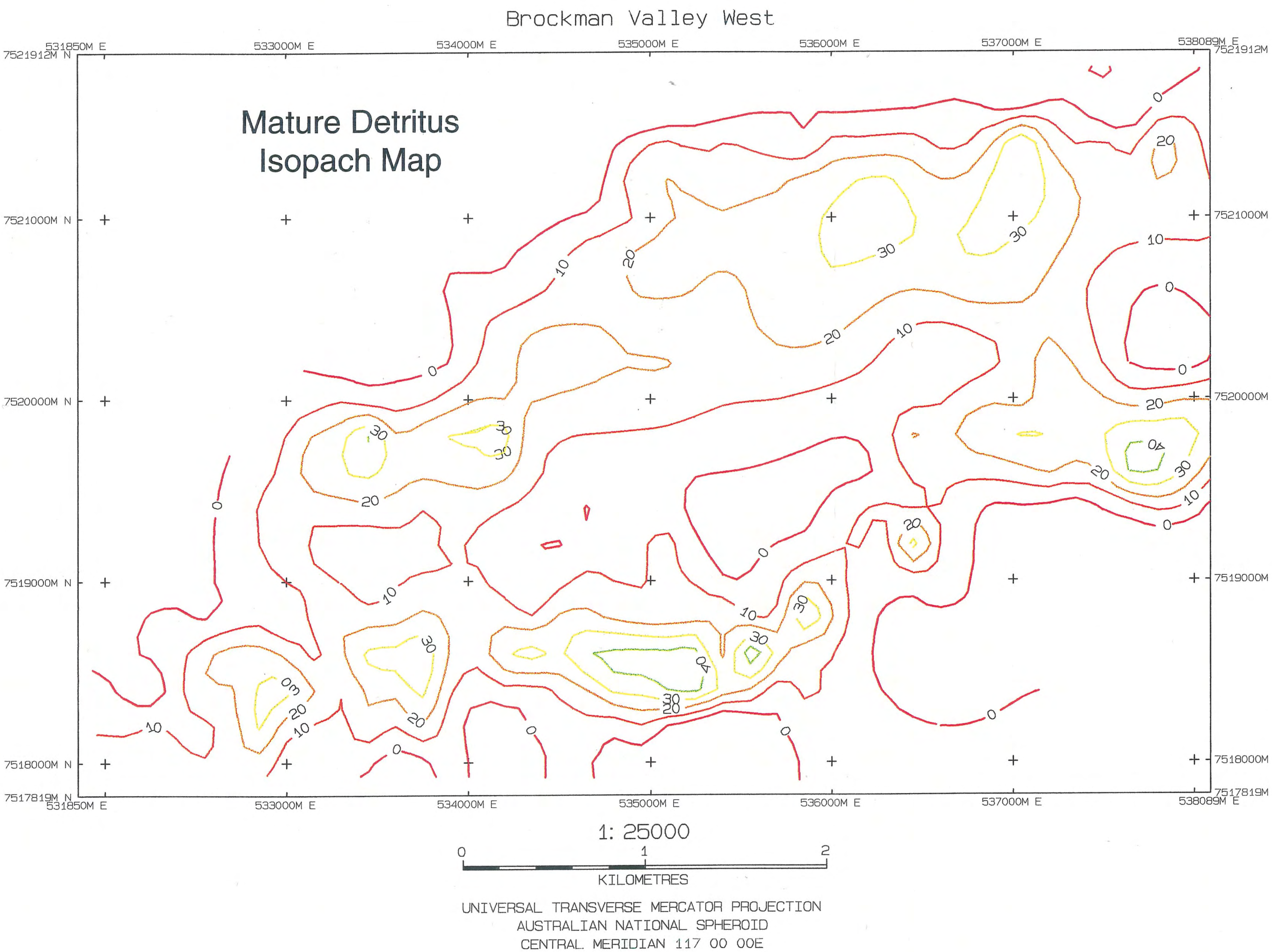

Figure 49C. Isopach map showing thickness of mature detritus, Brockman Valley West.

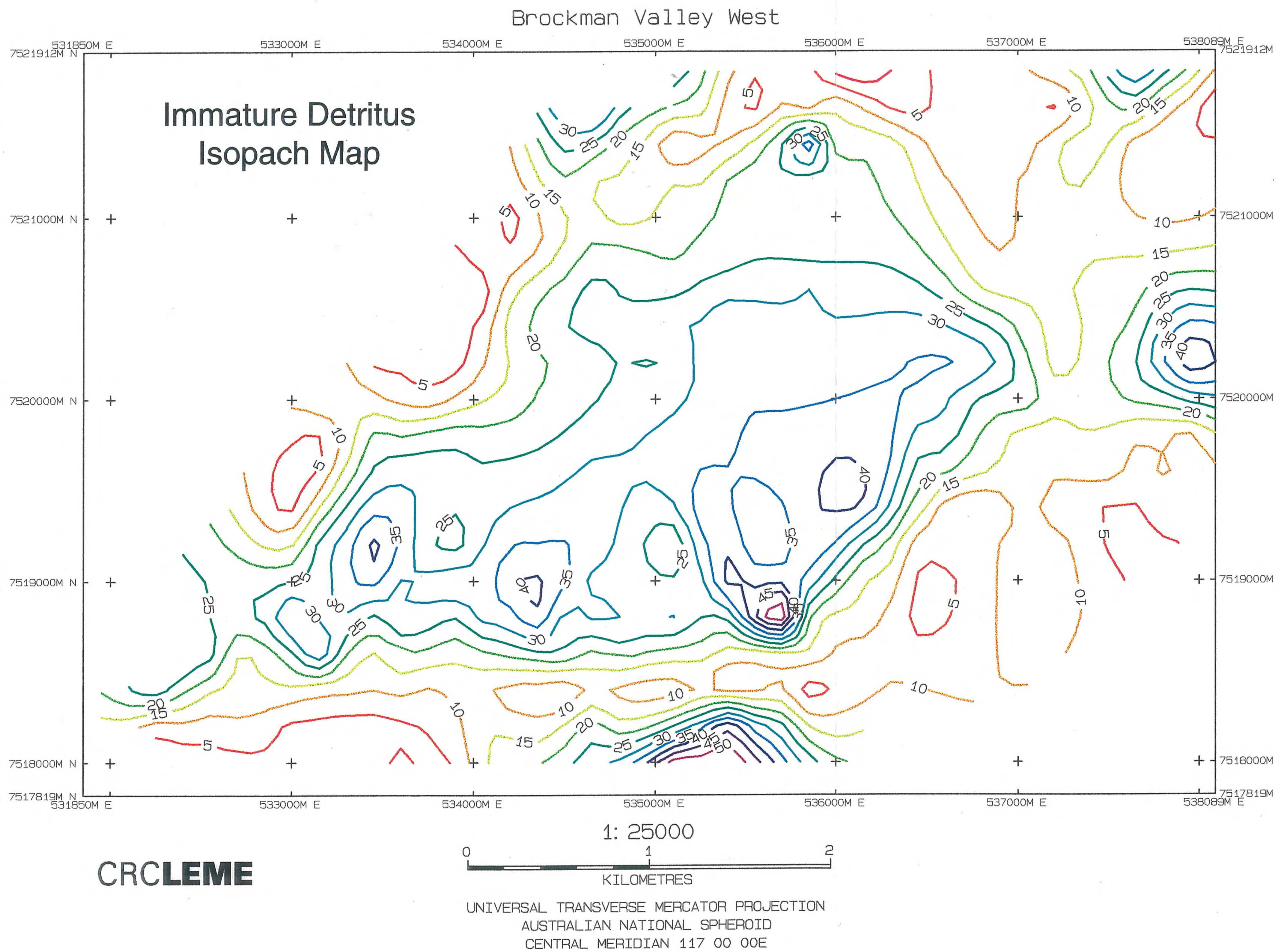

Figure 49D. Isopach map showing thickness of immature detritus, Brockman Valley West.

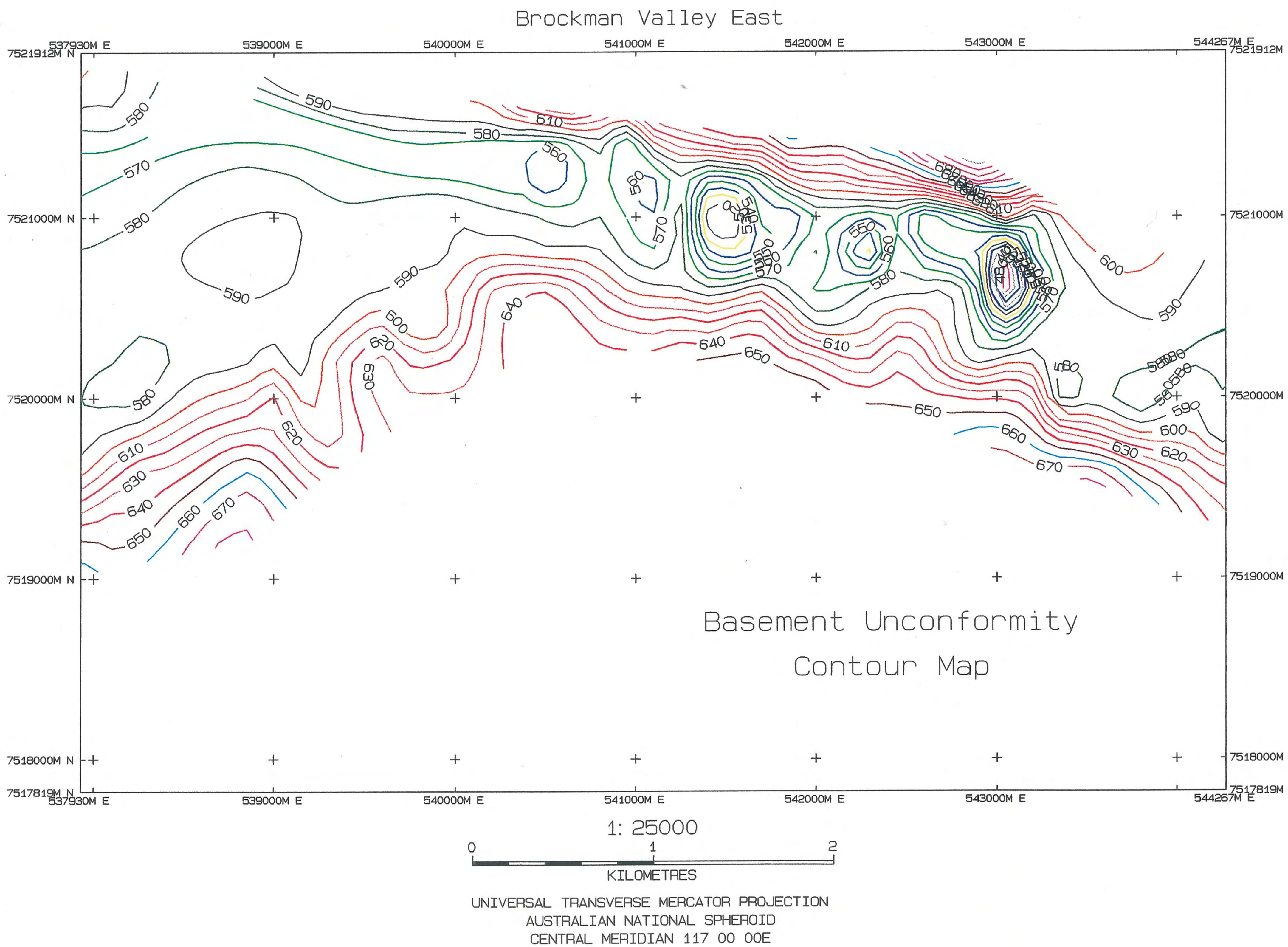

Figure 50A. Contour map of basal unconformity between basement and sediments, Brockman Valley East.

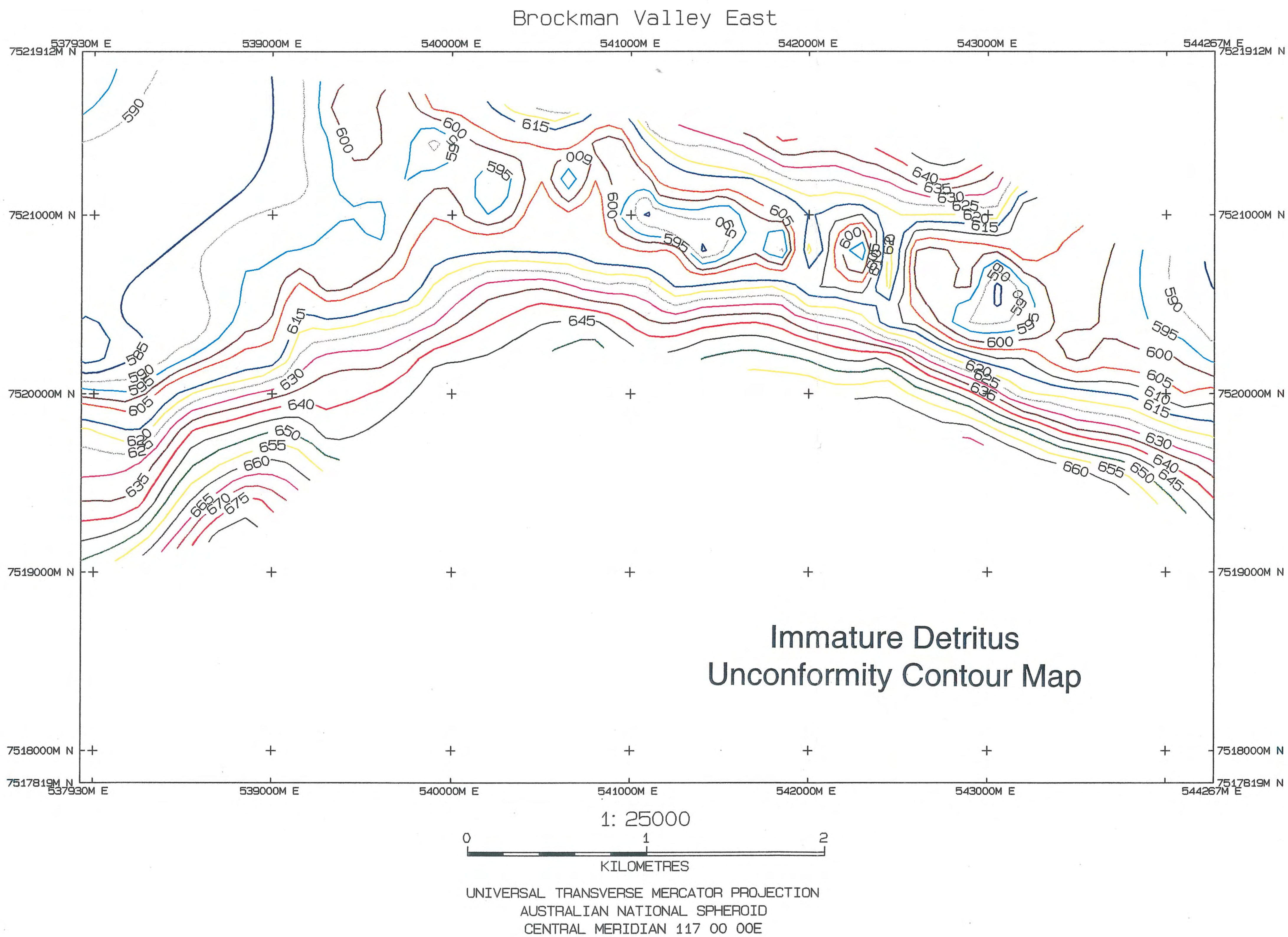

Figure 50B. Contour map of unconformity surface between immature detritus and mature detritus, Brockman Valley East.

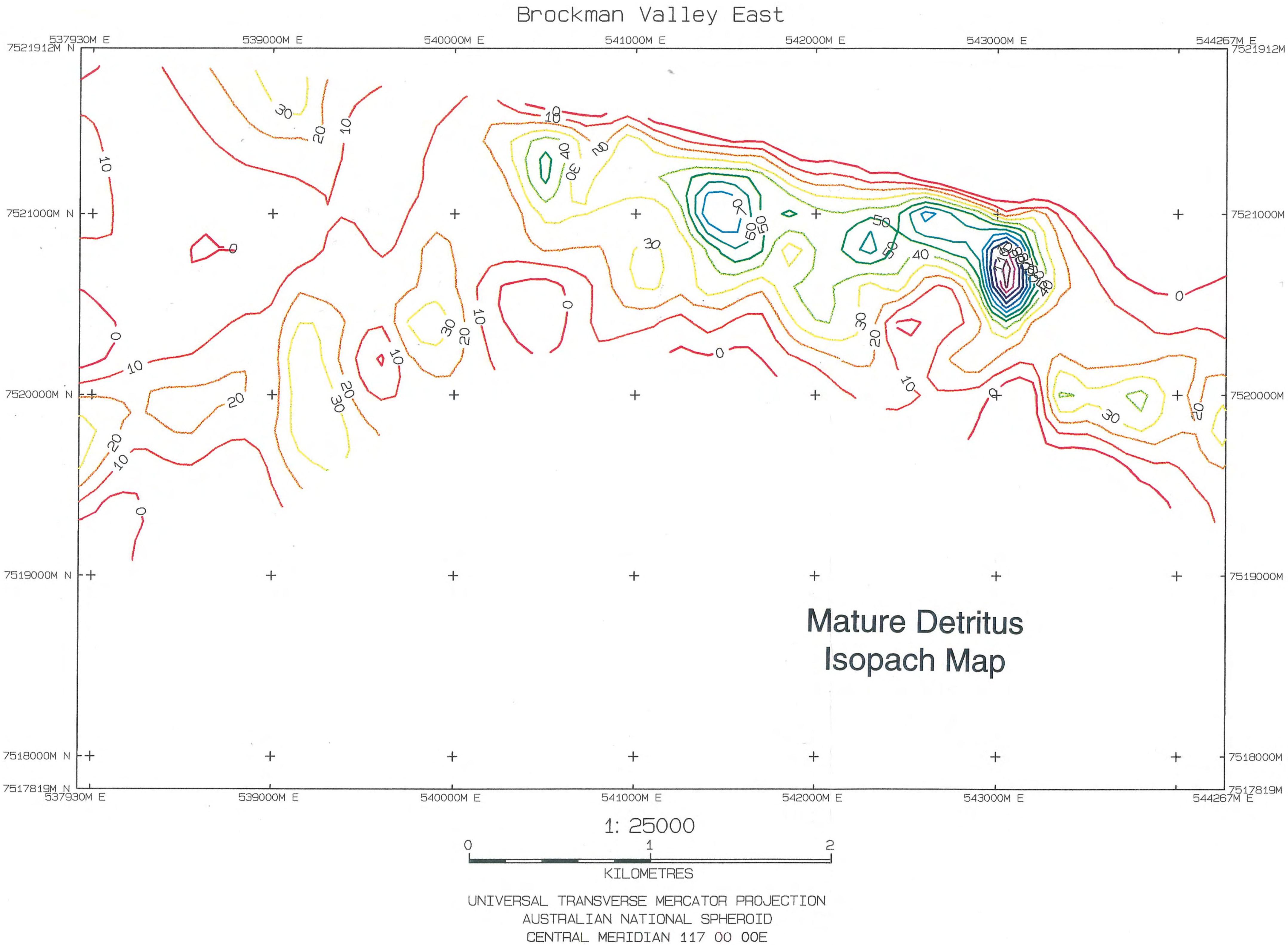

Figure 50C. Isopach map showing thickness of mature detritus, Brockman Valley East.

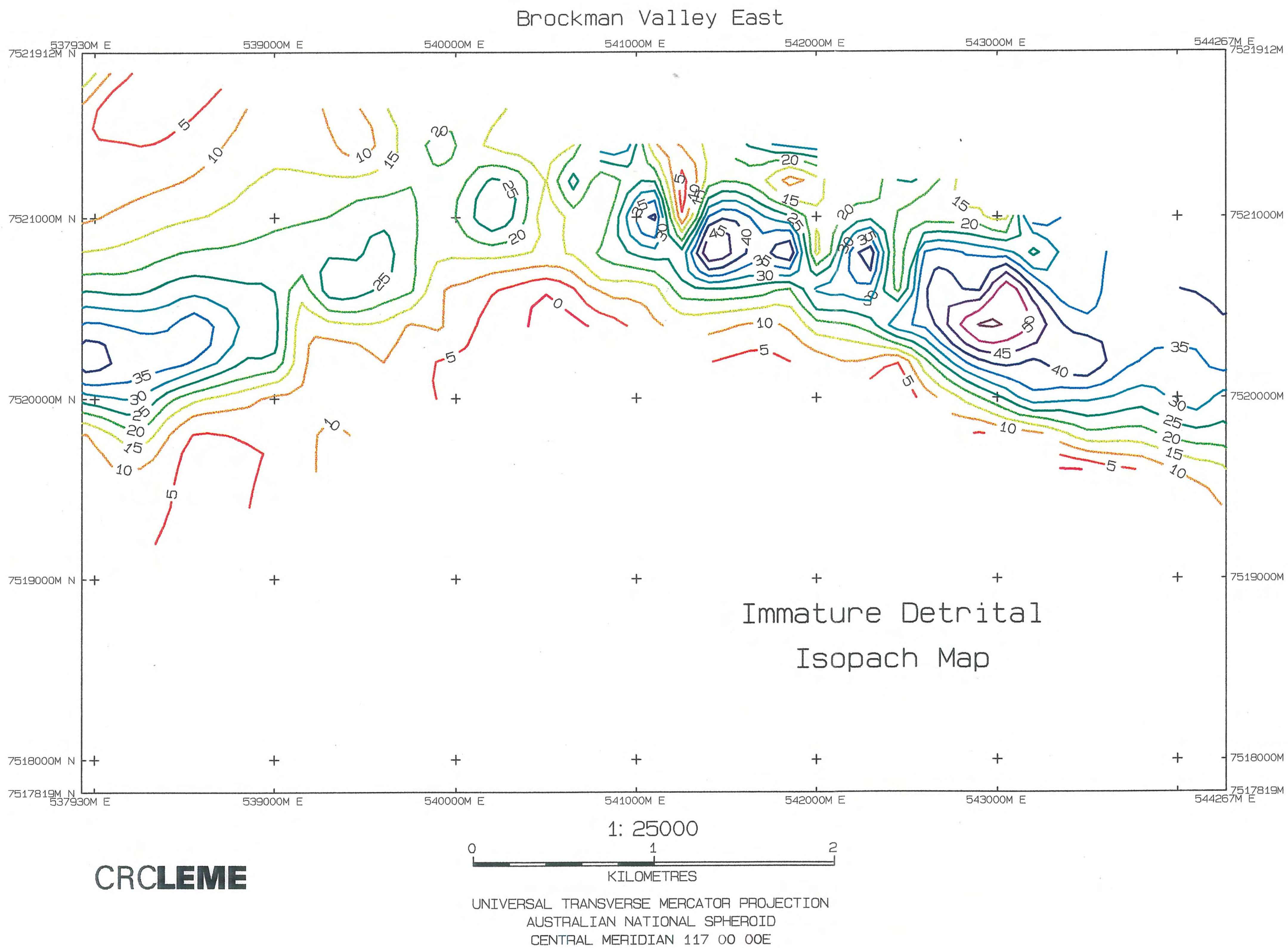

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Figure 50D. Isopach map showing thickness of immature detritus, Brockman Valley East.

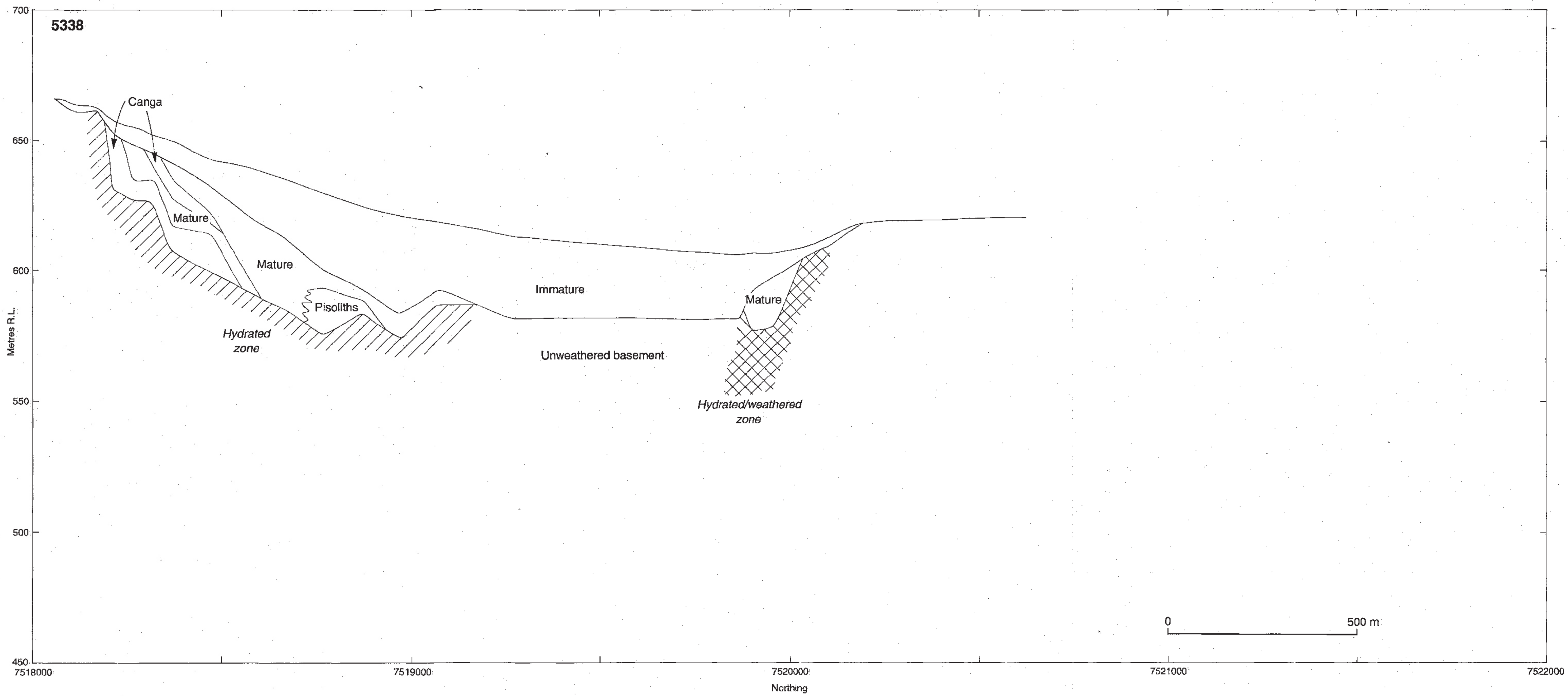

Figure 51A. South-to-north section of sediment fill in Brockman Valley, Pit 1 along easting 5338. Sections show areas of weathered, un-weathered and mineralised basement as well as classes of sediment.

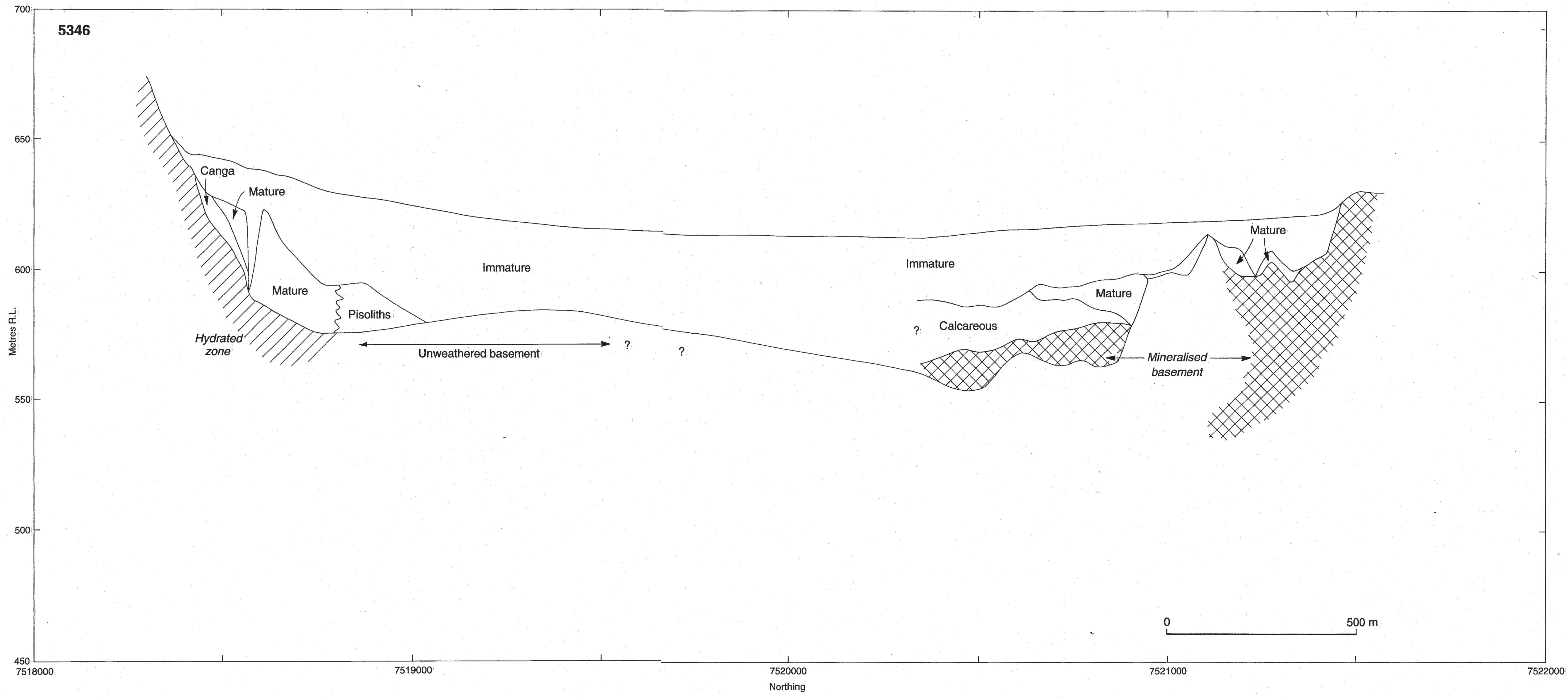

Figure 51B. South-to-north section of sediment fill in Brockman Valley, Pit 1 along easting 5346. Sections show areas of weathered, un-weathered and mineralised basement as well as classes of sediment.

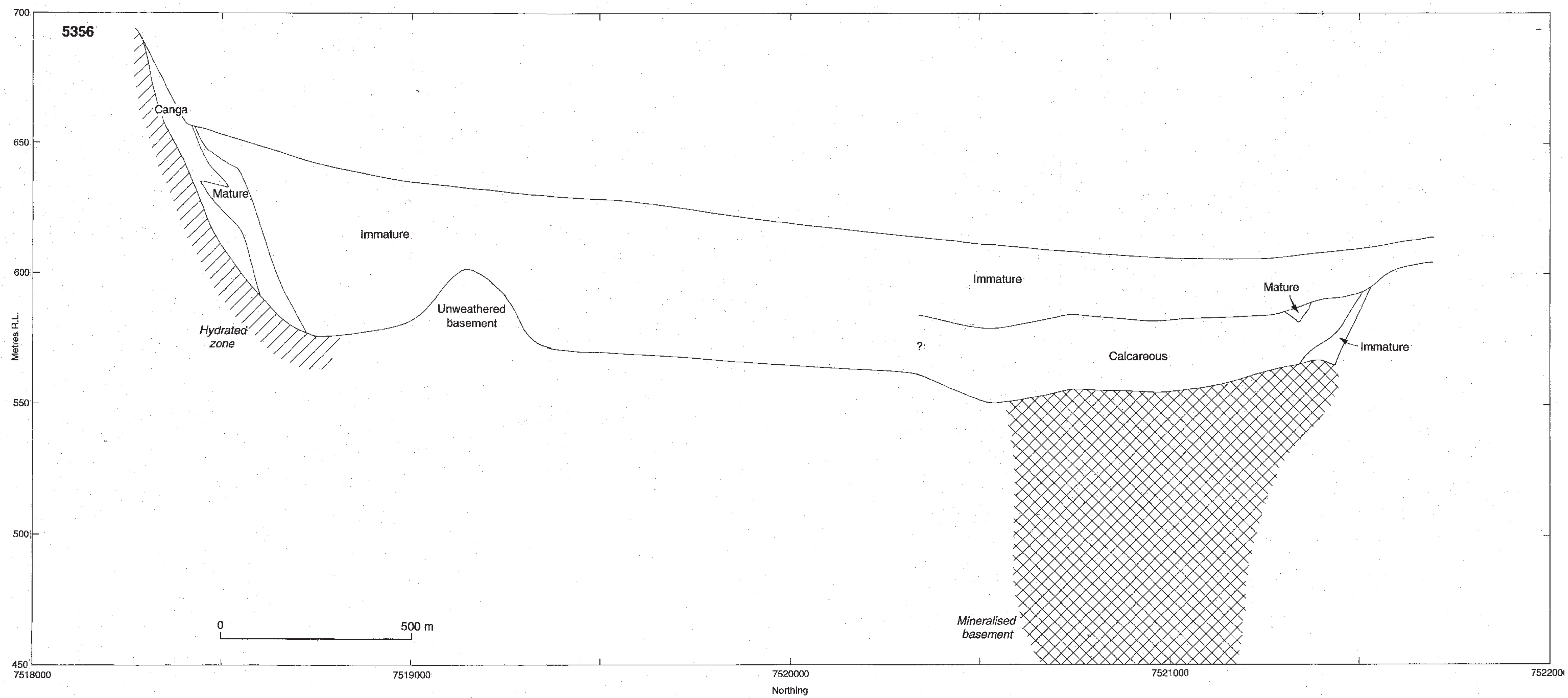

Figure 51C. South-to-north section of sediment fill in Brockman Valley, Pit 1 along easting 5356. Sections show areas of weathered, un-weathered and mineralised basement as well as classes of sediment.

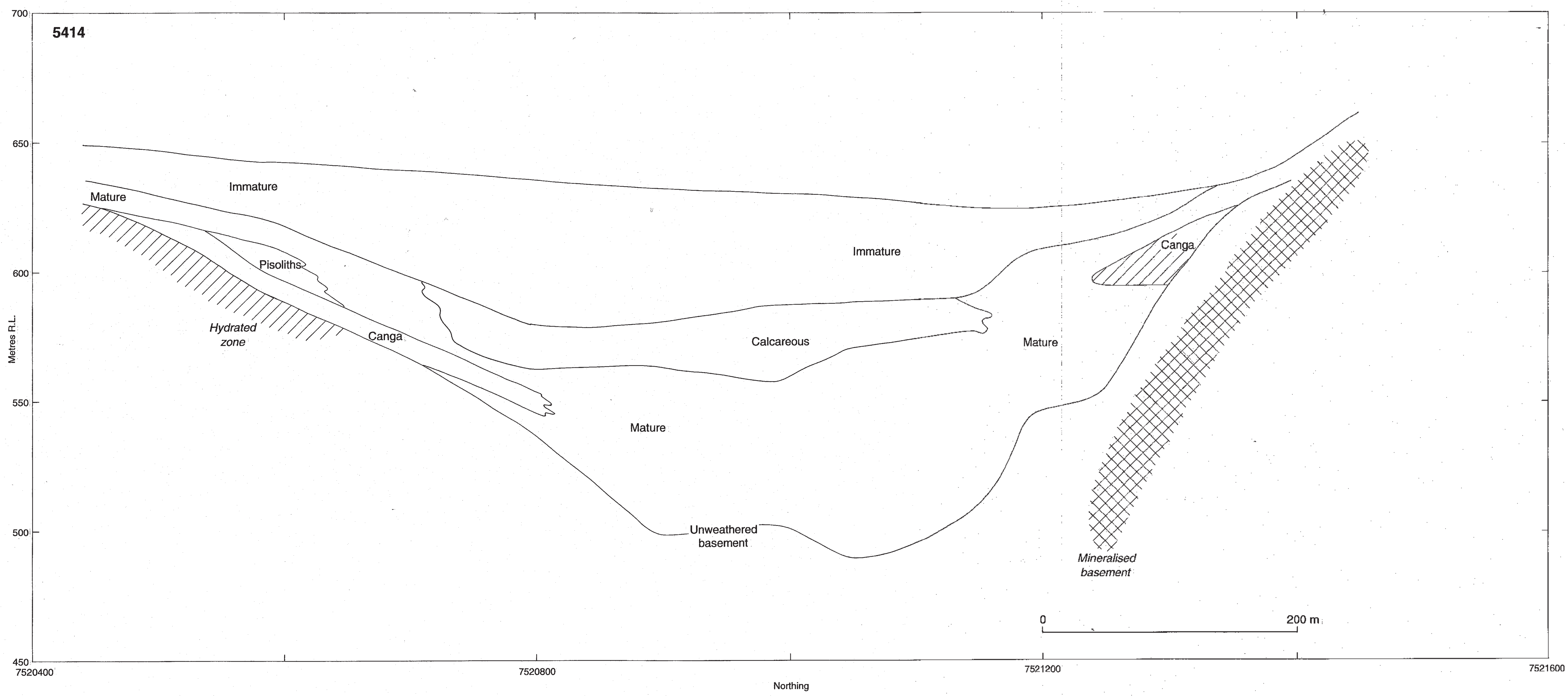

Figure 52. South-to-north section of sediment fill in east Brockman Valley along easting 5414. Section shows areas of weathered, un-weathered and mineralised basement as well as classes of sediment.

6.4 Eastern Brockman Valley

Modelling of the eastern end of the valley shows a number of apparently anomalous values, where depths to basement obtained from lines of drill-holes running north from the Dales Gorge Member are consistently several tens of metres shallower than neighbouring lines running south from the Marra Mamba Formation. Data from the eastern end of the Brockman valley need to be re-examined before modelling can proceed further.

The pattern shown by these maps show a line of deep depressions, up to greater than 140 metres below the modern surface, developed along the northern side of the valley (Fig. 50A). The depressions are typically filled with between 60-70 metres and 110 metres thickness of mature detritus (Fig. 50C). The upper surface of the mature detritus has an undulating relief of about 20 metres, arranged as a linear series of depressions (Fig. 50B) and is in turn overlain by between 5 metres and about 55 metres of immature detritus (Fig. 50D).

Assuming the maximum depths of these depression are real, then they may either be linked as a linear structure, or be true discrete features. At maximum depth, the depressions are about 100 metres below the thresholds of drainage from the modern Brockman Valley, 110 metres below the Tertiary base level in the neighbouring Nammuldi Plain, and about 70 metres below the sill at the western end of the system (see below).

If the depressions were to be linked as a fluvial channel system, then it would have required an exit from the Brockman Valley at equivalent depth, in order to have scoured that deep. We are unaware of any such feature, and know of no modern or ancient channel which has been so deeply scoured relative to potential sills, without the aid of an agent such as glacial ice. Alternatively, the depression(s) may have been generated chemically as dolines or similar collapse structures by dissolution of the Wittenoom Dolomite. Dolines are typically dry, and these features may or may not have contained lakes. If sedimentation proceeded at a similar rate to dissolution, they may have never had a significant surface expression.

6.5 Deposition and Preservation of Mature Detritus: Discussion

Controls on the processes responsible for the deposition, preservation and distribution of mature detritus are illustrated at the Brockman mine site. Mature sediments were deposited in a morphological trap at sites of flow expansion (Fig. 53) and gradient reduction (Fig. 54). Mature sediments were preserved because they were by-passed by the later immature sedimentary system (Fig. 51A-C).

By-passing will occur where one or more of three conditions are met. These are where the later erosive system passes:

1) through the earlier deposits,
2) around the earlier deposits,
3) over the earlier deposits.

For the convenience of illustration, these conditions are dealt with separately below, but in practice, they are intimately linked and usually indivisible.

Passage through earlier deposits typically occurs where base-level has been lowered. Base-level changes may be influenced by local- to global-scale controls (see *Section 7.4.2*). In the context of sediment deposition in the study areas, base-level lowering is interpreted to have resulted from erosion of source areas and feeder channels. Channel incision has propagated across the (early) proximal sediment deposits, causing the locus of activity to migrate downstream (Fig. 53).

Passage around earlier deposits occurs where controls intrinsic to the depositional system operate. An example of this is channel avulsion, where sediment accretion raises channel floors above the floodplain level, and ultimately causes the channel system to switch to a lower, more stable course. More specifically, at Brockman, the axis of the channel system associated with immature sediments is incised into both mature sediments and the buried basement ridge (Figs. 49B & 49D). This depositional system has switched its axial orientation, without regard to the origin (basement or sedimentary) of the underlying substrate.

Passage over earlier deposits occurs where base-level has been raised. On the scale of these deposits, base level raising can be attributed to an excess of sediment supply over the competence of the channels to transport it. Initially, this causes vertical accretion (Fig. 55), followed by a "plugging" of channel systems. The resultant backing-up of drainage may cause channels to find and cross alternative thresholds, and therefore pass around earlier deposits.

6.6 Conclusions

6.6.1 Deposition

Unconformity and isopach mapping indicates that the mature detritus of the Brockman mine site was deposited at sites of flow expansion and gradient reduction on leaving the Brockman Range. A series of range front alluvial fans delivered coarse sediment directly on to the southern margin of a wide and low gradient valley which was constrained by a structural ridge located north of the range front (Fig. 49A). Finer grained sediment was deposited from a fluvial system passing westwards along the valley axis (Fig. 56).

6.6.2 Preservation

The mature deposits were preserved because the axis of the fluvial system breached the northern structural ridge and veered to the NW, causing by-passing of these early deposits (Fig. 57). This possibly occurred because the low gradient valley was filled to spill point by mature detritus. The result was that the re-aligned channel system and its associated erosional activity was deflected from re-working and removing the mature detritus from its morphological trap. The more aggressively erosional nature of the later, immature system is demonstrated by the locally eroded surface of the mature detritus, and the deep NW aligned and immature detritus-filled scour which separates Brockman Pits 1 and 4 (Figs. 49D & 57).

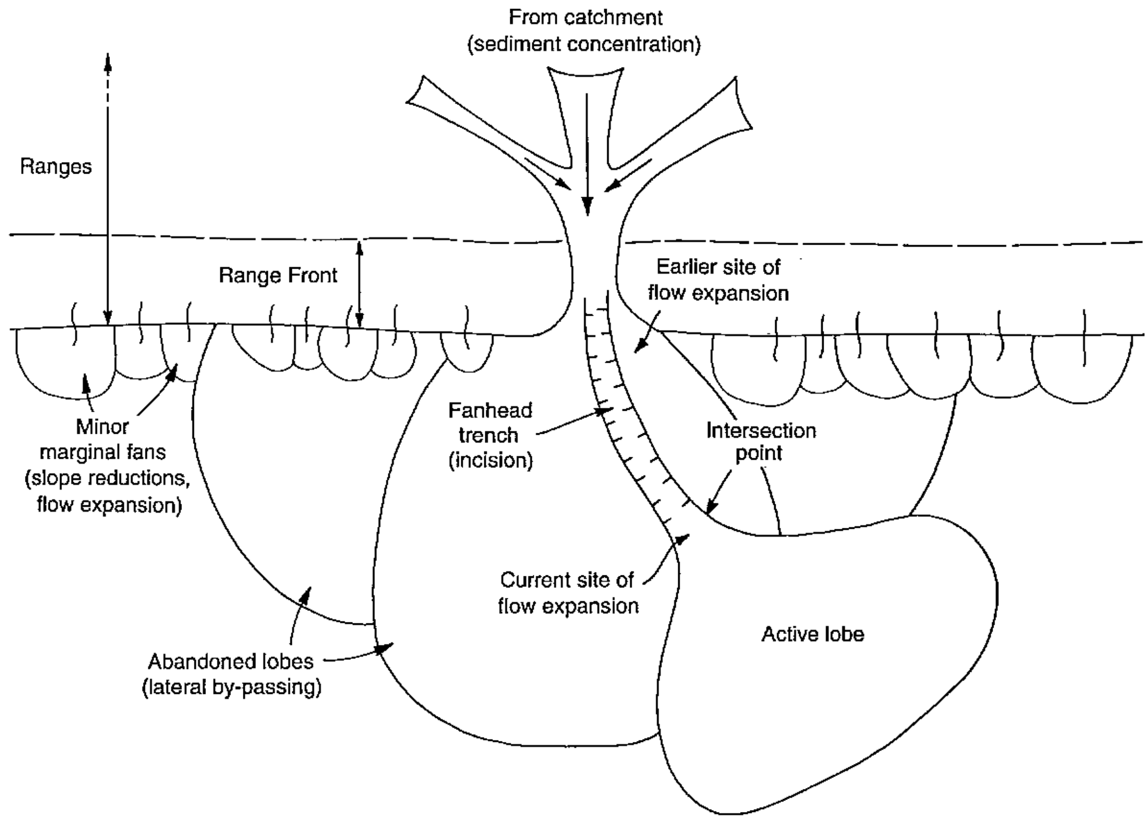

Figure 53. Conceptual model showing plan of sites of flow expansion and gradient reduction.

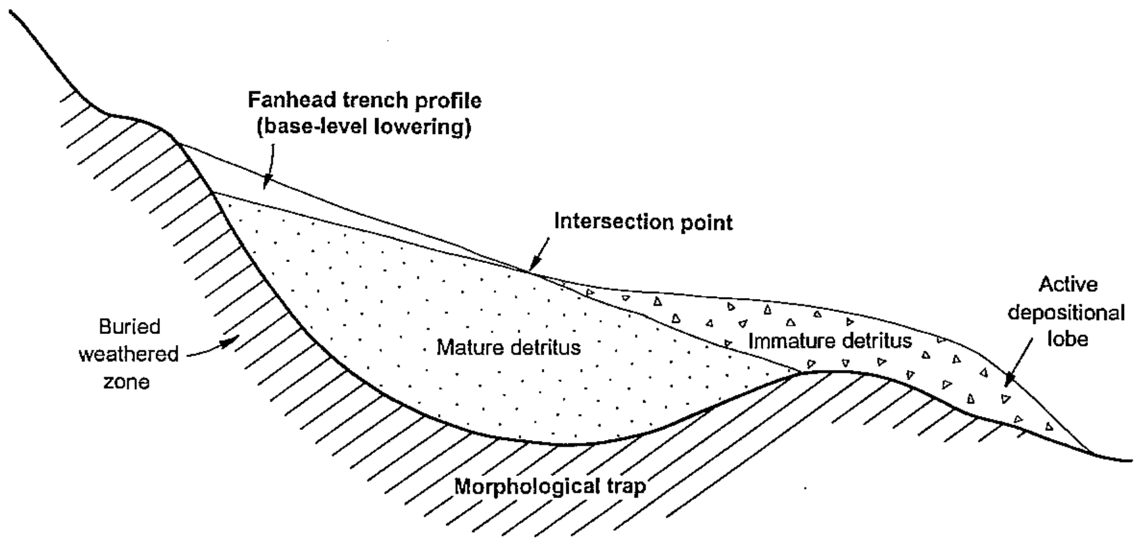

Figure 54. Conceptual model showing section of sites of flow expansion and gradient reduction.

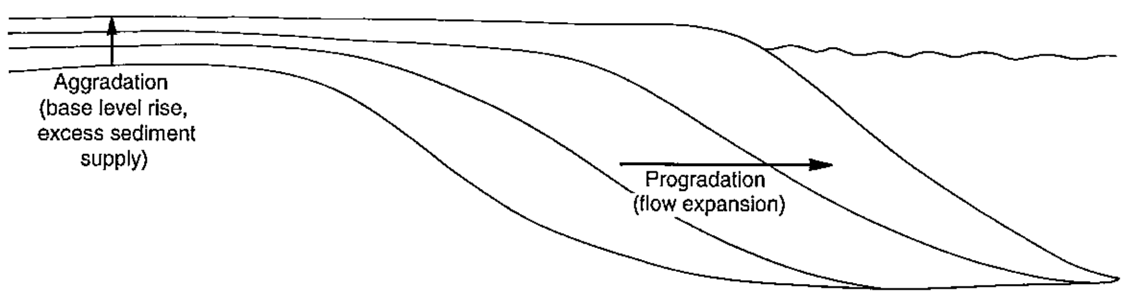

Figure 55. Conceptual model showing section through sediments deposited because of base level rise in conjunction with excess sediment supply or flow expansion.

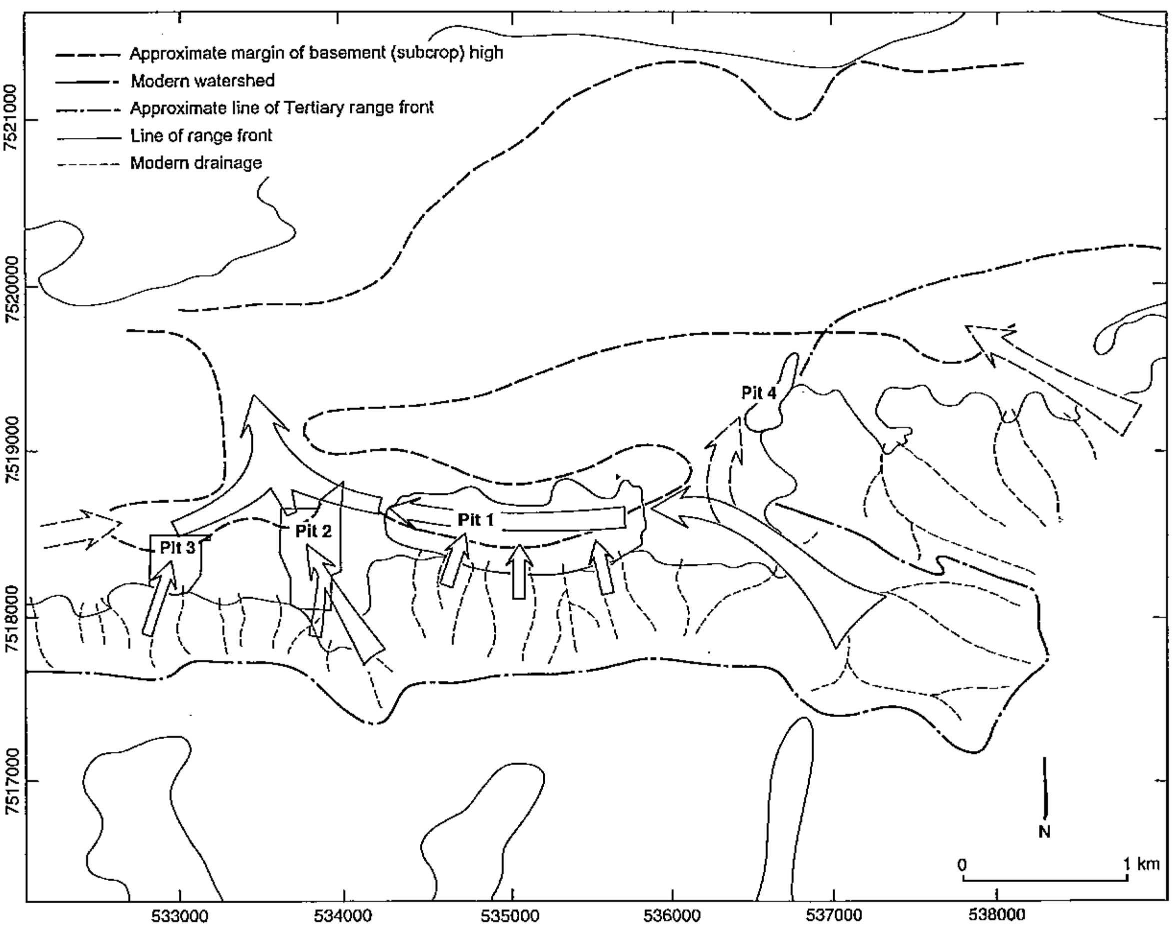

Figure 56. Map showing the relationships between outcrop and subcrop topography, commercial deposits, inferred catchment (source) area and palaeodrainage patterns for the Brockman Valley West for period of mature detritus deposition. Pits are located at sites where topographic highs enhanced combination of axial and marginal sedimentation.

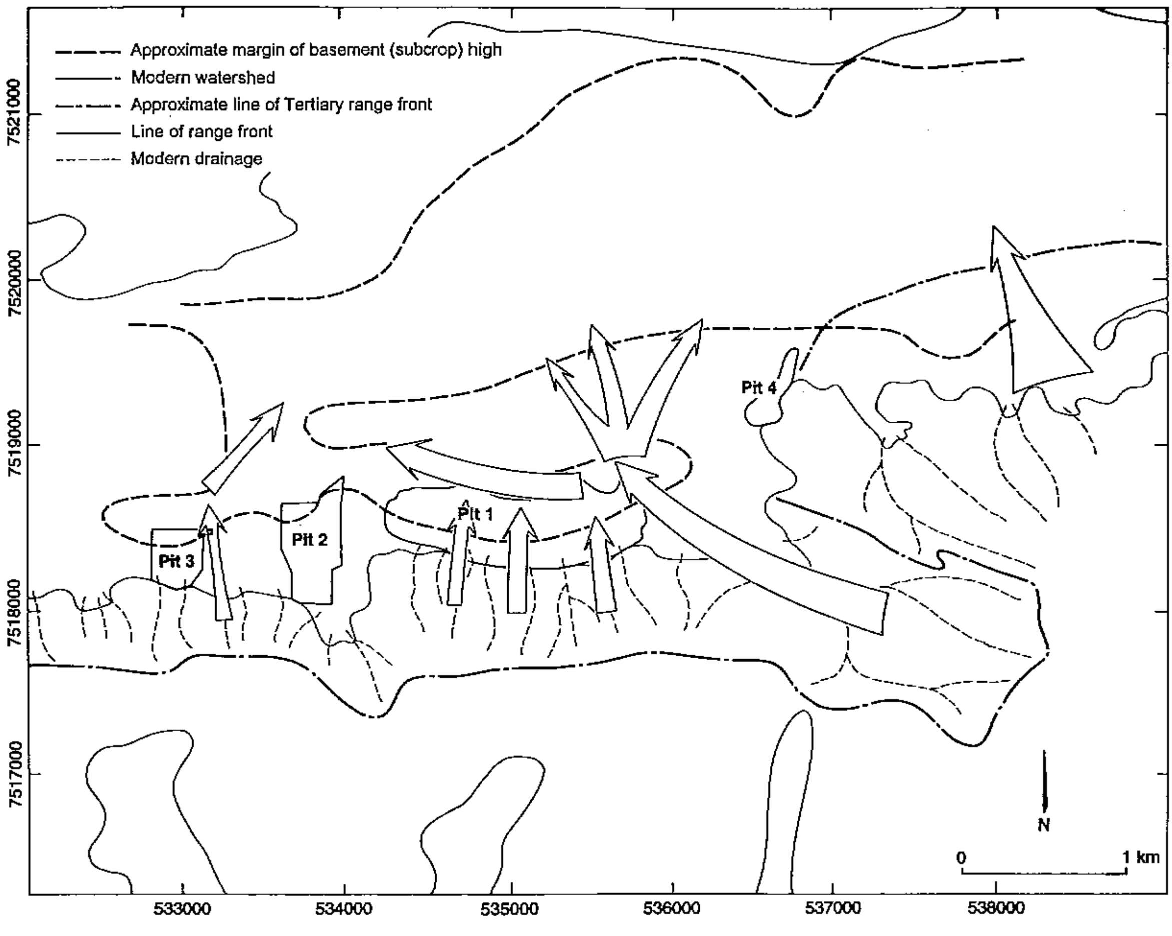

Figure 57. Map showing the relationships between outcrop and subcrop topography, commercial deposits, inferred catchment (source) area and palaeodrainage patterns for the Brockman Valley West for period of immature detritus deposition. Note that main range-parallel channel axis has migrated north to the margin of Pit 1, and that pattern of other channel axes shows re-orientation from range-parallel to range-normal directions.

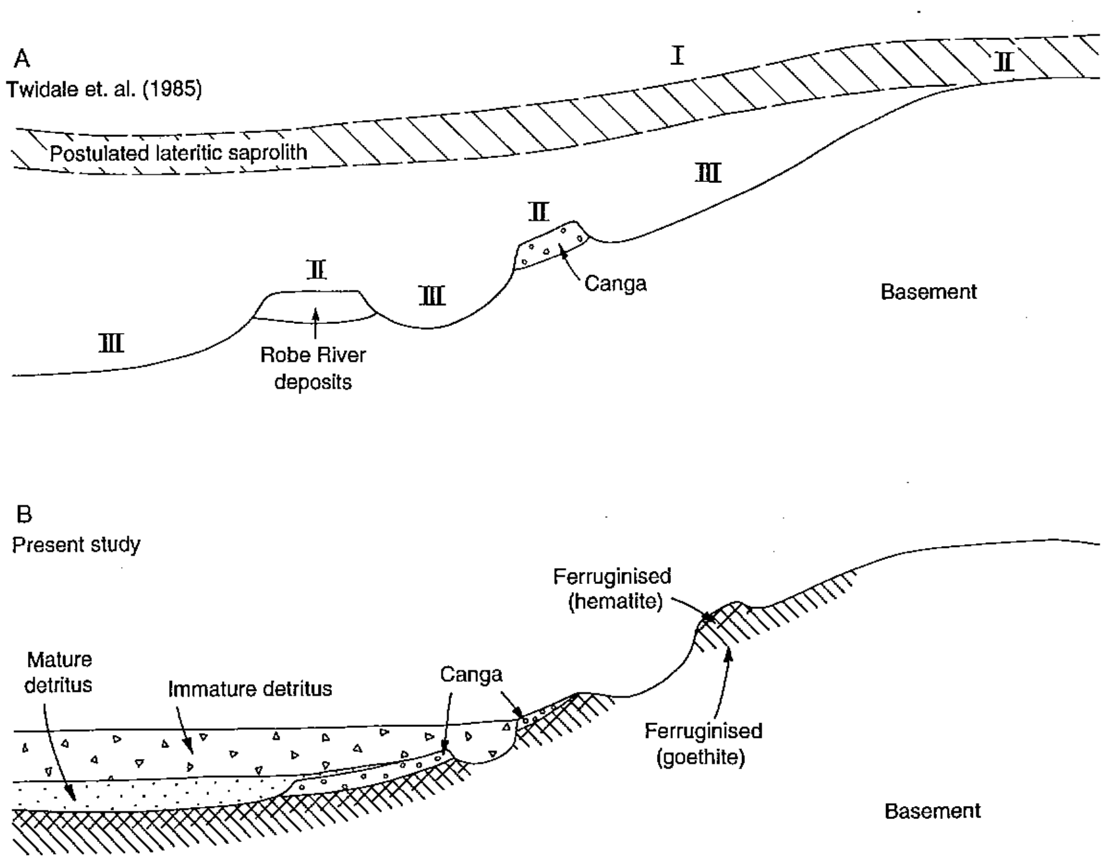

Figure 58. Two contrasting generalised landform models for the Hamersley region. Twidale *et al.* (1985) proposed that a postulated weathered zone was developed on a landscape of low relief, the Hamersley Landscape I. The weathered zone was then eroded, valleys were cut below the level of the upland complex, and some stripped weathered material was deposited (*e.g.* as Robe Pisolite) in the second landscape, the Hamersley Landscape II. This landscape has subsequently been dissected to form the (modern) Hamersley Landscape III. The present study demonstrates that deeply weathered (laterite) profiles of probable Tertiary and older age are commonly preserved in outcrop and underlying all depositional elements at low levels in the modern landscape. The modern landscape is significantly older and much more stable than has been previously recognised.

7 LANDSCAPE EVOLUTION

7.1 Introduction

This section examines our findings in favour of a weathered source for mature detritus (Section 4) in comparison with the results and interpretations previous work on weathered landscapes of the region.

We consider the potential causes of erosion of weathered material and its transport and deposition, and the possible volumes of material affected by this process.

7.2 The Hamersley Surface

The intention of the term "Hamersley Surface" is to convey the concept of a landscape of significant but smoothly rolling relief, with bedrock supporting a blanket of deeply weathered material "laterite crust" (Campana, 1964).

Twidale *et al.* (1985 fig. 3, Fig. 58) postulated the former presence of a high level lateritic Hamersley I Landscape of subdued relief, and that modern valleys hosting canga and Tertiary Pisolite crusts were incised after removal of this crust. Physical evidence supporting the postulated Hamersley Surface is patchily preserved in the study areas. High level areas have generally been stripped back to relatively fresh rock, although some saddles and other local topographic depressions retain pockets of *in situ* or probably locally derived weathered material.

This report finds that weathered zones (not noted or figured by Twidale *et al.*, 1985) are best preserved in the bases and lower margins of valleys, and as the ferruginous crusts and underlying saprolite of the Tertiary Pisolite. These *in situ* weathered elements patchily link with the "smooth" rolling surfaces preserved on some BIF units at high- and intermediate levels (Fig. 3).

7.2.1 Discussion

There is no evidence to support the landscape model proposed by (Twidale *et al.*, 1985). In the absence of bedded mineralisation, their proposed removal of the laterite zone prior to valley incision leaves no source for mature detritus. The preservation of weathered zones overlain by canga and Tertiary pisolite crusts in the flanks and floors of the valleys of the study areas, and their conformity with the current topography, indicates that significant elements of the modern Hamersley landscape have been stable since the Tertiary and earlier.

7.3 Palynology

Morris (1994) reviewed the available palynological evidence for the age and climatic conditions of mature detritus deposition from five Pilbara sites. The earliest ages are Early Cenozoic to uppermost Cretaceous from samples believed to have been obtained from the base of the Superband sequence. Late Oligocene to Middle Miocene ages have been obtained from below CID deposits at Yandi, Robe and Hope Downs. A Pliocene age for Brockman "proper" type detritus appears to be inferred on the basis of stratigraphic position.

These data suggest that during the Tertiary, the climate of the Pilbara region evolved from temperate-humid to more arid conditions. Flora typical of a cool-temperate climate were present until the Mid-Miocene. Palynology reports repeatedly stress the occurrence of swamps and other open fresh-water environments at this time. By the Early Pliocene, xerophytic plants of more arid affinities were established. The intervening Late Miocene is suggested as a period of climatic and vegetative transition. On the basis of these ages, Morris (1994) proposed the sequential development and erosion of three distinct weathered landscapes.

The first was the Tertiary Ore Detritals 1, where detritus derived mainly from mineralised Marra Mamba Formation were deposited in deeply scoured strike valleys developed along Marra Mamba Formation/Wittenoom Dolomite contacts.

The second was deposition of the CIDs on weathered basement. These represent the "*final product of an extremely mature, often meandering drainage system.. ..in places eroded into Tertiary Ore Detritals 1*", and not conforming to the underlying geology. At this time, the Hamersley Range was blanketed by a deep weathered mantle, which together with mineralised wood fragments, was the source of detrital clasts. They were subject to further mineralisation by ferruginous ground waters in a generally waterlogged landscape.

By the end of CID deposition, the laterite surface had been stripped and the valleys of the region had been filled with indurated iron deposits. Their resistance to erosion caused the locus of incision to migrate from the carbonate-floored to the shale floored areas of the Wittenoom Dolomite strike valleys. Weathering of exposed bedded mineralisation in the Dales Gorge Member at Brockman led to the development of "carapace ores". These were then eroded and deposited in a Brockman Valley largely (initially) stripped of sediment as the Tertiary Ore Detritals 3. Eventually, the inferred body of bedded mineralisation was removed, and exposure of the underlying BIF led to evolution from mature to immature detrital deposits.

7.3.1 Discussion

Assignment of ages to specific deposits fixes them in time and space, it does not necessarily indicate stepwise alternation or switching between discrete processes (*e.g.* lateritisation 1 - stripping 1; - lateritisation 2 - *etc.*). Local erosional and depositional events are common in modern landscapes, even where they are stable and dominated by weathering. We see no reason why these conditions should not have applied in the Tertiary, and therefore it seems appropriate to consider landscape modification to operate as a set of sub-continuous processes.

7.4 External Controls on Erosion and Sediment Storage

If the modern remnants of weathered zones are indicative of their previously more extensive development, then it is necessary to consider the likely conditions under which they were formed and the changes which caused their removal.

7.4.1 Climate

In areas receiving regular precipitation and with well established vegetation cover, landscapes tend to be relatively stable, and erosion is dominated by chemical dissolution. Physical transport tends to be restricted to removal of fines in suspension.

Where precipitation is erratic, especially in arid conditions, suppression of stabilising vegetation and the flashy nature of runoff encourages erosion. Given the established transition from cool-humid to more arid-seasonal condition, it is reasonable to assume that the erosion of a relatively stable and deeply weathered mantle (laterite) may have been precipitated by climatic change.

7.4.2 Base Level

The study areas are situated at about 450 metres above sea level and higher. No evidence for Cenozoic tectonism has been seen. Continental collision between the Australian and Eurasian plates (Veevers, 1988), may have caused regional uplift, but published evidence for this is not known to the authors. During the early Eocene, global sea level reached a Tertiary high of about 200 metres above current levels, and has been falling cyclically in the short term but consistently in the long term since then (Haq *et al.*, 1988).

The current difference in relief between the Tertiary Pisolite deposits of the Nammuldi Plain and its incised modern river system (Duck Creek) immediately downstream of the Brockman study area, is greater than 40 metres. Lowering of the base level of Duck Creek has caused its tributaries near Brockman to evolve from gulleys to gorges, breach the Marra Mamba Formation and capture the internal drainage of the Brockman Valley. Base level lowering of the Beasley river has had a similar effect at the south side of the Brockman area.

Base level lowering has caused the Fortescue River to incise to about 60 metres below the local Robe deposits at Millstream. This incision has not progressed sufficiently far upstream to influence erosion in the Mount Sheila or Mount Margaret areas.

Incision and erosion of the immature deposits of the Brockman Valley, and there is now greater than 30 metres difference in relief between the deepest incised sections and the playa watershed at Silvergrass Plains. The erosion of immature sediments has not excised mature detritus in the northern Brockman Valley. The lack of exposure of mature detritus at Brockman, combined with the failure of the headward incision of the Fortescue river to penetrate to the Mount Sheila and Mount Margaret study areas, indicates that base-level reduction is not responsible for significant loss of mature detritus in these areas.

7.5 Mass Balance

A test for the validity of the proposed weathering process as a regional source for mature detritus is presented below. This is a calculation of the potential mass of hematite which may be generated by weathering of the area defined in Fig. 56 (Table 3). The calculation is made for the catchment interpreted to have supplied Brockman Pits 1, 2 and 3. The boundaries of this area are defined by the line of the watersheds to the south and east, the 650 metre contour to the north, and the meridian of the western end of Pit 3. For comparison, Brockman Pits 1, 2 and 3 are calculated to contain about 36 million tonnes of mineralised detritus (Hamersley Iron data).

Table 3. Calculation of the potential mass of hematite generated from weathering of the area interpreted to have supplied Brockman Pits 1, 2 and 3 (defined in Fig. 103).

Area	4 620 000 m^2
x2 metres hematite	9 240 000 m^3
x5 tonnes m^{-3}	46 200 000 tonnes Total

(SG hematite=5.256, Deer *et al.* 1978).

The calculation depends on the simplifying assumptions:

1) The current land surface is grossly conformable with the Tertiary landscape.
2) The potential source area has not changed significantly.
3) The entire source area contributed two metres thickness of hematite.
4) There was a single mineralisation and stripping event.

7.5.1 Discussion

We have no reason to doubt the validity of assumption 1), although it is conceivable that the source area extended further south along the major gulley running in to the Brockman Range during the Tertiary. Assumption 3) is a set on the basis of our field observations of weathered zones in the study areas. At some locations in the Brockman area (*e.g.* AMG 545611: 7519362) thicknesses of between 6-10 metres of hematite mineralisation are preserved on spurs. The thickness of hematite removed from these outcrops since the Tertiary (if any) is unknown. Logic suggests that it is unlikely that weathering and subsequent stripping were single and un-related events, and there may have been a regular supply of mineralised sediment to the Brockman mine site area prior to the final stripping.

We have deliberately adopted a set of conservative assumptions for the calculation. The result is particularly sensitive to assumption 3). Despite this, it is clear that a weathering model can yield mature detrital volumes of similar magnitude to those preserved in the Brockman mine-site area without recourse to a significant contribution from bedded- or post-depositional mineralisation.

8 SUMMARY AND CONCLUSIONS

8.1 Introduction

We propose below a theory to unify the data and landscape evolution models of previous workers with our observations and interpretations. This theory simplifies the earlier work, replacing the three discrete stages of Twidale *et al.* (1985) and Morris (1994) with a single evolutionary progression. Our model invokes climatic change as the controlling factor in the evolution from a weathering-dominated dynamic steady state, to one dominated by erosion.

The model uses established palynological evidence for climatic change and sedimentological process-response theory to explain:

1) the preservation of weathered zones at topographically low levels and subcrop;
2) the widespread occurrence of hematite-rich and silica-deficient sediment (mature detritus), overlain by a heterogeneous mixture of mineralogically immature sediment;
3) the change from meandering river (Tertiary Pisolite/CID) to braided river systems;
4) the development of alluvial fans.

8.2 Regolith Terrain Analysis Model

A dynamic balance between rates of weathering and erosion controlled the interplay between development and preservation of the weathered crust, its erosion, transport, storage and/or removal from the region. For an extended period prior to the Mid-Miocene, the landscape of the region was one of extreme stability. Climatic conditions favoured weathering, resulting in continuous evolutionary pressure to develop and maintain ferruginous crusts, despite local erosion. Crusts developed over BIF retained their microstructure despite alteration to hematite. Shale substrates were altered to more amorphous and pisolitic material, while carbonates were subject to dissolution and deflation.

Landscape stability was maintained by weathering keeping pace with, and compensating for erosion. Where local erosion removed ferruginous crusts and underlying goethite zones, exposed BIF would have been resistant to further erosion and subject to a renewed cycle of weathering and ferruginisation. While of local importance, exposed pockets of BIF did not have made a significant regional contribution to sediment deposits.

Late Miocene climatic change, from humid to more arid and erratic seasonal conditions, reduced vegetation cover, which caused destabilisation of the weathered mantle. Weathering rates were unable to maintain balance with increased erosion rates, causing stripping of the weathered mantle from upper slopes and hill tops, and leaving fresh BIF exposed.

Major storms generated slides, slumps and debris-flows on unstable slopes. These flows accumulated at sites of flow expansion or slope reduction. Non-catastrophic events re-distributed the more mobile sediments downstream, and carried P-rich clay size-fraction sediments out of the system in suspension. Increased supply caused sediment to accumulate on the lower slopes of hills and in valleys, burying and preserving the weathered mantle in lower-lying areas. Supply of sediment exceeded the capacity of the now reduced fluvial systems to transport it, causing a change from lateral- to vertical accretion, and evolution of channel systems from meandering to braided.

The weathered crust was stripped sequentially, with hematite-rich mineralised BIF and ubiquitous pisoliths being the first to be removed and deposited, followed by goethitic material from the lower hydrated zones. As the source areas were stripped of readily mobilised material, transport systems evolved from sediment-rich (non-erosive) debris-flows to sediment-poor (erosive) flash floods. Introduced sediments became restricted to BIF clasts, which mixed with re-mobilised goethitic and mature hematite sediments where available. The progressive stripping of weathered zones led to sequential deposition of hematite-rich sediments, overlain by goethite rich sediments, creating an inversion of the *in situ* weathering stratigraphy.

The basement unconformity preserves significant elements of the Tertiary landscape, although weathered zones have been eroded from some areas. Structural and erosional lows in the resultant surface have the demonstrated capacity to retain commercial deposits of mature detritus. Alluvial fan, sheetflood and fluvial facies are recognised in subcrop. Mature detritus deposits are preserved where they were cemented, or were by-passed by later, erosive systems. By-passing was controlled by factors intrinsic to sedimentation, including excess supply of sediment, choking and causing avulsion of channel systems.

The preservation of weathered zones underlying modern rangefront spurs and re-entrants, demonstrates that the morphology of the study areas typically follows the Tertiary landscape. Scoured sediment traps are likely to be situated at the mouths of the Tertiary drainage systems. The presence of structural traps may be inferred from outcrop expression of faults and folds. Where conditions favouring preservation apply, traps may preserve commercial deposits of mature detritus.

The modern regional dominance of erosional over depositional landforms and lack of development of weathered surfaces indicate that the landscape has not yet attained stability. Valley fill sediments (mature and immature) are in temporary storage, and in the process of being transferred out of the study areas. Base level reduction may have caused erosion and loss of sediments from the region, but has not had significant effect on mature deposits in the study areas.

9 RECOMMENDATIONS

9.1 Potential Exploration Targets

9.1.1 Sediments

The greatest potential for deposition of commercial deposits of mature detritus exists where either of both of the following conditions are met.

1) Where transport systems change from being confined to unconfined, *e.g.* on exit from a confined channel to the unconfined surface of an alluvial fan, where channels broaden, or on encountering standing water (Fig. 53).

2) Where transport systems encounter a significant reduction in slope, *e.g.* passing from the range front to the valley floor (Fig. 54).

Concentration of mature detritus is enhanced where flow from a significant catchment has passed through a constriction such as a narrow gulley of gorge prior to flow expansion or gradient reduction.

Preservation of mature detritus is enhanced where these deposits were by-passed by the systems responsible for the transport and deposition of immature detritus. By-passing may occur where one or more of the following conditions are met:

1) By virtue of position (on lateral margin of fan, Fig. 53).

2) In structural or morphological traps (where mature sediments are preserved in topographic lows, Fig. 54).

3) Where base-level has been raised (thus preserving deposits, Fig. 55).

4) Where base level has been lowered (thus causing incision and "marooning" as terraces, Figs. 53 & 54).

9.1.2 In Situ *Mineralisation*

The demonstrated preservation of weathered mineralised zones and the fold geometry in areas such as Brockman require mineralised BIF to be present under the sediment cover. If present in sufficient volume, sites of *in situ* weathering mineralisation may prove to be an attractive exploration target.

9.2 Implications for Exploration

9.2.1 Geomorphology

With some exceptions (*e.g.* Figs. 42, 56; below), the modern surfaces of the hills and ranges of the study areas follow the morphology of the Tertiary landscape. This is demonstrated by the common preservation of ancient weathered zones on the lower slopes of hills. Weathered bedrock is particularly well exposed in section in the south wall of Brockman Pit 1, where the pattern of a (hematite-rich) ferruginised zone overlying a bleached zone of basement precisely follows the spur-and-gulley morphology of the present surface (Fig. 42). Preservation of this pattern of iron re-distribution suggests extreme landscape stability.

Figure 49A shows that a number of depressions are incised deeper than the neighbouring sub-surface basement immediately adjacent to the outlets of re-entrants from the range front. Parts of Brockman Pit 1 and (especially) Pits 2, 3 and 4 are preserved in these depressions. We propose that these features are scours which were eroded at the sites where the steeply descending flows in the larger channels were diverted by contact with the lower slopes of the valley floor.

If the argument (above) for landscape stability is accepted, then it is reasonable to use the current location of gulleys, channels and re-entrants (particularly where they are incised into weathered basement) as guides to the position and scale of Tertiary drainage systems. Favourable trap sites are likely to be situated immediately downstream from the mouths of the larger systems. Where conditions favouring preservation apply (Section 6), mature deposits may be present in commercial volume.

9.2.2 Exceptions

To the east of the Brockman Pits (Figs. 14, 56) a large volume of outcrop has been eroded, causing up to about 400 metres of range front retreat. This situation is possibly analogous to the majority of the length of range front north of Caves Creek and at Homestead in particular. In these areas there is little preservation of Tertiary weathered zones in outcrop. However, the Brockman Valley basement unconformity map (Fig. 49A) shows that the palaeotopography is largely preserved in subcrop. The Tertiary position of the range front is marked by an isolated outcrop of mineralised BIF overlain by canga. The area of range front retreat is marked by the presence of a shallowly buried basement shelf.

Brockman Detrital Lens C is preserved in a scour developed in re-entrant in the northern margin of this shelf. This geometry suggests that even where significant outcrop erosion has occurred, subsurface trap sites and their fills of mature detritus may be preserved. The absence of outcrop evidence for the location of these sites requires drilling for their identification. In these circumstances, drilling programmes should follow the margins of shelves.

9.3 Further Research

This study is a first formal attempt to attain a better understanding of those processes responsible for the mineralisation of BIF and the transport, deposition and storage of that mineralised material. We are confident that our conclusions are well supported by the evidence presented, particularly with respect to the transport, deposition and storage of mineralised materials. However, resource limits (most notably time) have meant that some proposals remain untested and certain questions unanswered. We believe that further quantitative and qualitative analysis of weathered profiles is required to test our source model hypothesis.

We believe that the following areas of research would repay study.

9.3.1 Quantitative Description and Analysis of Weathering Profiles

We have proposed the development and subsequent stripping of three-tiered weathered profiles (Section 4) as the principle source of mature detritus in the study areas. Evidence supporting this proposal includes the apparent petrographic continuity between *in situ* and detrital mineralisation, the general absence of siliceous BIF from mature detritus and the widespread preservation of weathered profiles comprising goethite capped with hematite. The validity of this proposal needs to be tested by quantitative analysis of the mineralogical and petrographic characteristics of these profiles. The work programme should comprise:

1) description and sampling of weathered zones from a number of sites in order to determine their common characteristics and the nature and range of variability;

2) petrographic analysis to establish the petrogenesis of hematite in zones of surface weathering;

3) comparison of the texture and mineralogy of samples from weathered zones developed on BIF, with fresh and weathered bedded mineralisation and mature detritus.

The juxtaposition of the Brockman 2 bedded and detrital mineralisation provides an opportunity to test the weathered BIF source model. Microplaty hematite is present in the bedded mineralisation, but has not been recognised in neighbouring weathered BIF crusts. Comparison of the abundance of microplaty hematite in mature detritus with its abundance and distribution in likely source areas may demonstrate the relative contributions of those sources.

9.3.2 Three-Dimensional Modelling

Unconformity surface and isopach maps generated from the Hamersley Iron data have revealed the geometry and distribution of different sets of sediment fills in the Brockman Valley. This information has been essential to the understanding of trapping mechanisms and the identification of potential exploration targets (Section 6). The full potential of this data modelling has not been realised in this study due to time- and software constraints. CSIRO now have access to a software package (EarthVision) which has been specifically designed for 3-D modelling of geochemical data.

We believe that the data are of sufficient quality to justify a dedicated modelling program. This program would be designed to identify and map the alluvial fans, channels, overbank deposits and lake sediments which make up the mature and immature sediment packages. It is proposed that this programme would help quantify the relative influence of different depositional systems to the sum total of mature detritus. This would enable better focus for exploration activity (*e.g.* whether commercial deposits are dominantly alluvial, fluvial or mixed in origin), and predictive modelling of transport systems (*e.g.* the size, direction and position of fluvial channels).

9.3.3 Regional Mass Balance Modelling

A simple mass balance calculation for the potential mass of hematite available to the Brockman mine (Pits 1-4) has been presented in this report (Section 7.5). A regional study using the Hamersley Iron database would allow better comparison of the potential mass with the preserved mass.

This comparison would illustrate the relative efficiency of depositional *versus* erosional events, and highlight any areas of enhanced deposition or preservation of sediments. This would improve our understanding of the controls on mature detritus distribution, most specifically in identifying whether the sediments are evenly distributed or whether their are any sites of enhanced storage of sediments, which post-date sediment mobilisation. It is possible, for example, that the sediment re-distribution has not reached a steady or balanced state, and there are localities where sediment has been brought in, the transport systems have not evolved sufficiently to carry them through.

This exercise would be relatively easy to complete using published maps and the Hamersley Iron database.

9.3.4 High-Resolution Shallow Seismic Reflection Survey

Where the basement unconformity is buried by greater than 20-30 metres of sediment (a likely requirement for commercial deposits), its position and relief should be resolvable by high-resolution shallow seismic reflection survey. In the case of the Brockman 2 morphological trap for example, the base of the sediment column (*Section 6.3.1*) is situated at 50-60 metres below ground surface. This technique offers the advantages of being a rapid and low impact reconnaissance exploration method for the location of potential trap sites. It gives continuous coverage between drill-holes, and can therefore identify structures smaller than the standard exploration grids. It also gives more precise delineation of the shape and nature of unconformities than interpolation between drill-holes.

It is proposed that a pilot high-resolution shallow seismic survey be run across an area of interest to Hamersley Iron. The Homestead site may be particularly suitable, offering an apparent variety of trap-site morphologies, and giving the opportunity to test the findings if mining commences.

9.3.5 Geochemical Fingerprinting

We propose a regolith characterisation study, to test for a geochemical or mineralogical signature for the presence of blind mineralisation under a cover of transported overburden.

Also, this study should test for any geological or geochemical controls on the apparent differences in degree and type of mineralisation (*e.g.* massive versus pisolitic hematite) between the Dales Gorge and Joffre Members, and between BIF and the sale units.

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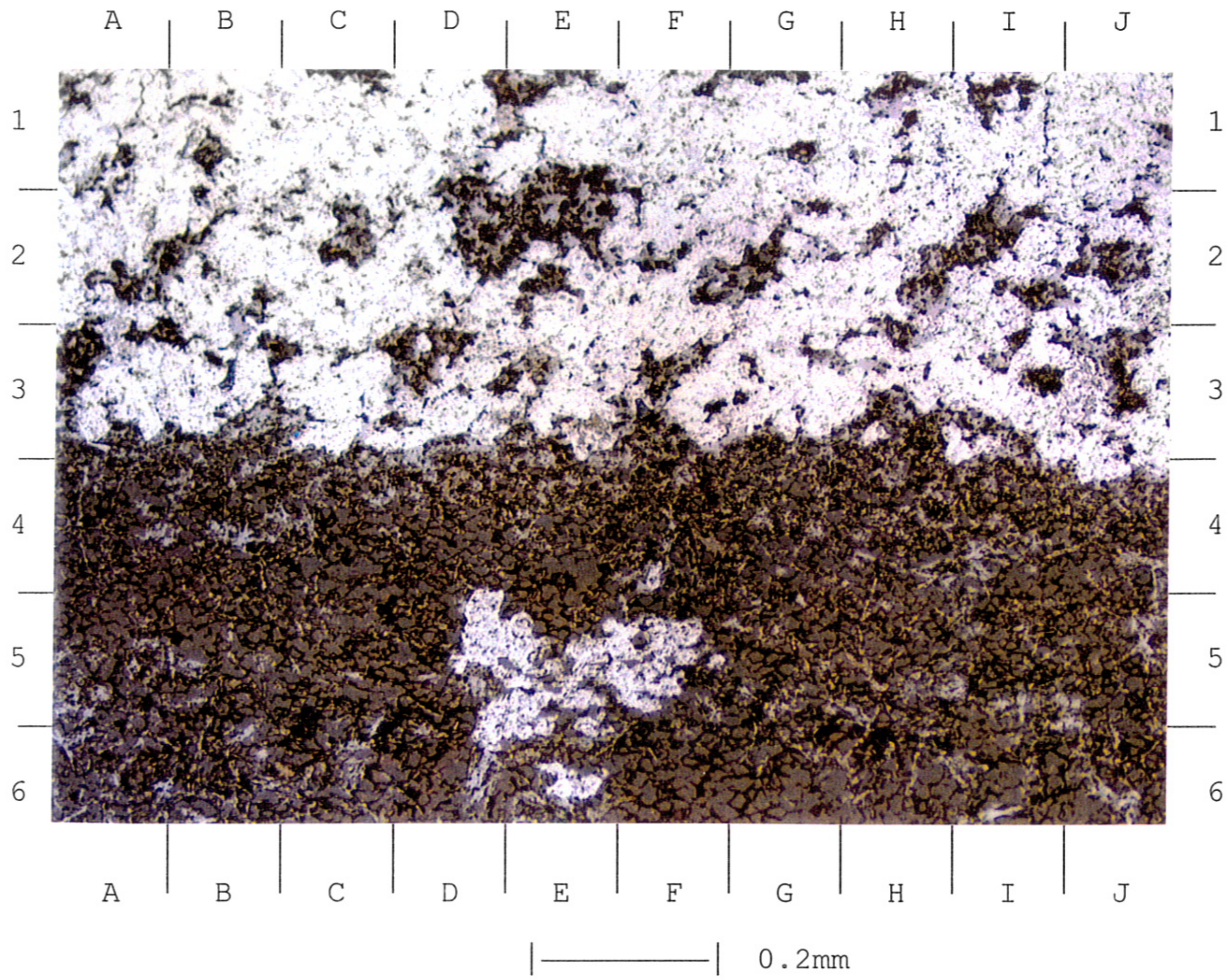
APPENDIX 2

DESCRIPTIONS OF REGOLITH MATERIALS

Petrographic descriptions and photomicrographs of a representative suite of *in situ* and transported samples from all of the study areas. Chemical analyses are presented in Table 2. Samples were prepared as polished blocks and examined and photographed under reflected light. Samples are classified according to their location at the time of collection, and their degree of alteration.

BIF

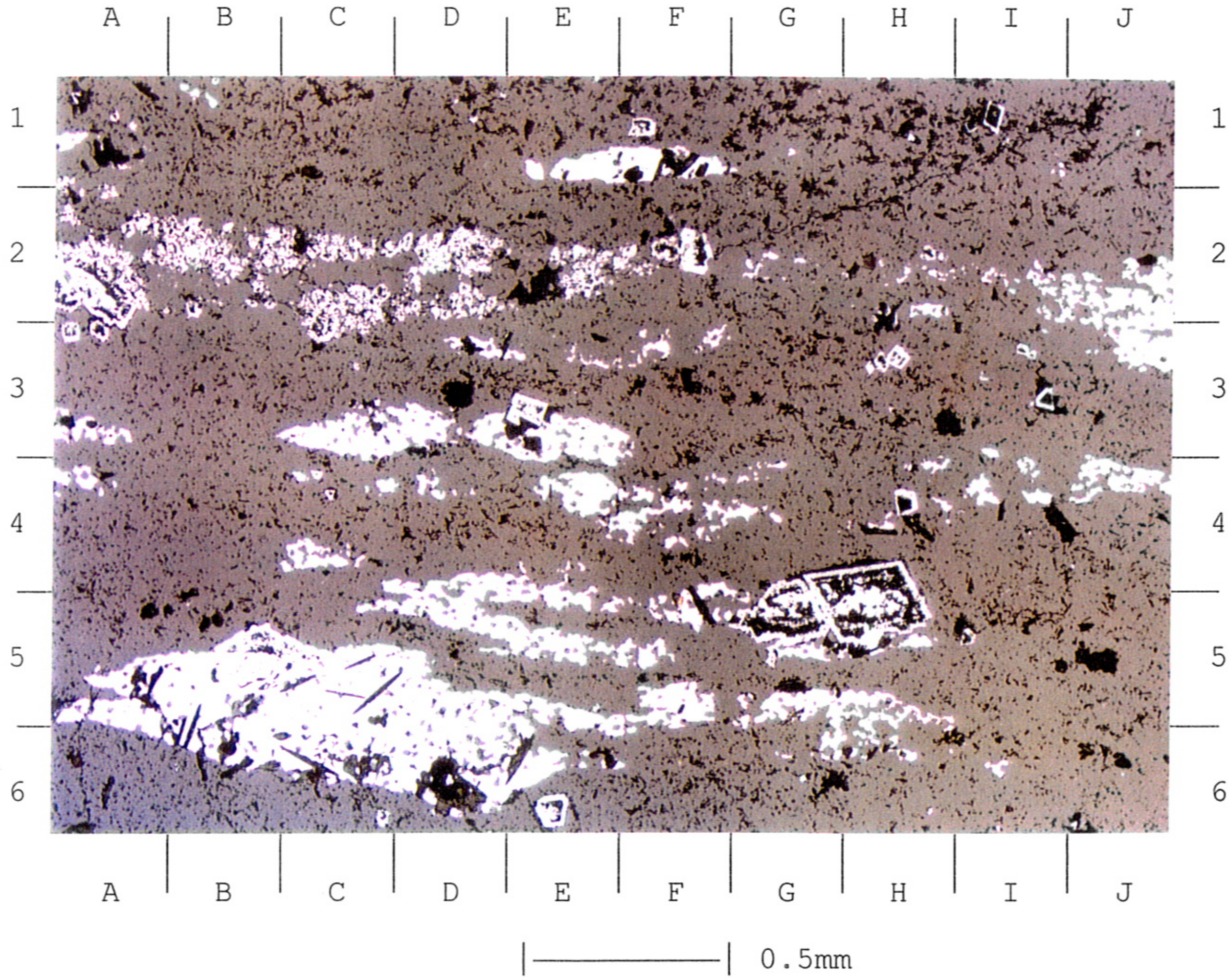


29/8/95/4A

Part mineralised BIF. Laminated silicate grading into laminated sections comprising hematite (martite?) and goethite. The silicate matrix of the sample is "brecciated" with and has been invaded by clay size-fraction goethite. Some of this goethite appears to have been altered to crystalline goethite in a fibrous form.

Photomicrograph

Interlaminated layers of hematite and goethitic silica in part-mineralised BIF. Hematite (top) is rich in goethite inclusions. Siliceous layer comprises mosaic of relict ferruginised silicate crystals separated by anastomosing network of clay size-fraction goethite (dark brown, e.g. F6) goethite.

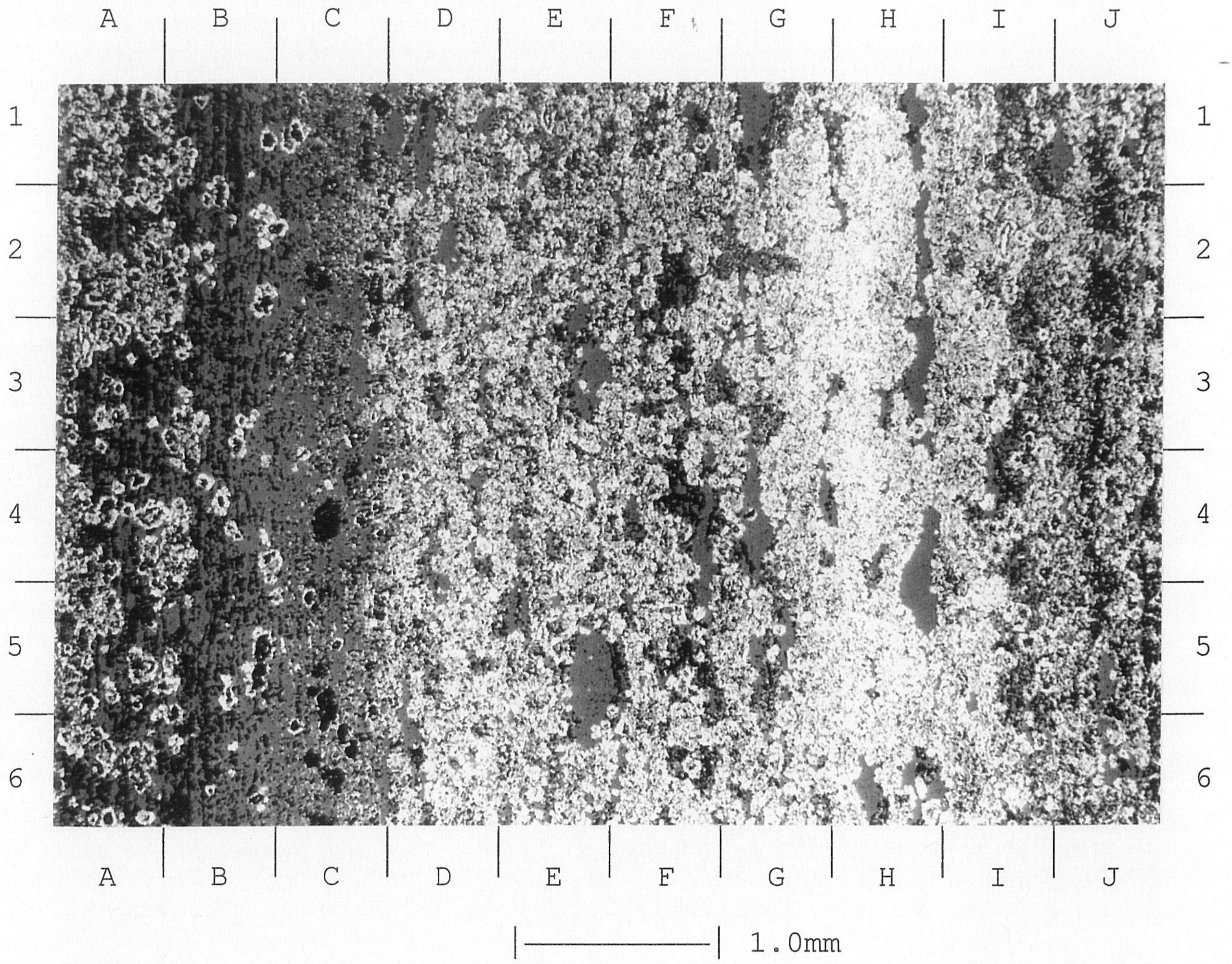


29/8/95/4

Immature detritus. Mainly pink silicate with laminae of hematite. Some hematite crystals are euhedral and appear to have replaced carbonate (rhombic, zoned) or magnetite. Some bladed/spindle-shaped crystal voids are also present. These generally contain clay size-fraction goethite. Sample has probably been metamorphosed (hence isolated martite crystals) but had not been mineralised prior to alteration.

Photomicrograph

BIF clast from immature detritus. Siliceous matrix (brown) is Fe-rich (goethite). Bright areas are hematite. Rhombic hematite (e.g. E6, H4-5) is pseudomorphous after carbonate and has corroded goethite cores.



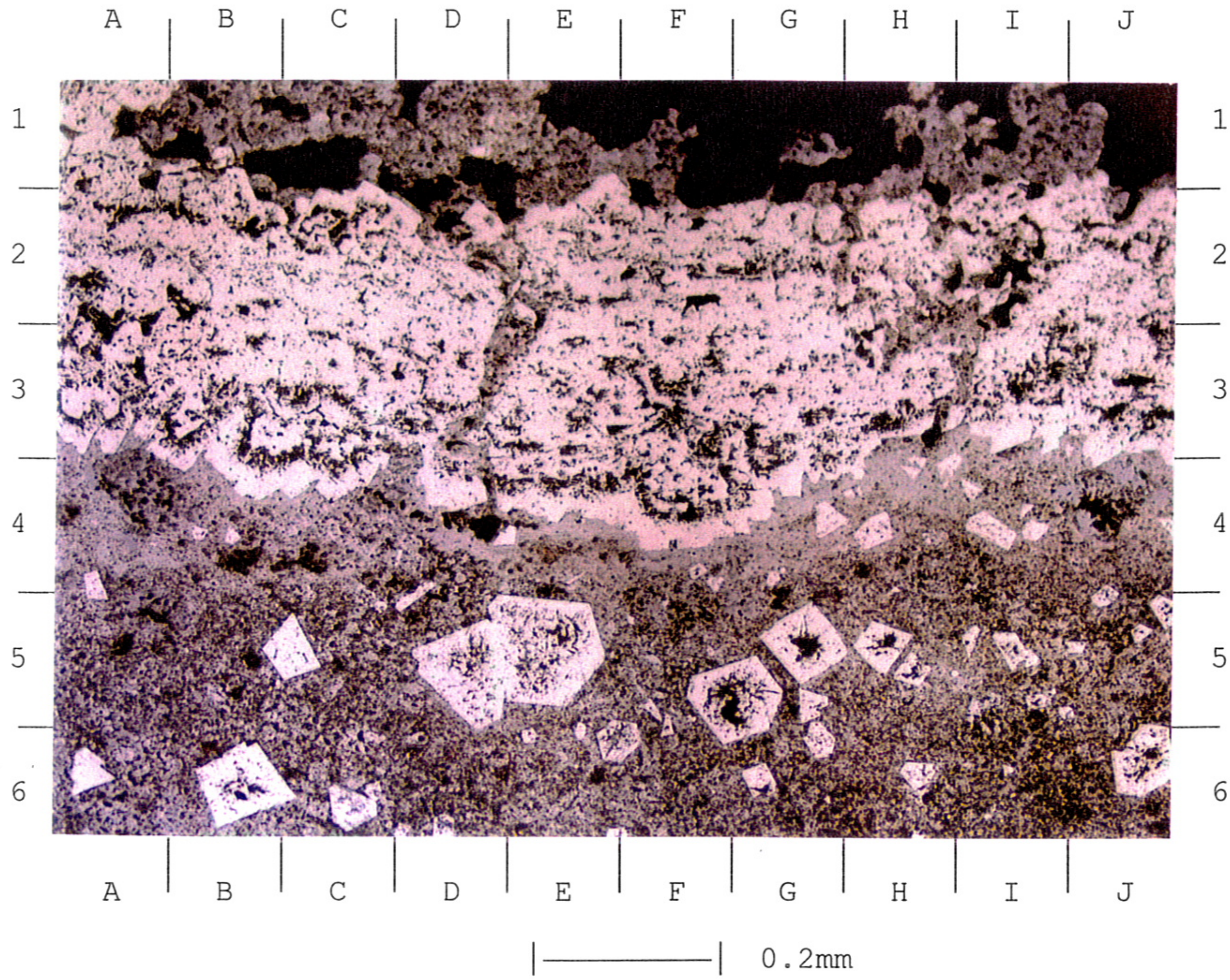
21/8/95/3

Part mineralised BIF. Laminated silicate grading into laminated hematite (martite?). Some hematite are strongly zoned with clay size-fraction goethite replacing cores.

Photomicrograph

Hematite (bright) interlaminated with siliceous laminae (mid brown) in part-mineralised BIF. Rhombic hematite crystals (left) are pseudomorphous after (probable) carbonate. These crystals have dark cores of clay size-fraction goethite.

Mineralised BIF

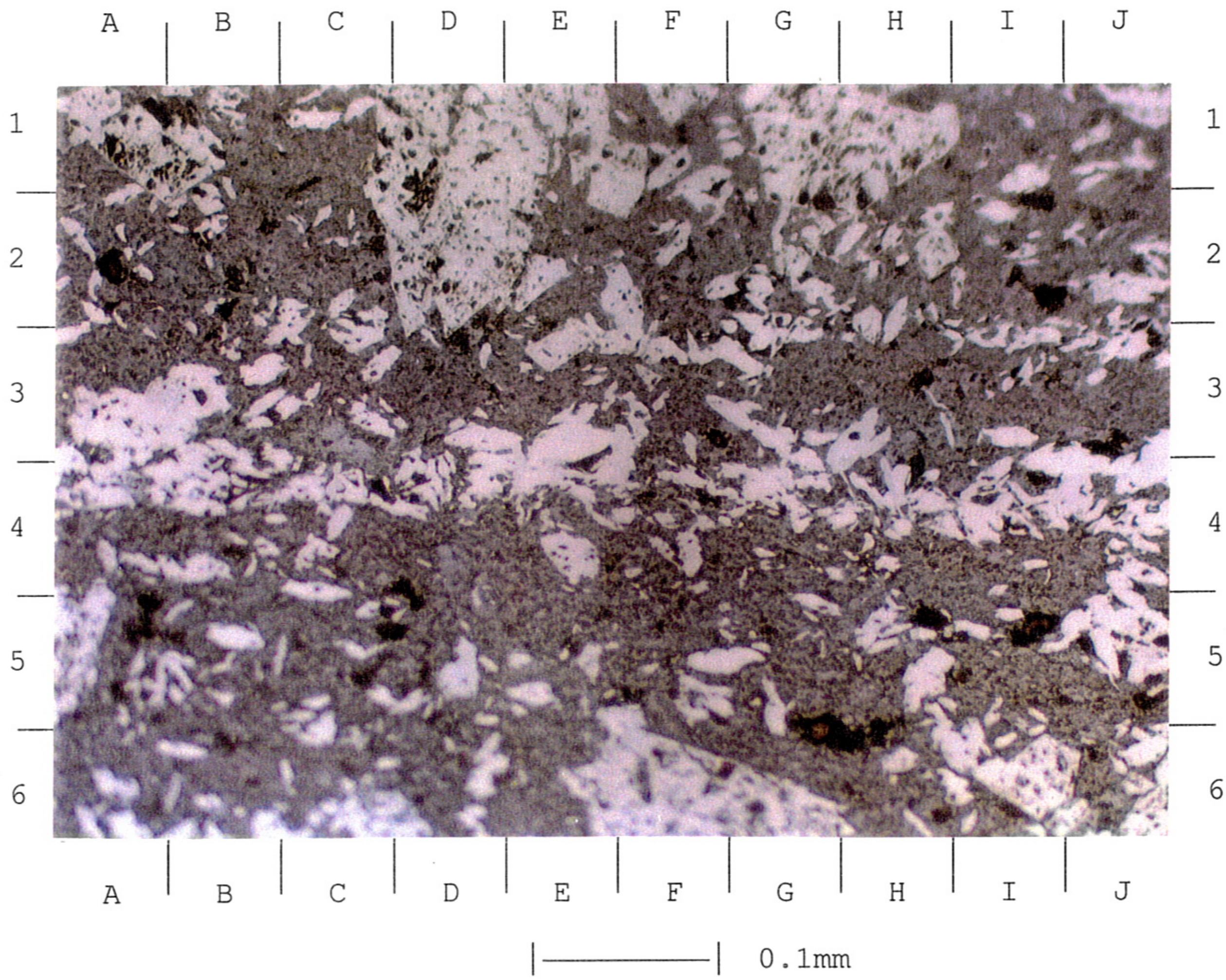


15/8/95/3

Mineralised BIF. Interlaminated hematite and goethite. Two phases of goethite (including fibrous cement, with vugs filled with chert) are present. Hematite crystals have numerous inclusions probably derived from replacement of crystalline goethite.

Photomicrograph

Interlaminated hematite (upper) and goethite (lower) laminae. Goethite matrix supports hematite crystals pseudomorphous after probable carbonate. These crystals have clay size-fraction goethite cores. Hematite lamina is rich in goethite inclusions except where rim of euhedral hematite crystals have developed in crystalline goethite along boundary of the laminae (A3-J3).

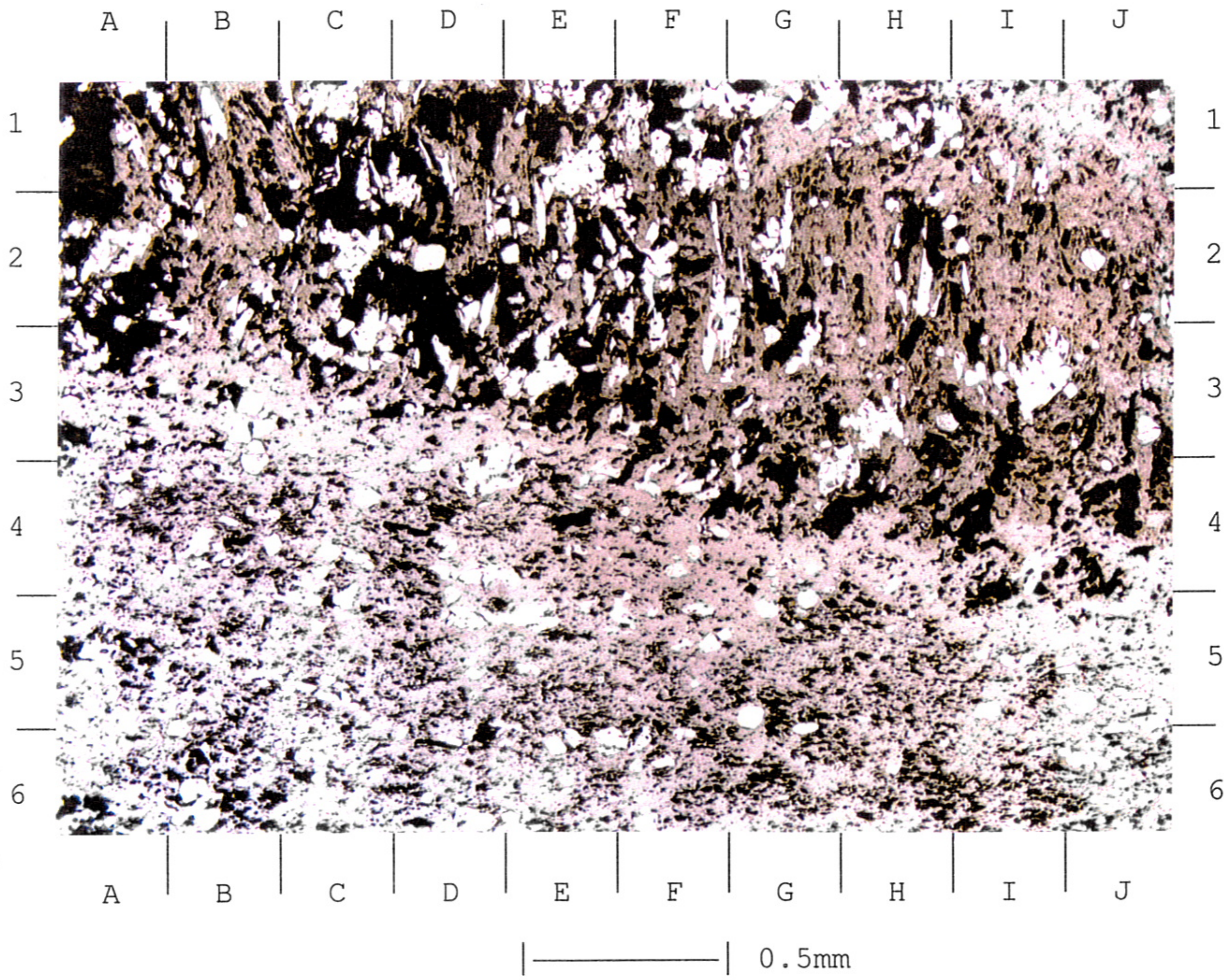


14/6/95/3

Mineralised BIF. Interlaminated hematite-rich and goethite-rich layers.

Photomicrograph

Crystalline goethite with laminae (A3-J4) and dispersed crystals (e.g. D1) of hematite. Lamination contains inclusion free crystals of possibly microplaty hematite. Dispersed hematite is rich in goethite inclusions.



21/6/95/1

Mineralised BIF. Laminated goethite with hematite crystals dispersed through matrix. Some possible microplaty hematite. Vugs are filled with clay size-fraction goethite and chert.

Photomicrograph

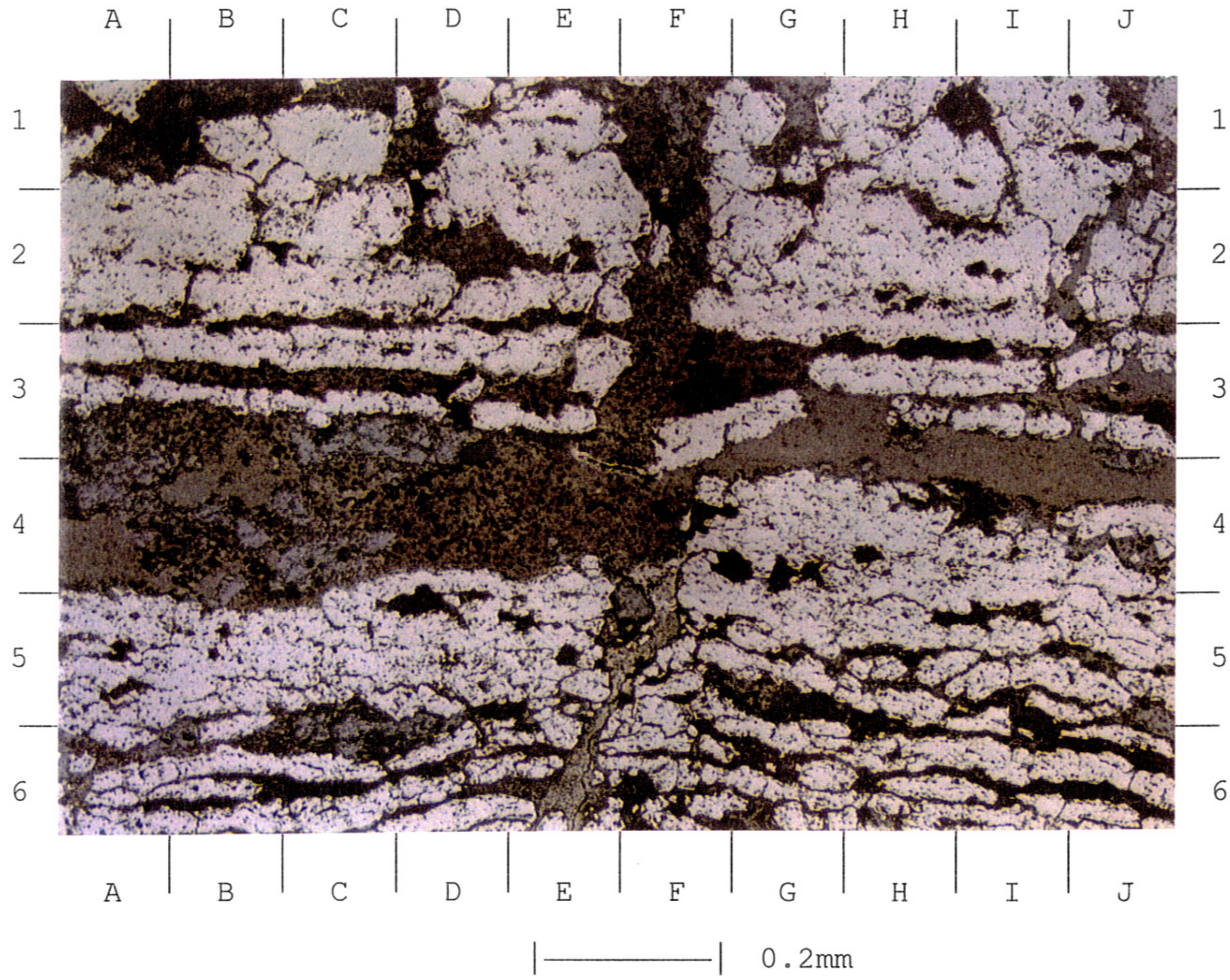
Laminated crystalline goethite (light brown/grey) matrix supporting isolated hematite grains (bright). Note orientation of hematite normal to bedding of original BIF in predominantly brown goethite in upper part of image.

16/8/95/4

Mineralised BIF. Interlaminated hematite and goethite. Two phases of goethite (including fibrous cement, with vugs filled with chert) are present. Hematite crystals have numerous inclusions probably derived from replacement of crystalline goethite.

Photomicrograph

Interlaminated hematite and goethite. Hematite crystals (e.g. F5, J2) are goethite inclusion rich. Crystalline goethite is present as pendant fibrous pore filling cement (e.g. G3, D5) in vugs and in laminae (C4). Some crystalline goethite and hematite is in apparent erosive contact with clay size-fraction goethite (dark brown).

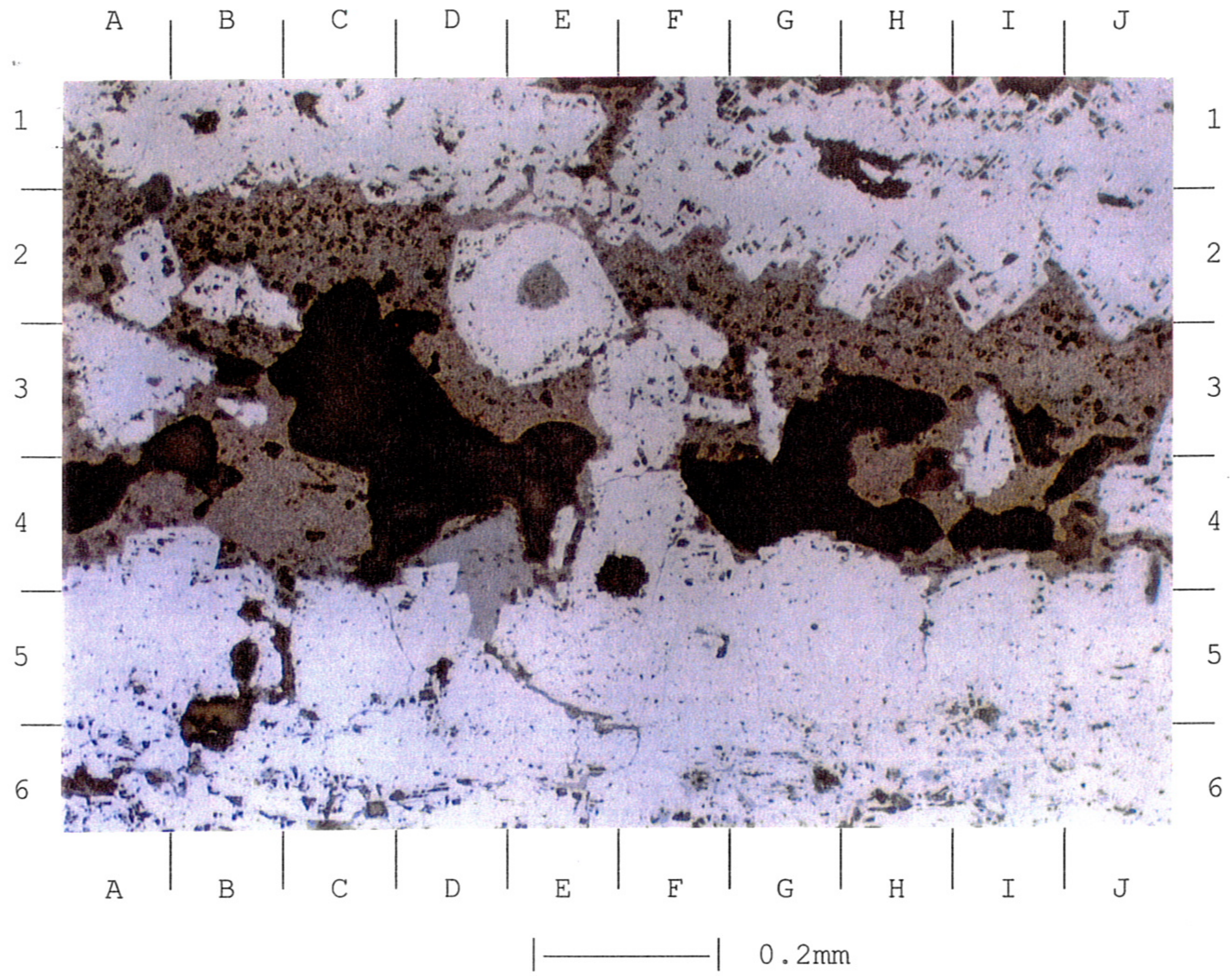


15/8/95/12

Mineralised BIF. Laminated structure is retained. Hematite laminae alternate with clay-size fraction and crystalline goethite. Vertical fractures are filled with goethite, as is low-angle thrust. Hematite crystals in hematite-rich layers are rich in goethite inclusions. At contact between hematite-rich and goethite rich laminae, euhedral crystals penetrate crystalline goethite. Where dissolution has occurred, vugs are lined by clay size-fraction goethite. Dissolution textures are preserved where vugs are in contact with goethite and hematite matrix.

Photomicrograph

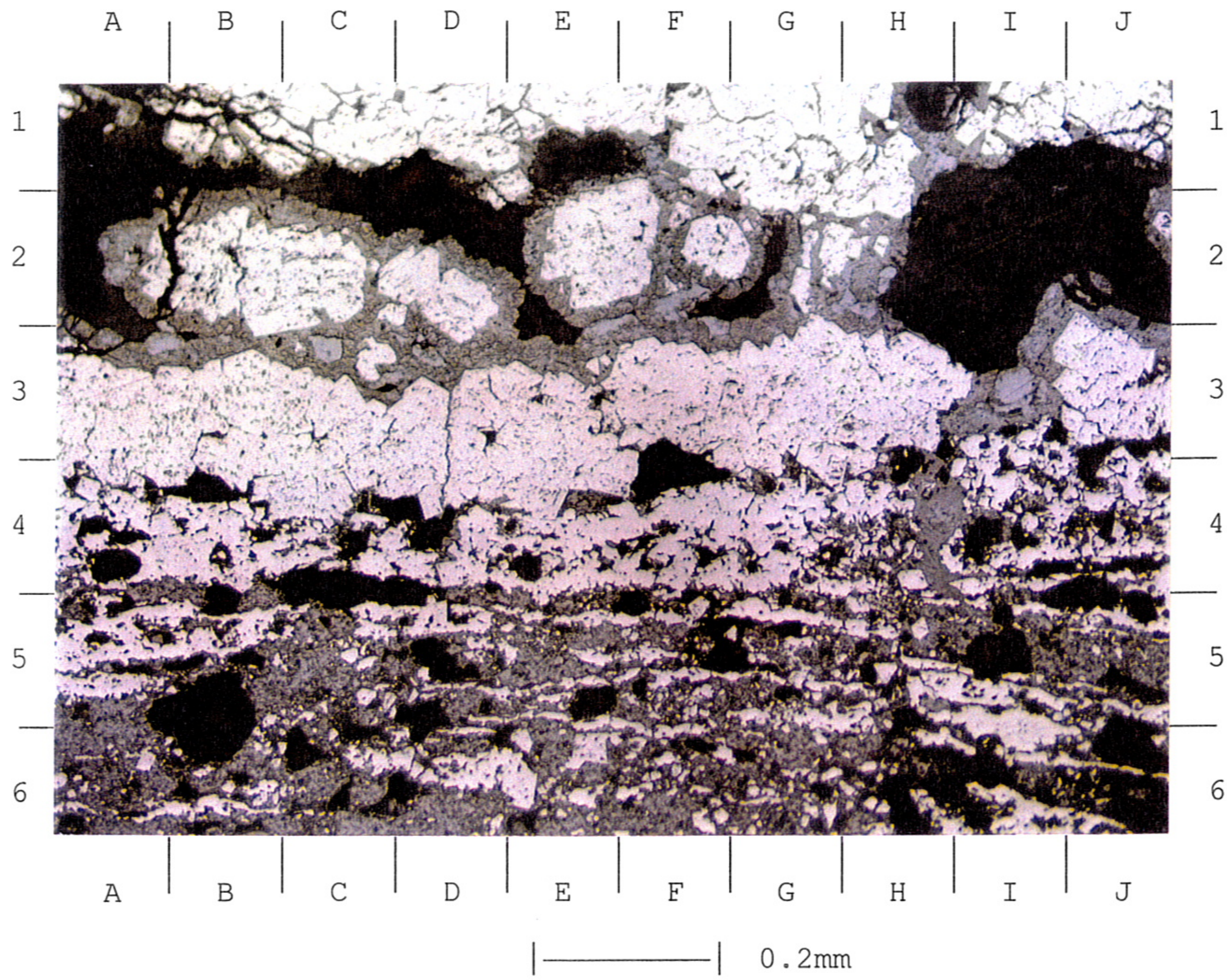
Alternating laminae of hematite and goethite. Goethite lamina at H3 has been fully dissolved and collapsed to less than 50% of its correlative at C4, where (grey) crystalline goethite is oxidising. Hematite crystals (bright) are rich in goethite inclusions. Apparently fully collapsed goethite laminae (bottom) retain residual goethite (dark brown).



15/8/95/12

Detail

Hematite with goethite inclusions (top and bottom) interlaminated with goethite (brown). Core of hematite crystal at E/F4 has been replaced by clay size-fraction goethite. Elsewhere, crystalline goethite is present in hematite cores (E2) or in goethite lamina margins (A1-J2, D4). The euhedral projections of crystalline hematite into crystalline goethite at D4 suggest replacement of goethite by hematite. Vugs in crystalline goethite are lined with dark brown clay size-fraction goethite.

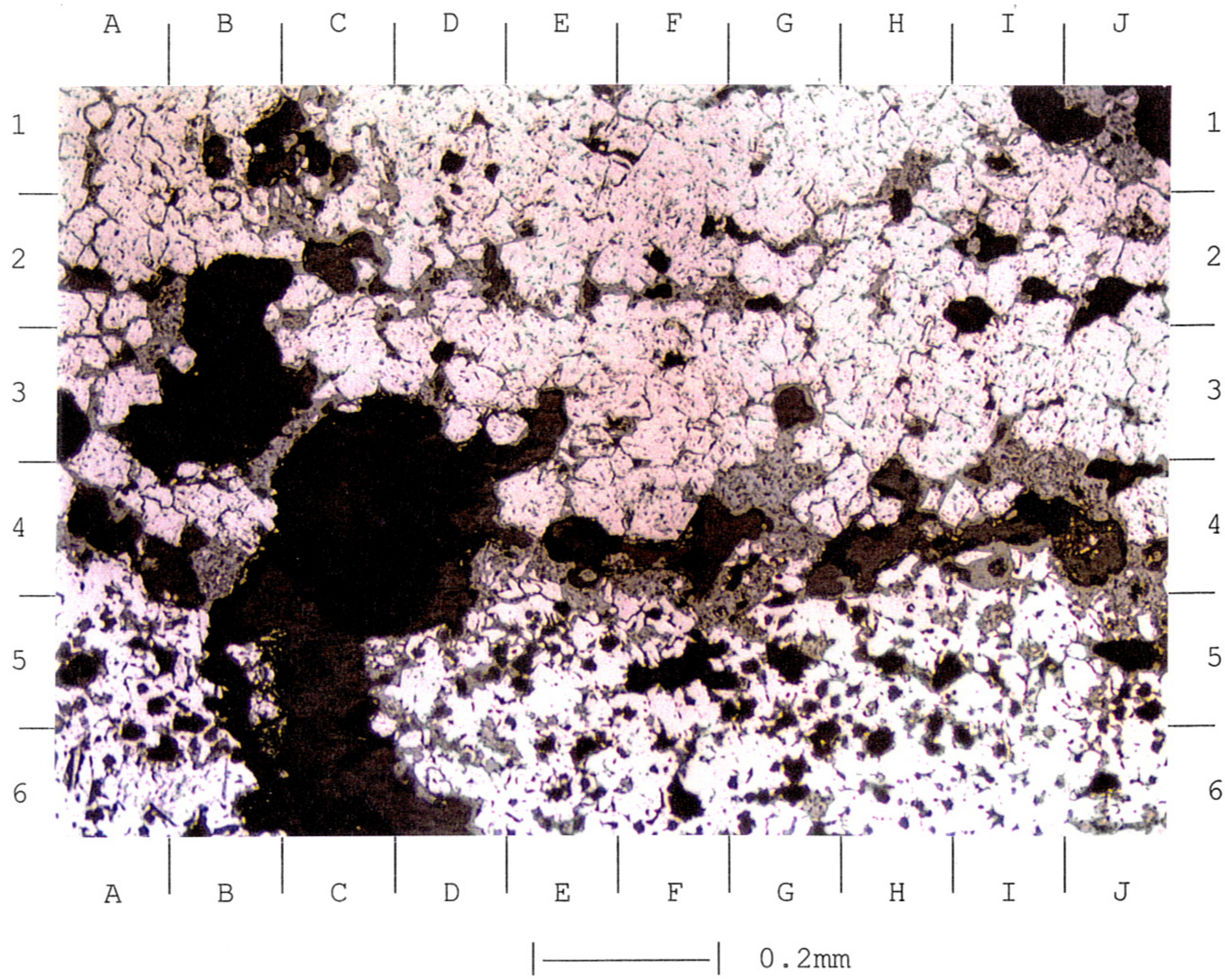


16/8/95/11

Mineralised BIF. Interlaminated hematite and goethite. Hematite is goethite inclusion-rich. Interlayer goethite contains laminae and relict(?) crystals of hematite. Goethite is present as euhedral crystals and acicular pore-lining cements, as well as clay size-fraction combined with chert in vugs.

Photomicrograph

Goethite (lower) and hematite rich laminae. Lower goethite lamina has numerous lines of hematite crystals. Massive hematite lamina (centre) passes up into line of vugs containing dislocated and fractured hematite crystals in a fringe cement of acicular goethite(e.g. D2). Vugs are filled with chert.

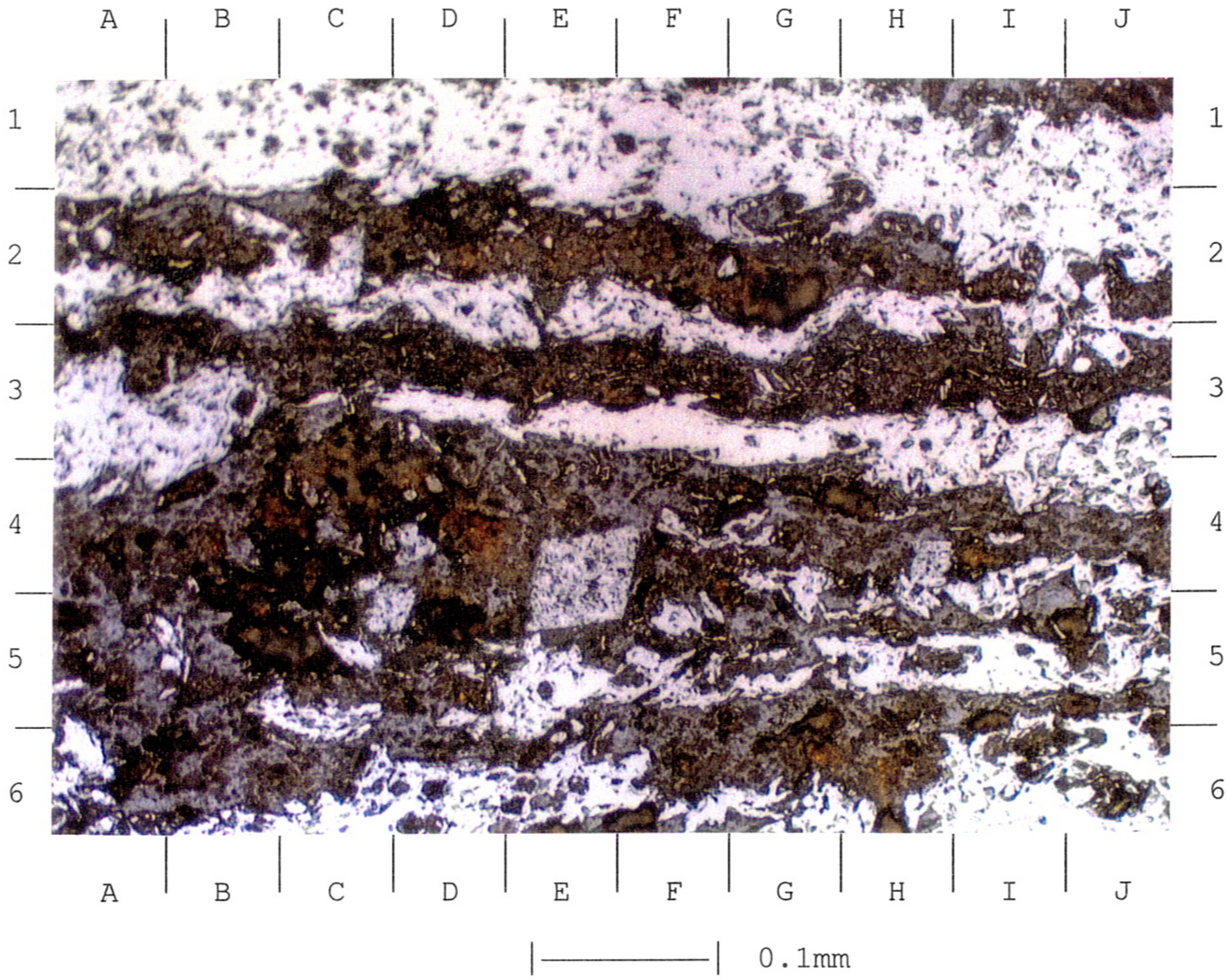


14/8/95/5

Mineralised BIF. Interlaminated hematite and goethite. Inclusion-rich hematite rhombs have numerous linear goethite inclusions. Bladed hematite crystals have more amorphous inclusions. Goethite is crystalline where being replaced by hematite, and clay size-fraction where in vugs now filled with chert.

Photomicrograph

Alternating laminae of inclusion-rich hematite (top), mainly crystalline goethite (centre) and inclusion poor hematite (bottom). Inclusion-rich hematite crystals are typically euhedral at contacts with crystalline goethite (F4, H/I4), suggesting hematite replacing goethite. Crystals of inclusion-poor hematite have cores of clay size-fraction goethite, and rhombic morphology typical of replaced carbonates (A5, G6). Vugs (e.g. C4) are filled with chert.

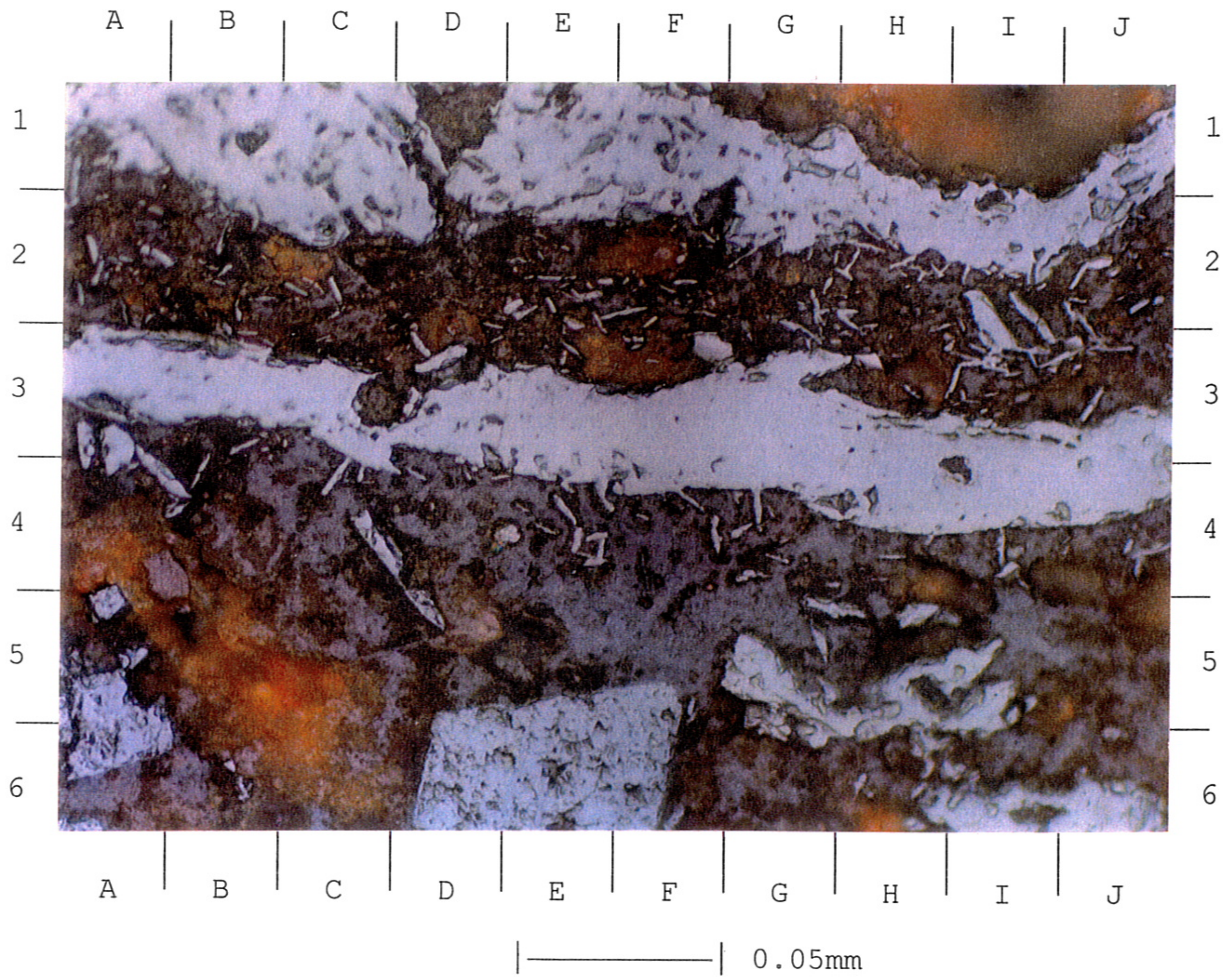


24/11/95/4

Mineralised BIF. Interlaminated hematite and goethite. Layered hematite crystals commonly contain goethite inclusions. Goethite layers contain bladed hematite crystals and have been partly weathered to clay size-fraction goethite. Vugs are filled with chert.

Photomicrograph

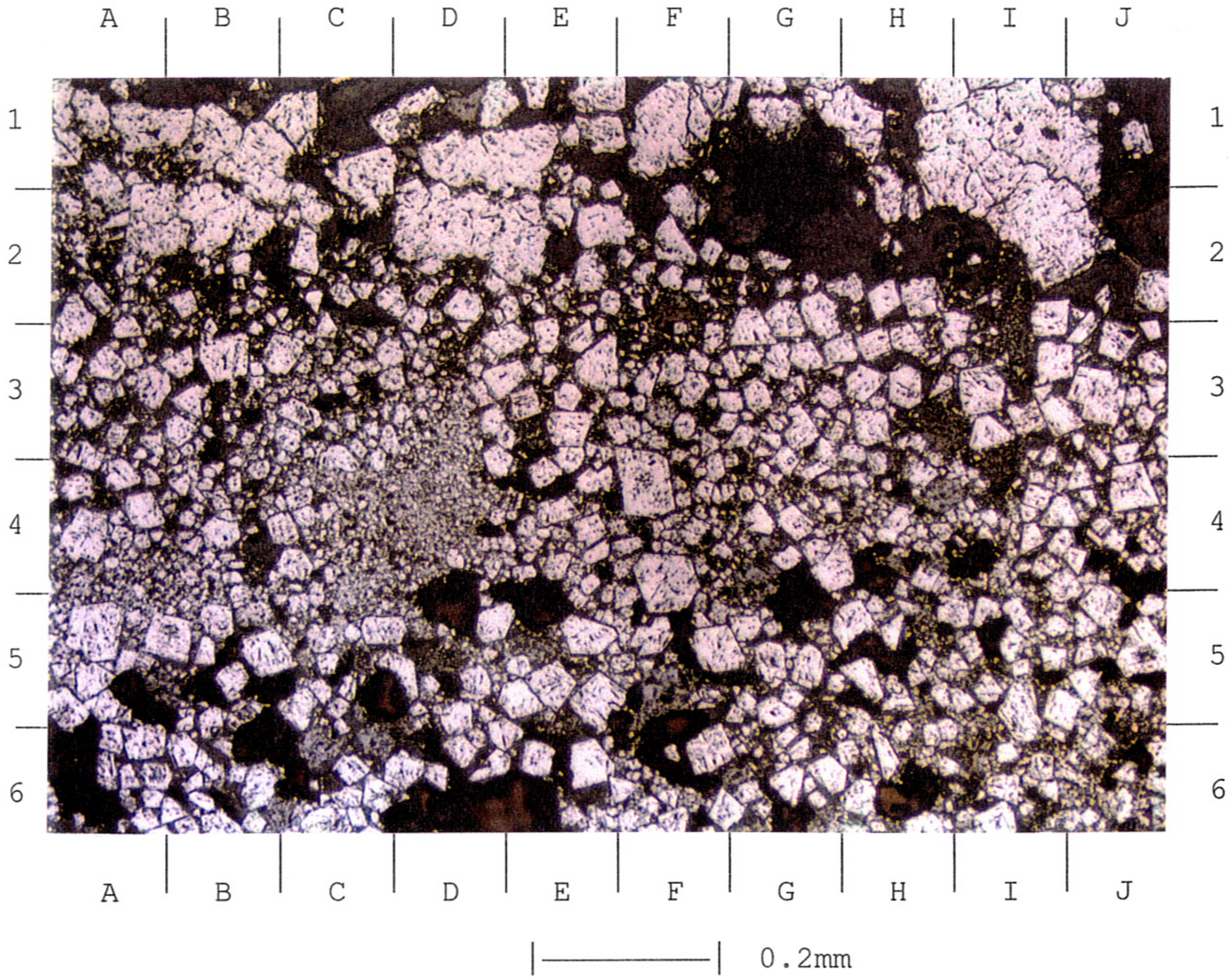
Interlaminations of hematite and goethite. Hematite laminae are rich in goethite inclusions. Goethite laminae contain numerous acicular hematite crystals. Some hematite crystals are rhombic, probably pseudomorphous after carbonate.



24/11/95/4

Detail

Detail shows goethite inclusions in hematite (E1) and numerous acicular hematite crystals in goethite (e.g. E4). Goethite varies from crystalline (E4) to dominantly clay size-fraction (E2) in some laminae and lining vugs (red). Vugs are filled with chert.

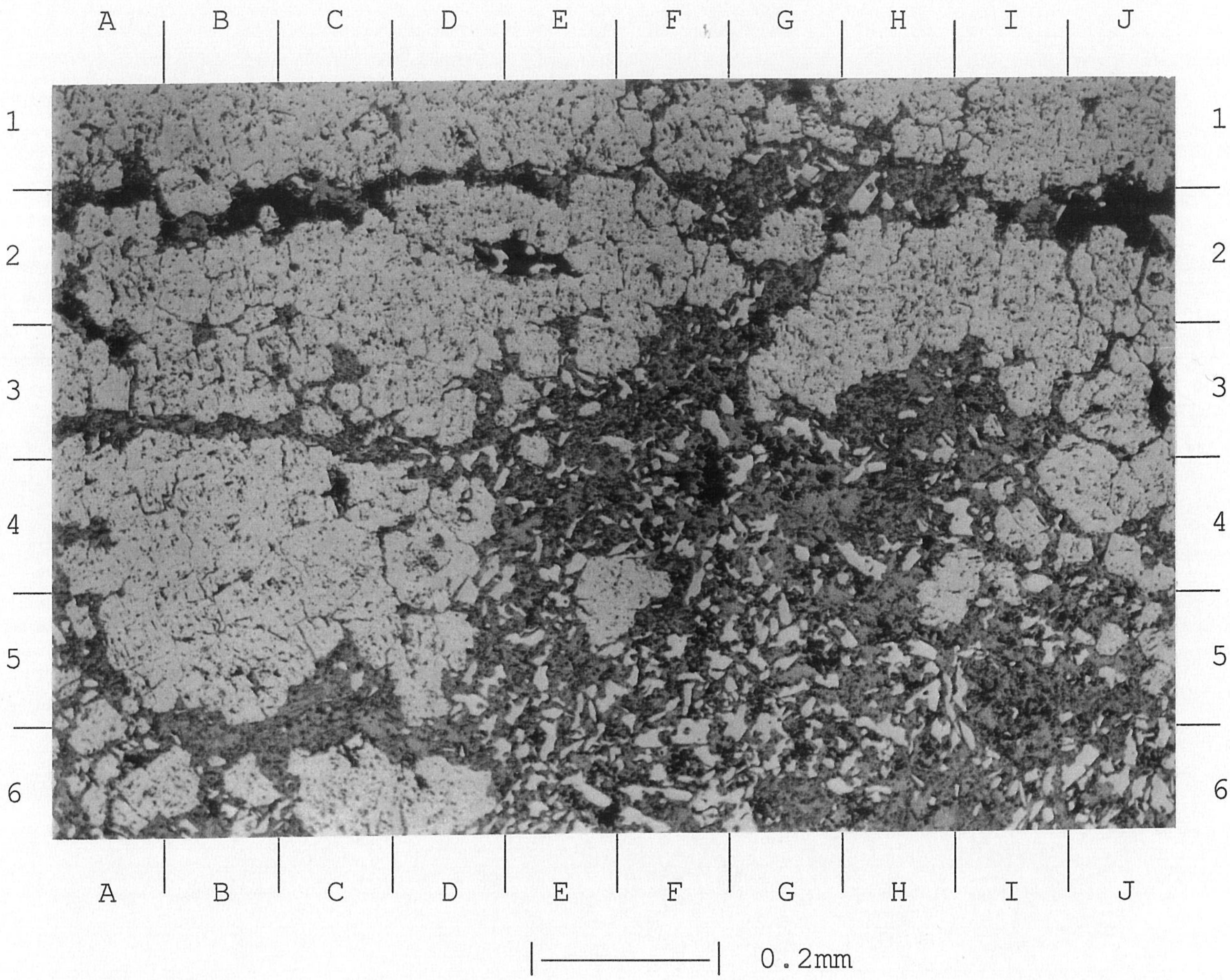


14/8/95/2

Mineralised BIF. Interlaminated hematite and goethite. Inclusion-rich hematite rhombs have numerous linear goethite inclusions. Bladed hematite crystals have more amorphous inclusions. Two phases of crystalline goethite, one as pore linings and one as pore fills are present. Goethite is crystalline where being replaced by hematite, and clay size-fraction where in vugs now filled with chert.

Photomicrograph

Zoned sample grading from hematite and crystalline goethite (bottom) up into aggregate of rhombic hematite crystals (probably replacive after carbonates) and goethite. Vugs (e.g. E1) are filled with chert.

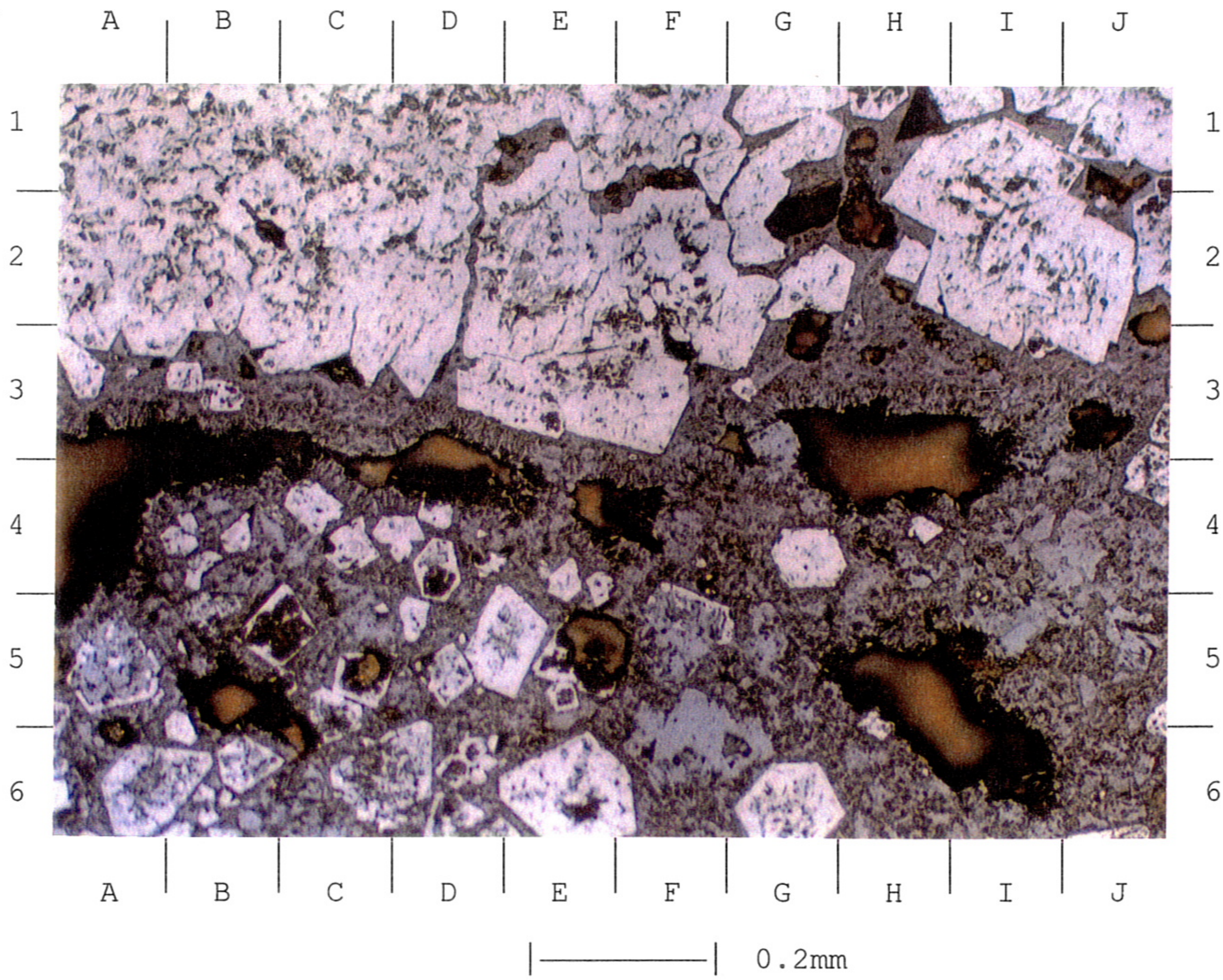


15/8/95/2

Mineralised BIF. Interlaminated hematite and goethite. Two phases of goethite (including fibrous cement, with vugs filled with chert) are present. Hematite crystals have numerous inclusions probably derived from replacement of crystalline goethite.

Photomicrograph

Interlaminated goethite and hematite. Hematite is rich with goethite inclusions. Matrix of crystalline goethite (lower right) supports relatively inclusion free hematite crystals.

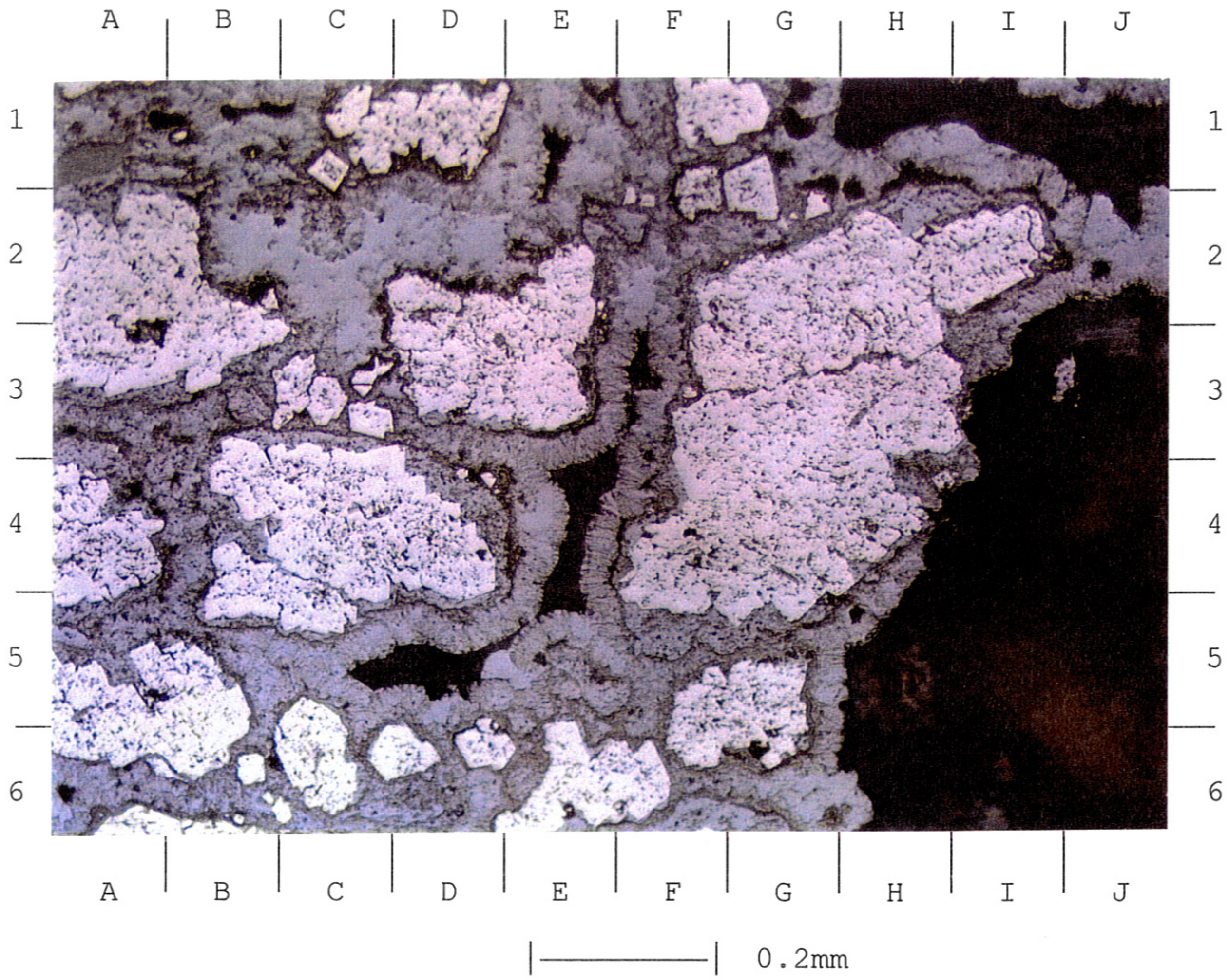


8/6/95/1

Mineralised BIF. Interlaminated hematite-rich and goethite-rich laminae. Hematite crystals contain numerous goethite inclusion. Goethite layers have euhedral hematite crystals, commonly with goethite inclusions and cores. Cores may be weathered to clay size-fraction goethite, or dissolved. Vugs are typically filled with chert. Goethite layers contain corroded euhedral crystals and weathered acicular cements.

Photomicrograph

Hematite dominated (upper) and goethite dominated (lower) laminae. Upper hematite crystals have euhedral terminations where they are in contact with goethite (D3). Hematite at E/F2 appears to be detached and dropping into dissolving/vuggy goethite. Goethite contains numerous rhombic crystals of hematite after carbonate. These hematite crystals may have crystalline goethite (A5) or clay size-fraction goethite (C5) cores. Fibrous goethite pore cements line vugs, which are now filled with chert (D3).

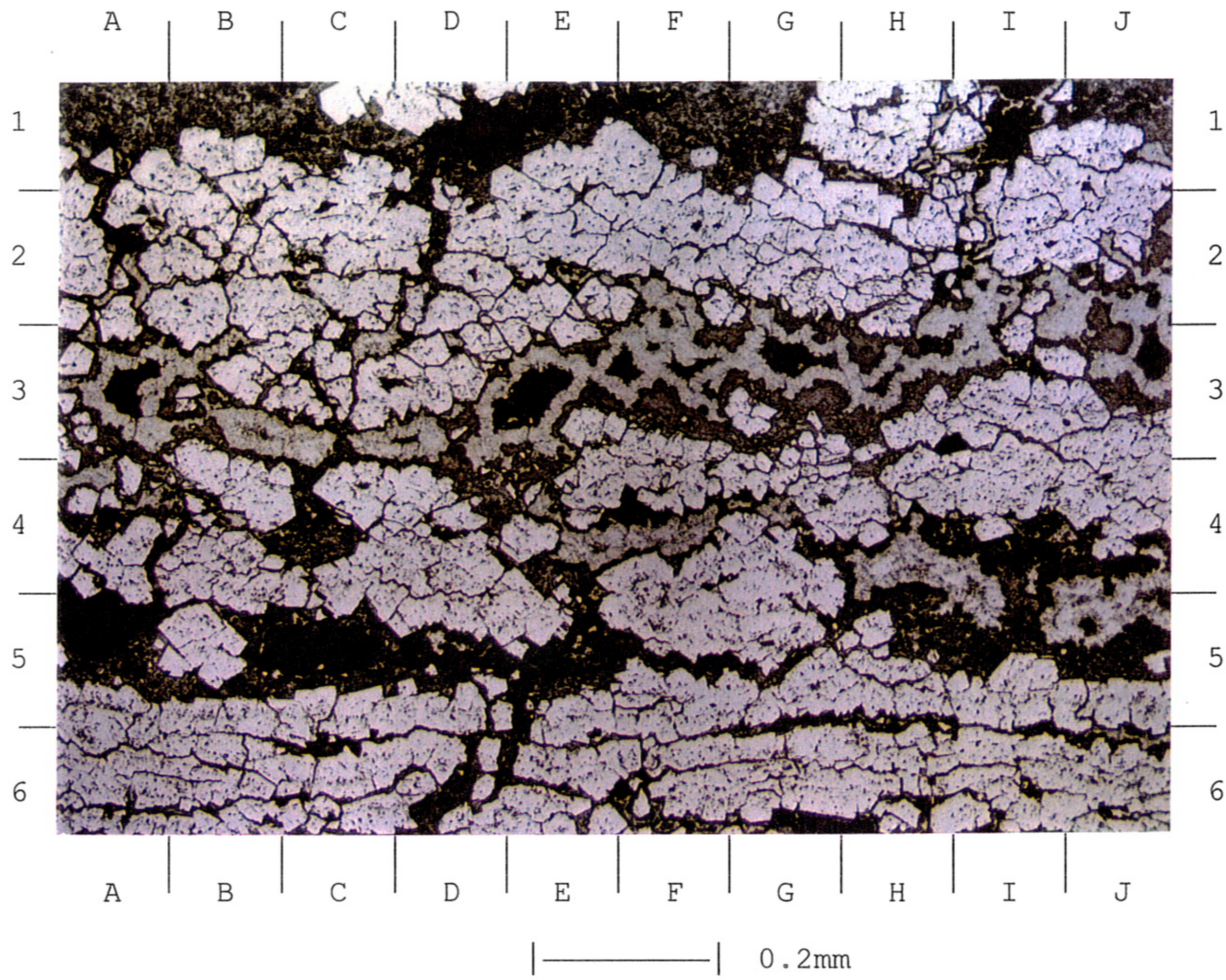


15/8/95/4

Mineralised BIF. Laminae are replaced by discontinuous lines of inclusion-rich hematite, separated by crystalline goethite. Two phases of goethite are present. One is in the form of discrete crystals, undergoing replacement by hematite, and the second is acicular pore-lining cement. Vugs are filled with chert.

Photomicrograph

Crystals of hematite forming discontinuous laminae (e.g. A5-G5). Hematite crystals are rich in goethite inclusions. Goethite is present as crystalline matrix (C2) and fibrous rim cements lining some vugs (E4). Vugs are filled with chert.



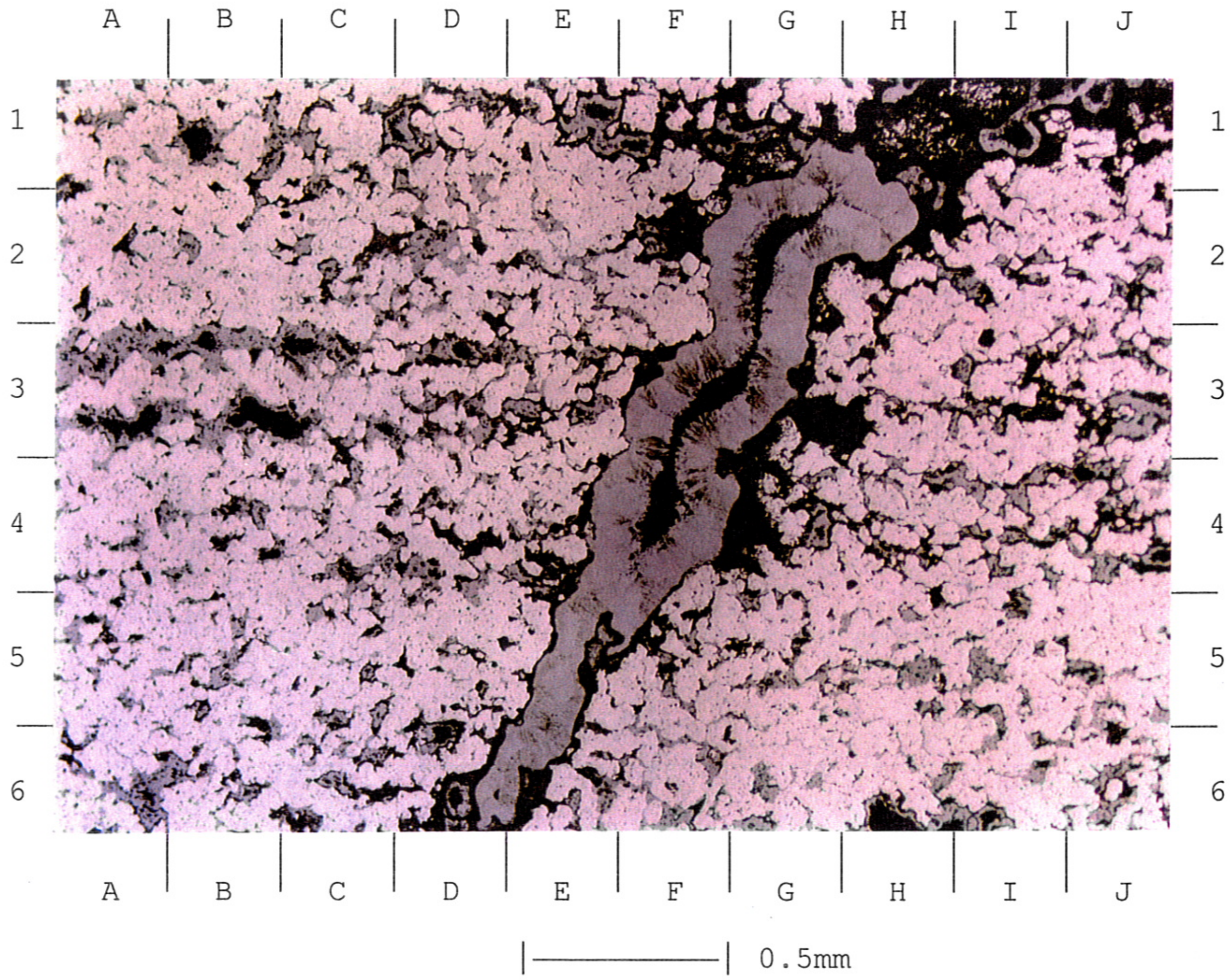
15/8/95/11

Mineralised BIF. Interlaminated hematite and goethite. Two phases of crystalline goethite, including a pore lining fibrous cement, are present . Vugs are filled with chert. Hematite crystals have numerous inclusions probably derived from replacement of crystalline goethite.

Photomicrograph

Interlaminated hematite and goethite. Hematite is rich with clay size-fraction goethite. Some hematite laminae are a single crystal wide and are continuous across the width of view (bottom). Neighbouring hematite laminae have interpenetrating crystalline fabrics (F6-J6, I3-J4) but are separated by thin layers of clay size-fraction goethite (stylolites).

Some goethite laminae retain dominantly clay size-fraction (A5-J5) goethite or crystalline (A3-J3) goethite. Stylolite development is confined mainly to hematite in contact with clay size-fraction goethite (F-G5, F4). The hematite crystal mass at G4/5 appears to have foundered into the clay size-fraction goethite mass below it, opening a void above. The solution/precipitation seen in this sample suggest Fe is being partitioned from crystalline goethite to precipitate as hematite or pore lining cement, leaving a resistate of clay size-fraction goethite laminae.



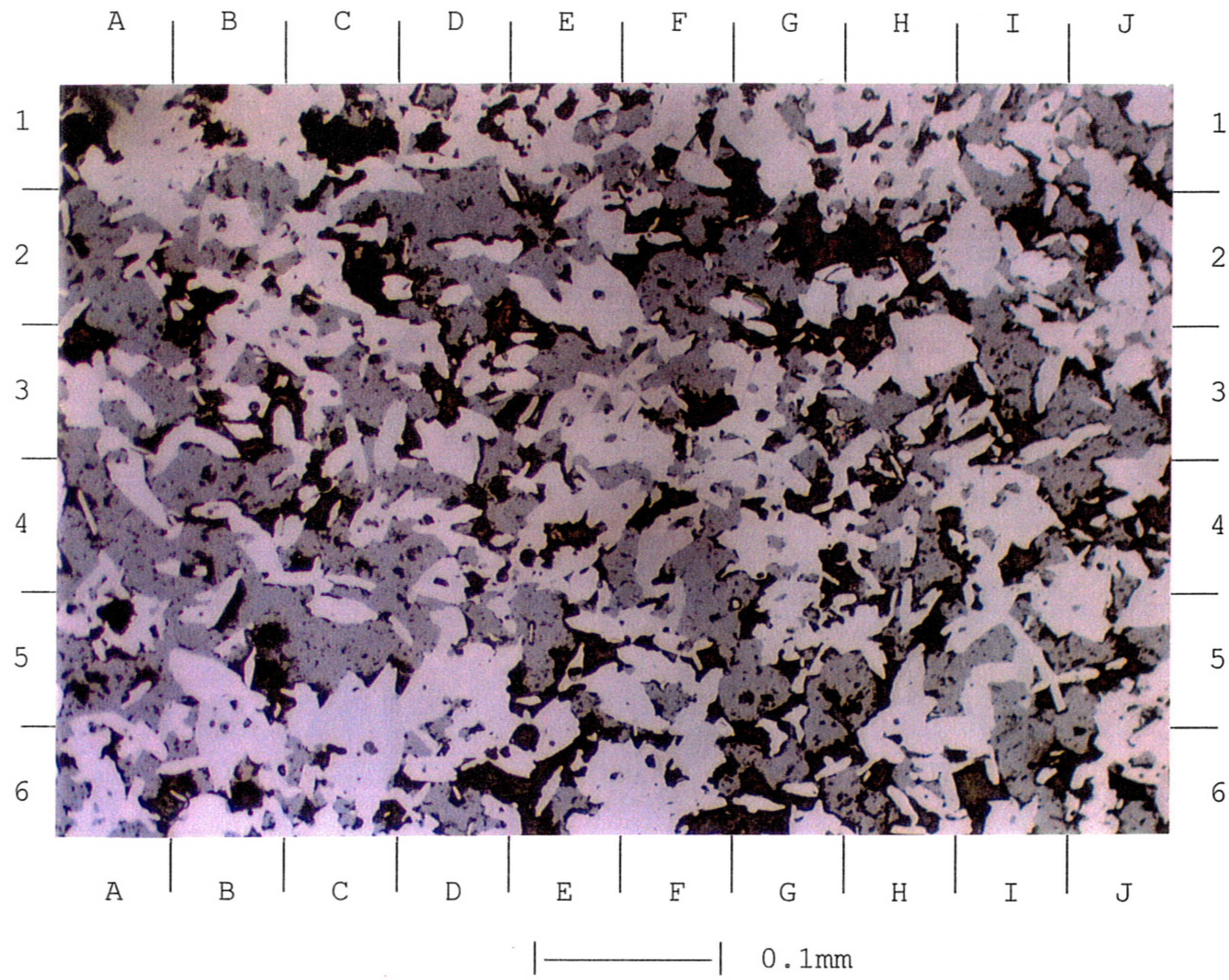
14/8/95/4

Mineralised BIF. Laminated texture is poorly to well preserved. The bulk of the sample matrix comprises a mosaic of interlocking hematite and goethite crystals. In polarised light there are two orthogonal preferred axes of orientation of the more bladed (microplaty hematite?) crystals. The sample has vertical fractures, some of which contain internal sediment comprising a mixture of autochthonous hematite and goethite, clay size-fraction goethite and crystalline goethite. Pores filled with clay size-fraction goethite are present throughout the sample. Crystalline goethite overlies the other detrital/authigenic minerals, and lines vuggy porosity, where is present as an isopachous acicular and slightly botryoidal cement.

The texture seen in this sample is tentatively interpreted as being of metamorphic origin.

Photomicrograph

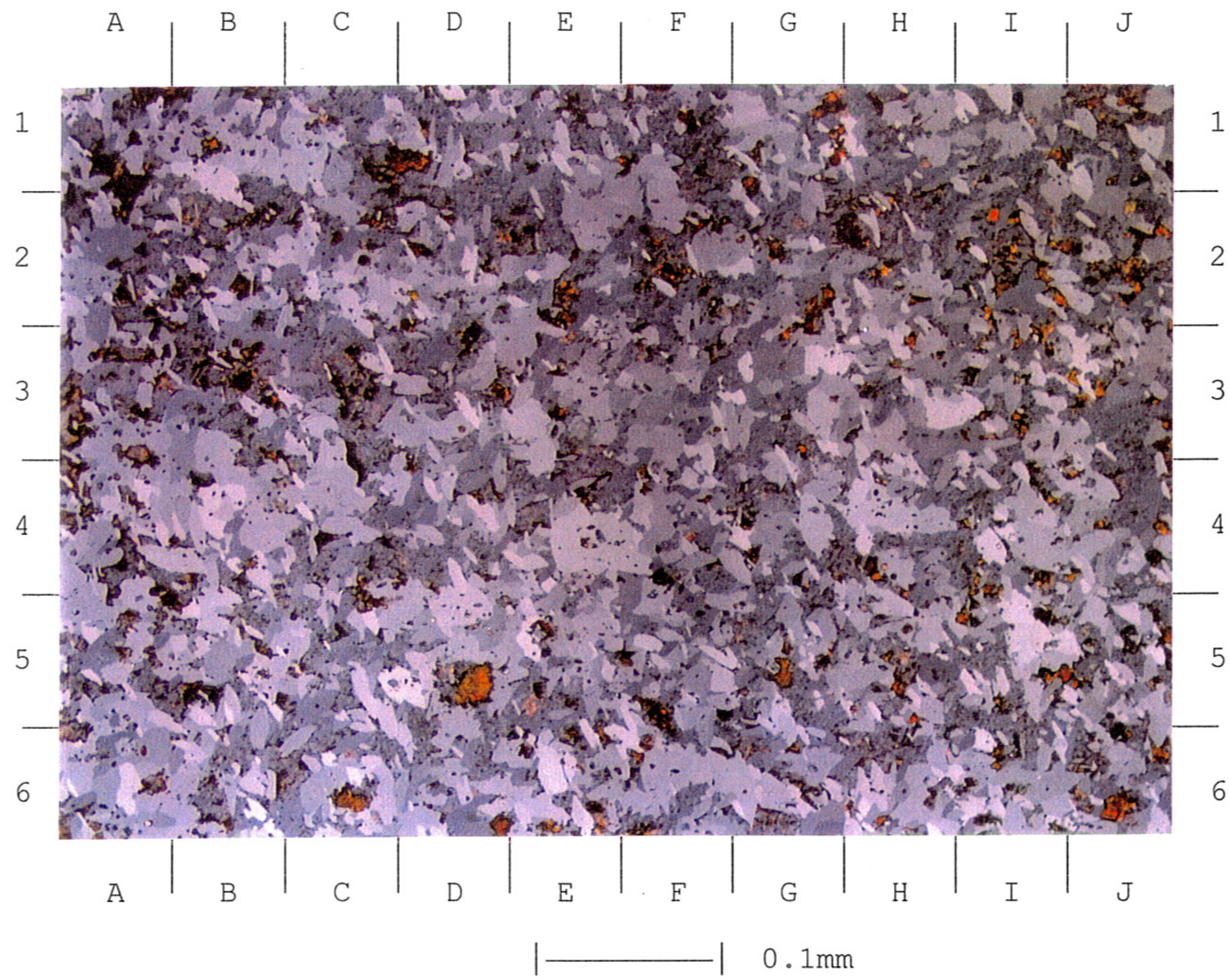
Mineralised BIF fabric comprising mainly hematite with goethite laminae (A3-D3) and crystals. Sample has been fractured and vug has been part filled with fibrous goethite cement (F4). Fibrous goethite is separated from mineralised BIF by variable thickness layer of clay size-fraction similar in appearance to the goethite in vug and distributed between hematite grains.



14/8/95/4

Detail

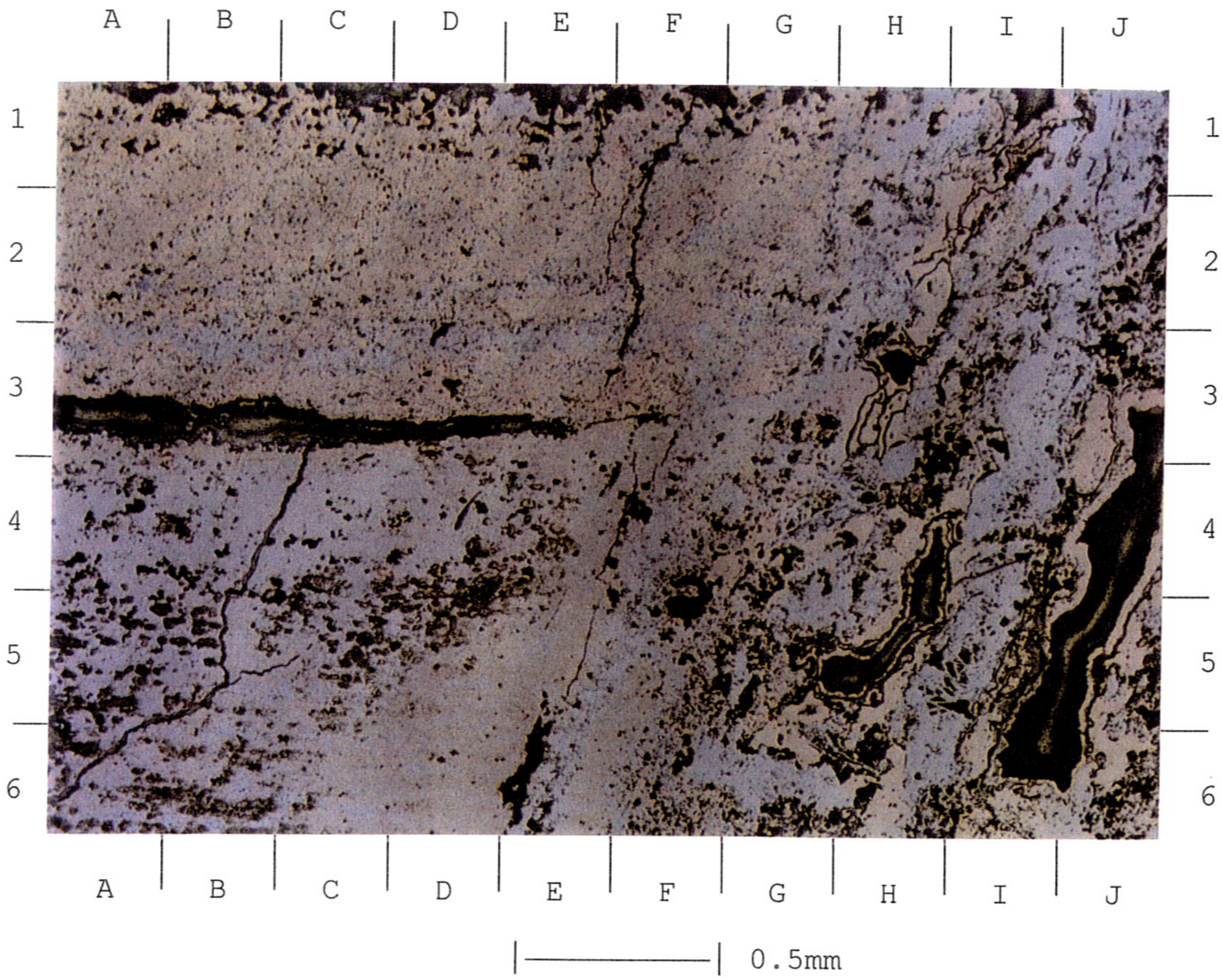
Microplaty hematite (bright bladed crystals) in matrix of crystalline (grey) goethite with clay size-fraction (dark brown) goethite inclusions.



14/8/95/4

Detail

Matrix of approximately equidimensional interlocking hematite and goethite crystals supporting dispersed microplaty hematite crystals exhibiting subtle preferred orientation. This is oriented approximately A1-D6. Both the interlocking crystal fabric and the microplaty hematite orientation are interpreted as metamorphic in origin. Crossed polarised light



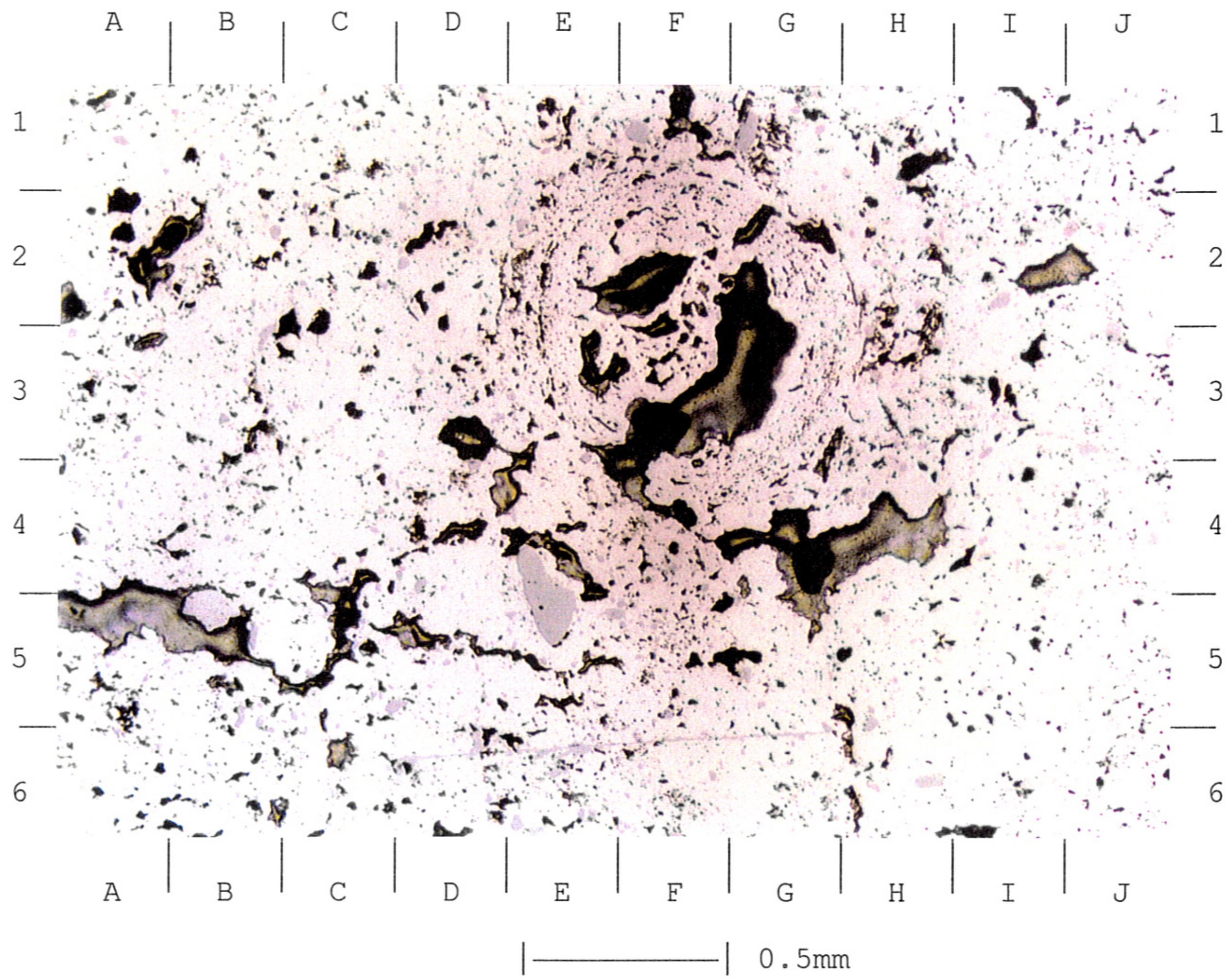
16/8/95/10

Mineralised BIF. Laminae are well preserved. Sample is strongly zoned into groups of laminae comprising either hematite with crystalline goethite or *vice versa*. The sample has numerous vertical and some horizontal fractures, and some vugs. Some voids contain internal sediment, either liberated crystals or pisoliths, and all are partly to fully cemented with crystalline goethite.

Photomicrograph

Alternate groups of horizontal laminae of BIF mineralised to mainly hematite (light grey) and mainly goethite (light brown). Laminated hematite is rich in goethite inclusions (dark brown). Sub-vertical fracture (right) has patchily alternating layers of cement, with open pores (J4) lined with isopachous fibrous goethite. Isopachous cements indicate precipitation in phreatic zone.

This texture seen in this sample is the closest *in situ* analogue to the mineralised BIF clasts in mature detritus and canga.



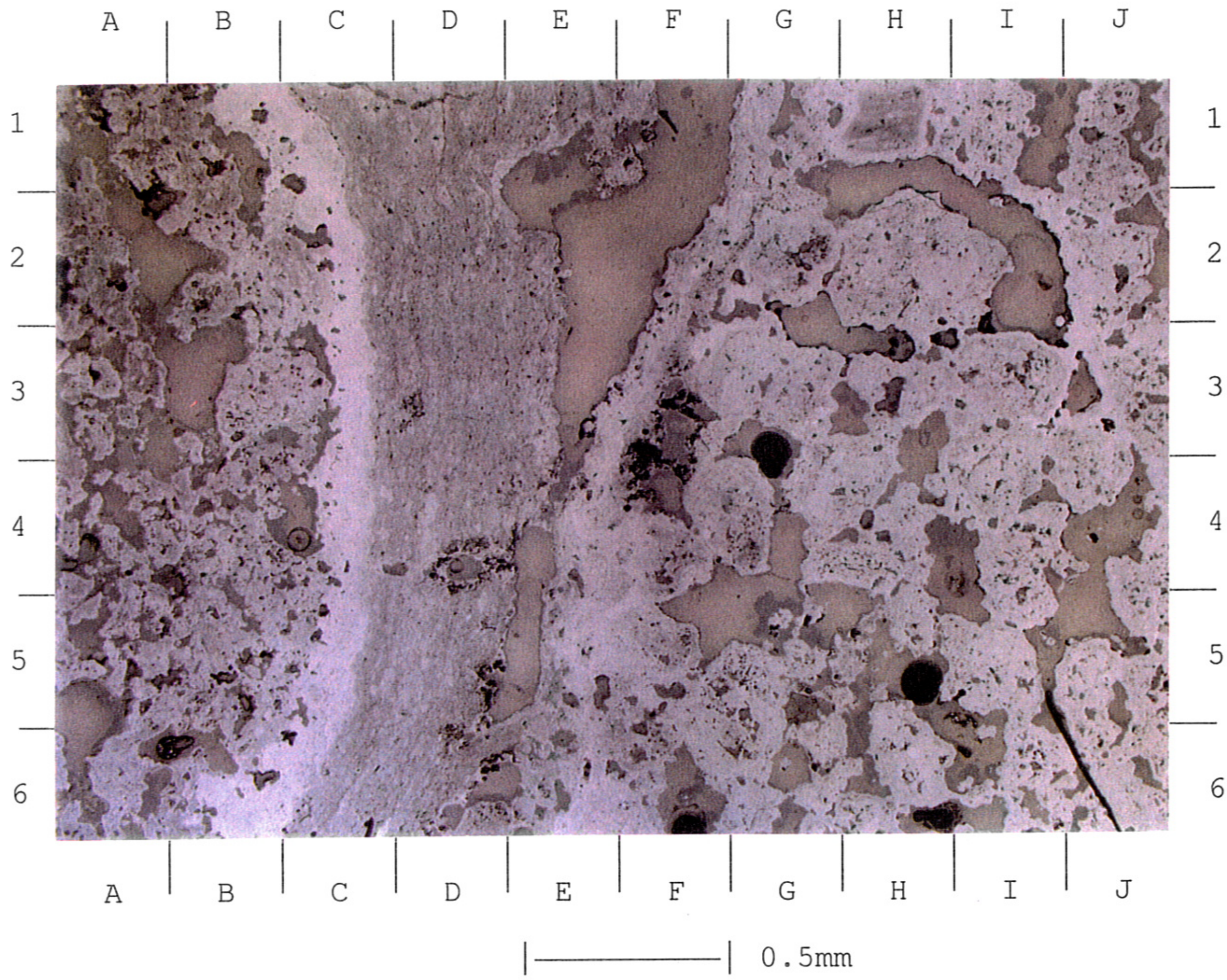
24/8/95/4

Massive hematite with only subtle lamination preserved as an indicator of probable BIF origin of part of the sample. Elsewhere, the presence of rounded/coated and botryoidal forms suggests a weathering origin for some of the sample/structures. Vugs are lined with thin goethite rims. The massive hematite contains isolated inclusions of kenomagnetite. Kenomagnetite inclusions vary from subhedral to rounded in shape. Kenomagnetite is also concentrated in the rounded cement rim of a structure interpreted to be the massive cement of a pisolith. Some kenomagnetite is also present in the botryoidal form.

This sample is interpreted as of weathering origin, and has been subsequently altered almost entirely to hematite.

Photomicrograph

Poorly preserved lamination running 5A-5G is probable relic BIF structure in otherwise massive hematite clast. Pisolitic structure is present at F2, and kenomagnetite grain at E4 (mid-grey). This sample is interpreted to have undergone extensive weathering/alteration.

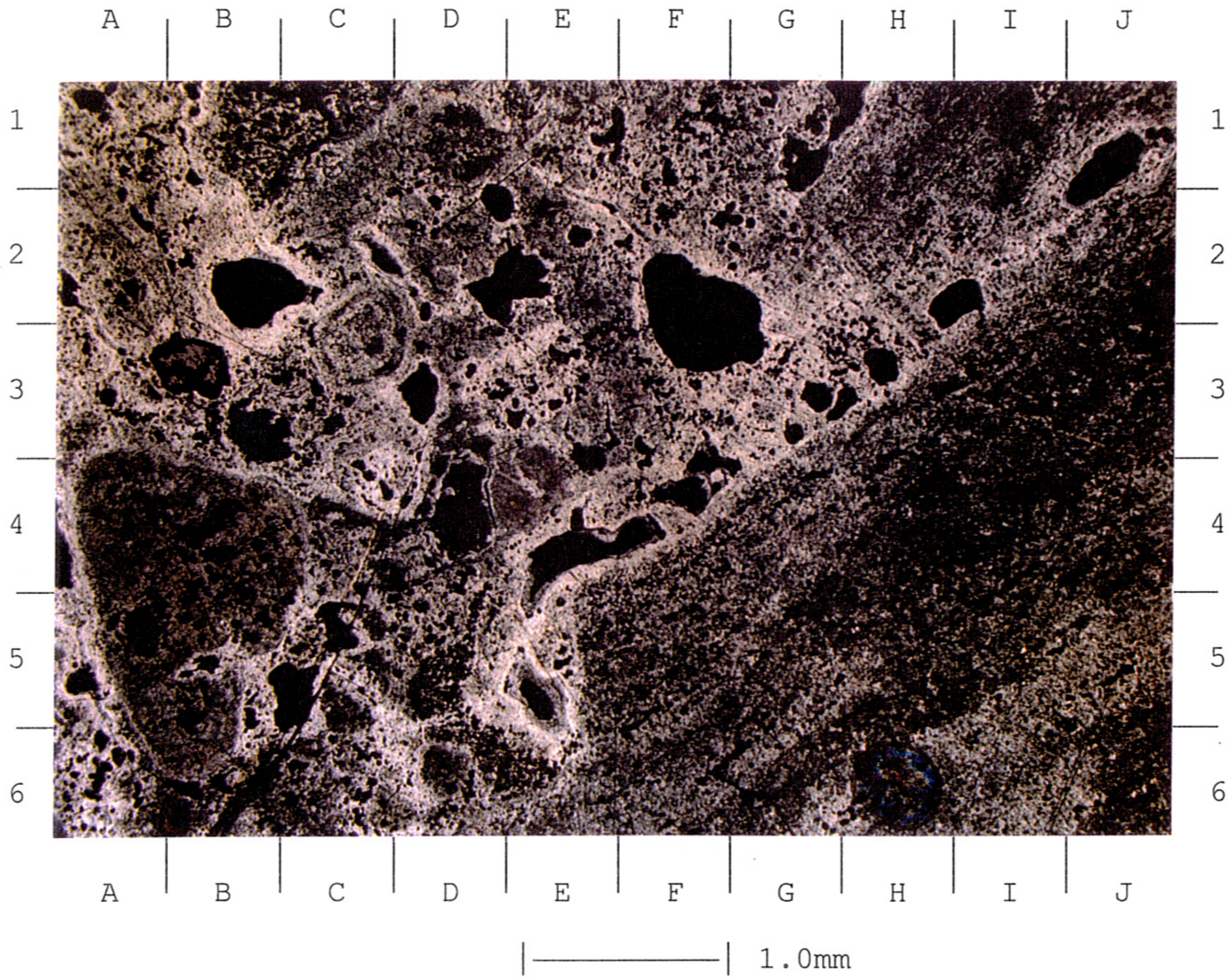


ACC276

Mineralised BIF. Some fractures with internal sediment, including pisoliths.

Photomicrograph

Pisolith (left) with hematite (B1-B6) and goethite (D1-C6) coatings. Core of pisolith and matrix (e.g. G4) has been partly dissolved to produce vuggy pore space now filled with milky chert (e.g. F1).



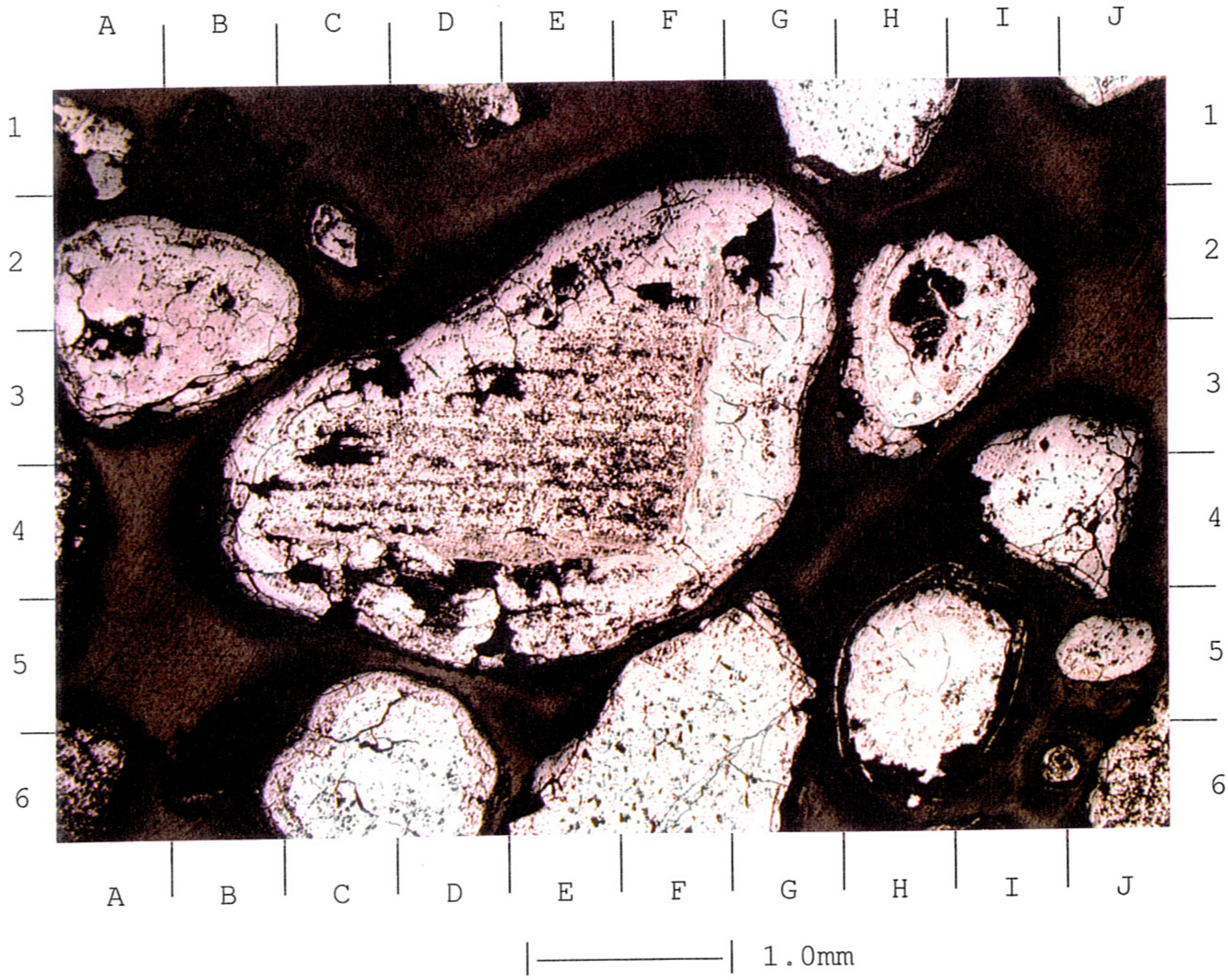
24/11/95/3

Mineralised BIF. Mainly composite hematite dominated clasts in a goethite cement matrix. Composite clasts commonly contain hematite preserving BIF structures as well as pisoliths and indeterminate clasts. The cement phase within composite clasts commonly comprises hematite, although some voids and clasts are goethitic. Cement is commonly crystalline goethite, overlain with some microcrystalline goethite. The cement includes some individual (ex BIF, pisoidal and indeterminate) detrital grains. Some of these last grains are fractured, suggesting relatively rapid dehydration from goethite to hematite.

Photomicrograph

Composite clast of mineralised BIF (bottom, right), pisoliths (C2) and indeterminate clasts in a hematite cement (bright).

Mature Detritus



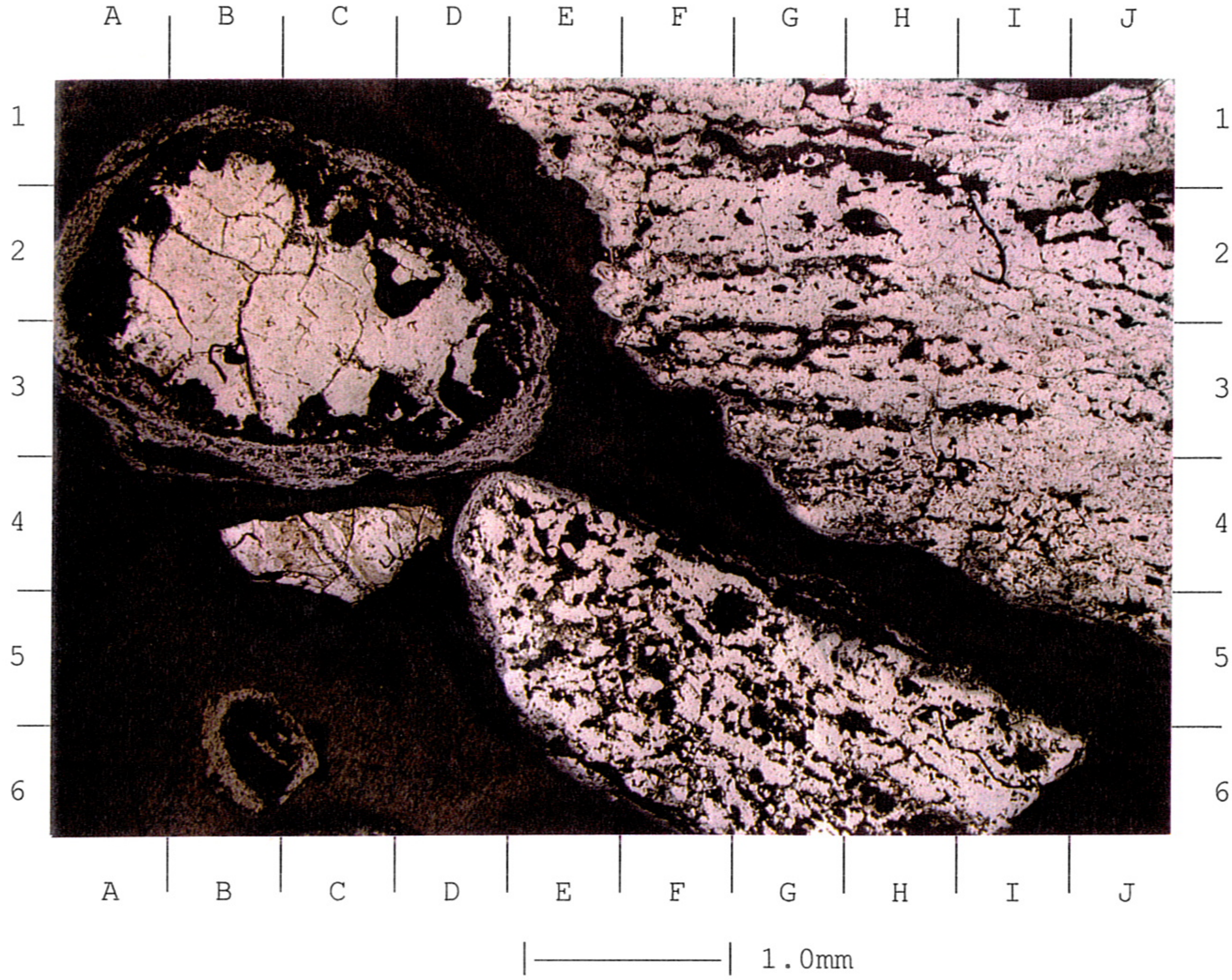
2/6/95/2

Pisoliths (loose; cast in resin) and altered BIF pebbles. The majority of pisoliths comprise rounded fragments of dehydrated goethite, and exhibit desiccation fractures as a result of the alteration to hematite. Cores may comprise individual or composite grains. More rarely, cores may retain recognisable BIF laminae. These ex-BIF fragments are typically much coarser (up to pebble size) than the pisoliths proper, and contain martite crystals.

All grains have a thin coat of clay size-fraction goethite/soil. A minority of pisoliths owe a significant part of their area to the presence of substantial thicknesses of hematite (dehydrated crystalline goethite) rims. A single large grain comprises a composite grain of re-worked pisolite.

Photomicrograph

Loose pisoliths. Mineralised (hematite) BIF core (centre) is enclosed in hematite rim cement of dehydrated (desiccated) goethite. Other pisoliths have mainly desiccated goethite cores of indeterminate origin.



7/6/95/4

Loose detrital grains cast in resin. Pisolitic with altered BIF pebbles. Approximately equal numbers of clasts are derived from desiccated crystalline goethite or from altered BIF fragments. The pisoliths comprise rounded fragments of dehydrated goethite, and exhibit desiccation fractures as a result of the alteration to hematite. Cores may comprise individual or composite grains. Clasts derived from ex-BIF fragments vary from coarse sand to up to pebble size. Typically, they contain martite crystals, and kenomagnetite. Composite grains are relatively rare.

Most grains are overlain by a variable coat of crystalline goethite, and all have a thin outer coat of clay size-fraction goethite/soil. A minority of pisoliths owe a significant part of their area to the presence of substantial thicknesses of crystalline goethite rims.

Photomicrograph

Pisolith with hematite core fractured by shrinkage on desiccation from goethite, and goethite cutan (C2). Two rounded to angular clasts of BIF have been mineralised to hematite (right, bottom). Broken clasts (bottom) has goethitic cutan similar to the pisolith.

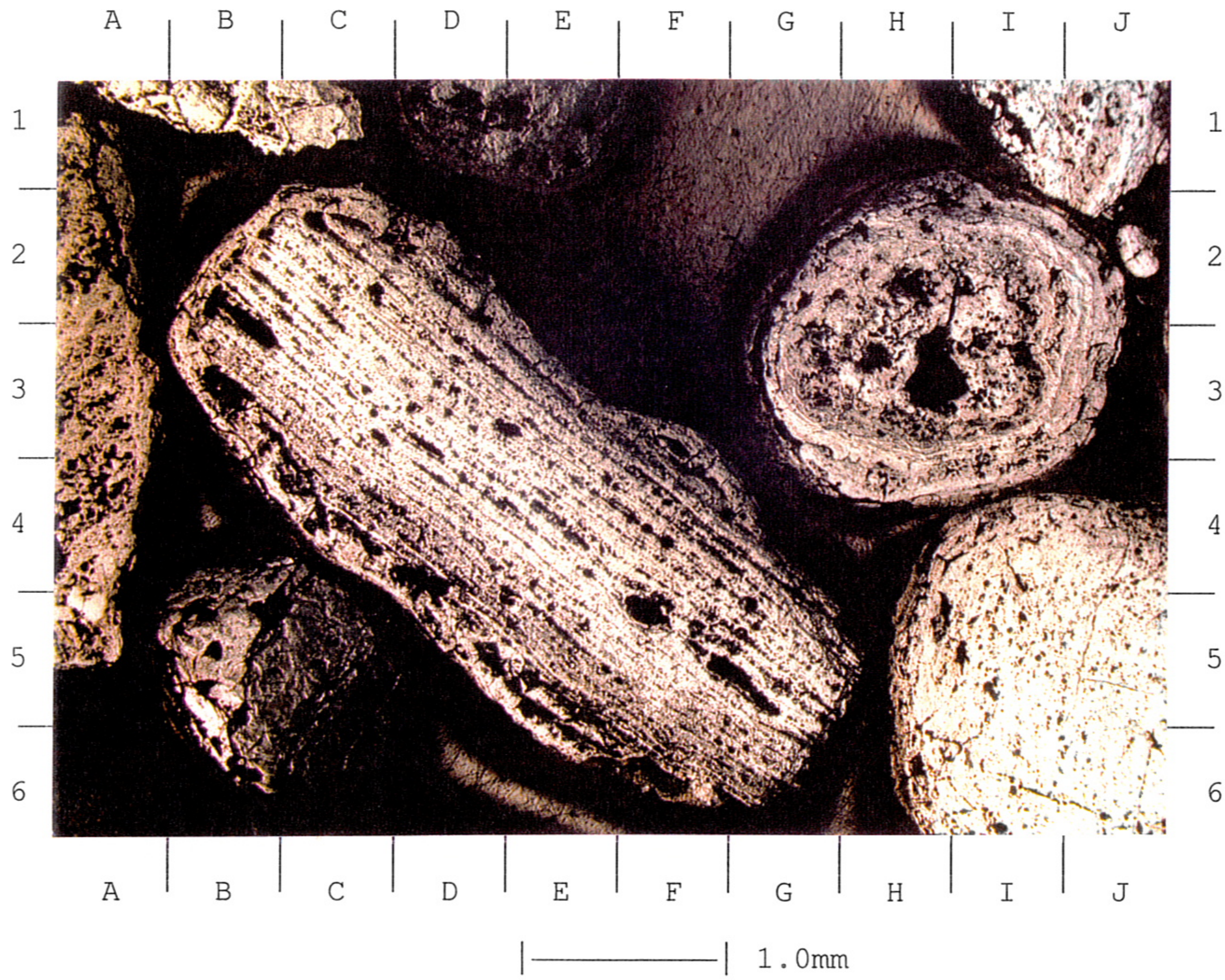
23/8/95/1

Pisolite. Coarse sand to pebble and cobble (?) sized clasts in a clay size-fraction goethite matrix. Clasts are almost invariably poly-nuclear, comprising conglomerations of hematite and goethite pisoliths in a crystalline goethite cement. Some nuclei are of indeterminate origin, which can only rarely be attributed to altered BIF. Individual nuclei may have multiple goethite coats, and they in turn may be cemented together in pebble sized clasts by further multiple coats of crystalline goethite. Vugs in some clasts are filled with chert. A single large detrital core has hematite crystals mimicking magnetite (martite). Some detrital nuclei are fractured by dehydration, and some of these fractures are filled with goethite, hematite or chert.

The whole is loosely cemented by further coats of red clay size-fraction goethite/soil.

Photomicrograph

Wood fragment (left) with cell structures preserved as clay-size fraction goethite. Wood has multiple goethite cement coats, as does pisolith with core at left. These grains are cemented by laminated goethite (centre).

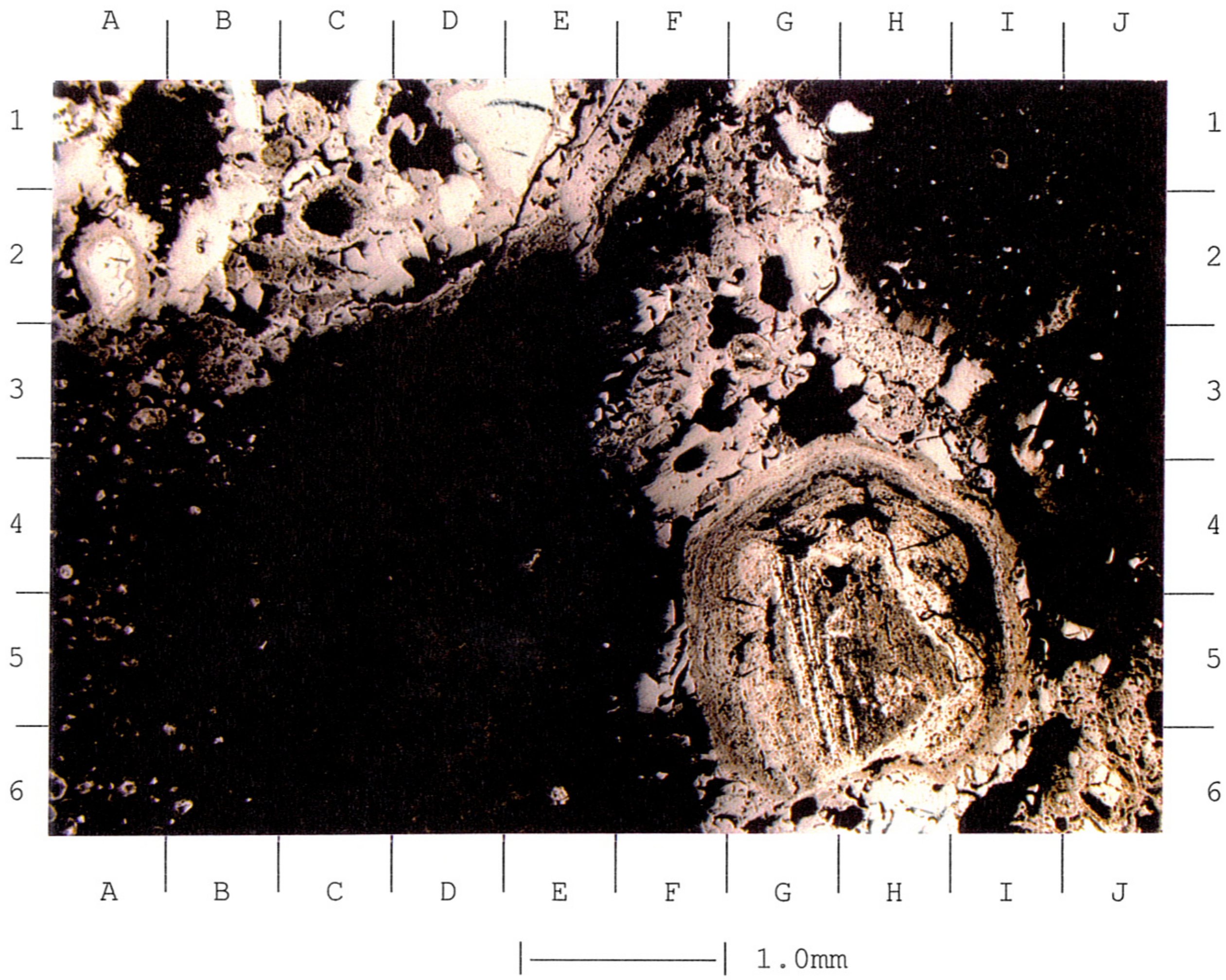


27/8/95/3-16m

Pisoliths and detrital grains (loose; cast in resin). Pisoliths may have desiccated (fractured hematite), un-desiccated goethite or composite cores. Composite cores may contain indeterminate grains of be pisolitic in turn. Skins on grains are of variable thickness, generally being thicker on pisoliths than on hematised BIF fragments, where they may be thin or absent. Skins are generally mainly hematite. Altered BIF fragments are mainly hematite, and commonly contain martite crystals.

Photomicrograph

Mineralised BIF (centre, bottom right) and unidentifiable hematite clasts with hematite (dehydrated goethite) rim cements (H4).



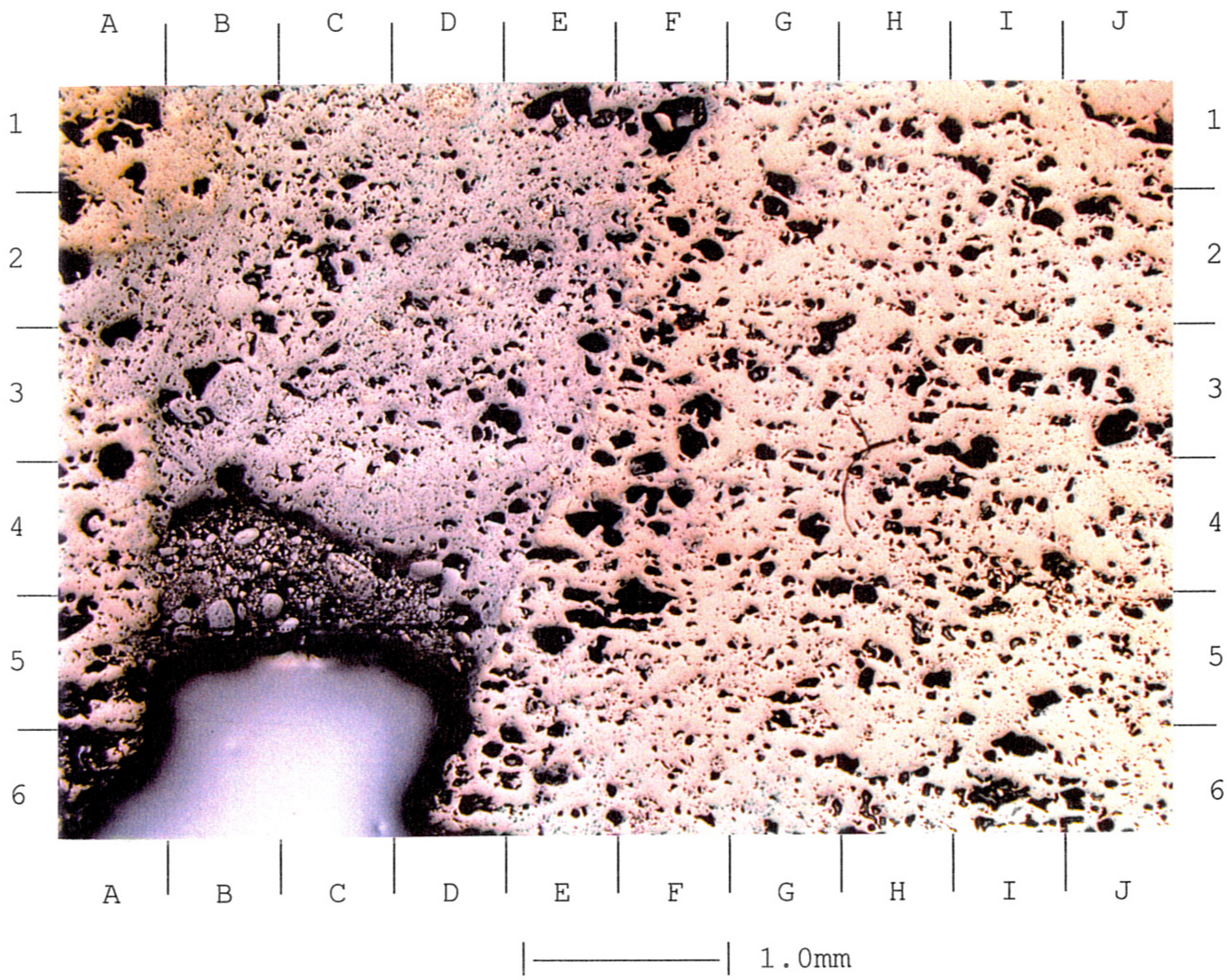
29/8/95/1

Pisolite. Sample comprises mainly patches of cemented pisoliths with large vugs lined/filled with clay size-fraction goethite. Pisoliths and associated cement comprises mainly hematite, with crystalline goethite comparatively rare. Altered BIF fragments are recognised and some chert is present.

Photomicrograph

Pisolith with core of mineralised BIF (H5) in hematite cement. Hematite may be fractured desiccated goethite (E1) of indeterminate origin. Dark areas are clay size-fraction goethite and clay with some hematite fragments.

Canga



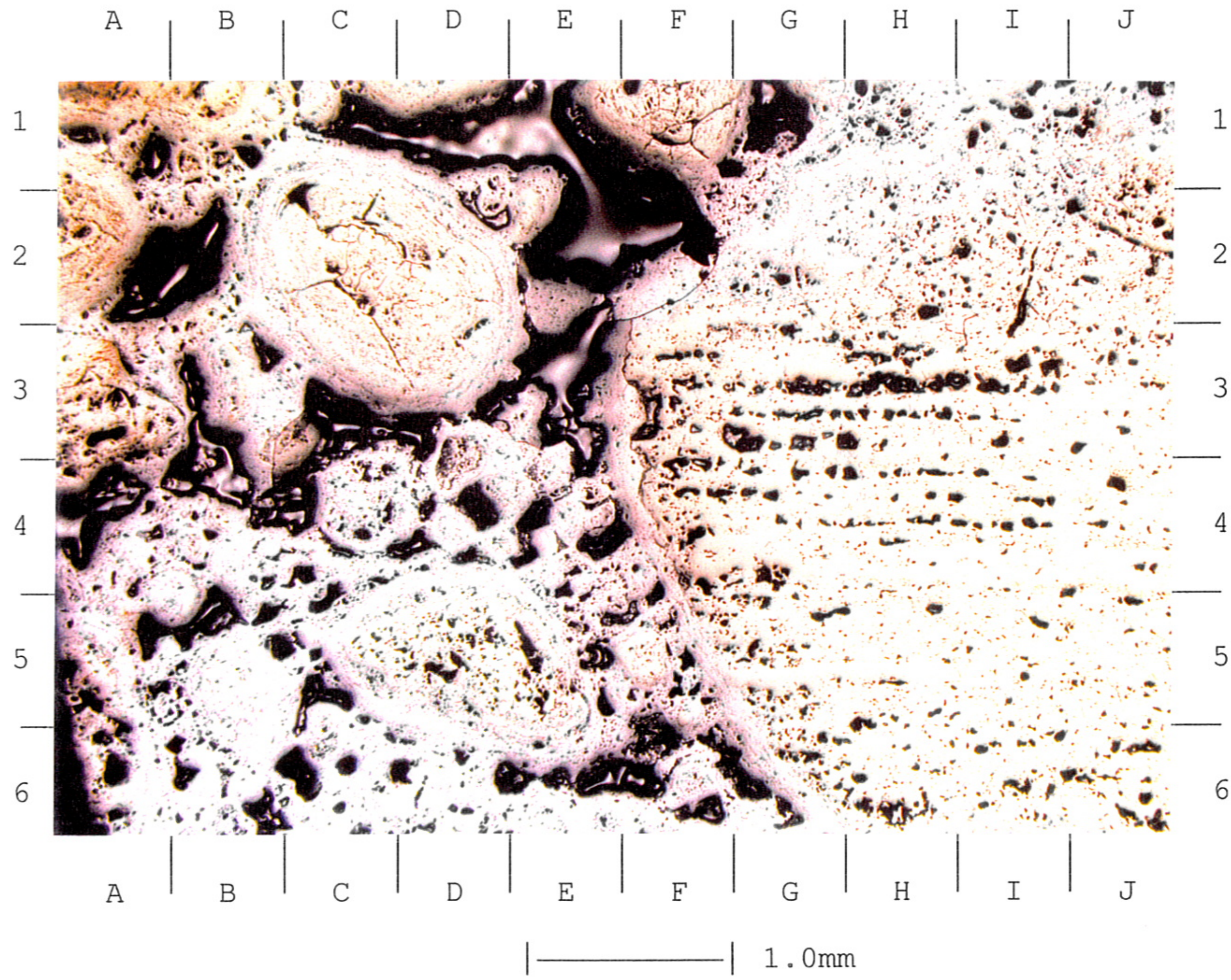
3/6/95/1

Piece of altered BIF from canga. Sample comprises mainly hematite preserving BIF lamination as lines of vugs. Some vugs located close to the clast margin are part- or fully filled with crystalline goethite. The clast is set in a crystalline cement which comprises a series of concordant/fractured laminae. Where the cement has been removed or lacunae developed, these may be overgrown by a later goethite generation containing heterogenous clasts of rounded crystals (goethite or hematite) and pisoliths. Some of this is clearly local sediment and forms cemented geopetals.

The hematite crystalline mass includes core crystals of possible kenomagnetite. The sample in general lacks fractures indicative of dehydration from goethite to hematite.

Photomicrograph

Mineralised BIF (hematite) clasts (left & right) with pisolitic goethite cement/matrix (G6). Vug contains sediment of goethite and hematite fragments plus "soil" and clay size fraction goethite.



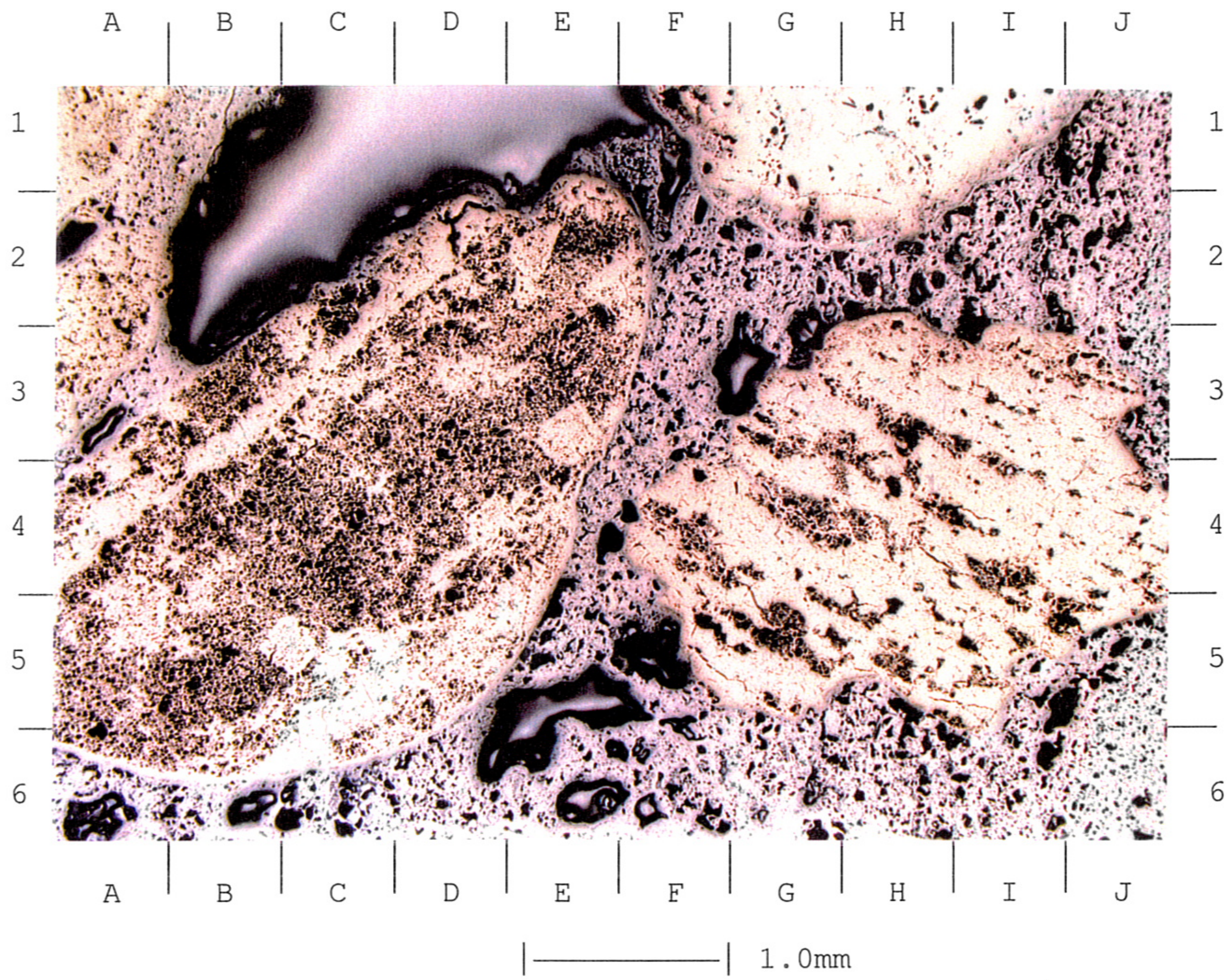
3/6/95/5

Canga. Pisolitic, with numerous coated grains. Clasts are mainly hematite in a crystalline goethite matrix. Cores are mainly monogenetic, being either altered BIF or desiccated goethite. Some clasts have fractured early cements overlain by continuous later cements, and one ex BIF clast has a part dehydrated goethite (hematite) and part goethite fragment cemented to it. Altered martite and magnetite grains are present in the altered BIF cores.

The goethite cement commonly supports pisoliths with cores varying from composite grains to hematite/martite crystals, fractured hematite and goethite.

Photomicrograph

Detrital hematite components of canga, including mineralised BIF (right) and pisoliths (C2) with goethite(?) rims and matrix (E-3-G6).



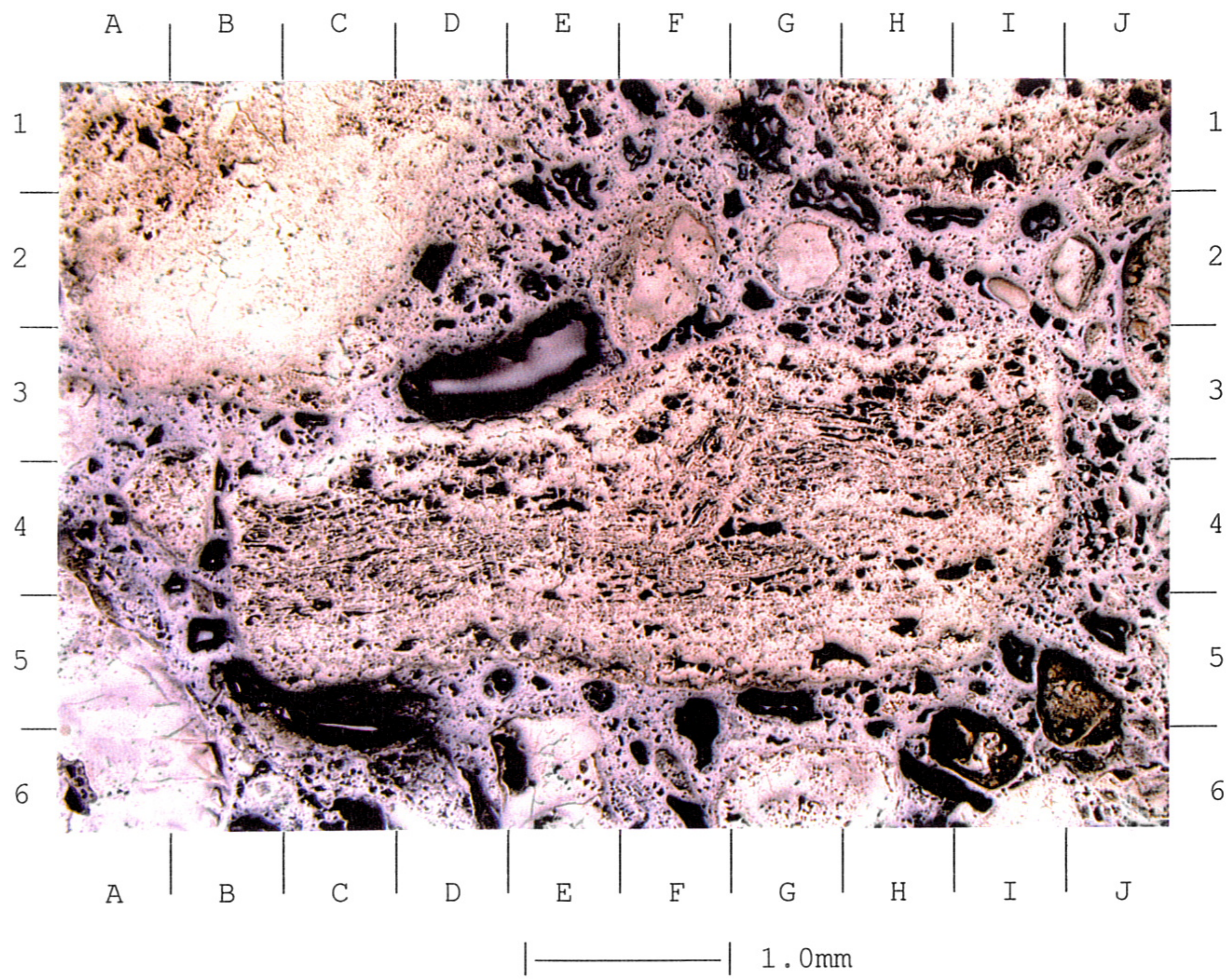
9/6/95/2

Canga. Detrital grains include altered BIF, desiccated (to hematite) crystalline goethite and some composite grains. Some of the detrital grains have a "fenestral" appearance where vugs have been filled with or patches have been included which once comprised agglomeration of very small goethitic/soil pisoliths. Clasts comprise mainly hematite with some goethite and small patches of kenomagnetite. Pisoliths are not recognised except as poorly developed weathering fabrics in other detrital grains.

Two generations of cement are present. The earlier generation comprises mainly kenomagnetite, and is overlain by crystalline goethite. "Soil" is rare. The kenomagnetite cement directly overlies clasts, indicating relatively early cementation and relatively little local erosion, re-working and re-cementation.

Photomicrograph

Clasts in canga including mineralised BIF (centre) and detrital grains with indeterminate hematite cores (H1). Cement and matrix is crystalline goethite (F2).

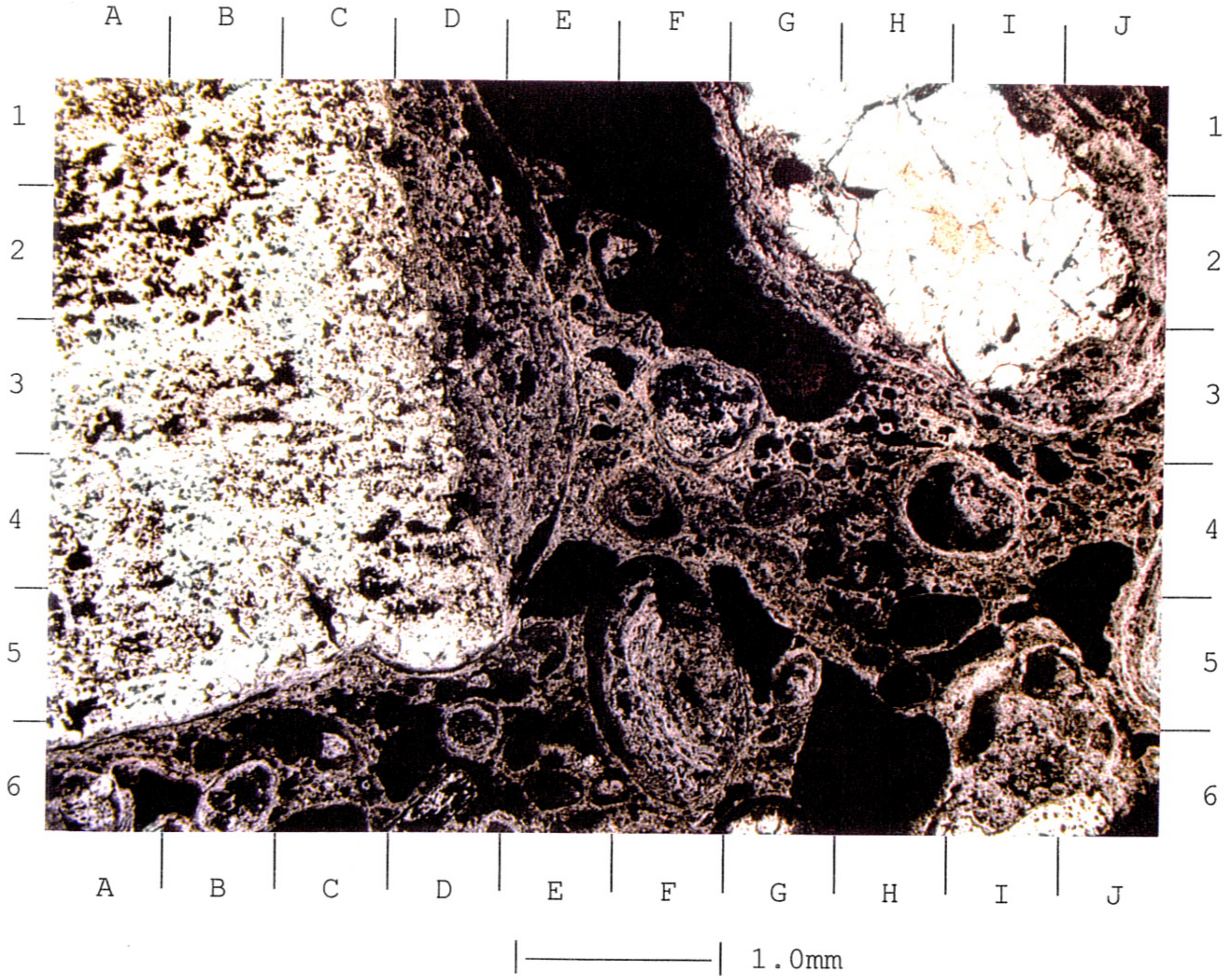


15/8/95/1A

Canga. Sample has a significant number of mineralised BIF clasts as well as (generally smaller) pisoliths, coated grains and a single probable wood fragment. Mineralised BIF is mainly hematite. Pisoliths and coated grains are more variable, although still dominated by hematite. Some have desiccation cracks. Coatings on grains varies from insignificant to moderately well developed. The sample is fully cemented with a vuggy crystalline goethite cement.

Photomicrograph

Clasts in canga including mineralised BIF (centre) and detrital grains with indeterminate hematite cores (B2). Cement and matrix is crystalline goethite (F6).



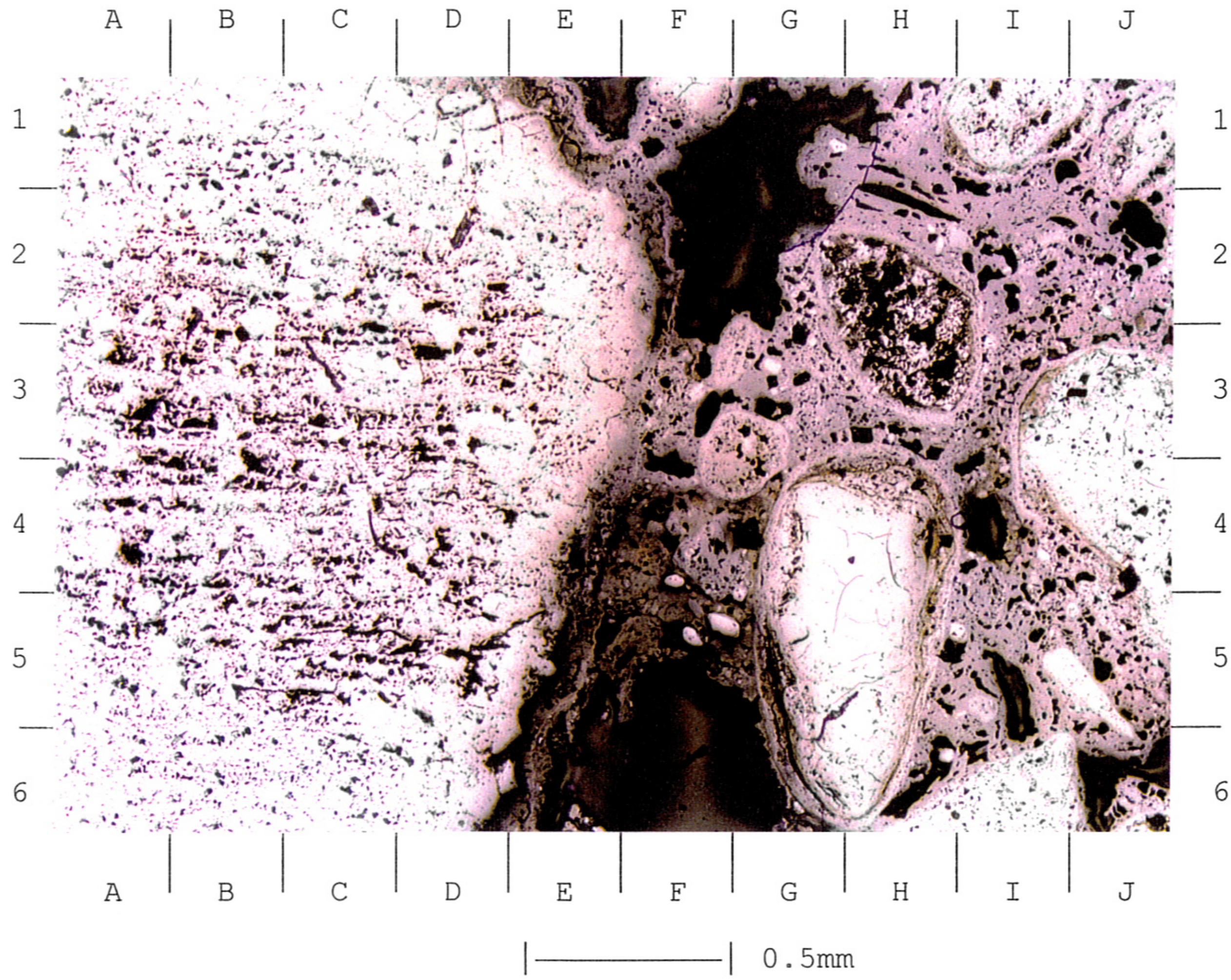
15/8/95/10

Canga. Cores of clasts include mineralised BIF, indeterminate cores (desiccated/fractured hematite) and polymorphic grains. These last may mineralised BIF, cement fragments and pisoliths. Most clasts are mainly hematitic, but some are goethitic. Clasts are angular to well rounded.

Clasts mostly have well developed goethitic cutans, commonly enveloping mineralised "soil" in addition to cores. Matrix is goethitic, and includes pisoliths.

Photomicrograph

Canga showing coated clast of mineralised BIF (left), desiccated hematite of indeterminate origin (H2) and pisoliths (centre0 in crystalline goethite matrix/cement.



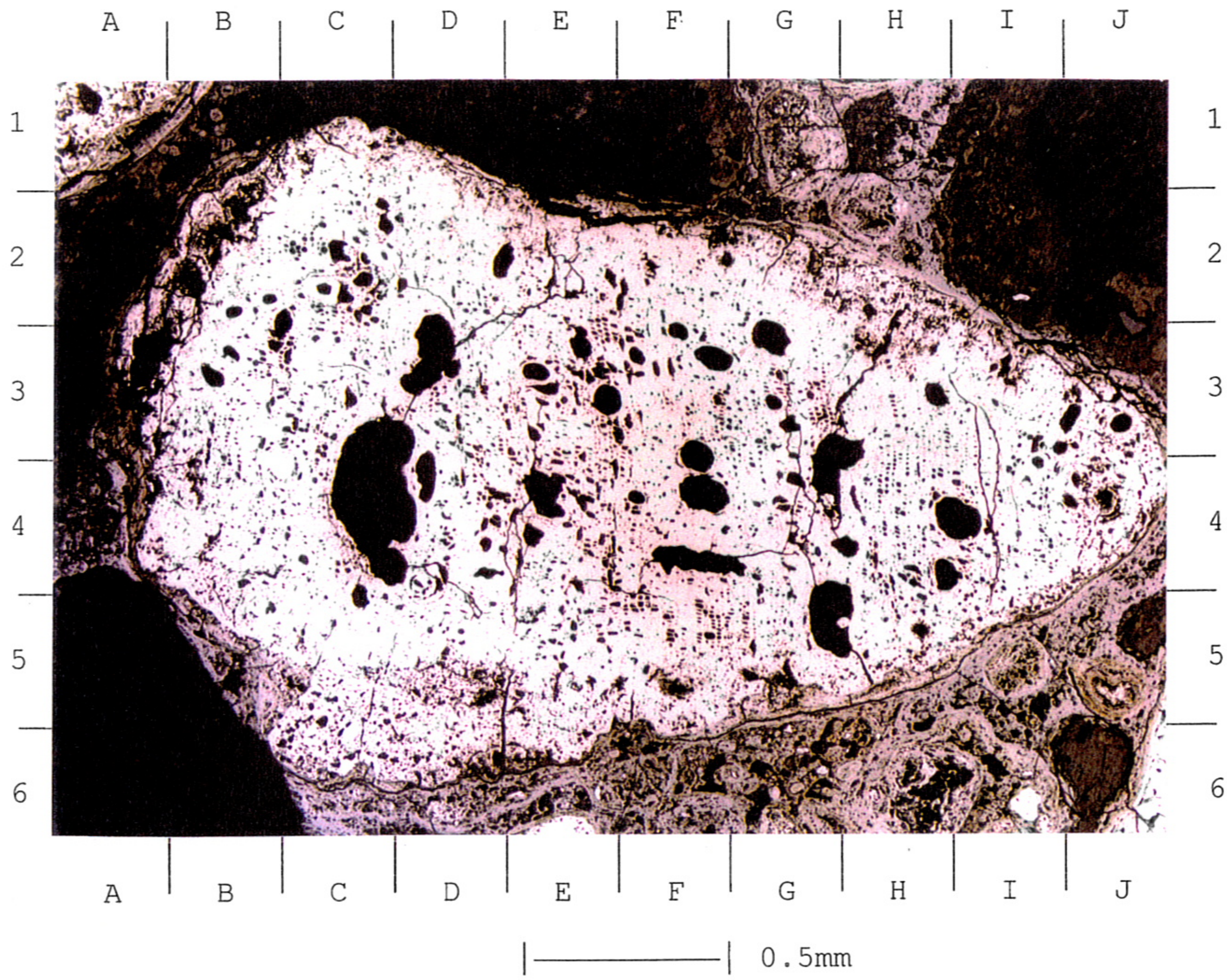
15/8/95/13

Canga. Detrital clasts comprise mainly goethite grains which are of have been dehydrated to hematite, leaving numerous shrinkage cracks. Some altered BIF clasts are also present. These vary from predominantly goethite to predominantly hematite. The latter are the most common, with textures varying from clearly dehydrated goethite to probable oxidised magnetite. Relict skeletal martite textures are visible in some samples as is possible hematised microplaty hematite.

The cement phase is polycyclic, comprising layers of vuggy goethite. Some pores are filled with soil. Pisoliths are relatively rare, but multiple coated grains with (commonly) fractured monocrystalline cores are recognised.

Photomicrograph

Clasts in canga comprising mineralised BIF (left) and pisoliths with cores of indeterminate origin (G5). Clasts have coatings of goethite cement set in a similarly crystalline goethite matrix (G3). Pores may contain goethitic "soil" material (F5).



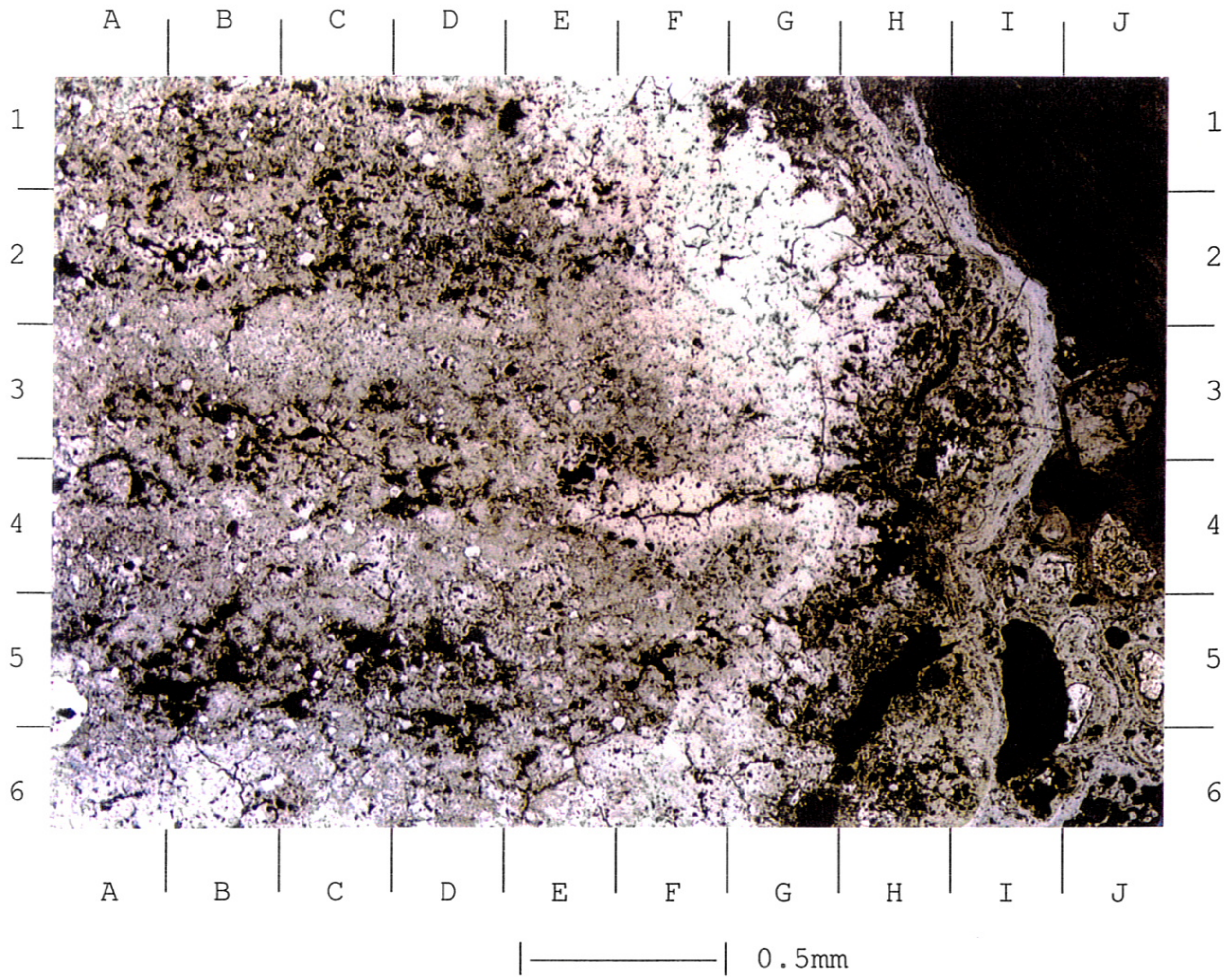
16/8/95/5

Canga. Contains mineralised (hematite) wood fragments. Clasts include goethitic and hematitic mineralised BIF fragments. Some clasts have goethite cores and have hematite margins where goethite has been desiccated to hematite. This texture is morphologically similar to the indeterminate cores of pisoliths and other detrital clasts ubiquitous in all detrital phases throughout the region. A single clast comprises a wood fragment which has been altered to hematite yet has retained its original structure, demonstrating that hematite mineralisation can occur in surface environments while original structure is retained.

Sample is cemented by crystalline goethite cement, and has matrix of pisoliths, "soil" and coated and un-coated intraclasts.

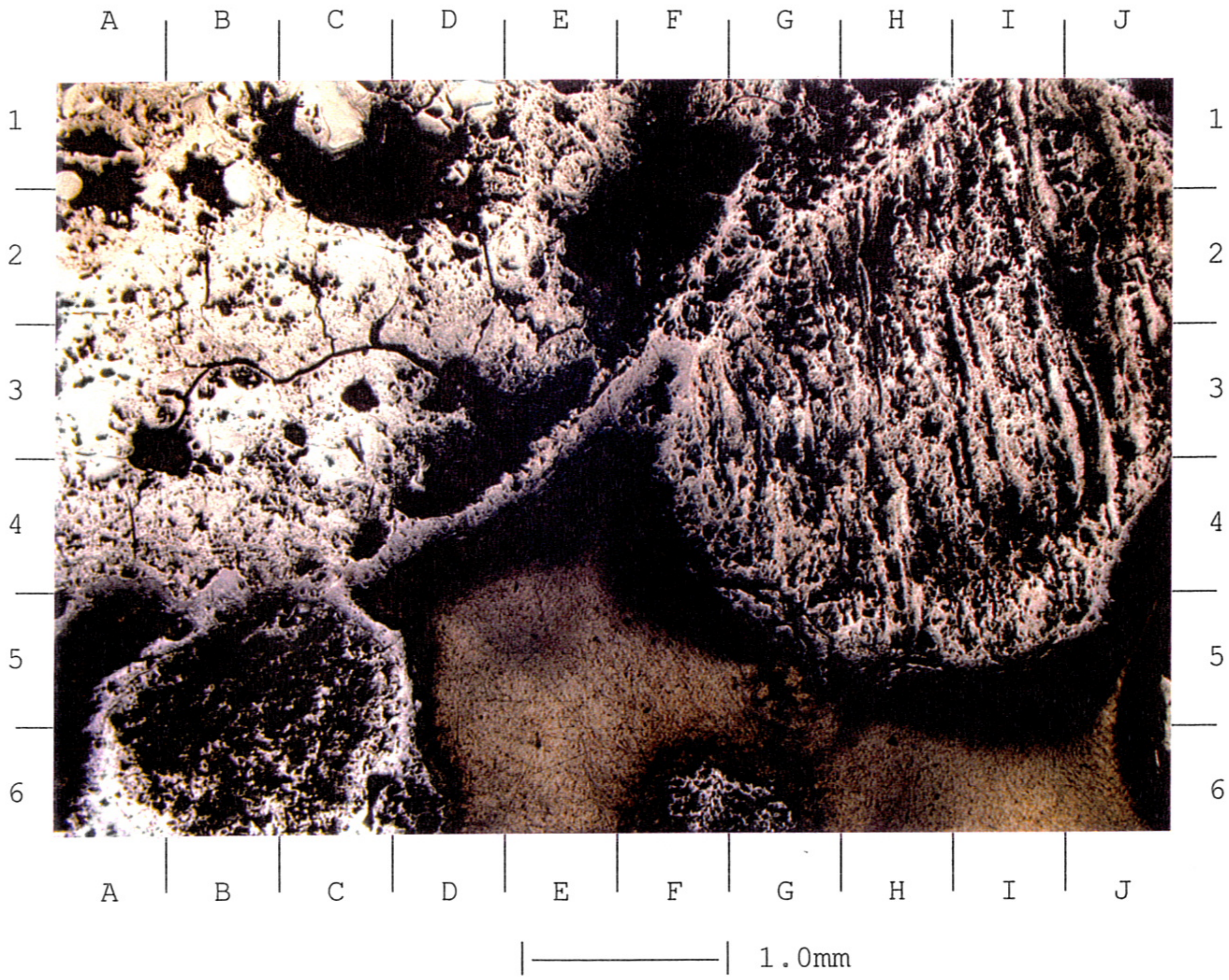
Photomicrograph

Wood fragment mineralised to hematite in canga. Detrital clasts including pisoliths (J5) are cemented with crystalline goethite (e.g. H5).



16/8/95/5

Mineralised BIF clast in canga. Clast is mainly goethite with dispersed hematite crystals (left) preserving laminated BIF texture. Margin of clast (F1-F6) comprises hematite with fractures typical of desiccation from goethite (F4, G2). Original BIF lamination is lost in conversion from goethite to hematite of similar appearance to indeterminate clasts and pisolith cores (F2). Clast is cemented with crystalline goethite (I3).



28/8/95/2

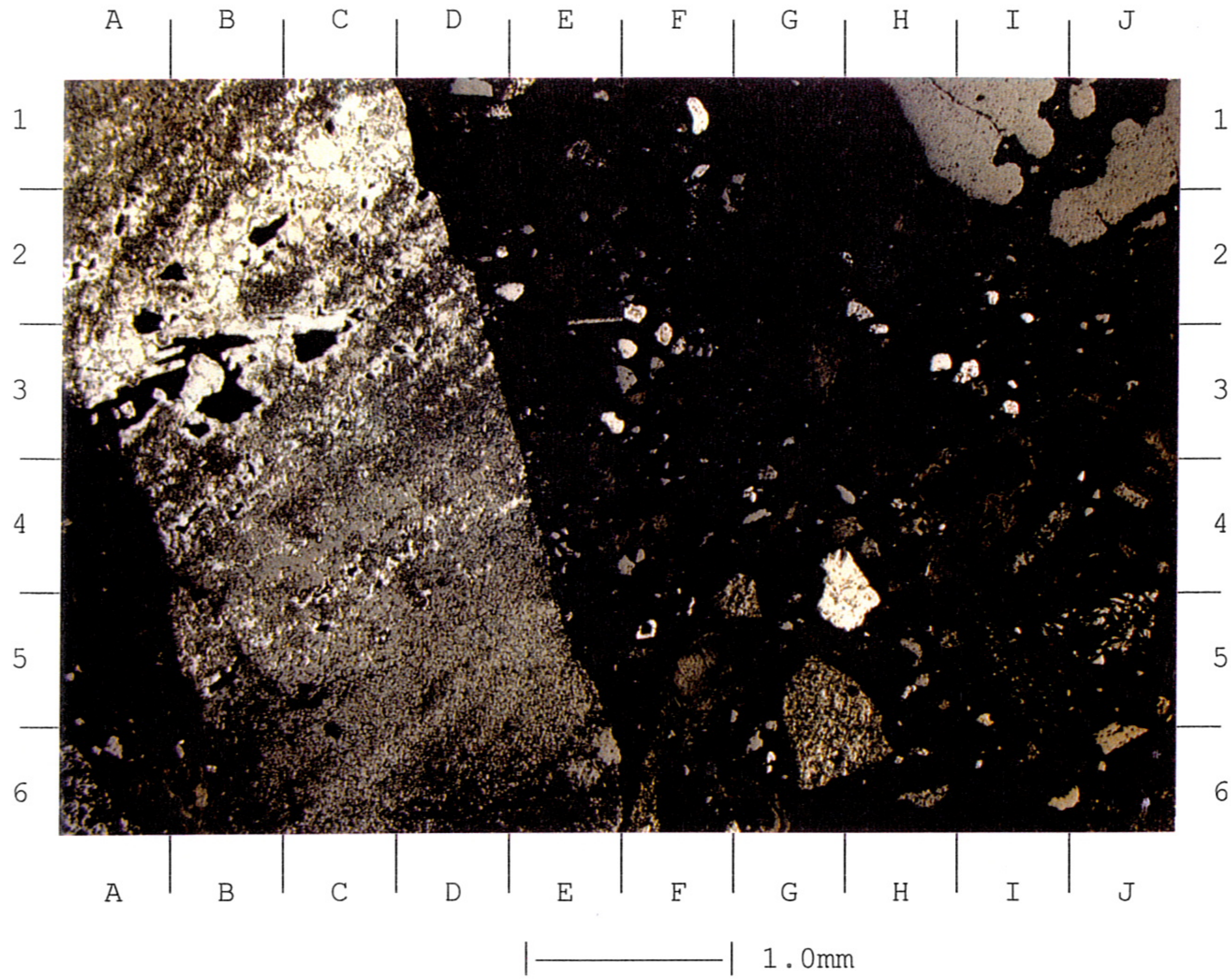
Canga. Sample comprises hematite clasts cemented in a crystalline goethite matrix. Clast are up to pebble size and generally well rounded. Clasts may be have single or poly-granular cores. Cores vary from recognisably altered BIF to featureless crystalline hematite or goethite of no identifiable provenance. Cores commonly contain both minerals. Laminae of BIF fragments may comprise both minerals, with fractures in goethite bordered by hematite. Fractures in goethite bordered by goethite are common in all clasts.

Poly-granular cores contain mixtures of BIF derived and un-attributable clasts. Clasts have multiple skins, the number and thickness of these skins is variable. Some are multi cyclic, and skins/grains have been fractured and re-cemented. Vugs in the sample are variably filled (geopetals?) with "soil".

Photomicrograph

Cemented mass of mineralised grains (canga) comprising mainly hematite mineralisation with a hematite cement. Cores of clasts vary from desiccation-fractured composites (top left) and to mineralised BIF (right).

Immature Detritus

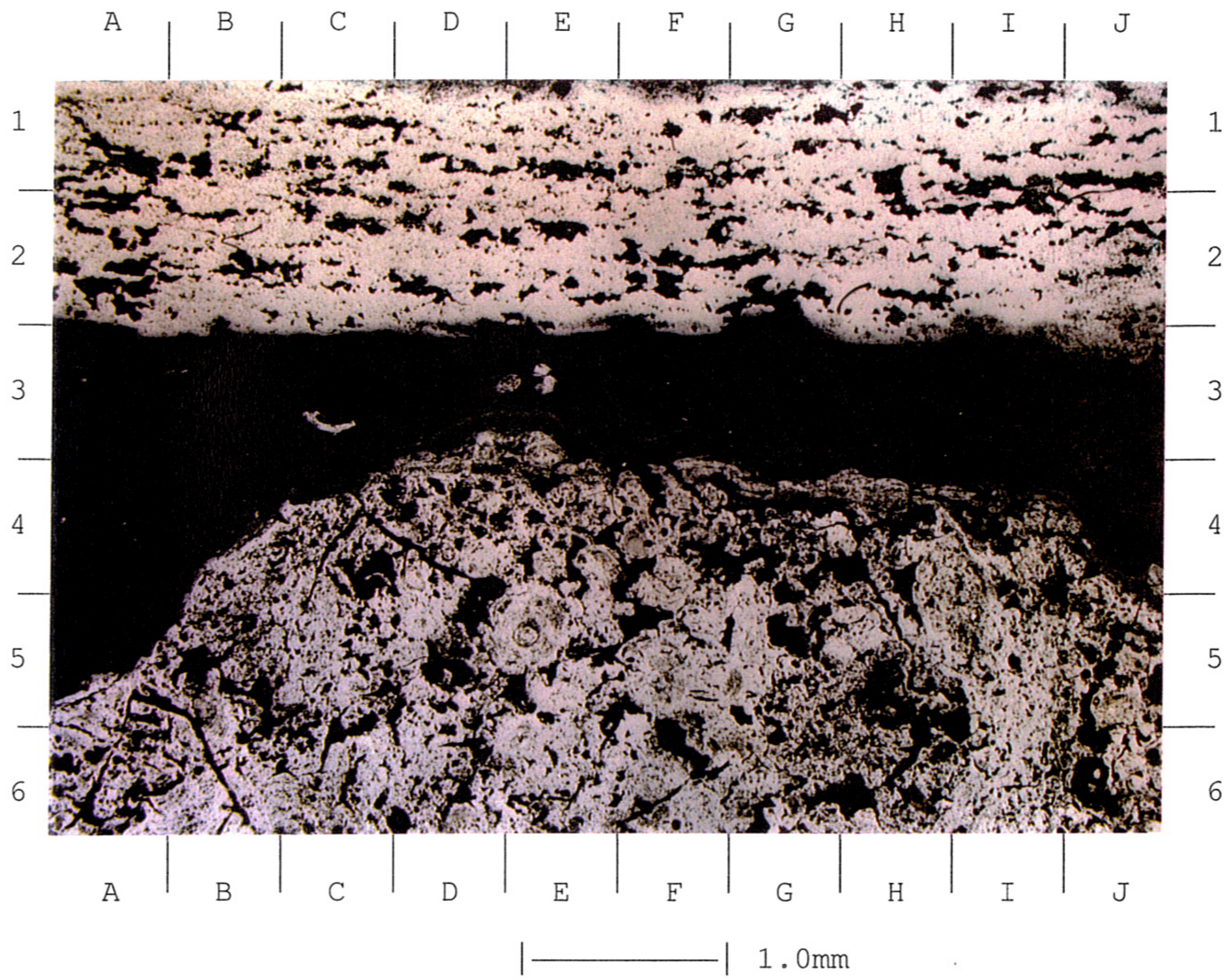


9/6/95/1

Immature detritus conglomerate. Angular clasts of mainly un-mineralised BIF supported in a goethite and kaolinite clay size-fraction matrix. Contains some part-mineralised BIF and hematite fragments. Chaotic texture with no preferred clast orientation.

Photomicrograph

Angular weathered (to goethite and hematite) BIF clast supported in clay size-fraction matrix containing numerous small angular goethitic (dull) and hematite (bright) clasts.



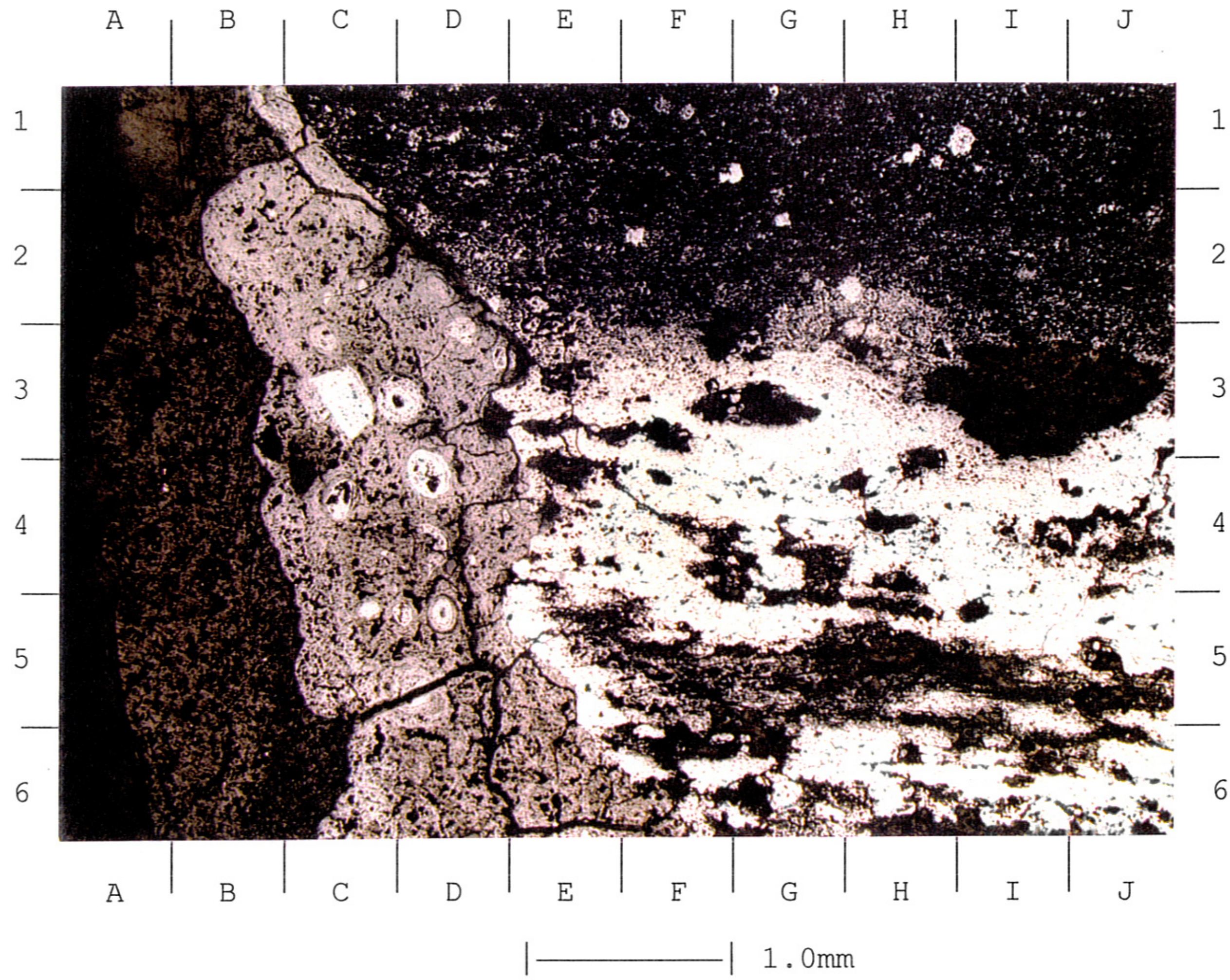
29/8/95/2

"Proto"-canga. Sand to pebble size clasts in a clay size-fraction goethite "soil" matrix. Clasts vary from large fragments of altered BIF to pieces of pisolite. Some clasts are poly-nucleic, and include BIF, pisolite, fractured cement, wood and dehydrated crystalline goethite. Some ex-BIF contains martite crystals, and some has a fenestral fabric. These fenestrae are commonly filled with clay size-fraction goethite of chert.

The cement phase commonly comprises a thin skin of goethite which grades out into clay size-fraction soil goethite.

Photomicrograph

Mineralised clasts, BIF (top) and rounded pisolitic (E5) composite (bottom). Both clasts are of mainly hematite. Dark matrix comprises combination of isopachous fibrous goethite and clay size-fraction goethite, with some pores filled with chert.

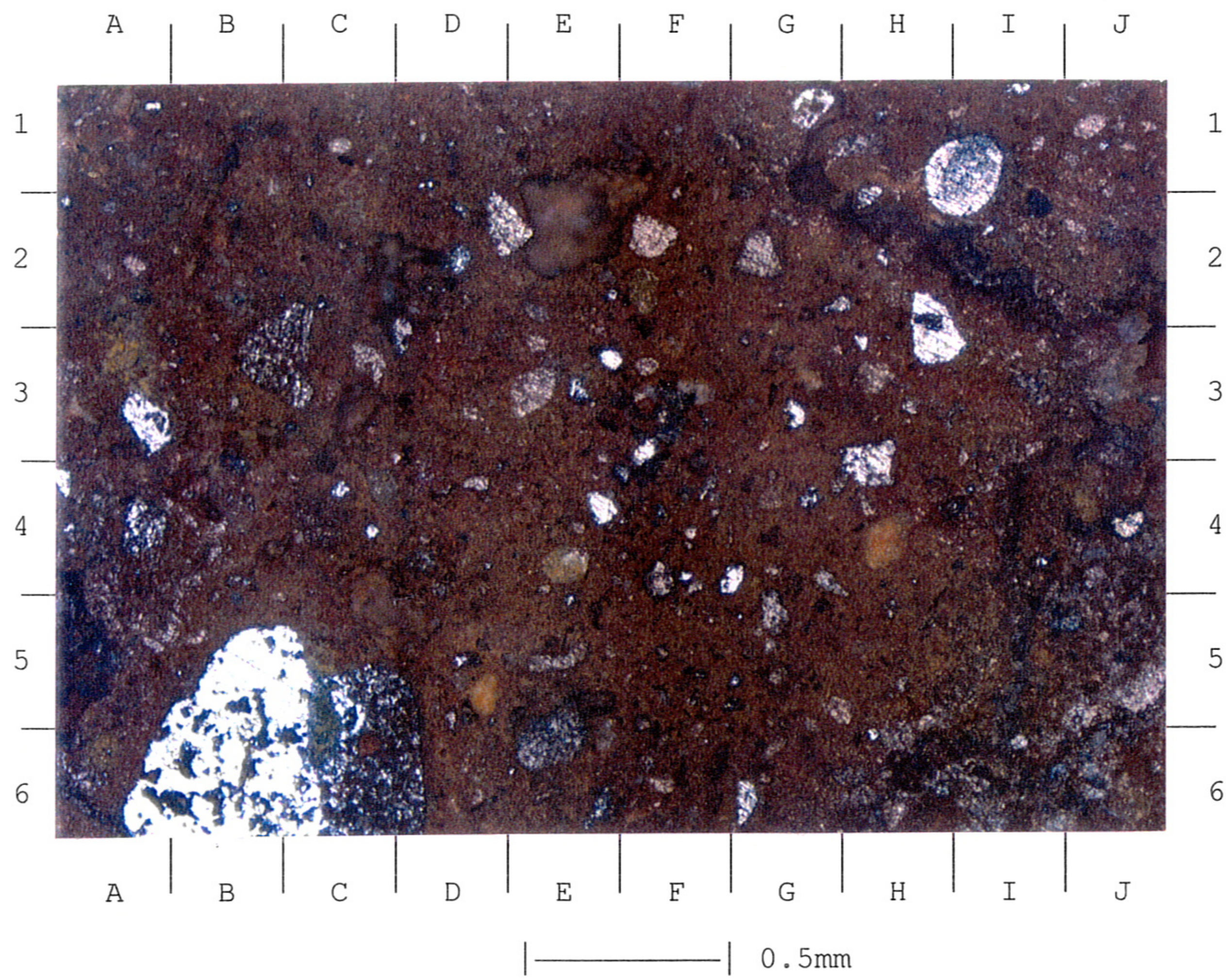


29/8/95/3

Un-cemented detritus (up to pebble size) cast in resin. Clasts vary from part-mineralised (siliceous) and fully mineralised BIF to composite pisolitic intraclasts. Cores of clasts are dominated by hematite. Skins on clasts are mainly goethitic, but with considerable variation. Some clasts have no skins while most have "modern" skins of clay size-fraction goethite. This commonly overlies part or fully preserved earlier hematite skins of dehydrated goethite. Some clasts also have dehydrated goethite cores.

Photomicrograph

Termination of a clast of mineralised BIF (hematite, right) overlain by two generations of goethite cement. The earlier cement is pisolitic (D4, D5) and more crystalline (lighter) than the later clay size-fraction layer (dark).



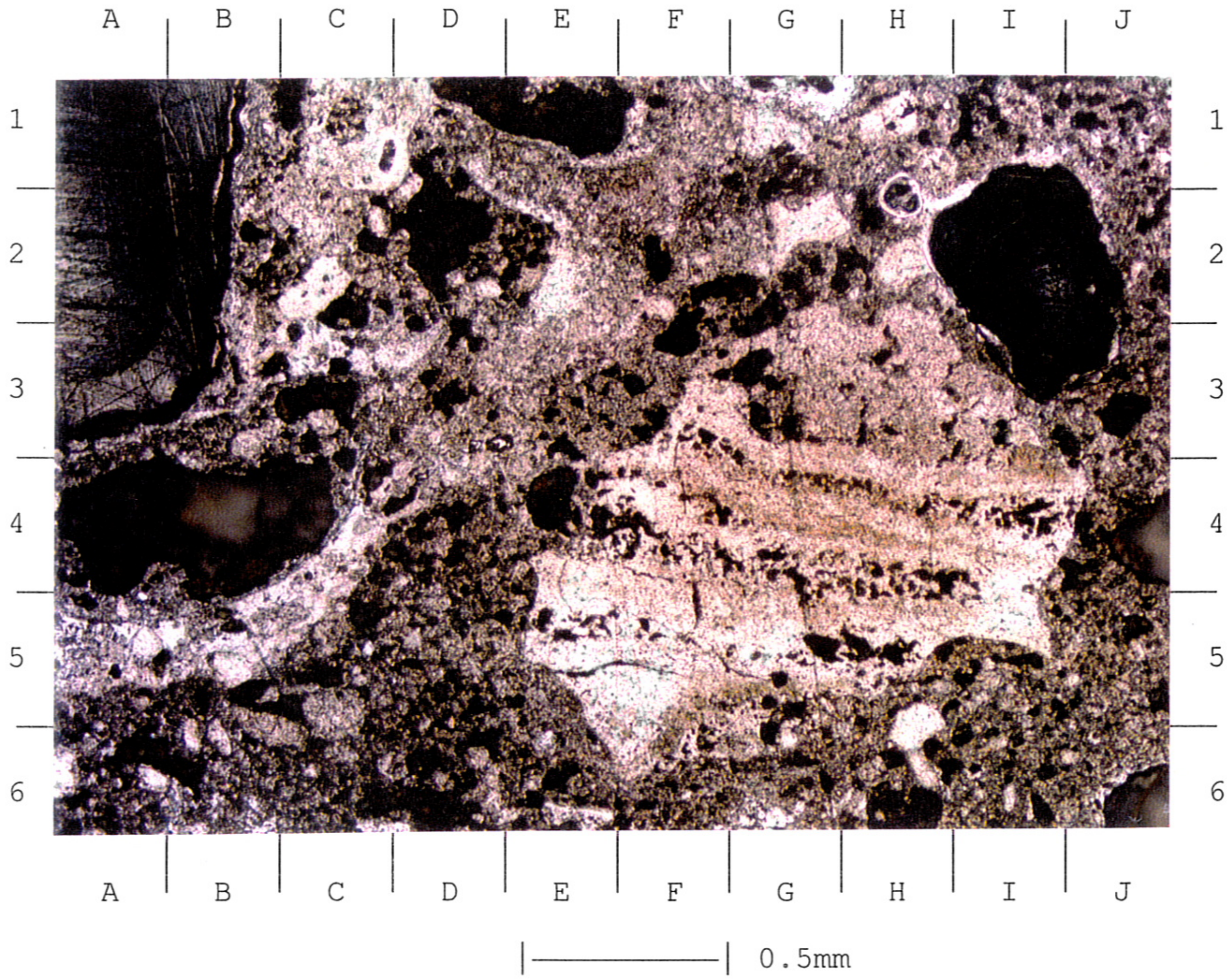
ACC277

Clay size-fraction cemented immature detritus. Goethitic "soil" clay size-fraction. Matrix supports clasts of martite crystals (angular) and other detrital hematite (including dehydrated/ fractured goethite).

Photomicrograph

Weathered goethite crust with hematite clasts (B6) and chert-filled vugs (E2).

Laterite

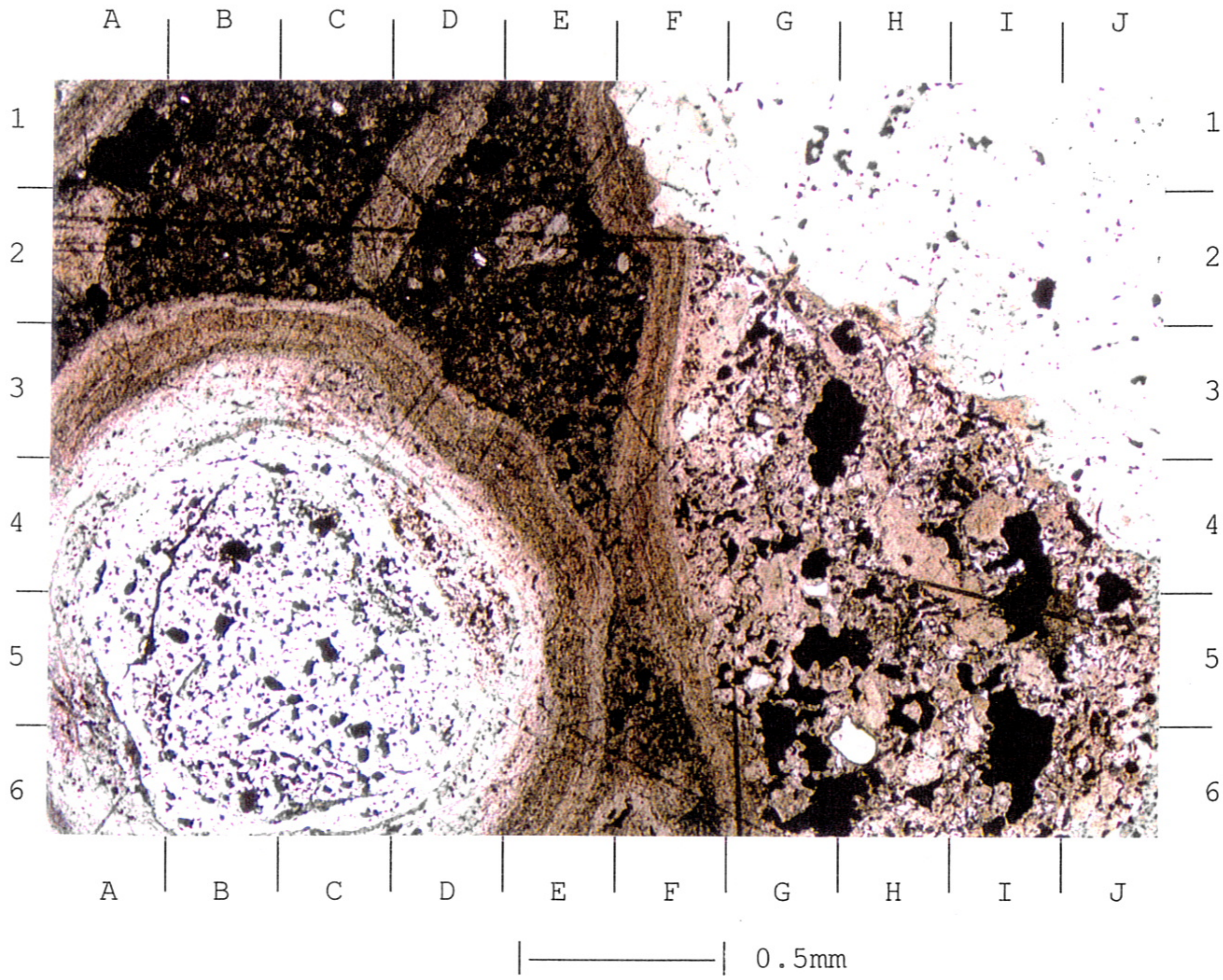


16/8/95/6

Weathered goethitic crust. Vuggy, with hematite fragments including mineralised (hematite) BIF.

Photomicrograph

Goethite crust (matrix) supporting clasts including laminated hematite (mineralised BIF?, G4).

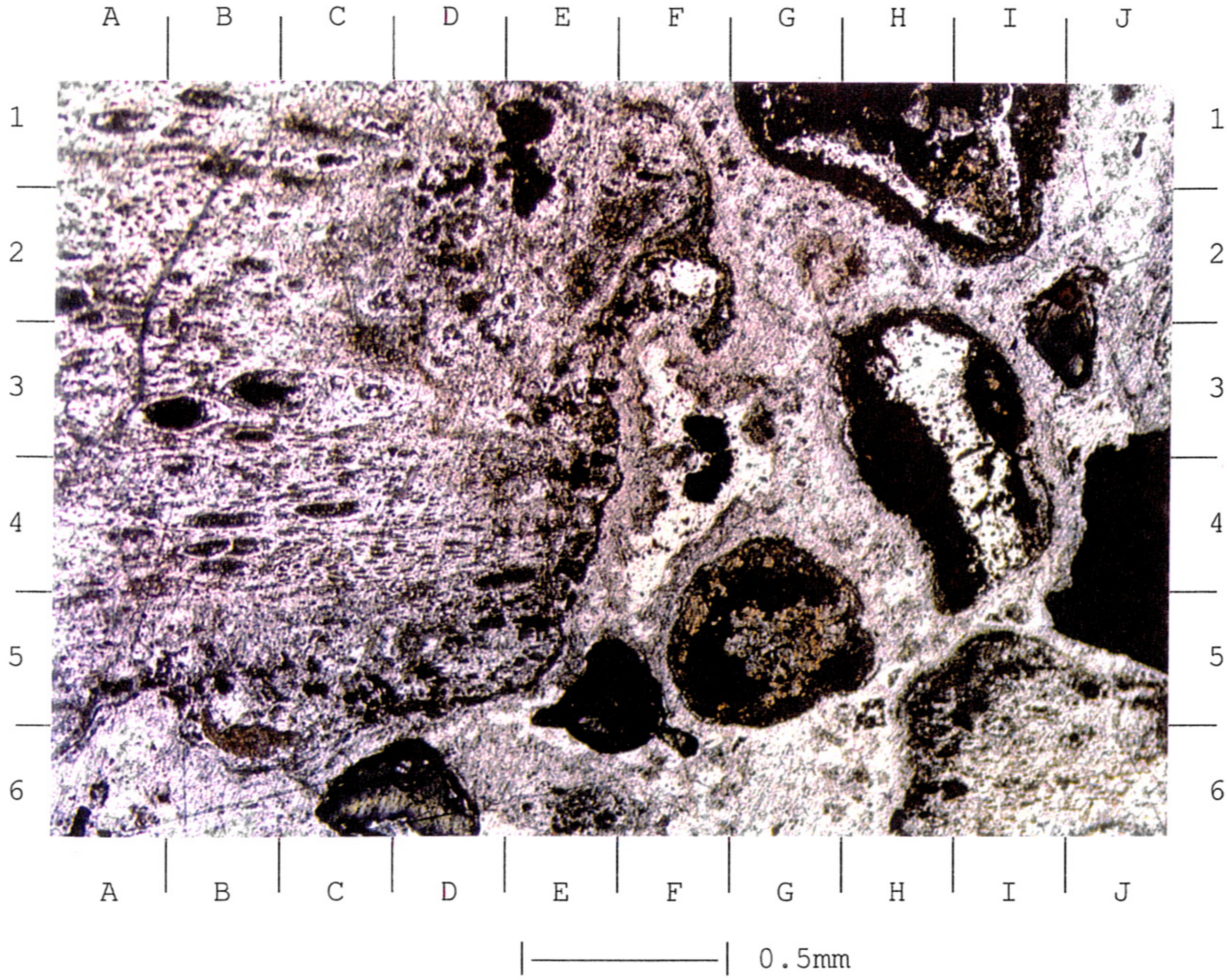


ACC275

Goethitic pisolite. Heavily weathered material now altered to goethitic clay size-fraction mass with some pisolites. Vuggy, with chert fill. Soil.

Photomicrograph

Pisoliths with indeterminate (B4) and compound (right) cores. Compound core varies from hematite to goethite in composition. Clasts have goethite cements (F4) and soil matrix (E2).

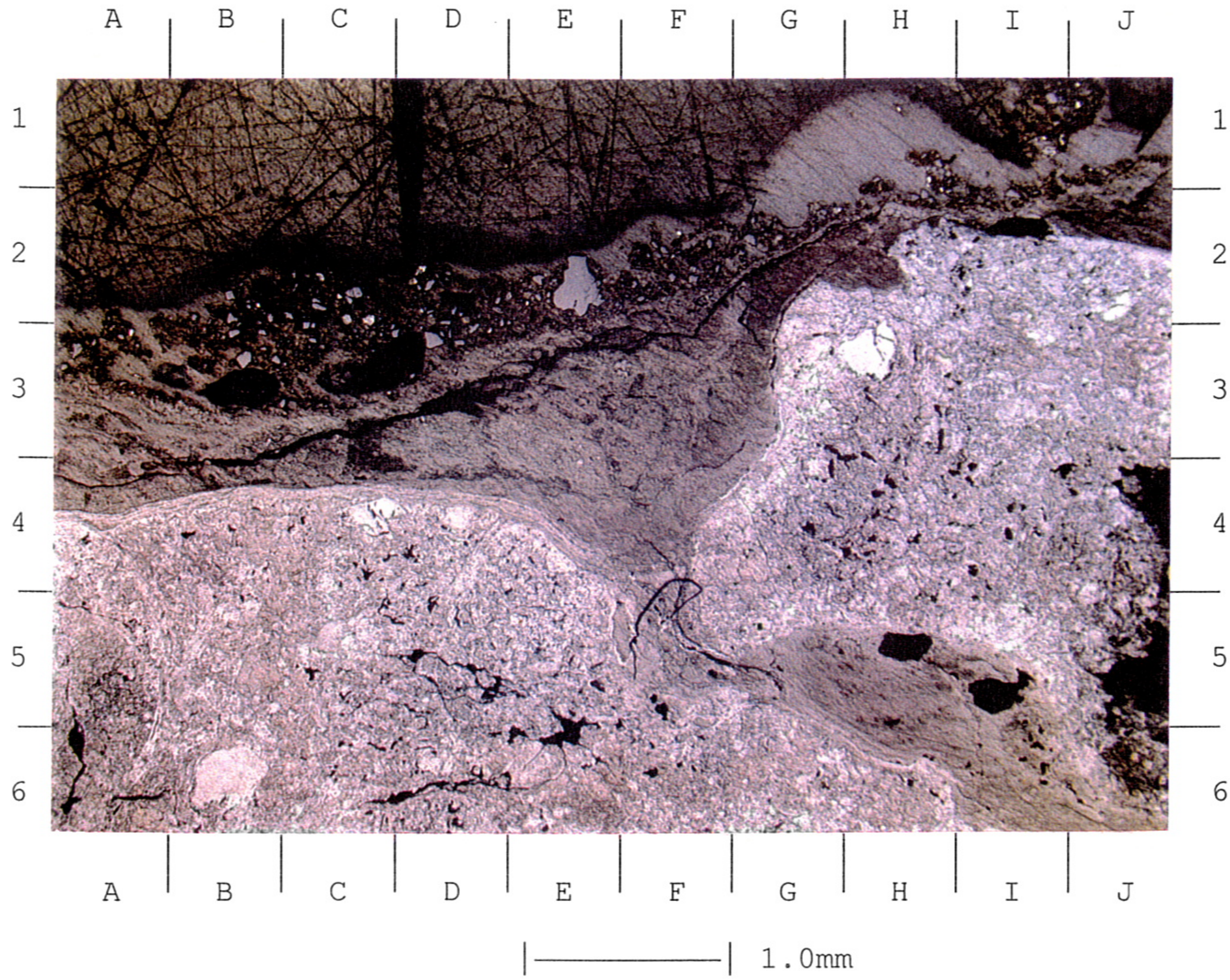


HMC12

Sample comprises mainly altered wood clasts with others of indeterminate origin. Clasts commonly have rims of clay size-fraction goethite, with the matrix comprising crystalline goethite cement. Many clasts have undergone partial dissolution, leaving mouldic porosity.

Photomicrograph

Wood fragment and other clasts (e.g. G5) in crystalline goethite cement (F1). Clasts may have indeterminate goethite or hematite cores, but typically have corrosive rims of clay size-fraction goethite (e.g. H3).



HMC7

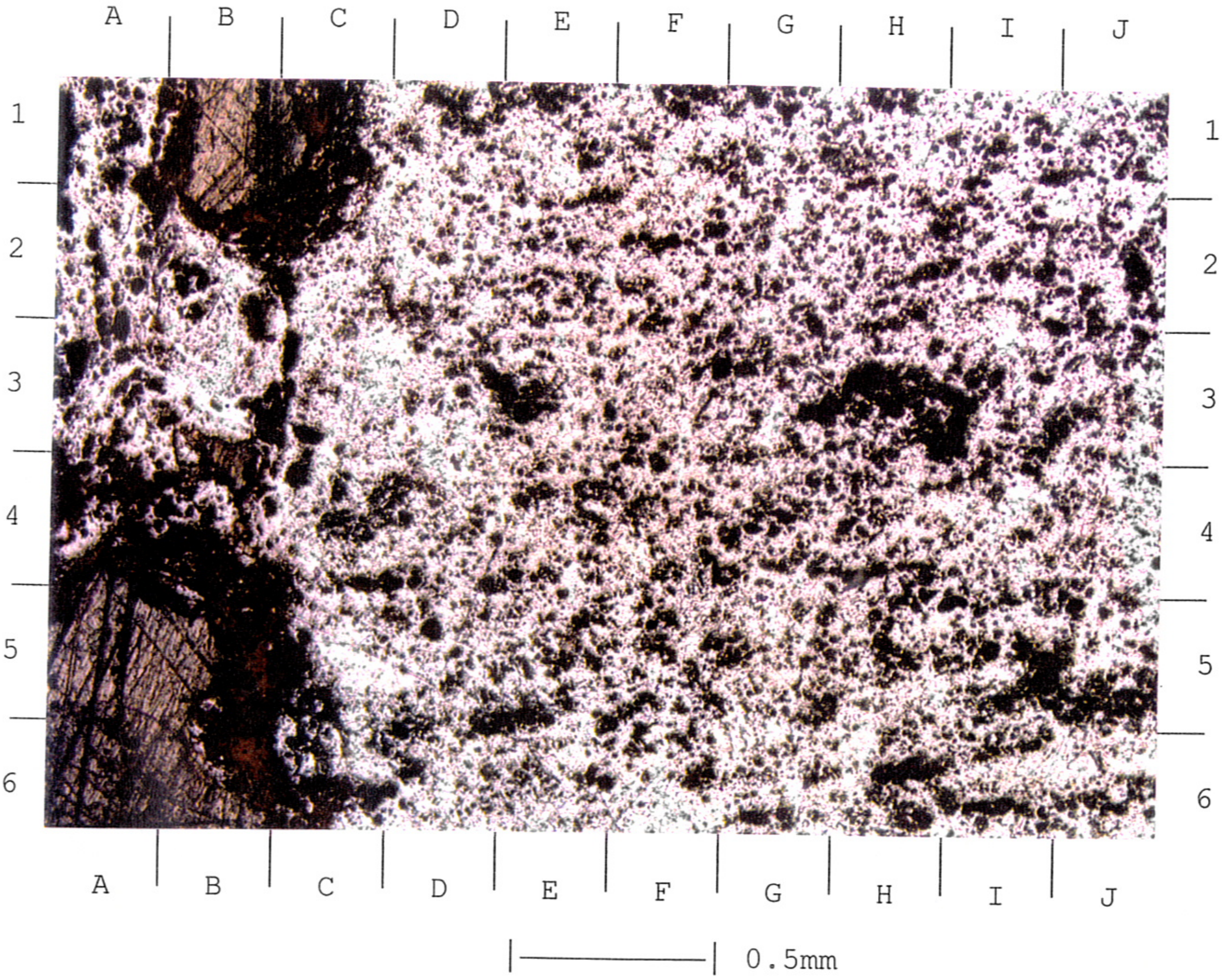
Laterite duricrust of mottled goethite over shale of the Jeerinah Formation, Fortescue Group. This generally indurated mass is diffusely mottled various shades of light- to dark brown. Few to many vermiform voids to 5mm diameter are present and can have yellow brown to pale brown linings. Irregular tongues, lenses and partings cross the mass and these comprise yellow brown red indurated clay. These elongate clay bodies appear to occupy the same type of voids described above, and in cross-section show the multi cutanic nature of their margins.

Some samples of this material can have a coarser pisoid structure. In these more pisoid parts of the mass, the multi cutanic zones, to 3mm wide, separate sub-rounded to ovate diffusely mottled patches (to 1cm across) that can form the core of individual gravel fragments that can be eventually released by weathering.

Photomicrograph

Goethite clasts (bottom left, right) in goethite cement (e.g. F3) overlain by "soil" with hematite crystals (E2).

Tertiary Pisolite



HMC29

Tp. Sample comprises hematite/goethite clasts in a clay size-fraction goethite matrix/cement. Cores of clasts are typically of uncertain origin, although some mineralised wood (to hematite) cores are recognisable. Some possible mineralised (hematite) BIF fragments are present. Some clasts are pisolitic or may be fractured cement/pisolite intraclasts.

Photomicrograph

Hematite clast preserving laminae suggesting provenance from mineralised BIF in Tp sample.