The Geology and Origin of Sedimentary Manganese From the Boolcunda, Etna, and Muttabee Deposits, central Flinders Ranges, South Australia

CHRISTOPHER T. GREGORY B.Sc.

Thesis submitted as partial fulfilment of
the Honours Degree of Bachelor of Science

Department of Geology and Geophysics
University of Adelaide
November, 1988

National Grid Reference : ORROROO Sheet SI 54-1 (1:250,000)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The origin of small manganese deposits from the central Southern Flinders Ranges, has not previously been adequately discussed. The region comprising these sedimentary manganese accumulations incorporates a sinuous folded sequence of thick variegated clastic and carbonate sediments deposited within the Adelaide Geosyncline, the stratotype basin for the Adelaidean sediments delineated.

Extended exposure of the craton to the west provided a dominant source of both sedimentary detritus and manganese ore constituent. Paragenesis involved leaching of manganese from this source region, transport into the aqueous system and subsequent precipitation in favourable shallow-marine environments meridionally within the Adelaide Geosyncline.

Cyclic eustatic fluctuations increased potential ionic manganese concentration, with remobilisation and concentration during transgressive oxygen deficient phases and oxidation and precipitaition during alternate regressive more oxygenated phases.

The precipitation of particulate manganese-oxides, from pre-existing particulate and dissolved manganese from an enriched reservoir, was controlled by the interactive response of a number of features : estuarine circulation, anoxic-oxic water stratification; and sediment-water interface relationships, at specific geomorphological sites on a stable shallow-marine continental platform. Retention of the precipitated manganese resulted from rapid burial by regressive sands and silts, with little post-genetic supergene alteration of the deposits observed.

1. INTRODUCTION

1.1 AIMS AND METHODS

Sedimentary manganese deposits of early Cambrian to Late Proterozoic age are known from several locations in the Adelaide Geosyncline in South Australia. In this study the geology of three such accumulations at Boolcunda, Etna, and Muttabee are analysed. The aims involved in this study are:

(1) to establish the geologic setting of the deposits, via delineation of the regional stratigraphic sequence aiding deposit interpretation relative to the regional geological framework;

(2) precise lithological logging, enhancing genetic interpretation by providing concise data on the prevailing terrestrial sedimentological conditions during deposit formation.

(3) to establish a geochemical and mineralogical profile of all ore types and associated host rocks, thereby delineating the configuration and extent of the ore horizons;

(4) to interpret the depositional history (genesis) of the deposits and to assess the role of secondary processes in ore formation;

(5) to compare the deposits with terrestrial manganese accumulations described elsewhere.

The importance of field mapping is highlighted implying precise geological environment and deposit character interpretation, and collection of relevant geological data. This field mapping was performed using 1:10,000 scale planimetric base maps, expanded from and supported by 1:40,000 scale aerial photographs. In the ensuing discussion, methods utilised and results obtained for the data collection techniques used are described - techniques involving detailed mine site description, precise lithologic logging, petrographic and mineralogic analysis of thirty thin sections and polished slabs, and the geochemical analysis of thirty-three field samples.

1.2 LOCATION AND PHYSIOGRAPHY

Boolcunda, Etna, and Muttabee are located within the central Southern Flinders Ranges of the Adelaide Geosyncline, South Australia (Fig 1). Mapping was centred, at each locality, on a sedimentary manganese accumulation with analysis of these deposits forming the bulk of the following discussion.

Units mapped consist of upper Adelaidean sediments, forming essentially rounded hills and ranges separated by broad alluvial valleys, cut dominantly by ephemeral creeks.

As indicated from Fig. 1, the most southern field area is that of Muttabee. Located 268 km NNW of Adelaide and 15 km WSW of the township of Carrieton, at latitude 32°30'07" S and longitude 138°34'10" E. Muttabee encompasses a map area with the highest relief features encountered - parallel ridges of approximately 450 m elevation, incised by erosional valleys.

Boolcunda forms the central field locality, 294 km NNW of Adelaide and 20 km NNW of Carrieton, and has its position centred on 32°16'30" S latitude and 138°24'50" E longitude. It is characteristic of the Carrieton region in physiography - rolling subdued-relief hills and low ridges interspersed with dominantly alluvium-covered, broad shallow valleys.

The Etna mapping area comprises the most northerly of the field areas at latitude 32°04'10" S and longitude 138°22'50" E, situated 320 km NNW from Adelaide. The physiography is a repeat of that already described, albeit of somewhat flatter rolling hills comprising the siltstones, sandstones, and carbonates of the Late Sturtian to Marinoan sequence differentiated from field mapping.

1.3 PREVIOUS GEOLOGICAL INVESTIGATIONS

Apart from Reports of Investigations, Mining Records, and Mining Reviews undertaken by the Department of Mines and Energy of South Australia, no detailed and precise geological investigation of the Boolcunda, Etna, and Muttabee manganese deposits of this nature has previously been performed. The following information is the result of a literature review of these and other unpublished reports.

Operations at the Boolcunda manganese mine, initially named the *South Australian* mine, commenced in 1882-3 with the removal of ore from four lodes parallel to strike of the host sands and silts of the Wilmington Formation. Descriptive reports of deposit character, mining techniques and approximate tonnage removed exist (Browns, 1908; Armstrong, 1938; Cornelius, 1940). However, only one report, by Shepherd and Thatcher (p:16, 1959) gives any insight into the mineralisation form, describing it as a botryoidal ore "in brecciated material apparently as a cavity filling deposit." Since the early 1900's little removal of manganese has occurred from this essentially stratiform accumulation.

Commencement of mining at the small Etna deposit is not precisely known but a similar period as that for the other two accumulations is likely. Armstrong (1941) was the first to mention this accumulation in any detail, observing that the ore horizon was difficult to delineate because of minimal exposure, but that it appeared to have a NE strike and shallow 25^{o} NW dip, having been exploited by small shallow open cut mining of less than 10 m penetration.

The Muttabee deposit, worked in the 1890's and then sporadically between 1940-49 (Binks, 1971) is also a thin stratiform ore body. Although stratiform with a well defined hanging wall boundary, the two 0.5 to 5 m thick ore horizons are rather distorted, a response to its postulated replacement genesis model - replacement of sand and debris filled cavities and small caves (Binks, 1971). Dominated by massive mammilliated pyrolusite with grades in excess of 50% Mn, this deposit was producing some 16 tonnes of ore per week from 11 to 15 m shafts over a strike length of 70 m (Mansfield, 1949; Ridgway, 1951).

Considerable information is also available from regional geological studies of the rock suites and stratigraphic relationships encountered in this study. In particular work by Binks (1971) and Preiss (1987) aided greatly the analysis and interpretation of the field rock relationships. These and other authors will be duly recognised in the ensuing chapters.

This outline highlights the need for a genesis study of these sedimentary manganese accumulations - as a study to further enhance the understanding of manganese mineralisation, and mineralisation in general, within the Adelaide Geosyncline.

2 GEOLOGICAL SETTING

2.1 REGIONAL GEOLOGICAL HISTORY

The tectonic regime of the deposits forming the basis of this study is the Adelaide Geosyncline - a depositional trough forming a thick sequence of Adelaidean and Cambrian sediments, deformed into a complex sinuous and branching system of folds by the Cambro-Ordovician Delamerian Orogeny (Rutland et al., 1981). Ultimately resting on Precambrian crystalline basement, the general tectonic framework is revealed in Fig. 1.

The Geosyncline is the stratotype basin for the thick Adelaidean (Late Proterozoic) sedimentary sequence, subdivided into four lithostratigraphic units: the Callanna, Burra, Umberatana, and Wilpena Groups representing four cycles of dominantly shallow-water sedimentation (Preiss and Forbes, 1981). Chronostratigraphic subdivisions relative to these units are the: Willouran, Torrensian, Sturtian, and Marinoan, the boundaries of which are not always coincident with the lithostratigraphic nomenclature (Fig. 2).

Repeated transgressions and regressions within the partly intracratonic trough and partly miogeoclinal continental shelf to the southeast (Preiss and Forbes, 1981) formed the thick sedimentary sequence observed, with partly time-equivalent correlatable sedimentation on the Stuart Shelf to the west and to the north in central and northern Australia (von der Borch, 1980).

Chronostratigraphic and lithostratigraphic relationships are outlined by Fig 2, and expanded in Fig. 4, accounting for observed field relationships. Comprehensive summaries of the sedimentary and tectonic history of the Geosyncline are given by Parkin (1969), Preiss and Forbes (1981), Rutland et al. (1981), and by Preiss (1987).

As a general overview, the initial history reveals early rifting indicated by widespread Willouran volcanics. This is followed by shelf-carbonate and deltaic cycle development during the Torrensian, succeeded by early Sturtian glaciation, late Sturtian marine transgression and regression, and finally a late Marinoan glacial phase (Preiss and Forbes, 1981).

The evaluation of sedimentation within the Late Sturtian to Late Marinoan interglacial and initial post-glacial phases of facies development is required, as this sedimentation phase encompasses those rock units delineated during field mapping. Meridionally positioned within the Adelaide Geosyncline, between the Torrens Hinge Zone to the west and the geosynclinal depocentre trough-axis to the east, the zone of sedimentation under consideration encompasses a shallow broad stable platform, deepening to the east and southeast.

Initiation of Adelaidean sedimentation began with basal clastics of fluviatile and shallow marine origin (Rutland et al., 1981), overlain by shelf carbonates and ubiquitous basic volcanic rocks (Beda and Wooltana Volcanics). These are succeeded by Willouran aged mixed carbonate, clastic, and evaporitic depositional conditions, dominantly in the north, represented by the Callanna Group (Preiss and Forbes, 1981).

The Burra Group of sediments follows, either disconformably or transitionally overlying the Callanna Group. Basal coarse immature sandstones are transgressed by a cyclic sequence of silts, sands, and carbonates interpreted as eastward prograding deltaic complexes.

Again unconformably or disconformably overlying is the unified lithogenetic Umberatana Group - described as such because this group encompasses all glaciogene sediments of the Adelaidean, as well as a thick interglacial rock sequence of similar Adelaidean age.

Two Sturtian glacial phases occurred, outlined by an older restricted unit and a younger more widespread accumulation, signified by the Appila and Sturt Tillite (Preiss, 1987). The interglacial phase of sedimentation consists of the shallow-shelf Willochra Sub-Group toward the west and the basinal deeper-water Farina Sub-Group to the east. The Farina Sub-Group encompasses important sediments encountered during field work, within which the manganese mineralisationsstudied are located.

The second glacial phase is followed by a widespread marine transgression, represented by the finely laminated carbonaceous silt of the Tapley Hill Formation. It is an ubiquitous unit, grading upward into a coarse calcareous silt reflecting late Sturtian regression (Rutland et al., 1981). It is succeeded by the Willochra Sub-Group, notably comprising the Tarcowie Siltstone in basinal localities, and more proximal basin-margin redbed sediments. This latter lithology is characteristic of the Willochra Sub-Group.

Diachronous allochemical precipitation of the Etina Formation ensued younging and thinning to the south, with continued Tarcowie Siltstone deposition in an agitated environment (characteristic flaser bedding). This phase of sedimentation is reflected in further clastic and expanded carbonate platform sedimentation (Etina Formation), whereupon deposition of the

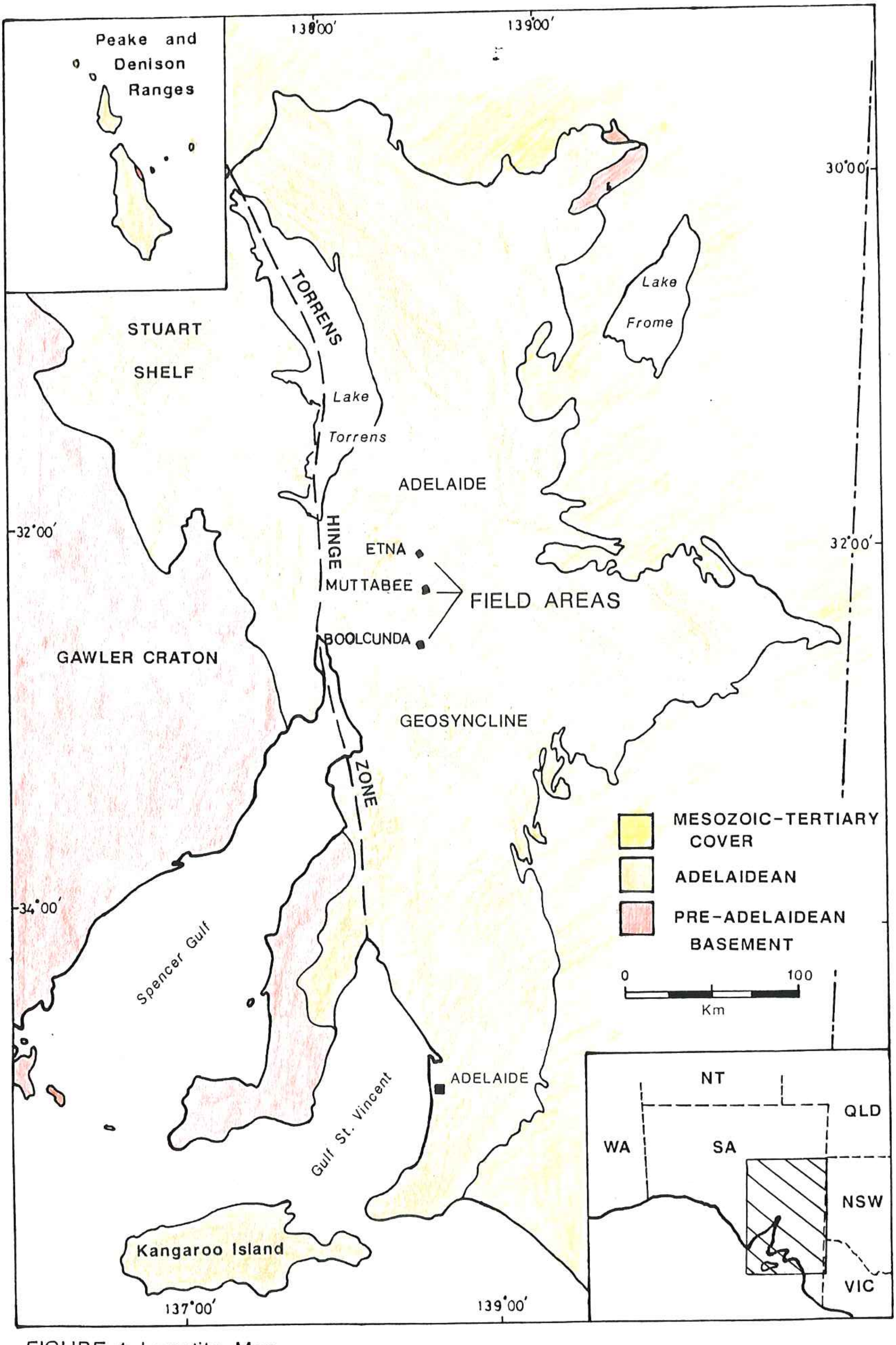


FIGURE 1: Locality Map

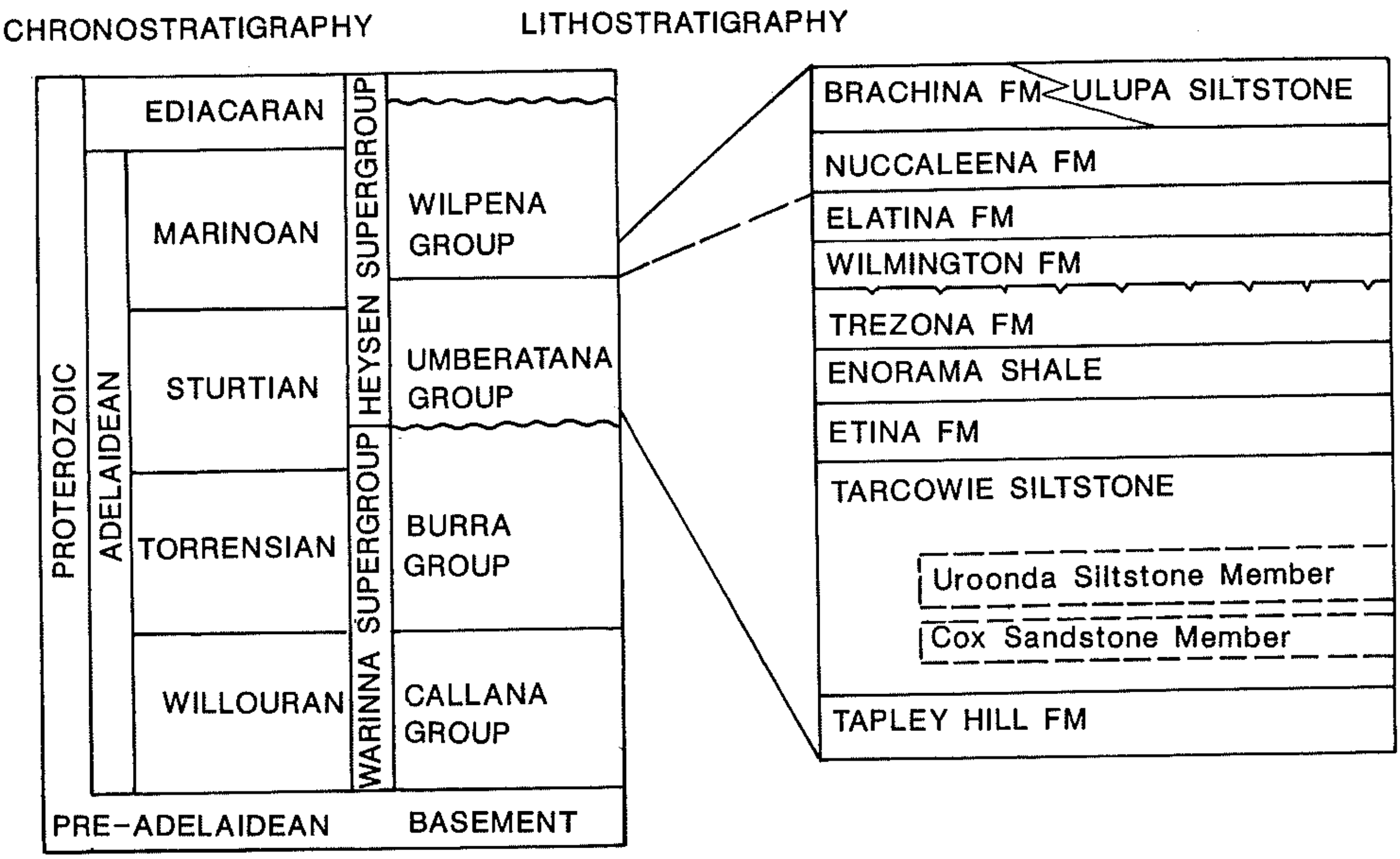


FIGURE 2: STRATIGRAPHY OF ADELAIDE GEOSYNCLINE AND FIELD AREAS

transgressive calcareous Enorama Shale occurred, itself overlain by the regressive Trezona Formation of marginal redbed and very shallow marine character.

Marinoan glaciation was then instigated, represented in the north by an hiatus and glaciogene sediments, but in the south by the similar Wilmington Formation sands and the clastics of the Elatina Formation, all still reflecting a shallow shelf environment of deposition (Preiss, 1987) with no glaciogene characteristics.

Post-glacial sedimentation is represented by uniform and laterally persistent Wilpena Group sediments with at least two transgressive and regressive phases of sedimentation - early Marinoan Brachina Formation and its basinal equivalent Ulupa Siltstone, and the upper Marinoan Wilpena Group.

Transgression of the Cambrian sea then occurred, and along with persistent subsidence of the Adelaide Geosyncline (Parkin, 1969) formed sediments of the Hawker Group. Subsequent Phanerozoic sedimentation is very minor in outcrop, represented by post-Triassic and Cainozoic cover. This lack of appreciable Phanerozoic sedimentation reflects the influence of the Cambro-Ordovician Delamerian orogeny, which produced profound structural changes in the sediments of the Adelaide Geosyncline, and effectively halted Adelaidean sedimentation.

2.2 GEOLOGY OF THE BOOLCUNDA, ETNA, AND MUTTABEE REGIONS

An analysis of the local geology was made, together with precise and detailed ore deposit description, as part of an extensive field mapping exercise to delineate the upper Proterozoic sedimentary rocks involved. Fig. 3 is a summary of the field areas mapped and their surrounding environs, indicating a sequence of rocks which have been simply deformed into a parallel series of north and northeast trending folds found within the ORROROO 1:250000 map area (National Grid Ref. SI 54-1). Gentle folding of the sedimentary sequence was the only observed structural complication, apart from an inference of past very minor faulting indicated by small zones of quartz-breccia seen dispersed at all localities, generally as gibber material. Correlations of the stratigraphic sequences and sedimentary manganese accumulations was envisaged initially, because of the similar spatial and temporal character of the three deposits. Located within units of the Adelaidean Series, from Late Sturtian Tapley Hill Formation to Late Marinoan Ulupa Siltstone and Brachina Formation, the sedimentary rocks incorporate the thick interglacial sequence of the Umberatana Group and basal Wilpena Group (Fig 2).

This proposed correlation regionally is quite adequate but on the local scale mapped the variable lithostratigraphic nature of the Adelaide Geosyncline becomes apparent, with Fig 4 and Appendix A highlighting this variability. Suffice to say, differentiation of members was on a finer scale than found on either 1:250000 or 1:50000 scale maps.

All rocks outcropping are represented on the accompanying maps (Appendix A), with their corresponding hand specimen and thin section descriptions given in Appendix B.1.

2.3 DESCRIPTION OF SEDIMENTARY UNITS

2.3.1 General

Rocks encountered are incorporated in the Umberatana Group (Farina Sub-Group and Willochra Sub-Group), and the early Wilpena Group of sediments, consisting of a variegated sequence of clastic and carbonate sediments of the interglacial phase of Sturtian-Marinoan sedimentation.

Occurring within a meridional position of the subsiding trough forming the Adelaide Geosyncline, the facies observed are mostly fine clastics, with interstitial coarse clastics and carbonate units, as differentiated in Fig 4.

2.3.2 Tapley Hill Formation

This late Sturtian unit forms the oldest lithology mapped (Fig 4), encountered only within the Muttabee field area. The portion mapped represents the upper 500 to 1100 metres of the Tapley Hill Formation. The unit is very uniform, consisting of a well sorted bluish-grey to dark olive grey finely parallel laminated siltstone. This is in accordance with its type section - near

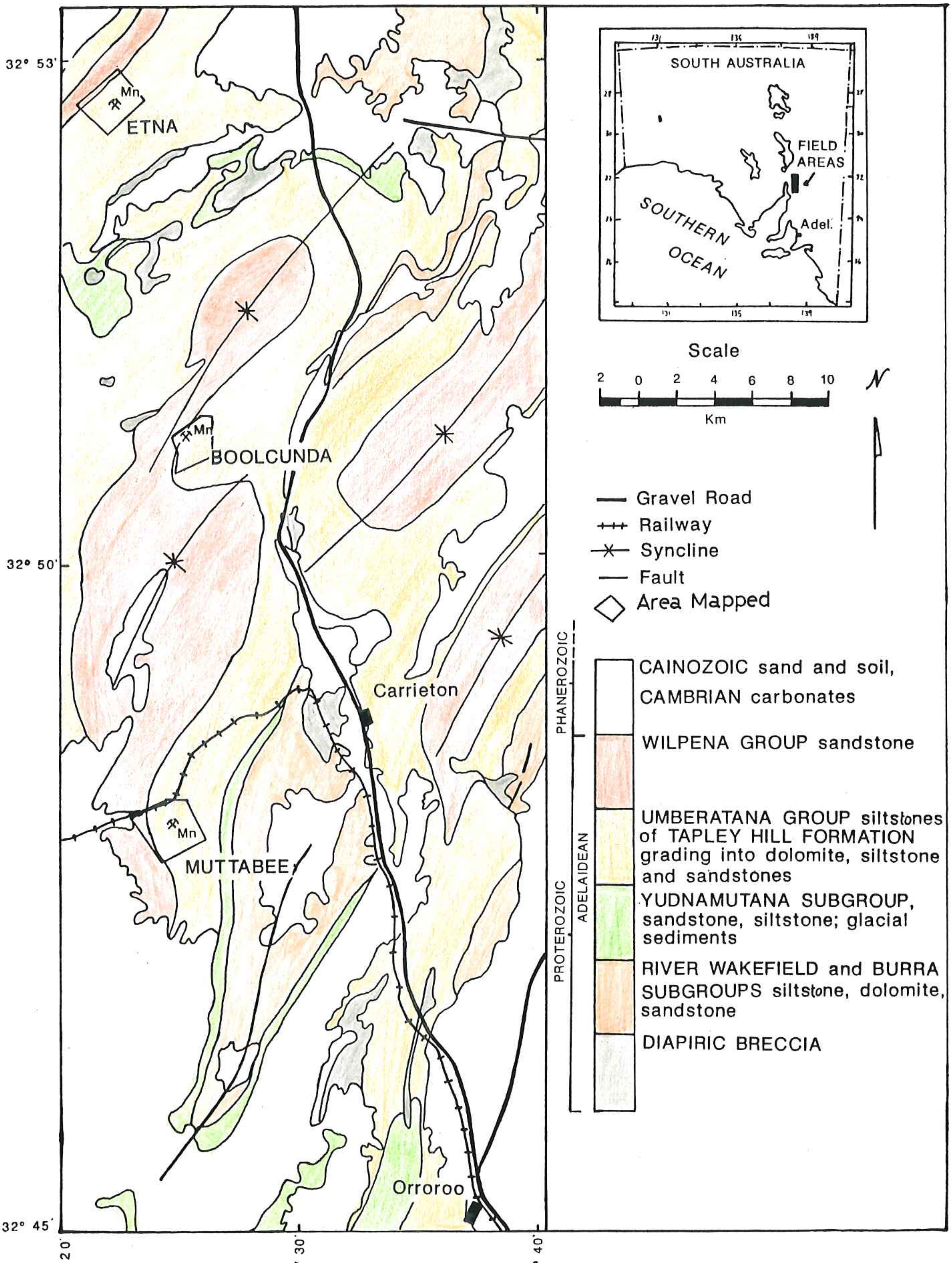


FIGURE 3: Gross Geology of Field Areas and Environs

(Adapted from S.A.D.M.E. unpubl. rep.)

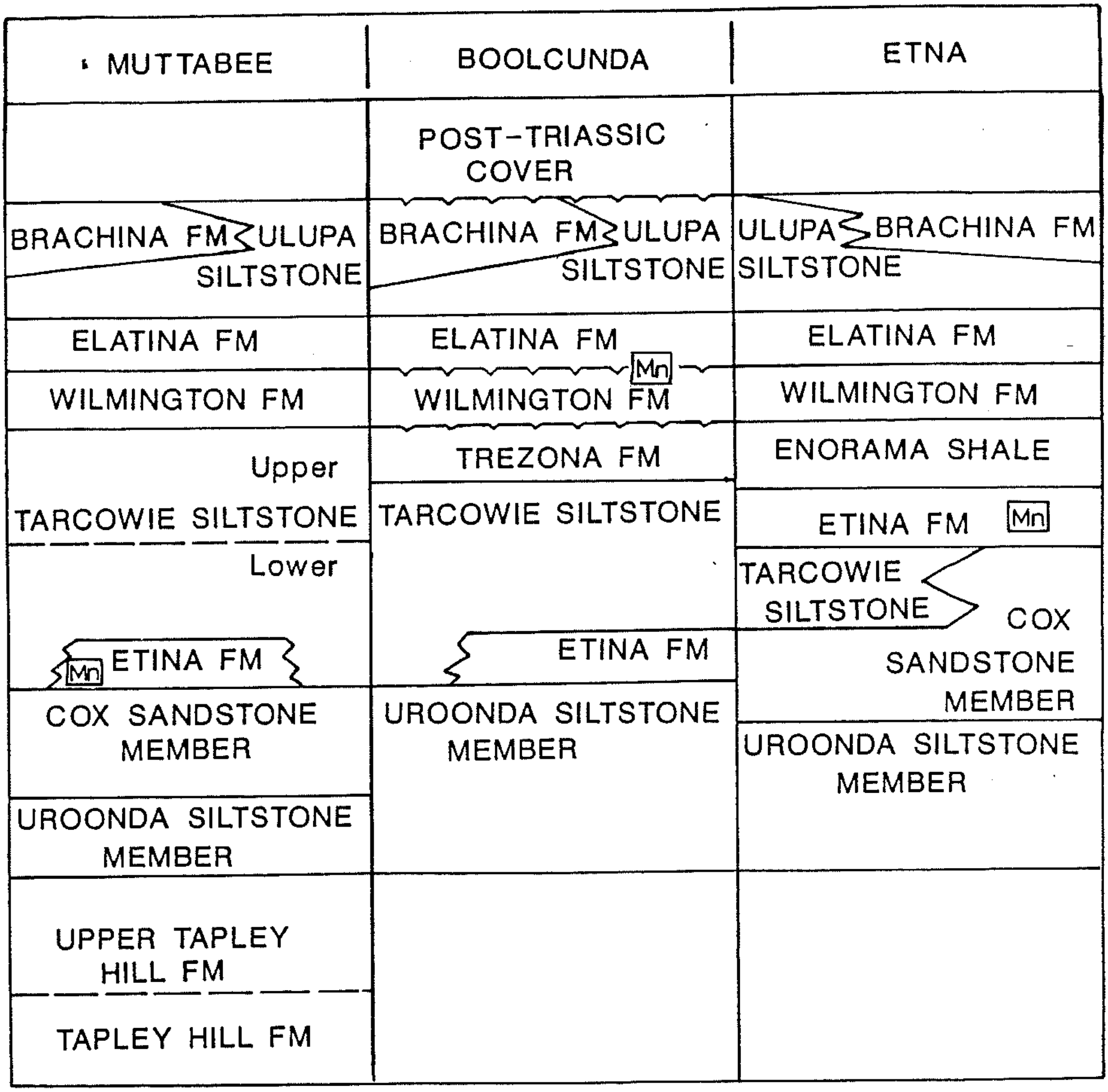


FIGURE 4: LOCAL STRATIGRAPHY

Darlington just south of Adelaide - comprising 1500 m of dark grey well laminated shales and silts (Plummer, 1974). The Tapley Hill Formation is slightly calcareous and forms low rolling hills bounding the eastern margin of the Muttabee map area (Plate 1a).

Field relationships observed, and those described by numerous authors (Binks, 1971; Preiss and Forbes, 1981; Preiss, 1987) show that the Tapley Hill Formation undergoes an increase in both grainsize and carbonate content up sequence. This change is gradual over some 50 m and is succeeded by planar bedded massive coarse siltstones and fine to medium grained sandstone and calcarenite units. Internally massive, the coarse interbeds form more resistant thin outcrops (< 2 m) as low-relief ridges, easily identifiable in the field and from aerial photographs (Plate 1b), representing lithological change in response to eustatic sea level fall.

The aerial extent, uniformity, and fine calcareous clastic nature of the Tapley Hill Formation implies marine deposition (Preiss, 1987). Occurring across the Adelaide Geosyncline and Stuart Shelf, this unit represents deposition during the first major transgression following the Sturtian glacial event (Parkin, 1969; Preiss and Forbes, 1981) with a shallow marine environment postulated (Preiss, 1987), followed by shallowing and a regressive phase of sedimentation.

2.3.3 Tarcowie Siltstone

The Tarcowie Siltstone and its members, the Uroonda Siltstone and the Cox Sandstone Member, from field mapping differentiation,were found to incorporate the dominant and thickest units encountered. Appendix A reflects the variability of possible subdivisions of the Tarcowie Siltstone and its members, with the dominant Tarcowie Siltstone lithology ranging from very poor sandy siltstone exposure and thin interbeds within the Cox Sandstone Member at Etna, to its characteristic indurated and flaser bedded siltstone lithology at Muttabee, some 900 m in thickness.

A diagnostic feature of this unit is its nearly all-pervasive flaser bedding - wavy and lenticular laminations of brown-grey coarse silt or fine sand, and thin laminae of olive-grey silt (Plate 1c), with a corresponding characteristic ribboned weathering profile. Petrographic analysis indicates a lithology with slightly coarser clastic portion than the underlying Tapley Hill

Formation, indicating a rock composed of subangular quartz grains and rare plagioclase feldspar in a very fine sericite-chlorite matrix (Plate 1d), developed under slightly shallower and higher energy conditions than the Tapley Hill Formation siltstone.

The Cox Sandstone Member is a flesh-pink feldspathic medium-grained sandstone, designated as a basal Tarcowie Siltstone member from recent mapping and drilling by the S.A.D.M.E. (Preiss, 1987). Although Appendix A shows differentiation of this member within the Etna and Muttabee regions, only the Etna field area reflects the true character of this lithology. Within the Muttabee area, the unit is somewhat finer grained and structured than the proposed type section. However, it is sufficiently different from the underlying Tapley Hill Formation and the conformably overlying Tarcowie Siltstone to warrant differentiation as the Cox Sandstone Member (Plate 1e).

The Uroonda Siltstone Member is a massively outcropping grey-green coarse siltstone delineated at Boolcunda and Etna between the Tapley Hill and Etina Formations, and questionably as a thin 30-50 m massive sandy siltstone at Muttabee, separating the upper Tapley Hill Formation and the Cox Sandstone Member in a similar manner as its regional differentiation suggests (Fig. 2).

A meridional position relative to the margins of the Adelaide Geosyncline implies a broad shallow shelf environment of accumulation for this unit, specifically within a subtidal setting where wave activity influenced the accumulation of fine clastics, thereby accounting for the flaser bedded character.

2.3.4 Etina Formation

Of Marinoan age residing in the Willochra Sub-Group of the Umberatana Group (Fig. 2) the Etina Formation is a well sorted, cross-bedded, ooid and sandy lime grainstone and stromatolitic limestone (Preiss, 1987) with interbeds of shale and silt. All these features were exposed within the field areas, although stromatolitic structures were rare (Plate 1f). Reflecting its northward thickening and diachronous nature the Etina Formation ooid and sandy lime grainstone was observed as an isolated lens at Muttabee, a thin partially dolomitized oolitic sandy limestone at Boolcunda (Plate 1g), and as two thick limestone units with interbedded calcareous

Plate 1A	Symmetric ripples on bedding surface of the thinly bedded slightly calcareous Tapley Hill Formation siltstone
Plate 1B	Upper Tapley Hill Formation, showing interbeds of thick coarse sandstone-calcarenite layers between coarse calcareous thinly bedded siltstone
Plate 1C	Characteristic ribboned weathering profile of the flaser bedded Tarcowie Siltstone
Plate 1D	Microphotograph of the Tarcowie Siltstone indicating quartzose nature of this unit, set in chlorite-sericite matrix. Part of flaser bedding is outlined, represented by reduced grainsize and quartz content.
Plate 1E	Cox Sandstone Member -poor rubbly outcrop of a generally coarse massive quartzofeldspathic sandstone
Plate 1F	Oolitic and sandy Etina Formation limestone. This facies also shows thin stylolites, typical for the Etina Formation carbonate lithologies.
Plate 1G	Microphotograph of partially dolomitized oolitic and sandy Etina Formation limestone, taken from Boolcunda region where this unit has undergone extensive exposure to stream flow, and therefore percolating fluids.


1A

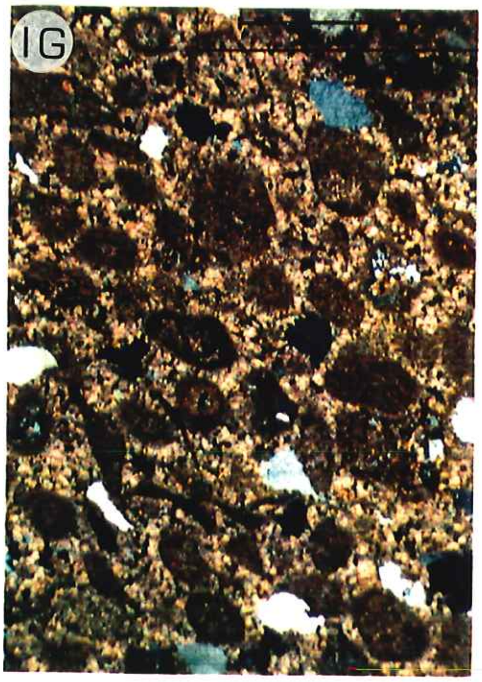

1B


1C


1D


1E


1F


1G

siltstone at Etna. The intertonguing character of this limestone with the Tarcowie Siltstone and its own siltstone interbeds is represented by thin layers of coarse calcarenite horizons, thinning along strike, principally observed at Muttabee and Etna.

Stratigraphic logs (Appendix D) show the variable nature of this lithology reflecting a number of discrete facies, including: oolitic limestone; sandy limestone; sandy and oolitic grainstone; minor intraformational limestone; and interbeds of coarse grey-green siltstones and dark orange massive fine to coarse sandstones. These features are best observed at Etna where the Etina Formation is thickest and most continuous.

The Etina Formation reflects high energy allochemical precipitation of the oolitic and sandy oolitic grainstone lithology, while the intercalated silts and sands represent alternating low energy deposition (Preiss, 1973). This alternation of high and low energy conditions has been postulated to imply an intertidal to shallow subtidal environment (Rutland et al., 1981) representing the formation of marginal marine and offshore ooid banks and minor carbonate platforms (Preiss, 1985). The importance of this unit is highlighted as two of the three manganese deposits studied occur within this formation.

2.3.5 Enorama Shale

Conformably overlying the Etina Formation, the Enorama Shale crops out only within the Etna map area. As at the type section the unit consists of a light olive grey to dusky green calcareous shale and silty shale. A well laminated and bedded unit, it forms some 150-400 m of topographically low-lying outcrop (Plate 2a).

Dalgarno and Johnson (in Thomson et al., 1964) and Binks (1971) described thin conformable limestone interbeds near the top. As shown in Appendix A, two thin sandy limestone interbeds were delineated, composed of a poorly sorted limestone with subangular granules of quartz and minor red feldspar set in micritic carbonate cement. Minor stylolites within the dominantly sandy limestone were also observed.

Preiss (1987) describes a transitional depositional environment for this unit, essentially a shallow shelf region with quiet water conditions - a variation on that postulated for the Tarcowie Siltstone, also showing a shallow shelf environment but with higher energy conditions. The

Enorama Shale principally occurs in the central and northern Flinders Ranges following an early Marinoan marine transgressive phase (Rutland et al., 1981), reflecting fine clastic calcareous deposition.

2.3.6 Trezona Formation

Encountered within the Boolcunda map area on the western limb of the Uroonda Syncline, this unit lies at an erosional contact with the overlying Wilmington Formation sandstone. Exposure is very poor, consisting of two discontinuous and thin (2-5 m) lenses of red intraclastic calcareous mud-flake breccia (Plate 2b). This represents only part of the total unit, the remainder being dominantly a grey limestone (Binks, 1971) not encountered in any of the areas mapped. The red mud-flake breccia occurs as an interbedded limestone having an "heiroglyphic" exposure character (Preiss, 1973), and subsequently is an excellent marker horizon.

A very shallow water environment is envisaged, perhaps an extensive shallow lagoonal setting subject to periodic flooding and dessication (Preiss, 1973). This would account for the minute, curled calcareous red mudflakes in a micritic sparry calcite cement.

2.3.7 Wilmington and Elatina Formations

These two formations occur within the Willochra Sub-Group - a sequence of shallow water sediments in the upper part of the Umberatana Group (Fig. 4). They are easily recognisable in the field due to lithologic characteristics and their exposure as the most prominent ridge relief physiography encountered.

A response to coarse sediment influx associated with Marinoan glacio-eustatic regression, the deposition of the Wilmington Formation continued uninterrupted into almost lithologically identical Elatina Formation sandstone and minor siltstone deposition - the variability being an indication of rapidly fluctuating paralic environmental conditions (Preiss, 1987).

Differentiation between these two lithologies proved almost unattainable, because of their near-identical nature. The best approximation for subdivision is relative to the structured nature of each formation. The Wilmington sandstones have a dominantly massive nature while the

Elatina Formation sandstone is typified by a basal festoon trough cross-bedded lithology, outlined by heavy minerals. Thus an approximate formation boundary is placed where this trough cross-bedded lithology dominates, underlain by mostly massive sandstone of the Wilmington Formation (Appendix D).

Dominant lithological character of the Wilmington Formation is a fine- to medium- grained, subangular quartzo-feldspathic sand with a massive to thickly planar bedded red-brown to orange-grey sandstone character. It forms the lower 100 to 400 m of the section. Variations include a uniform fine-grained sandstone at Etna, poor outctrop at Boolcunda of a generally massive morphology, and a typical rounded hilly outcrop at Muttabee (Appendix A). Further noteworthy characteristics of this Wilmington Formation sandstone are the existence of: a strike discontinuous mauve fine chloritic-sericitic siltstone interbed occurring at Etna: a thick interbed analogy at Muttabee; and a series of local disconformity surface which aided ore accumulation at Boolcunda.

The Elatina Formation has a far more distinctive nature, typified by Plate 2d. A red-brown subangular moderately well-sorted arkosic sandstone, this unit ranges from internally massive and thickly bedded to the illustrated festoon trough cross-bedded lithology, outlined by subangular heavy mineral grains (Appendix B.1). Also a feature are minor coarse granular trains dominantly of quartz grains (Plate 2c).

The lithological form and sedimentary structures of these two formations allude to a paralic depositional environment. Both units are associated with a strong influx of coarse detritus from the west (Preiss, 1987) and form as redbed sediments under oxidising conditions. Field palaeocurrent measurements (Fig. 6) agree with this westerly provenance, with associated easterly and east-southeasterly current directions. Although not comprehensively determined, the accumulation of these formations was related to a series of transgressive-regressive phases of sedimentation within a shallow marginal shelf regime, dominated by sand accumulation, interspersed with massive silt development (Appendix D).

2.3.8 Brachina Formation - Ulupa Siltstone

This sequence of sediments forms the youngest Adelaidean lithologies mapped (Fig. 4), forming part of the most widespread rock sequence found within the Geosyncline, namely the Wilpena Group.

Observations resulted in the differentiation of two lithologies, found to be the shallow water Brachina Formation red siltstone to fine sandstone, and its basinal equivalent, the Ulupa Siltstone which is composed of a planar bedded olive grey siltstone and minor fine sandstone. Petrographic distinction shows the Ulupa Siltstone to be higher in phyllosilicates and somewhat finer grained than its marginal shelf equivalent (Appendix B.1).

These two units showed intertonguing relationships at each locality. The Ulupa Siltstone was the most pervasive unit reflecting more basinal deposition in the central southern Flinders Ranges region during this Late Marinoan period of sedimentation, with best Brachina Formation outcrop encountered at Etna. Intertonguing and overlapping between the two units further suggests some form of transgressive - regressive cyclicity. Typically a flaggy to thinly well planar bedded olive grey silstone (Plate 2e), the Ulupa Siltstone unit forms low relief topography often cut by major creeks (as seen at Boolcunda and Etna).

The postulated relatively shallow, permanently submerged oxidising environment of deposition for the Brachina Formation (Preiss, 1987) is supported by field observations - red-brown colour; lack of any subaerial features; both planar and ripple features (Plate 2f). Similarly, the basinal equivalence of the Ulupa Siltstone is supported by its grey green (reducing environment) colour, its very uniform planar bedding (low energy conditions), and its fine clastic character.

2.3.9 Post-Triassic Cover

Post-Triassic cover rocks have not previously been mapped within the Boolcunda map region. Unconformably overlying the Etina Formation, and in part the Uroonda Siltstone, minor exposure, of a fluvial sequence has developed and appears to be related to the ancient drainage pattern of the region. Plate 2g illustrates the siliceous cemented clean mature nature of this very

Plate 2A Enorama Shale - light olive grey well laminated calcareous shale.

Plate 2B Trezona Formation red intraclastic calcareous mud-flake breccia.
Represents thin lens exposure at Boolcunda between TarcowieSiltstone and the overlying sands of the Wilmington Formation.

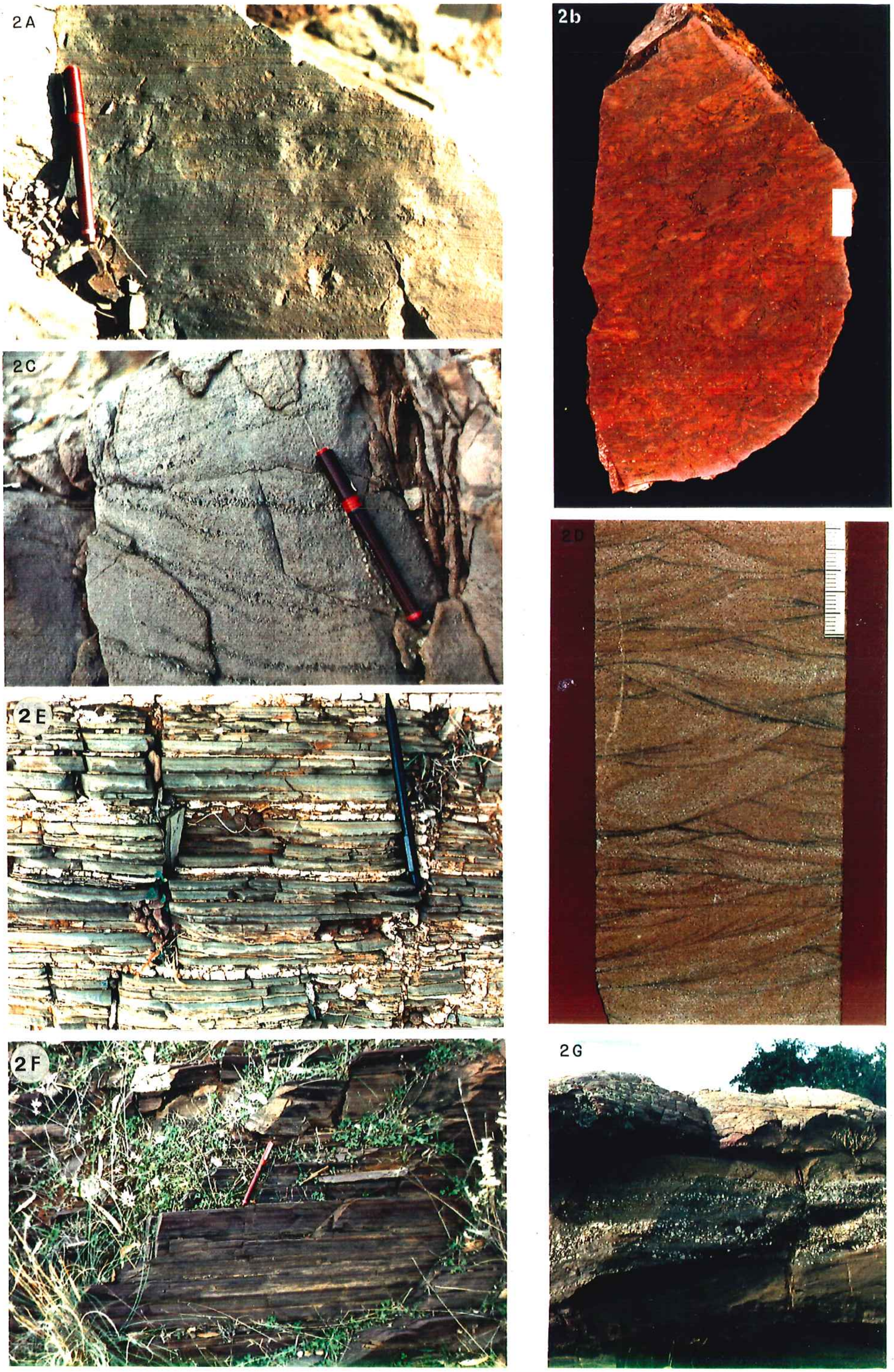
Plate 2C Quartz granule trains within upper massive quartzofeldspathic sandstone of the Elatina Formation, caused by rapid influx of coarse detritus.

Plate 2D Elatina Formation diagnostic heavy-mineral outlined festoon trough cross-bedded sandstone.
Generally situated in lower part of the unit.

Plate 2E Ulupa Siltstone - planar bedded olive grey siltstone and fine sandstone.
White material is recent stream-flow chemical weathering.

Plate 2F Brachina Formation red-brown thinly bedded coarse siltstone.
Forms intertonguing relationships seen as thin interbeds with the Ulupa Siltstone.

Plate 2G Large-scale planar cross-bedding and conglomerate lag bands in Post-Triassic Cover, Boolcunda.


2A
2b
2C
2D
2E
2F
2G

coarse quartzite, with internal large-scale planar cross-bedding and basal conglomeratic lag bands, indicating a north to northwest palaeocurrent correlatable to the northerly drainage pattern of the region.

The inference is of a post-Triassic age for this outcrop, as similar strata affiliated with basin drainage are observed within the Triassic basin to the northwest (pers. comm. V Gostin, 1988). Precise descriptions can be found in Appendix B.1 with field relationships in Appendix A.

2.4 SUMMARY

The stratigraphic description and collection of palaeo - environmental data was an important part of the field studies undertaken - relevant because this study deals with the accumulation of sedimentary manganese, and therefore detailed analysis of the lithological character, sedimentological structures and field rock relationships encountered is required, to establish a basis for the interpretation of the manganese accumulations. Fig. 5 illustrates the gross depositional relationships and facies distributions of the sediments within the Adelaide Geosyncline depocentre, separated into three broad sedimentation phases, indicating deposition ranging from nearshore to deeper marine basinal facies development, dependant on the prevailing eustatic levels.

Precise stratigraphic logs (Appendix D) and rose diagram analysis of palaeocurrent directions (Fig. 6) gives an overview of the environment affecting the accumulation of the sedimentary rock sequence, which can be used to aid manganese accumulation genesis interpretation.

A westerly provenance dominates for these sediments, but also with minor northerly and easterly input (Preiss, 1987). Current ripple rose diagrams and averaged cross bedding directions indicate a south, southeast, and east palaeocurrent direction spread. This corresponds with other workers (Plummer, 1974; Preiss, 1973), and the envisaged reconstructed palaeogeographic form of the Adelaide Geosyncline (Preiss, 1987).

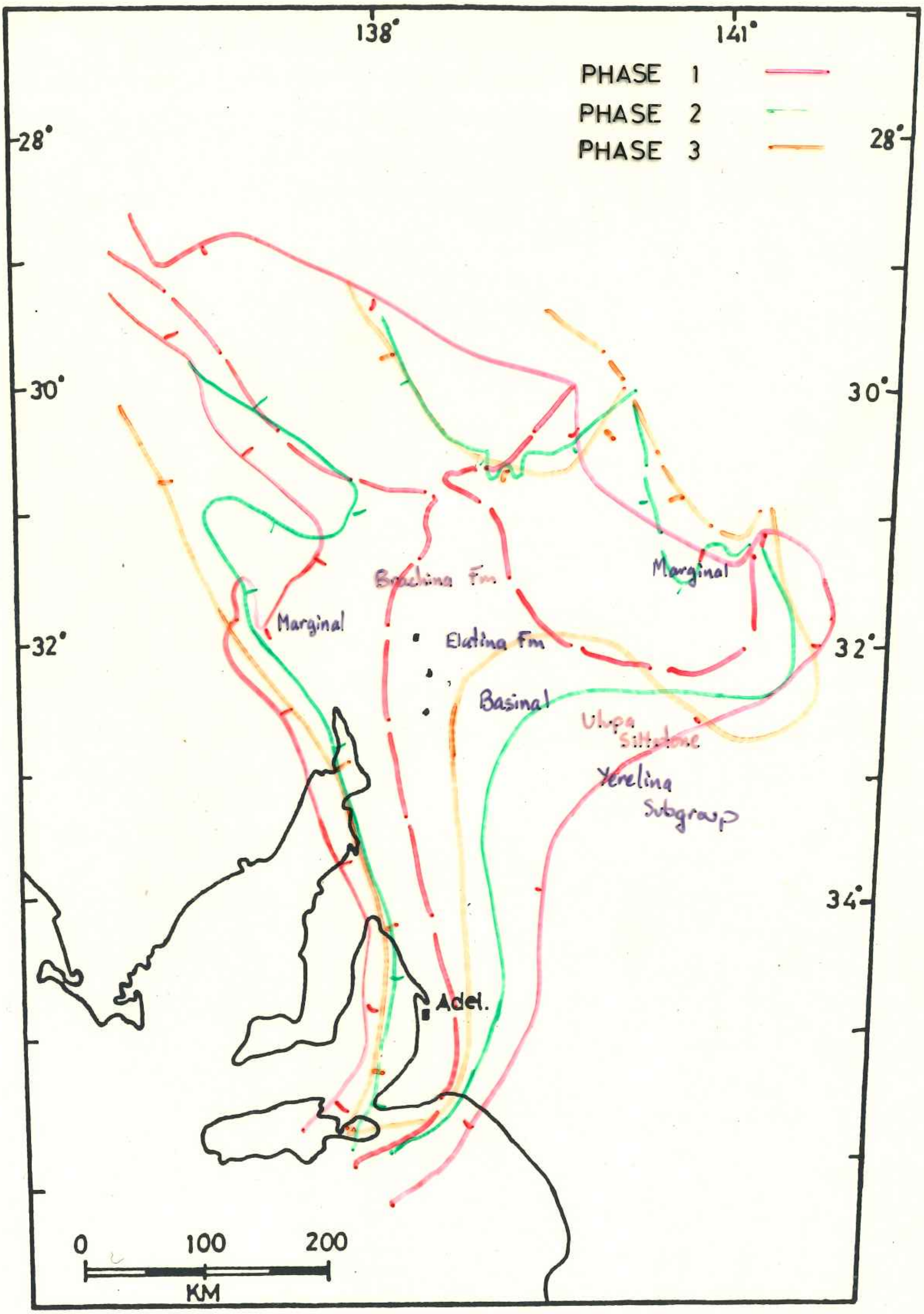


FIGURE 5: Three broad phases of Adelaidean sedimentation relative to strata encountered in the field, comprising: lower Umberatana Group (phase 1); upper Umberatana Group (phase 2); and lower Wilpena Group (phase 3). (adapted from Preiss, 1987)

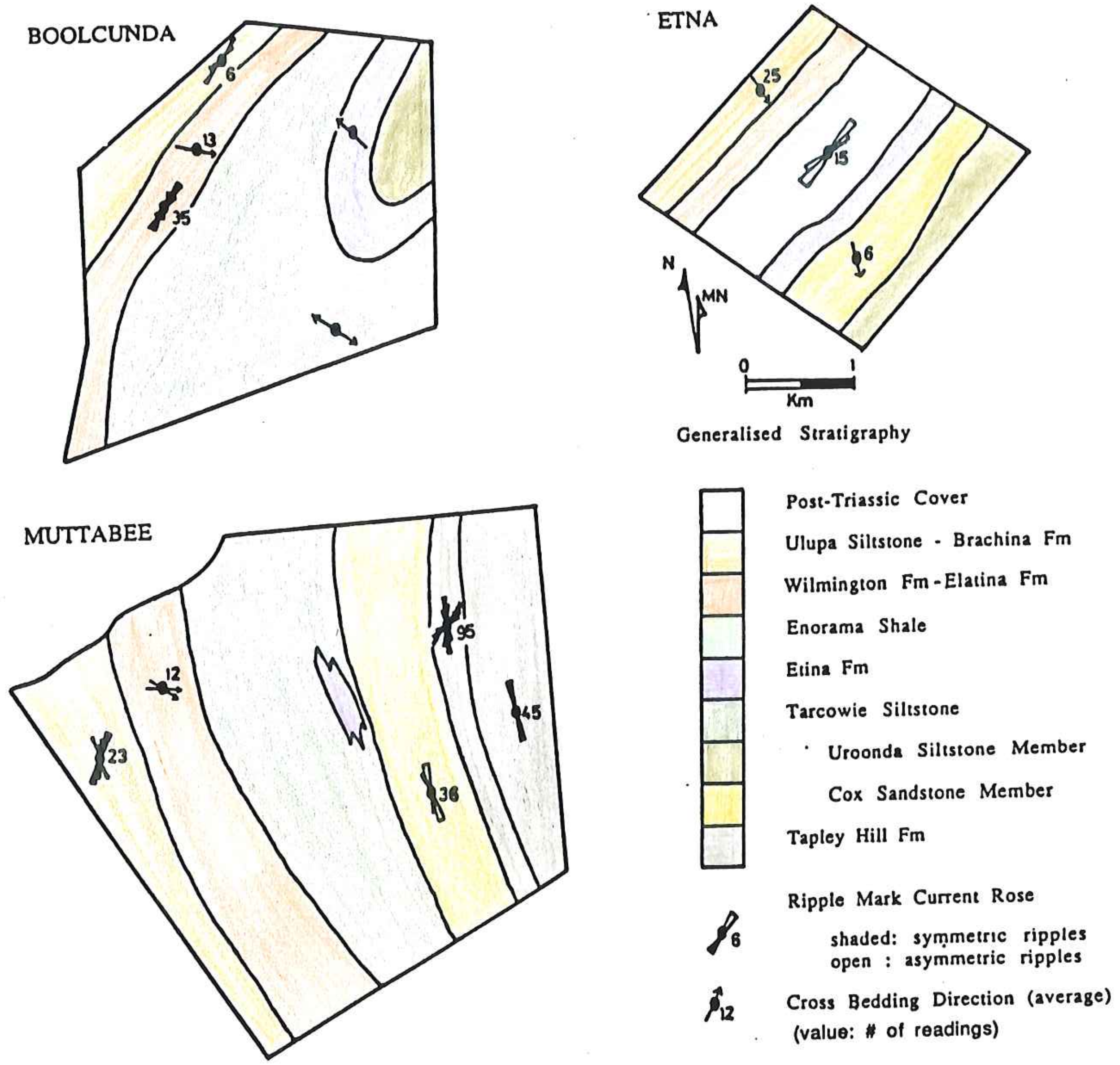


FIGURE 6: Palaeocurrent Sketch Maps

3. THE ORE DEPOSITS

3.1 INTRODUCTION

The main exercise of this study is to analyse the manganese deposits within the three study areas, something which has not previously been performed. Figs. 7(a)-(c) indicate the geometry and stratigraphic relationships surrounding each of the accumulations, as determined from interpretation of mine site plans and cross-sections produced during mapping.

3.2 OCCURRENCE

The term mineralisation is probably more appropriate than ore when describing these deposits, because although geochemical results show mineable grades (up to 75% Mn) the size of the accumulations limit them in economic terms.

This mineralisation is discernible from specks, dendritic markings and heavy mineral outlining, up to appreciable concentrations. The Muttabee and Etna deposits are associated with the Etina Formation calcarenite-sandstone lithology, while the Boolcunda accumulation is associated with the stratigraphically younger Wilmington Formation cyclic sands and silts.

3.2.1 Boolcunda

The Boolcunda manganese accumulation is found within a cyclic sequence of massive to thickly bedded sands and silts from the upper Wilmington Formation, the majority of which show non-deposition erosional contacts developed immediately prior to the overlying Elatina Formation sandstone. The mineralisation is centred on the eastern limb of the Uroonda Syncline (Binks, 1971).

Mineralisation consists of 4 parallel lodes - one major and three minor - being stratiform horizons with a very limited strike-length of approximately 200 m. Dipping to the west by 35^{o} 45^{o}, the 4 lodes vary from 0.5 to 3.0 m, with an inferred depth not exceeding 30 m (Fig 7a). Outside of this mineralised zone two similar ore zones occur. They are very small, mentioned only because of their position stratigraphically adjacent to this main manganese mineralisation with characteristics suggesting similar strike-adjacent genesis conditions.

3.2.2 Etna

This manganese accumulation is located within flat-lying country stratigraphically midway within sandy and oolitic limestones and minor sandstones of the Etina Formation.

Mineralisation occurs as two strike-discontinous pods separated by a distance of approximately 1.5 kilometres (Fig 7b). The pods average 1 to 3 m in thickness, pinching out along strike and down dip - inferred dimensions no greater than 40 by 30 m. Minimal exposure and only minor mine workings make this deposit difficult to delineate and analyse.

The upper ore boundary is easily discernible, outlined by an olive-grey fine festoon trough cross-bedded well-sorted sandstone with a strong southeasterly palaeocurrent direction. The lower boundary of mineralisation is more ambiguous, with a very irregular outline but is generally delineated by a bluish-grey oolitic and partly sandy grainstone.

Within the mapped area no other manganese mineralisation is observed, apart from some minor associations with quartz veins within a coarse sandstone underlying the main mineralised zone - postulated to be of post-Adelaidean derivation, plausibly associated with the main tectonic event that affected these sediments, the Cambro-Ordovician Delamerian Orogeny.

3.2.3 Muttabee

Similar to the Etna manganese accumulation, the Muttabee deposit occurs within the Etina Formation, represented here as a small area, 500m by 100m, of sandy and oolitic limestone facies interpreted as a shoal/ooid bank within the Tarcowie Siltstone.

Mineralisation is confined to two calcarenite interbeds within the limestone. The ore zone is stratiform, parallel to the NNW-SSE strike and 35^{o}-45^{o} dip of the enclosing sedimentary rocks (Fig 7c). The mineralised zone varies from 0.5 to 3.0 m in thickness with 70 m of strike outcrop. It has a well defined hanging-wall fine sandstone boundary but a distorted weathered calcareous shale footwall contact (Appendix D). Within the mapped area only one other

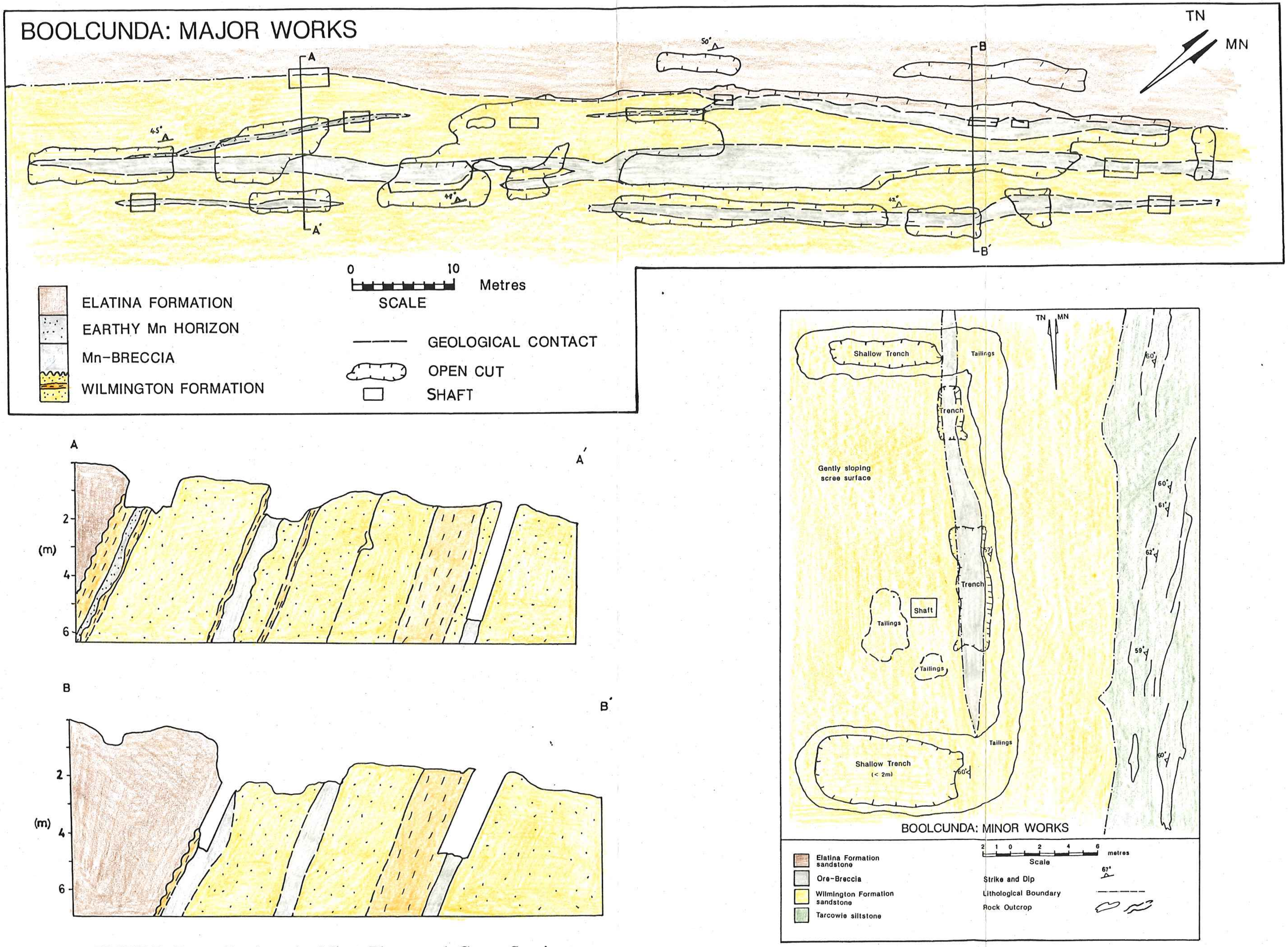


FIGURE 7a : Boolcunda Mine Plans and Cross-Sections

FIGURE 7b : Etna Mine Plan and Cross-Section

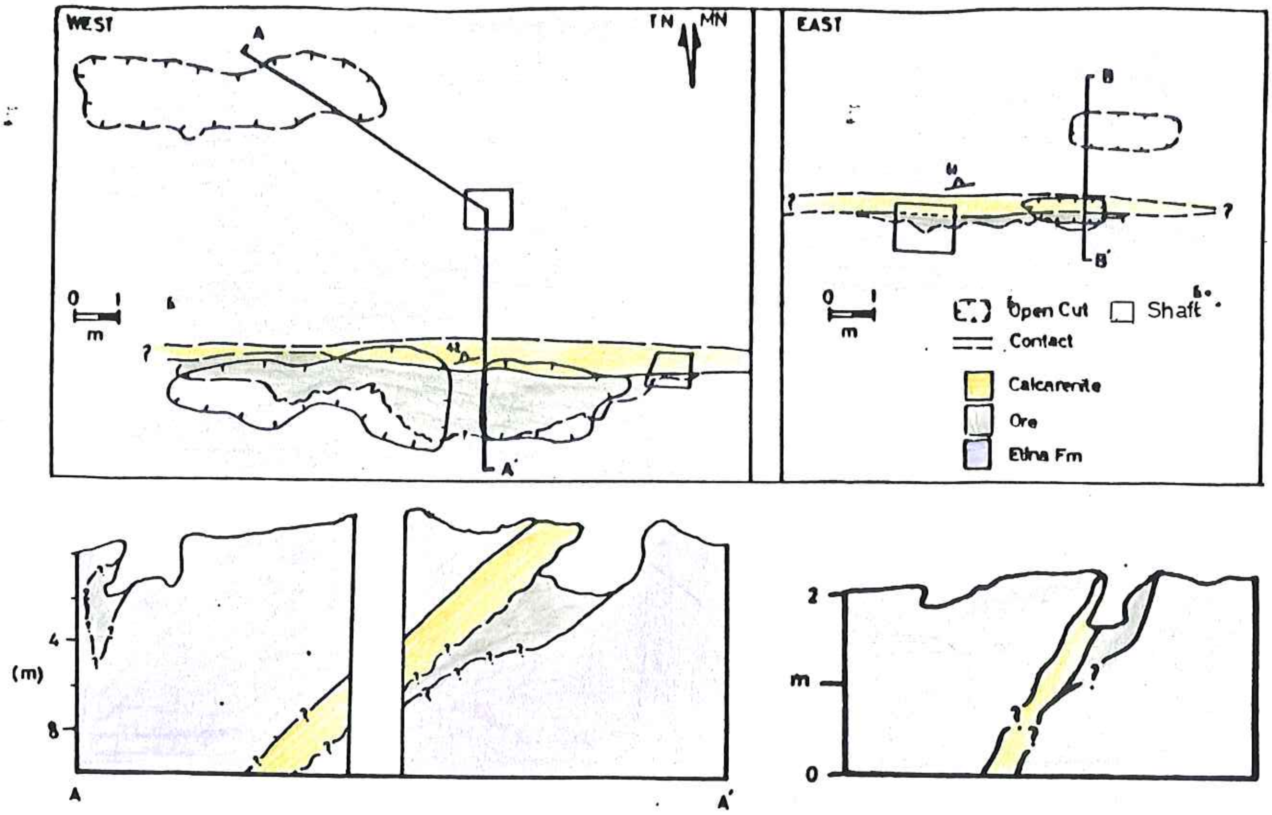
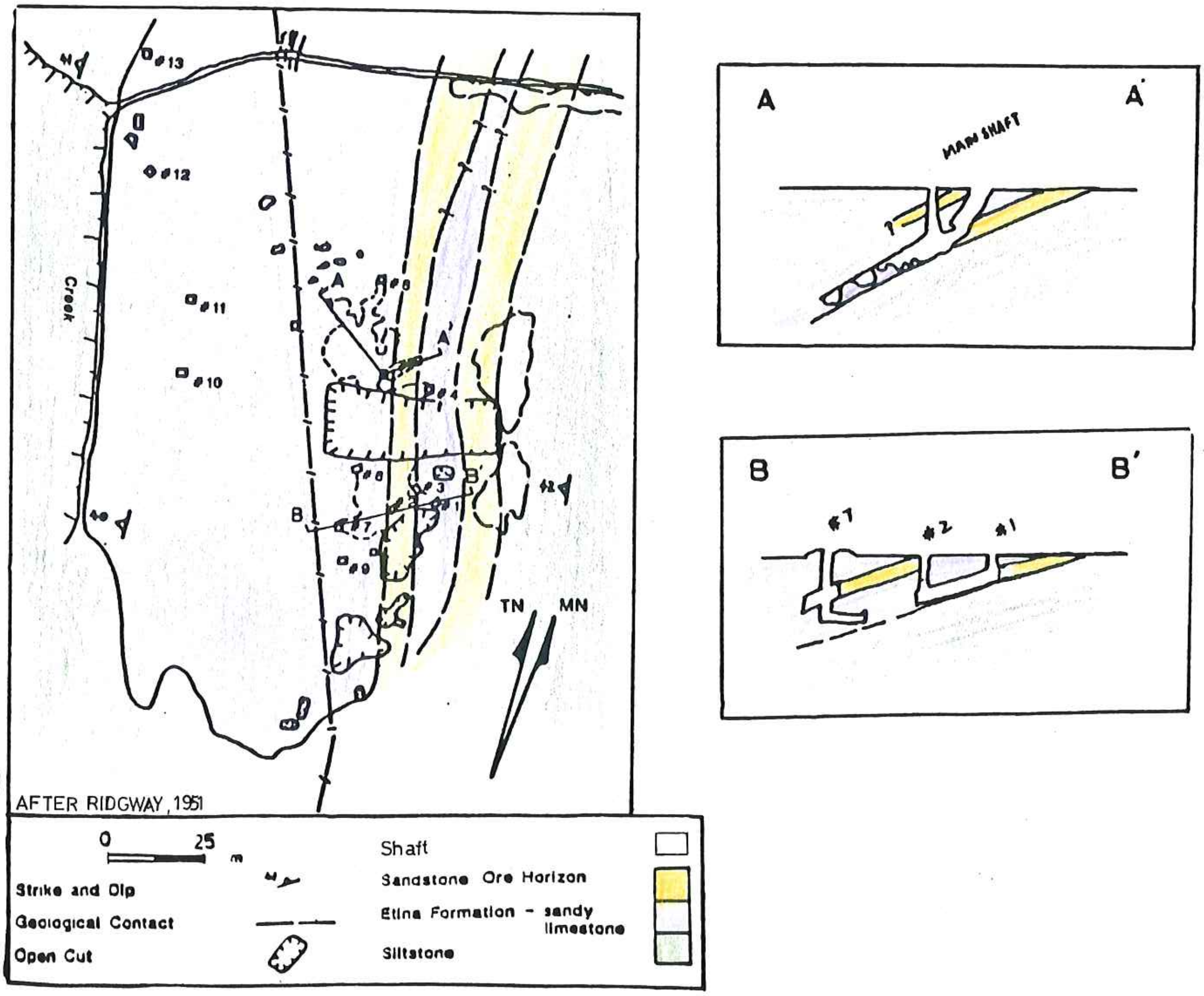


FIGURE 7c : Muttabee Mine Plan and Cross-Section



mineralised zone was found. It occurs in the upper Elatina Formation, as a small 2 by 6 m pod associated with a thin siltstone interbed within a medium-grained pink to red-brown sandstone, interpreted to be analogous to the Boolcunda manganese accumulation.

3.3 PETROGRAPHY

3.3.1 Boolcunda

Mineralisation here is seen in an excellently exposed sedimentary breccia, supported by a manganese cemented matrix (Plate 3a). The ore lithology varies from dominantly a botryoidal and nodular form as primary cavity filling (Plate 3b), to replacement of a sandy detrital matrix.

Overprinting by secondary weathering processes has produced a minor wad lithology incorporated as part of the post-genetic phase of mineralisation, typified by stringer-ore along fractures and bedding planes.

The paragenetic sequence appears to have a bimodal character - concomitant with primary ore nucleation in a botryoidal and nodular form was the development of a manganiferous mud, a composite of accumulating manganese and very fine clastic material. Overprinting these features are secondary enrichment indicators, represented by continued and enhanced silty-sand matrix replacement, plus wad and stringer ore development, the latter along fractures.

The manganese matrix-supported sedimentary breccia has angular well-lithified fragments of both the underlying sand and silt lithologies, with no clast imbrication (Appendix D). The clast form reflects the marine aqueous conditions of the surrounding sediments without any karstic features. Clast dimensions range from small cobbles averaging 1-6 cm., and rare fragments up to 50-80 cm. in size. These competent clasts show no infiltration or replacement manganese mineralisation effects. These features have undergone some distortion due to overprinting of Recent weathering effects (Plate 3c).

Analysis of the polished sections support the formation of a manganiferous mud, within which debris flows deposited lithified clasts, producing the observed sedimentary breccia supported by a manganese matrix-cement. This is reflected in the impure nature of the ore, composed of approximately equal proportions of gangue material and pyrolusite mineralisation with an amorphous to massive texture. Minor psilomelane also forms intergrowths with pyrolusite, both of which were observed to wrap around and also infiltrate gangue material. Primary and secondary mineralisation textures exist, indicating a paragenetic sequence incorporating primary cavity filling and replacement plus secondary enrichment of both the replacement and cavity-fill mineralisation.

3.3.2 Etna

Restricted exposures observed only in subsurface workings typify a minor accumulation of manganese here. Petrographic study of the ore shows two basic lithological features, each distinctive. The observations suggest a replacement genetic model, producing firstly mineralisation in a botryoidal-nodular nature, and secondly a massive replacement ore. These features are shown in Plate 3d and Plate 3e, indicating mineralisation has replaced a well-sorted subangular medium-grained grainstone unit within the Etina Formation carbonate sequence.

A third minor form of mineralisation exists, namely secondary stringer-ore along fracture planes, filling the dilational spaces. Also, marginal replacement of the limestone into which the fractures splay was observed at the western workings (Fig 7b). All these ores reside in a strongly weathered friable sandstone (Plate 3f) indicating quite extensive groundwater percolation through this host unit.

Reflecting microscope petrographic analysis supports replacement of detrital material by manganese phases for ore genesis at Etna, represented by the appreciable gangue content and void spaces observed for this ore facies. Similar to Boolcunda and Muttabee, there is a minor association of botryoidal ore, indicated by massive psilomelane growth layers.

Replacement genesis by percolating waters is also supported in the microscopic determination of the ore, dominantly a loose fibrous psilomelane reflecting an amorphous partly crystalline wad (c.f Varentsov and Grasselly, 1980), implying sedimentary origin from mineralised hydrous phases.

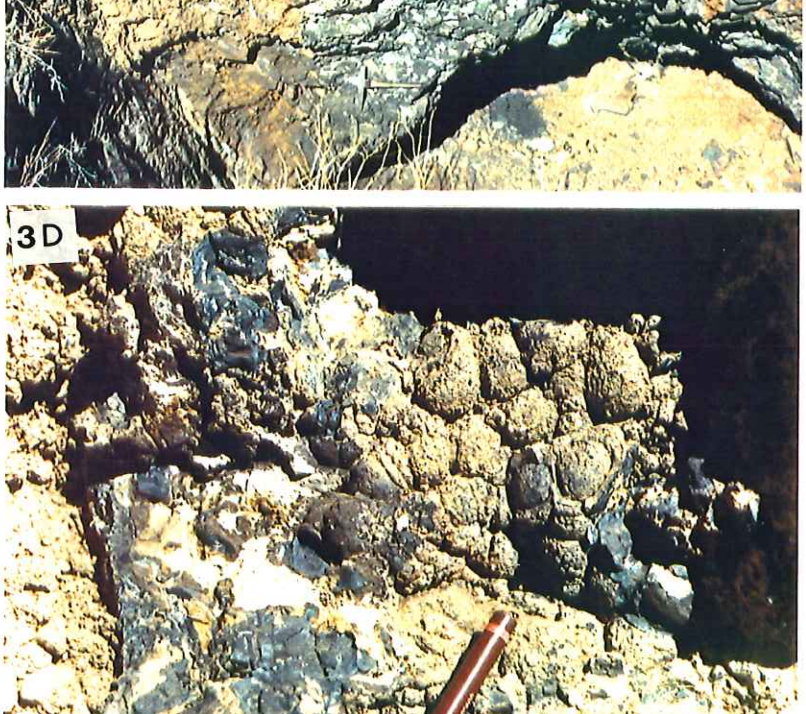
Plate 3A	Boolcunda Sedimentary breccia supported by manganese matrix cement.
Plate 3B	Boolcunda Sedimentary breccia ore and massive to vuggy mineralisation.
Plate 3C	Boolcunda Sedimentary breccia ore reflecting strong weathered appearance of the lithified clasts forming the breccia.
Plate 3D	Etna Botryoidal manganese ore morphology, representing primary void-cavity nucleation.
Plate 3E	Etna Manganese mineralisation replacing calcarenite host along thin layers.
Plate 3F	Etna Present nature of the host calcarenite, as a strongly weathered friable sandstone. Note selective replacement of thin calcarenite bedding.

3A

3B

3C

3D



3E

3F

3.3.3 Muttabee

Again mineralisation is observed to take a number of morphological forms. Most pervasive is a replacement manganese ore, having a massive sandy-detrital appearance reflecting the inferred model of sandstone replacement genesis (Plate 4a). Accompanying this massive ore is the minor occurrence of hard botryoidal manganese (Plate 4b), presumably as void and cavity filling.

Also, very minor appearance of high grade manganese nodules were seen within the sandstone host, which appeared to diminish when the sandy host had a high argillaceous content. As will be shown later supergene enrichment was excellently developed here, thus indicating a fourth lithological manganese character.

Again, petrographic analysis indicates a relatively impure ore, similar to Boolcunda and Etna, contaminated by fine grained siliceous detritus and numerous voids and spaces. The main manganese phase is pyrolusite, dispersed and surrounding an almost equal proportion of gangue. This texture highlights the primary replacement character of this ore, with the final paragenetic mineralisation phase indicated by secondary psilomelane coating, and replacing the primary pyrolusite.

3.3.4 Comparison of Deposits

Similarities exist amongst all the deposits, particularly relative to the visible lithological features. All three reflect botryoidal nucleation of manganese infilling cavities within host material (Plate 4d). This botryoidal growth showed a pristine morphology irrespective of paragenesis or post-genetic alteration, although the replacement nodules naturally had a rougher texture (Compare Plates 4a & 4d).

The replacement features too bear a close resemblance, contaminating the ores to a variable degree depending on content of impurities (sand and silt) and the degree of post-genetic weathering.

All show a plausible similar genetic association, relative to a coarse clastic sandstone lithology, bound in two cases at least, by carbonate allochemical sediments. However, Boolcunda appears related to some form of hiatus in sedimentation and therefore implies a different genetic origin, one contemporaneous with sediment accumulation and not post-sedimentary concentration genesis as postulated for Etna and Muttabee.

Chapter 4 is a critical account of proposed formation models for each of the accumulations studied, and where possible, correlations are made alluding to similar basic genesis parameters for these deposits within different geographical but similar sedimentological and geological settings.

3.4 GEOCHEMISTRY

Critical for any complete analysis of an ore accumulation is the geochemical fingerprint, or basic constituents, of the mineralised zone and surrounding rocks. Thus, geochemical analysis of 33 rock and ore samples was performed, not only to provide information as to the ore character but also to differentiate background manganese values useful for source analysis.

The geochemical methods and resultant data is listed in Appendix C, where the techniques of Whole Rock (wet chemical) Analysis (WRA), Atomic Absorption Spectroscopy (AAS) and X-Ray Fluorescence were used to determine both major and trace element concentrations. Mineralogical identification is aided by X-Ray Diffractometry and microscopic analyses.

The importance of representative sampling of the rocks encompassing each ore accumulation is highlighted as no previous source for the manganese has been postulated. It is relevant to also note that although ore samples show appreciable MnO values, the concentrations have a finite degree of accuracy essentially a result of the inhomogeneity of the manganese mineralised horizons - a common problem to many manganese accumulations (Hewett, 1966).

The results for the ore constituents (Table 1) show appreciable MnO, while analysis of the surrounding lithologies, summarized in Table 2, have MnO readings ranging from 100 and 1000 ppm. Only the Tapley Hill Formation and the Tarcowie Siltstone have appreciable values of

MnO with values ranging from 1000-1300 ppm, probably a response of their deposition within somewhat deeper marine conditions than other lithologies encountered.

The average values of MnO from the geochemical analyses compare favourably with those of the crustal average for manganese of around 1000 ppm (Roy, 1981) but are somewhat enriched relative to calculated sedimentary rock manganese abundances of 0.0166-0.025 Mn/Fe by Stanton (1972). This suggests a number of likely interpretations: that these encompassing sedimentary rocks provided an additive input to the concentration history of deposit formation; or that post-genetic remobilisation of the manganese has resulted, depleting the ore accumulation and enriching surrounding lithologies. However, the most plausible interpretation is that the hydrologic and sedimentary environment during formation of the enclosing sedimentary rocks was somewhat enriched in manganese, resulting in the slightly higher-than-average geochemical MnO fingerprint. Thus in a broad sense comparison with global values, as indicated in Tables 3 and 4, allude to similarities between the deposits studied, and those of the Earth in general.

Using the WRA and AAS techniques, and petrographic analysis, an attempt at differentiation of the mineralised zones was also performed, aiding interpretation of their internal variability and gross deposit differences. Manganese ore samples from each deposit revealed high percentages of MnO, although the Etna deposit mineralisation is lower than Boolcunda or Muttabee. Concentrations of MnO ranged from 45% - 48% at Etna, 63% - 64% at Boolcunda, to a maximum of 75% at the Muttabee deposit (Table 1).

Relative to the surrounding lithologies, the concentrations of trace elements, Ba, Cu, Ni, and Co in the ores are significant, while a converse relationship for Fe_2O_3 values exists when again compared to the enclosing lithologies. These values suggest that ore-forming fluids and/or percolating groundwaters passing through these sediments were enriched in trace elements, but depleted in iron.

The overall implication is that primary ore-forming fluids had strong manganese and trace element concentrations, a natural requirement for sedimentary manganese accumulation (Roy, 1981), and that secondary processes did not effectively reduce these concentrations.

TABLE 1 MnO Ore Sample Elemental Constituents

	Boolcunda			Muttabee			Etna	
	895-W1	895-W2	895-W5	895-113	895-161	895-2.14	895-375	895-376
Major Elements (%)								
SiO2	72.53	2.61	0.23	2.56	0.8	5.64	10.68	18.46
Al2O3	5.71	1.09	0.75	2.9	0.78	1.35	2.21	2.67
Fe2O3	12.73	0.71	0.26	0.69	0.36	0.58	0.8	1.58
MnO	**1.93**	**63.6**	**64.69**	**69.49**	**75.47**	**68.07**	**45.49**	**48.19**
MgO	1.22	0.5	0.69	0.39	0.32	0.4	0.68	0.91
CaO	0.27	0.44	4	0.41	0.39	1.24	10.57	1.24
Na2O	1.27	3.51	0.62	0.7	0.58	0.17	0.22	0.26
K2O	1.77	0.01	1.46	3.48	0.77	1.08	0.76	0.81
TiO2	0.37	0.05	0.02	0.06	0.03	0.08	0.16	0.14
P2O5	0.17	0.4	0.3	0.6	0.26	0.36	0.34	0.41
SO3	0.02	0.41	0.1	0.05	0.16	0.05	0.06	0.09
Trace Elements (ppm)								
Cu	6	96	1503	3539	120	117	87	42
Co	163	113	113	8626	74	411	174	194
Ni	68	105	64	159	15	15	77	52
Pb	<7	-	-	<3	-	-	-	-
Cr	25	12	12	<9	<9	12	19	25
Zn	122	319	222	2134	98	95	344	378
Sr	177	2018	6394	2315	3177	2623	1887	1551
Ba	1311	1425	47802	14145	30617	25374	38684	65945
LOSS	1.63	19.78	11.96	11.71	11.86	11.76	16.01	10.05
TOTAL	99.61	93.1	85.06	93.05	91.78	90.78	87.98	84.82

TABLE 2 Background lithology geochemistry

%	Brachina Fm	Ulupa Siltstone	Wilmington Fm	Elatina Fm	Enorama Shale	Tarcowie Siltstone	Cox Sandstone
SiO2	64.99	63.38	67.04	72.36	33.78	67-70	85.03
Al2O3	14.91	15.04	12.79	10.97	4.58	9 to 11	6.34
Fe2O3	7.97	8.42	5.55	6.16	1.93	5	2.47
MnO	0.05	0.05	0.05	0.048	0.05	0.05-0.1	0.027
MgO	2.58	2.68	2.61	1.56	1.68	3	9.03
CaO	0.37	0.45	1.67	0.83	30.83	2 to 3	0.21
ppm							
Cu	6	23	33	28	38	4 to 24	12
Co	42	60	40	44	28	54 to 60	121
Ni	37	59	41.2	47	<7	24 to 29	21
Cr	81	91	64.4	17	28	66 to 75	40
Zn	112	132	52.2	91	29	73	55
Ba	388	517	-	102	-	-	149
TOTAL	99.68	99.68	99.74	99.59	100.49	99.4	99.68
Samples	1	1	5	3	1	2	3

%	Uroonda Siltstone	Etina Fm sandstone	Etina Fm limestone	Tapley Hill Fm
SiO2	70.83	53-79	16.86	24-60
Al2O3	10.28	8 to 11	2.4	4.5-7.9
Fe2O3	4.52	3 to 6	1.91	2-3.1
MnO	0.06	0.02-0.11	0.1	0.11-0.13
MgO	3.2	2.2-4.3	10.72	1.4-2.0
CaO	1.28	0.2-9	31.2	10.9-36
ppm				
Cu	31	6 to 16	21	14
Co	66	30-56	27	34-49
Ni	27	12 to 37	10	12 to 17
Cr	59	6 to 75	23	41-56
Zn	60	11 to 78	33	25-38
Ba	-	227-306	33	-
TOTAL	99.17	99.55	99.81	100.1
Samples	1	2	3	2

TABLE 3: GLOBAL Mn ABUNDANCES RELATIVE TO ROCK TYPE

	ROY (1981)		STANTON (1972)		WEDEPOHL 1969	CRERAR 1980
ROCK TYPE	Mn%	Mn/Fe	Mn%	Mn/Fe	Mn%	Mn%
Igneous	0.086	-	-	-	0.18	-
Ultrabasic	0.15	0.015	0.15	0.016	0.19	0.162
Basic	0.2	0.023	0.23	0.026	0.19	0.15
Intermediate	0.12	0.2	0.19	0.038	0.131	-
Acidic	0.06	0.002	0.15	0.028	-	0.05
Sandstone	0.026-0.05	-	-	0.0166-0.025	0.045	-
Shale	0.07-0.085	-	-	-	0.085	0.085
Pelagic Clay	0.17-0.85	-	0.23	0.036	2	0.1

TABLE 4: MnO VALUES OF VARIOUS STUART SHELF LITHOLOGIES (%)

	1	2	3	4
Beda Volcanics	0.22	0.24	0.45	0.27
Roopena Volcanics	0.26	-	-	0.22
Wooltana Volcanics	-	-	0.25	-
Gairdner Dyke Swarm	-	0.39	-	0.78

1 Giles and Teale (1979) : 5 samples

2 Knutson et. al. (1983) : 10 samples

3 Preiss (1987)

4 South Australian Dept. Mines and Energy (unpubl. rep.)
Knutson et. al. (1983)
In Williamson (1987)

TABLE 5: COMPARISON GEOCHEMISTRY of background lithologies encountered From Binks (1971)

	Fe %	Mg %	Ca %	Mn	Ba	Cu	Pb	Zn	Co	Ni	Cr
Ulupa Siltstone	<1	1 to 10	<1	**500**	600	25	10	70	15	25	120
	<1	<1	<1	**200**	2000	20	20	40	7	15	115
	<1	<1	<1	**5000**	2000	20	50	30	40	40	300
Brachina Formation	>3	1 to 10	1 to 10	**300**	2000	20	50	70	20	50	400
	>3	<1	<1	**150**	3000	50	15	30	20	50	500
Elatina Formation	2	<1	<1	**300**	1000	8	8	<20	4	8	150
	0.6	1 to 10	1 to 10	**2000**	1200	20	10	<20	10	20	300
Enorama Shale	<3	1 to 10	<1	**250**	2000	40	50	60	12	30	150
Tarcowie Siltstone	3	>10	>10	**1000**	2000	20	8	<20	8	15	500
	3	1 to 10	1 to 10	**300**	3000	10	15	40	15	30	500
	3	1 to 10	1 to 10	**200**	1000	60	70	25	10	30	250
	3	1 to 10	<1	**300**	2000	12	30	60	10	20	300
Etina Formation	0.5	>10	>10	**200**	800	8	6	<20	3	1	8
	0.03	1 to 10	>10	**300**	800	8	3	<20	1	1	8
Tapley Hill Formation	<3	>10	>10	**250**	1500	40	20	30	12	30	200
	3	>10	>10	**400**	1200	20	3	30	15	40	200
	3	1 to 10	>10	**500**	1200	50	40	40	10	50	300

3.5 MINERALOGY

The minerology of the main ore types and host rocks of all three localities was determined by X-Ray Diffractometry. This study indicates that the manganese occurs entirely as crystalline manganese oxides.

At Boolcunda, mineralisation is dominantly pyrolusite (β-MnO_2) with minor secondary associations of the low temperature manganese-hydroxide, manganite (γ-MnOOH) and psilomelane ($(Ba,K,Mn,Co)_2Mn_5O_{10}$) Other phases found to be present in lesser amounts include quartz, albite, hematite and possibly ilmenite.

The Muttabee accumulation again is dominated by pyrolusite, as both primary replacement ore and secondary coatings. A minor mineralised pod accumulation within the stratigraphically younger Elatina Formation has cryptomelane ($K_2Mn_8O_{16}$) occurring as botryoidal ore (Plate 4.d).

Finally, manganese phases identified at the Etna deposit include low temperature (sedimentary) psilomelane, romanechite ($BaMn_9O_{16}(OH)_4$) and hollandite ($Ba_2Mn_8O_{10}$).

The dominant phase encountered is seen to be pyrolusite, a manganese oxide which forms the most commonly occurring manganese species in the oxidised zone (Roy 1981). Along with manganite, psilomelane, and cryptomelane, this phase reflects general mineralisation as weathered material with source derivation from pre-existing surrounding crystalline phases, inferring genesis under low temperature (sedimentary) conditions. This interpretation of low temperature accumulation from a weathered source is supported from basic descriptive analyses of manganese phases outlined by Ford (1932), Frenzel (1980), and Roy (1981).

These manganese phases present agree with similar global distributions of variable phase low temperature manganese minerals. Variability in both ore texture and mineralogy of these phases found is a response to the high mobility of the manganese element and also its capacity to incorporate foreign cations (Frenzel, 1980). This ease of cation adsorption is aided by the low temperature conditions and large range of potential redox variations attainable at the Earth's surface where sedimentary accumulations of the manganese may develop (Wedepohl, 1980).

4. ORIGIN AND DISCUSSION

4.1 SOURCE OF MANGANESE

The formation of a mineral accumulation cannot be viewed in the singular, but must be analysed as a dynamic, interacting multivariate system of mechanisms and processes leading to ultimate mineral accumulation. In the same manner that sedimentary material passes through the denudation cycle, so to will the development of a sedimentary manganese accumulation undergo the stages of derivation, transportation, concentration and deposition.

Derivation of possible source material reflects this multivariate nature of ore genesis. Hewett (1966) and Roy (1981) indicate this in highlighting three broad settings for source derivation: denudation of pre-existing continental material; thermal fluids, and volcanogenic associations; or localised diagenetic affiliations.

In the context of the deposits examined here, limiting the source analysis to the exogenic system is applicable, hence negating discussion on possible hydrothermal source affiliations. This is supported by a lack of any contemporaneous or adjacent volcanogenic activity to the deposits.

We are left, then, with either a diagenetic or continental-derived source, those "telethermal" accumulations of Smirnov (1968). The most likely potential euxinic process is seen to be continental runoff: the weathering of pre-existing material with manganese derivation through transportation in surface and ground waters (Roy, 1981).

This continental source model is applicable in a number of aspects to the deposits analysed. Initially, it is seen that maximum derivation of manganese is generally attained during tectonic quiescence, a feature similar to many ore accumulations (Roy, 1981) and a situation envisaged to have prevailed in the stable platform setting under which the accumulations examined here concentrated. This stable tectonism points to the second factor controlling manganese source derivation, namely reduced detrital input into the system. This effectively implies the dominance of chemical weathering activity over mechanical weathering, a clear sign indicating enhanced liberation of elements from the weathered source material. Finally, the decomposition of basic and intermediate volcanic suites is seen as an appreciable manganese source (Williamson, 1987), because of their typical geochemical make-up highlighting higher-than-average crustal MnO abundances, relative to other rock types (Table 4).

These features of tectonic quiescence, dominant chemical denudation, and the existence of a rock suite which when denuded may release appreciable manganese, are all applicable to the Boolcunda, Etna, and Muttabee manganese accumulations, to varying degrees .

However, even though the geological history of the area suggests tectonic stability during ore formation, and palaeoenvironmental features support provenance from basic and intermediate rocks to the west, and at least localised cessation of sedimentation occurred (Boolcunda), other processes of manganese derivation within an aqueous system cannot be precluded. This aspect still cannot be adequately interpreted (Roy, 1981) and thus derivation of manganese from the processes of halmyrolysis or diagenesis is unclear, suffice to say their timing and duration within the conducive geological niche already supporting metallogenesis will either complement or diminish the ore accumulation, here seen not to have appreciably affected ore genesis.

4.2 CONCENTRATION HISTORY

The interpretation of palaeoenvironmental indicators studied suggests an almost all-pervasive westerly provenance for the detritus and possible ore constituents forming sedimentary and mineralogic accumulations within the geosynclinal region analysed. The continued emergent nature, and therefore source potential of this provenance region during the Proterozoic allows for the possibility of appreciable manganese dispersal as weathering products with the accumulating sediments. However, to negate possible dissemination and loss of this manganese within the accumulating Sturtian-Marinoan sediments, there is the proviso for a favourable hydrologic regime and suitable accumulation environment for retention of the manganese, producing the observed sedimentary manganese deposits.

The hydrologic regime favourable for manganese concentration is one where anoxia, or at least oxygen deficiency, exist (Roy, 1981; Frakes and Bolton, 1984). This results in dissolution of manganese phases, a result of its characteristic high solubility under reducing conditions. The prevailing circulation pattern, the result of basin configuration and eustatic conditions, is also applicable in possible retention and concentration of manganese.

Envisaged for the Boolcunda, Etna, and Muttabee accumulation of host and ore facies is the existence of a cyclic transgressive-regressive system, affected by a restricted circulation pattern (Preiss and Kinsman, 1978; Preiss, 1987). This effectively causes the build-up of manganese within the hydrologic regime over time, involving: concentration of dissolved and particulate manganese during oxygen deficient transgressive phases, followed by dominantly particulate manganese precipitation (Glasby, 1977; Frakes and Bolton, 1984) upon regression, as the hydrologic system moves toward a more equiable redox potential, further implying increased oxygenation and manganese precipitation.

The nature of transgressive phases causing reducing conditions have been documented by Roy (1981), Frakes and Bolton (1984), Force et al.(1986), and Evans (1987), particularly in relation to the solubility and possible concentration of manganese. The physiochemical conditions produced by this transgressive-regressive system is conducive to the dissolution, remobilisation, and concentration of the manganese ore constituent (White, 1966; Frakes and Bolton, 1984), and are conditions postulated to be responsible for aiding the manganese concentration observed as ore deposits.

Considered thus far have been the gross environmental parameters affecting possible mineral concentration. Of equal importance, however, is the geochemical characteristic responses of manganese, and its input to the concentration of the element (Wedepohl, 1980). The multivariate nature of the genesis process is again indicated relative to the geochemical behaviour of manganese, which has a response governed by many parameters, including: rate and volume of watershed into the depositional basin; Eh-pH contrasts between inflowing surface and ground waters, and the marine hydrologic regime; prevailing climatic conditions; and the rate and type of source rock weathering. These important features indicated by Roy (1981), Frakes and Bolton (1984), and Baturin (1988) intrinsically affect the possible potential for ore concentration and mineralisation. They aid transport of manganese as suspended adsorbed or hydroxide complexes,or as mineral or organic complexes (Baturin, 1988); concentration as particulate but dominantly dissolved phases; and final deposition into metallogenic accumulation;

parameters which respond to the geochemical behaviour of the manganese element and the environment it interacts with.

Also requiring interpretation for possible manganese concentration and ore formation is the fractionation of the manganese from iron. This separation can occur at any stage of the manganese derivation, transportation, and deposition genesis cycle (Roy, 1981), but is largely a response to the prevailing climatic, hydrodynamic, and Eh-pH conditions. These features lead to solubility variations within the transporting/mineralising fluids as they migrate within the aqueous system (Hewett, 1966). Other effects found within the hydrologic regime which may accentuate manganese-iron fractionation include: the rate of ore accumulation; rate of possible element fractionation; and the differential transport of particulate and dissolved phases (Glasby, 1977).

The major precept supporting manganese-iron segregation relative to the Boolcunda, Etna, and Muttabee deposits is the higher and more complete rate of oxidation of iron over manganese, alluding to the greater solubility of manganese. This supports the concept of iron retention in the sedimentary pile under natural Eh-pH conditions, while manganese is soluble and still mobile. Therefore, at the accumulations studied it is envisaged that the fixation and dissemination of iron within the accumulating sediments had already been appreciable. The added effect of further manganese concentration from its solubility response to the varying redox conditions, resulting from the interpreted eustatic fluctuations, also inhibited manganese-iron joint concentration. The distal location of the deposits within the shallow-marine shelf zone of genesis further supported fractionation of these two elements, again a result of the lower solubility of iron in the aqueous environment relative to manganese. Thus, gross environmental segregation of manganese and iron is envisaged to be the dominant fractionation process at all three deposits.

Accompanying this mode of differentiation, at least at Boolcunda where more redbed marginal sedimentation and concomitant ore genesis occurred, is the precipitation of minor iron sulphide. Field observations delineated a series of coarse blackish-red sandstones interbedded with massive silts and the breccia-ore horizons (Appendix D). These sands, in their basal sections, showed very fine disseminated pyritic material, indicating iron fixation. No such features were observed at the Etna or Muttabee accumulations, and with petrographic analysis indicating negligible iron mineral associations (Appendix B.1), support for iron removal relative to the hydrologic system is suggested, enhancing the solubility differences and therefore segregation of iron and manganese. This effective removal of iron from the mineralising system must also be seen in the context of the generally low iron values, compared with manganese, in the surrounding lithologies differentiated, listed in Table 2. These values also support a lack of fractionation of the two elements via remobilisation, an observation inferred from the general lack of appreciable supergene features at each of the mineralised sites.

The concentration of dissolved manganese is thus interpreted as a response to transgressive conditions, with accumulation within a reducing aqueous system. The concentration parameters of a prevailing estuarine circulation pattern, a reducing hydrologic regime, interaction between anoxic-oxic water masses and the sedimentary pile, and the geochemical behaviour of manganese are all required for interpretation of genesis within the dynamic system of ore genesis envisaged. Finally, due to the isolated nature of each sedimentary accumulation studied, specific analysis of the conducive geomorphological conditions aiding final accumulation must also be analysed and interpreted, as discussed below.

4.3 DEPOSITIONAL HISTORY

4.3.1 Introduction

The formation of a sedimentary manganese accumulation involves a polygenetic interpretation, a dynamic response to the interacting processes and mechanisms affecting possible mineral deposition (Glasby, 1977) Of particular relevance for the deposits studied here is the sedimentological framework under which ore deposition proceeded.

Assuming a system already concentrated in manganese, parameters affecting possible accumulation in the aqueous environment require consideration. Thus development of the Boolcunda, Etna, and Muttabee ore deposits under shallow-marine conditions in a marginal setting of an evolving intracratonic basin is noted, similar to environments proposed for a number of other manganese accumulations (Groote Eylandt: Frakes and Bolton, 1984; Imini, Morocco: Force et al., 1986). This deposit setting implies ore deposition affected by transgressive-regressive phases - represented in the Adelaide Geosyncline by paralic and marine fluctuations in the sequence of Sturtian and Marinoan sediments mapped, following maximal transgression of the Tapley Hill Formation (Preiss, 1987).

Consideration of the basins configuration and hydrologic system characteristics is also needed for deposit interpretation. The importance of the depocentre configuration is its determinative effect on the water circulation pattern, interpreted for the geosyncline at this period to be partly estuarine, with open marine conditions to the southeast (Preiss and Kinsman, 1978; Preiss, 1987).

This restricted flow is seen to be accountable in the effective trapment of land-derived and sea manganese (Frakes and Bolton, 1984), with land-derived manganese considered to be the dominant source for the accumulations examined. This circulation pattern also enhances simple manganese precipitation, at suitable Eh-pH conditions, when there is an absence of significant organic complexes in the aqueous system (Roy, 1981), a condition plausibly existing during this Late Precambrian period of deposit development where terrestrial organic activity is interpreted to be negligible.

The sluggish circulation further implies the existence of a stratified water column with a strong oxic-anoxic interface, observed to be a common loci for the oxidation and precipitation of Mn^{2+} (Roy, 1981). The position of this interface between oxidised and reduced systems is an important control in the deposition of the manganese. The concentration of the manganese in the aqueous system is a response to the amount of source input, the postulated prevailing reducing hydrologic regime, and the transgressive and initial regressive sedimentological environment under which manganese accumulated.

Ultimate deposition in this aqueous regime is controlled by the geochemical behaviour of manganese, principally its solubility-mobility character affected dominantly by Eh-pH relationships. Accumulation and deposition appears to be caused by the oxidation and precipitation as particulate matter from dissolved manganese via interaction with: (1) the oxic-anoxic water boundary and the sediment interface, or (2) direct particulate manganese formation from the water column in response to varying Eh-pH (Roy, 1981).

A lack of input of manganese from the sedimentary pile already established (diagenetic source) is inferred from the geochemical results (Appendix C), and also supported by the work of Glasby (1977) and Sundby and Silverberg (1980) where it is shown that near-surface sediments in modern-day marine basins do not provide an adequate supply of possible ore-forming manganese; an affect of the mobility and solubility of manganese phases.

The supposition is therefore for an established water mass reservoir of concentrated dissolved and particulate manganese, a result of a continental source high in backgroud MnO, the inferred palaeoenvironmental conditions of transgression and regression, and the palaeo-circulation pattern.

Apart from these chemical variations affecting manganese deposition, the rate and supply of detritus to the system and a conducive location for ore accumulation must also be considered. Due to the shallow-marine environment envisaged during accumulation, some process for retention of the dominantly particulate and dissolved manganese in required, otherwise dispersion is likely resulting in no ore accumulation. Discussed below are the two models proposed for this retention and deposition: a mixing model due to interaction of the manganese reservoir with the sedimentary pile at Etna and Muttabee; and a model related to isolated depressions in the sediment surface, within which particulate manganese accumulated, removed from physiochemical changes occurring in the overlying water mass.

4.3.2 Deposit Formation at Etna and Muttabee

The mineralisation at Etna and Muttabee is found within allochemical precipitates of the Etina Formation, represented as an isolated shoal at Muttabee and a somewhat more extensive carbonate platform development at Etna (Fig. 8a-b).

As indicated in the previous discussion the petrography and physical character of the ores at these sites implies manganese development as replacement in form. In both cases the replaced host consists of a calcarenite-sandstone lithology conformably lying within bounding carbonates (Appendix D). This indicates preferential migration of ore-forming fluids along permeable and porous sedimentary layers, with deposition-precipitation caused by redox changes in the mineralising fluids as migration developed.

The configuration of the environment of ore accumulation is a further factor for analysis. As shown by Fig. 8(a)-(b), and analyses of the lithological characteristics, the deposition site is within a shallow-marine environment, a zone partial to the effects of eustatic variations and the corresponding physiochemical changes intrinsic to this system: varying salinity, Pco_2, Eh, pH, water circulation, sediment supply, influx, and rate of accumulation. This has the implication of ore accumulation correlated to transgressive-concentration and regressive-deposition manganese genesis modelling in the aqueous environment as discussed by Frakes and Bolton (1984) and Force et al. (1986), because of the similar aspects of deposit setting and the interpreted transgressive-regressive sedimentation history.

The ooid bank structure of the Etina Formation carbonates at Muttabee (Fig. 8a) suggests possible interference of the sediments with a possible anoxic-oxic manganese reaction boundary in the water column, or simply exposure to the postulated manganese reservoir. Either way, migration of fluids rich in dissolved manganese and possibly particulate material occurred. Thus formation of the replacement ore and minor primary ore developed, in cavities produced by the dissolution effect of the migrating fluids resulted. Final retention of the manganese is supported by a continuation of regressive sedimentation blanketing the zone in oxidised sediments, effectively trapping the mineral and inhibiting further remobilisation. This sequence of events is depicted in Fig. 9

Deposition at Etna is closer to the configuration of deposit setting envisaged by Force et al. (1986), in that the accumulation is situated on a carbonate platform, a zone not unlike that envisaged at Muttabee, with similar interacting processes. A mixing zone is indicated, in response to the intersection of the sediment-water interface causing oxidation and precipitation of dissolved manganese, concentrated in the water mass during the transgressive phase of sedimentation prior to the regressive system under which dominant ore deposition is seen to have occurred. Added to this precipitation from dissolved material is particulate manganese residing in the aqueous system, and a negligible source from remobilisation of manganese precipitated during the preceding transgression. The preference for replacement of a calcarenite-sandstone lithology is again indicated, with percolating fluids rich in manganese dissolving and replacing the permeable horizon. It is readily known that preferential replacement of Ca by Mn does occur (Rankama and Schama, 1950) and also that Mn associates with Ca in preference to Fe (Roy, 1981) indicating two features which further imply possible manganese enrichment within these calcareous sediments studied.

FIGURE 8(a) : Emergent Ooid Bank Morphology (Muttabee Etina Formation exposure)

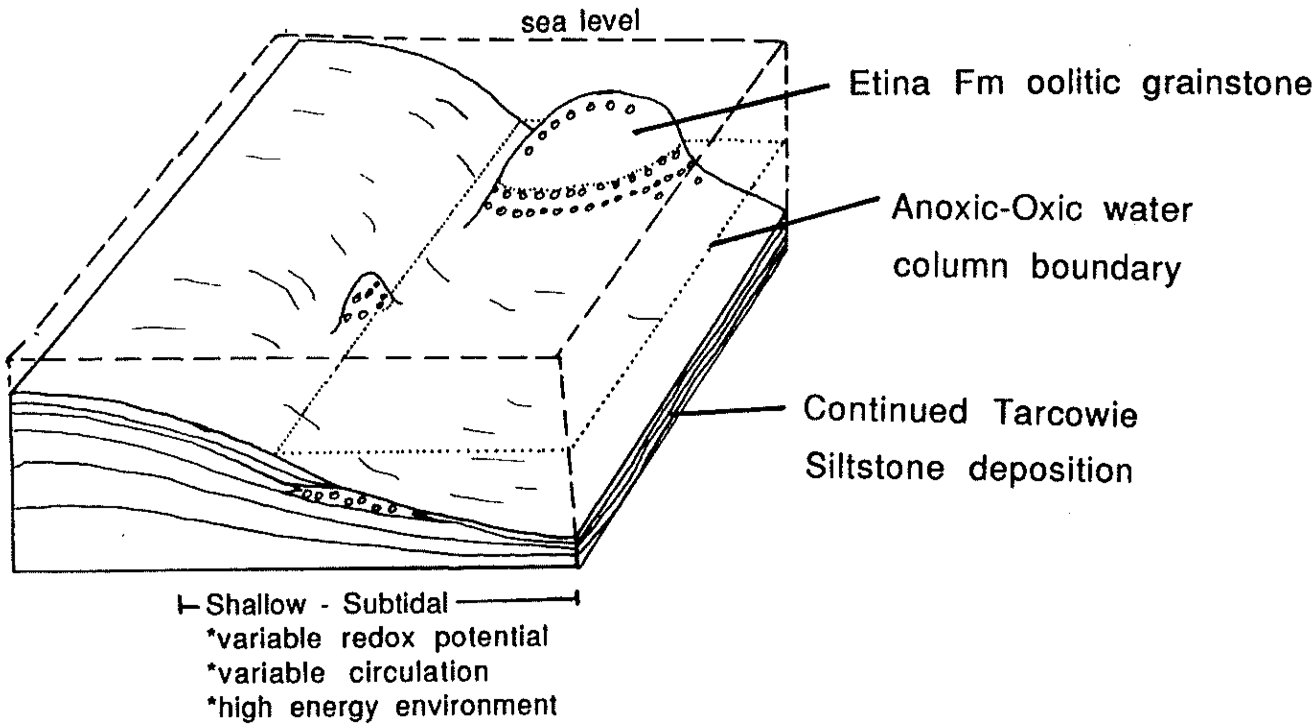
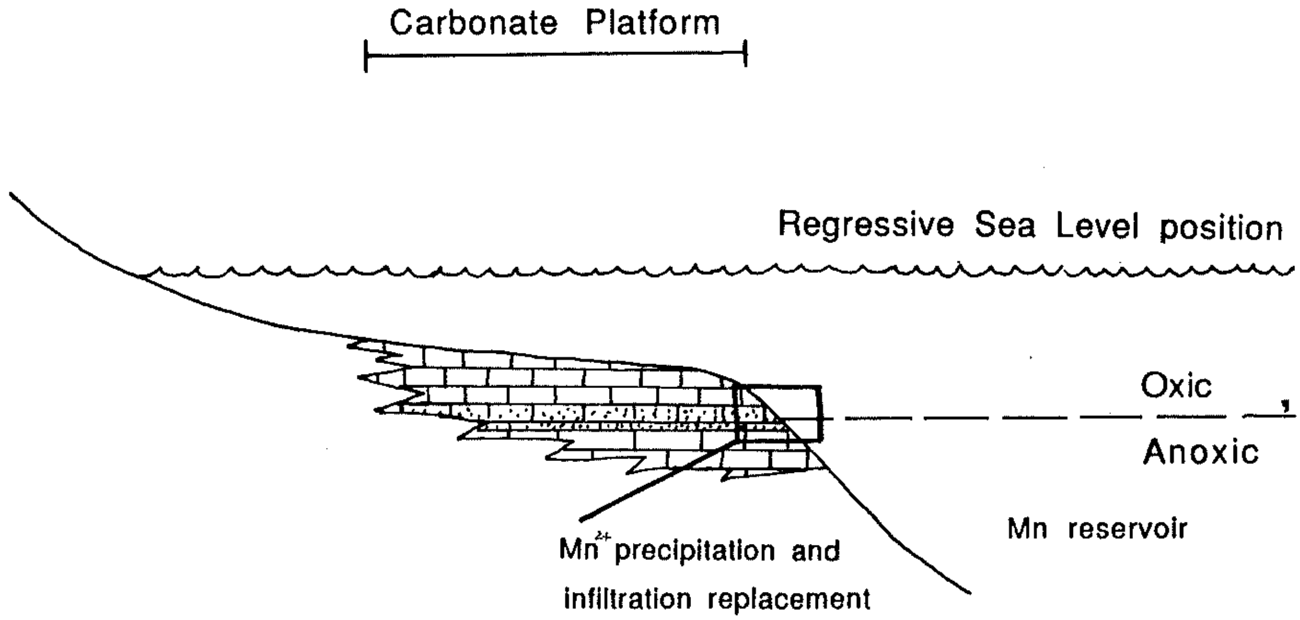


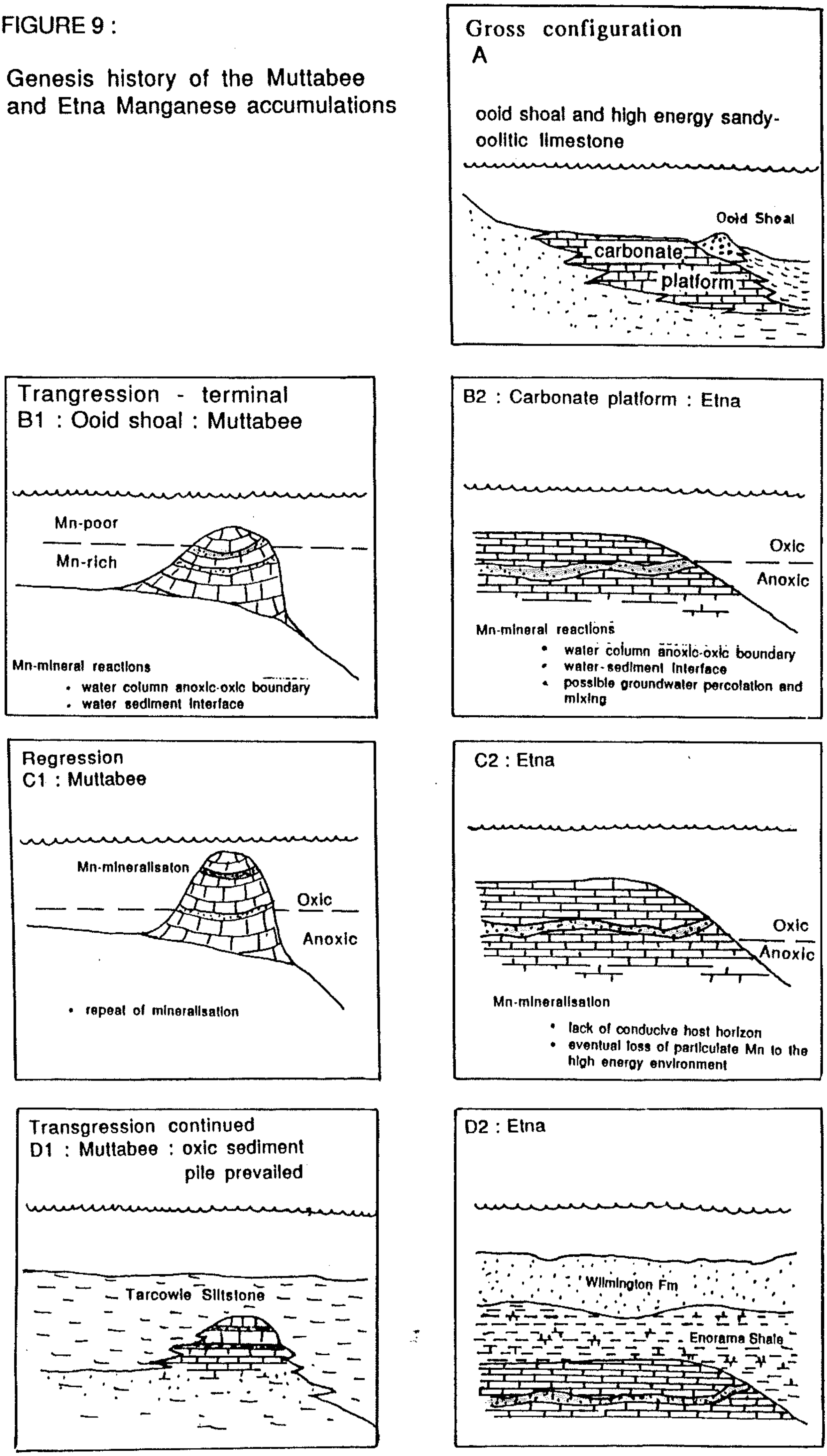
FIGURE 8(b): Configuration of carbonate platform (Etna map area)



(Adapted from : Bolton and Frakes, 1984; Force et. al., 1986)

FIGURE 9 :

Genesis history of the Muttabee and Etna Manganese accumulations



Overall, the mineralised ore horizons are thus pseudomorphs of an original calcarenite lithology, with deposition a result of favourable interaction between this permeable lithology and the aqueous regime supporting a concentrated manganese reservoir.

4.3.3 Deposit Formation at Boolcunda

Discussion of the formation of the Boolcunda manganese deposit warrants specific individual analysis, in the light of processes of genesis already discussed, for a number of reasons. The two basic factors for differentiation apply firstly to the timing of ore accumulation, and secondly to the deposits character, alluding to a totally different mechanism of formation than that postulated for the Etna and Muttabee deposits.

Formation of the Boolcunda deposit occurred in a later stage of development of the Adelaide Geosyncline, coupled to sedimentation in the mid to late Marinoan. The sequence enclosing the manganese mineralisation is the upper Wilmington Formation, comprising a cyclic facies distribution of sands and massive silts separating four thin ore horizons (Appendix D). This unit accumulated under increasingly regressive conditions associated with glacio-eustatic sea level reduction during the Upper Marinoan (Preiss, 1987). This followed eustatic fluctuations after the maximal transgression of the Tapley Hill Formation Sea.

Ore deposition in a similar manner to the Etna and Muttabee accumulations occurred in a shallow-marine subtidal setting. However, unlike these older deposits, the marginal location for Boolcunda was dominated by paralic-redbed clastic sedimentation which resulted in an accumulation involving a very different mode of genesis than that considered at Etna and Muttabee.

Genesis modelling here revolves around postulated topographic and erosionally produced sediment-surface irregularities and depressions upon the shelf palaeoslope, effectively isolating and retaining dominantly particulate manganese. This inferred major nondeposition unconformity to erosional unconformity developed as a limited spatial and temporal hiatus, only observed at the Boolcunda location, and occurred as a diachronous feature in upper sand-silt cycle of the Wilmington Formation. This time-spanning nature is reflected in four separate mineralised horizons all with the same characteristics, segregated by intermittant renewed sand and silt deposition.

This hiatus allowed for lithification of sediments, followed by slurry/debris flow into the localised palaeoslope depressions in which particulate manganese, possibly as a muddy lithology, had been accumulating. Angular lithified clasts mixed with this manganese-mud to produce the observed sedimentary breccia supported by a manganese-matrix (Plate 3a; Plate 3c). Episodic rapid sediment influx caused resumption of clastic sedimentation, effectively covering and isolating the thin ore horizons with sands and minor less permeable silts (Appendix D).

As indicated by Baturin (1988) manganese concentration within the aqueous system is implied to be as oxide particulate matter, precipitated dominantly from colloidal and oxide-complexes. The concentration and retention of this dominantly flocculant material is in response to the water column and circulation dynamics. Thus in the same way as the geosynclines circulation pattern aided deposit formation at Etna and Muttabee, the restricted estuarine flow (Preiss & Kinsman, 1978; Priess, 1987) played a significant role in the retention of the precipitated manganese matter at Boolcunda.

The estuarine circulation pattern indicates a net shoreward migration of bottom waters and a net seaward migration of surface waters (Sundby & Silverberg, 1980). This is conducive to the proposed deposition scheme because it allows for addition of manganese into the palaeodepressions, not only from fallout from bottom waters but also from recirculated fallout from seaward migrating surface waters (Fig. 10).

This source of manganese is a result of concentration of the element in the water mass during suitable transgressive reducing-anoxic conditions, subsequently becoming increasingly oxidised as the aqueous system moves toward a more uniform redox potential. Little diagenetic remobilisation is inferred during the regressive phase of sedimentation and ore deposition, a feature not uncommon to many shallow-marine sedimentary environments (Glasby, 1977), where the sedimentary pile is effectively oxidised to depth inhibiting diffusion and possible diminishment of the ore.

The rapid influx and accumulation of the sands and silts immediately enclosing the mineralised horizons suggest high energy conditions - this rapidity of deposition aids ore retention by (1) implying separate processes of sedimentary formation distinct from manganese

Plate 4A	Muttabee Sandstone replacement manganese mineralisation. Note sandy-detrital appearance of this mineralisation.
Plate 4B	Muttabee Hard high-grade relatively pure botryoidal ore.
Plate 4C	Botryoidal manganese growth within sandy host material. Similar to all three deposits studied. Note primary replacement features (A).
Plate 4D	Muttabee Massive impure ore from main mine (A) and botryoidal cryptomelane growth (B) from small mineralised pod in the younger Elatina Formation.
Plate 4E	Muttabee Supergene enrichment of thinly bedded sandstone immediately overlying calcarenite host lithology.
Plate 4F	Muttabee Supergene enrichment along fracture-drag planes where percolating surface and ground waters preferentially migrated.
Plate 4G	Boolcunda Supergene enrichment of manganese and minor iron (reddish staining) into sandstone bounding sedimentary breccia ore. Note large-scale slumping indicating high energy unstable sedimentary environment,supporting genesis model of debris flows of lithified material into depressionscontaining manganese mud.
Plate 4H	Boolcunda Supergene calcification along fractures, veins and within voids of the sedimentary breccia ore.

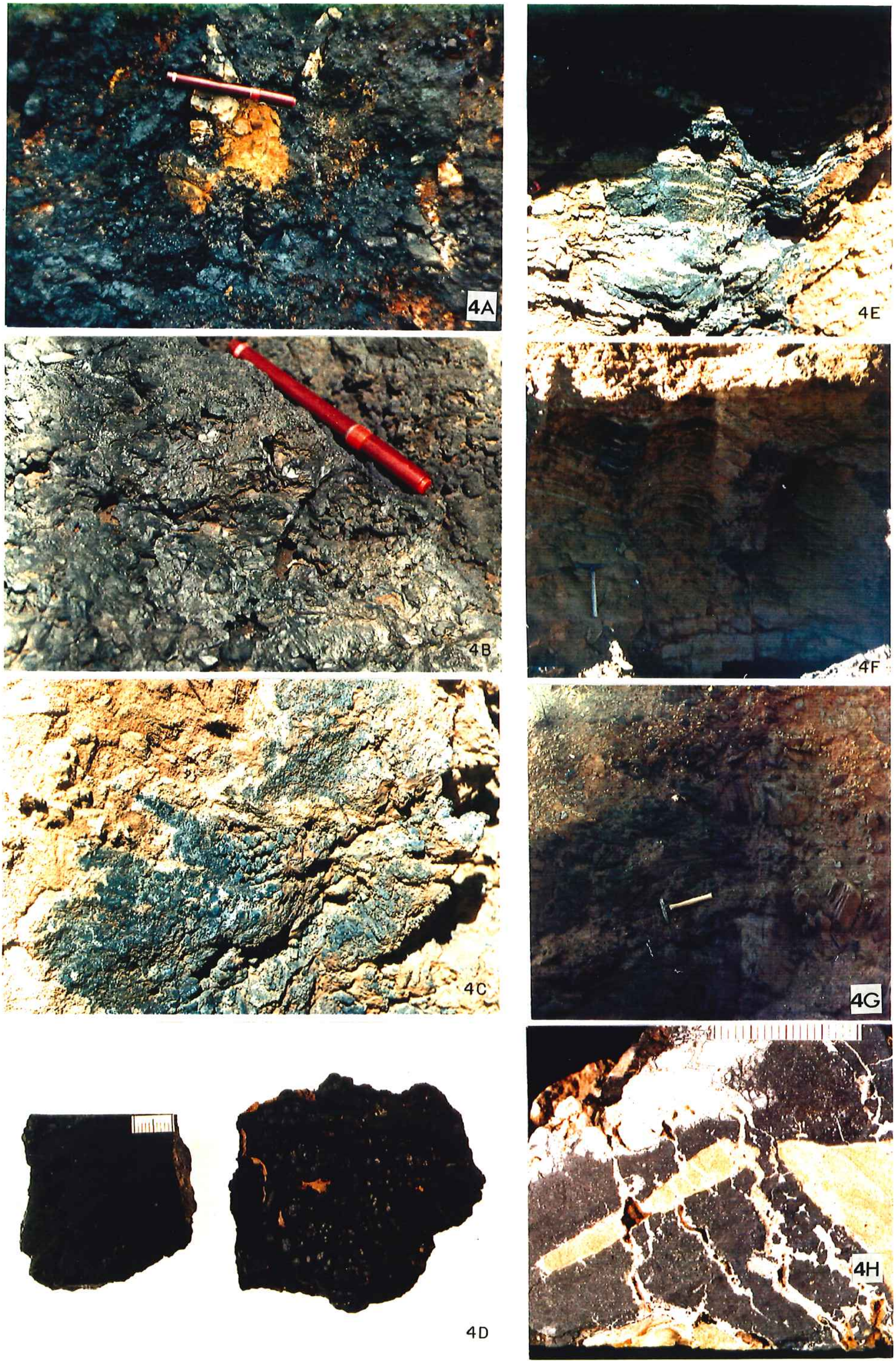
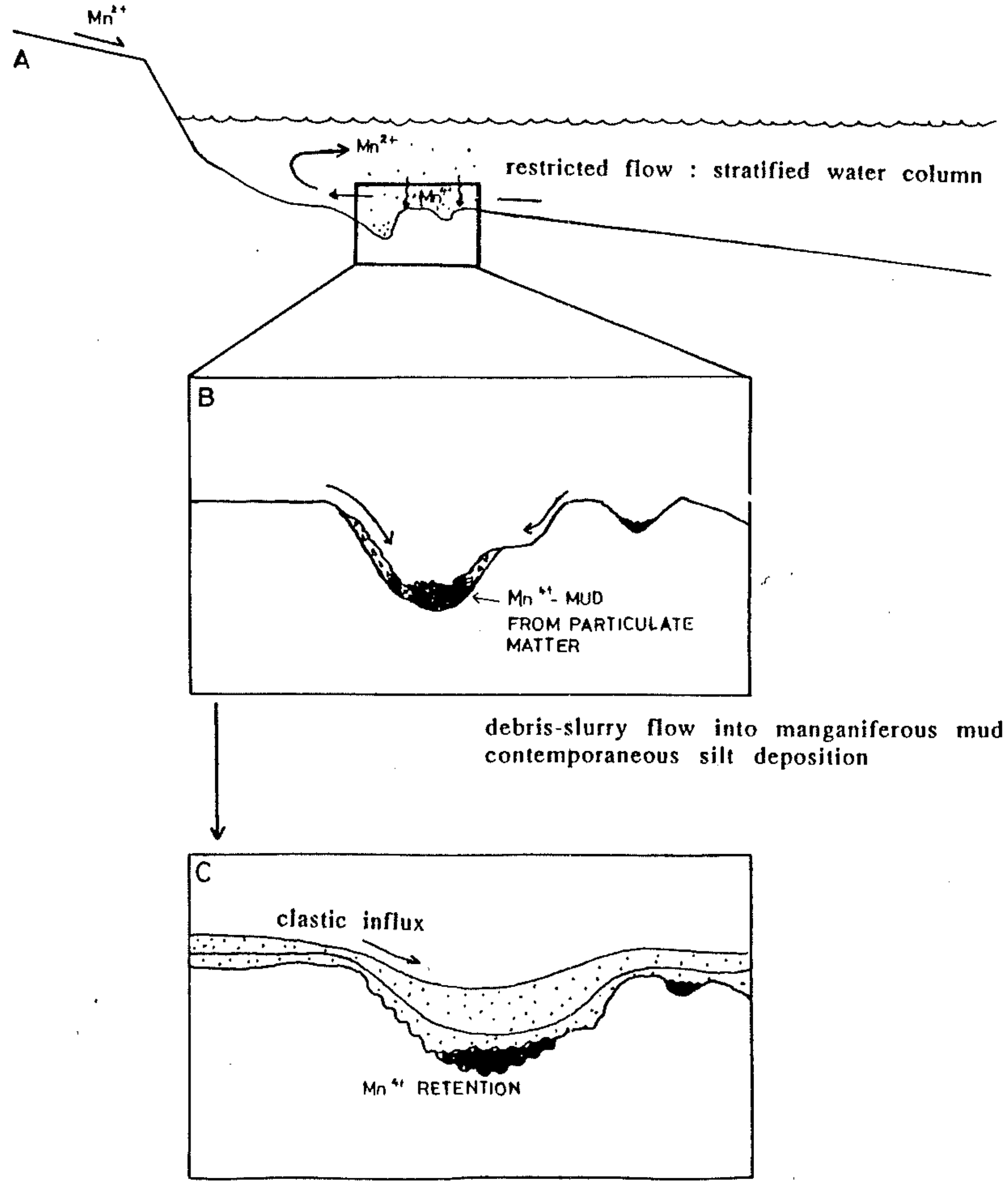

4A
4E
4B
4F
4C
4G
4D
4H

FIGURE 10 : Genesis of the Boolcunda Manganese accumulation



accumulation, intrinsic in its episodic nature of deposition between ore horizons thereby not inhibiting possible nucleation, and (2) isolating the mineralised zones within oxic sediments, removing the manganese from further interaction with the hyrologic mineralising system.

4.4 SUPERGENE HISTORY

The sedimentary sequence comprising the manganese accumulations remained intact, isolated from weathering effects up until the Late Tertiary (Binks, 1971). During this time block-faulting and uplift resulted in the initiation of sediment peneplanation. This began the supergene history of the accumulations, as they were once again exposed to the aqueous regime. This involved processes of pedogenesis, physical and chemical weathering, and erosion (Lelong et al., 1976).

Accompanying a favourable weathering climate of normal-arid to tropical-arid conditions (Veiser, 1976; Wopfner and Schwarzbach, 1976), a conducive hydrolysing climate too must exist to effectively release the crystalline manganese-species into the aqueous weathering cycle (Lelong et al., 1976). These suitable conditions are inferred to have existed during the supergene phase of deposit history, up to the present, with the variable response correlated to global climatological changes and the local geological framework.

Indications from field observations suggests supergene remobilisation of manganese at each deposit has been minimal, the only appreciable features seen at Muttabee.

At Muttabee it is clearly seen that dissolution, mobilisation and reprecipitation replacing a sandstone host has developed (Plate 4e). This is interpreted to be a direct result of preferred surface and ground water migration along post-genetic fracture-drag planes (Plate 4f). The manganese has been leached dominantly from a thin manganiferous pedogenic soil, itself a residual deposit concentrated from degradation of one of two calcarenite mineralised horizons overlying this supergene concentration.

This feature correlates well with the duplicity of the supergene process, discussed by Lelong et al.(1976). This duplicity relates to the additative/concentration mechanism of more mobile elements existing simultaneously with a subtractive/removal effect depleting the system of the same mobile elements. Relative to the Muttabee supergene features, concentration at the expense of the existing mineralised zones and partially from background source liberation (Tarcowie Siltstone) reflect this duplicate character in supergene development.

Although minimal supergene effects exist at the Boolcunda deposit, the above subtractive response or supergene depletion can be observed. The aqueous weathering process has leached manganese from the mineralised zone into surrounding sands and silts (Plate 4g) resulting in both higher manganese and Fe_2O_3 values (Appendix C: 895-090/092) but a corresponding (negligible) depletion of the same constituents within the ore horizons. The observation of calcite cementation within voids and fractures of the ore horizons represents recent surface water alteration (Plate 4h), indicating an example of non-mineralising supergene enrichment.

Percolation of groundwaters has resulted in the strong weathering and denudation of the sandstone host at the Etna deposit. Alteration to an argillaceous friable sandstone has resulted (Plate 3f), a reflection on the mineral genesis character of this deposit in that migrating waters still appear to move preferentially along the more permeable layers in the carbonate sequence bounding the deposit.

Actual ore constituents further provide evidence for supergene concentration of manganese. This is represented by minor manganite and psilomelane at Boolcunda, and psilomelane development at Etna and Muttabee. These manganese phases are represented as thin coatings, mostly, nucleated upon pre-existing ore but also forming rubbly masses replacing previously unaffected sediments. They have also developed as a minor residual wad (Mn-hydroxide) evident notably at Boolcunda.

Outside of the main zones of mineralisation, the only appreciable supergene effect is seen as the residual-lateritic development, represented by black amorphous manganese gossan, often diagnostic of an adjacent zone of mineralisation. No other supergene features were encountered.

4.5 COMPARISONS WITH MANGANESE DEPOSITS ELSEWHERE

Now that the deposits of sedimentary manganese at Boolcunda, Etna, and Muttabee have been interpreted, their comparison to other sedimentary manganese accumulations is made, indicating possible similarities.

The differentiation of manganese-ore deposits represents a different but predictable response of mineralisation to a specific geological environment, with accumulation governed by a relatively few simple chemical patterns (Crerar et al., 1980). The meridional position of the three deposits on a stable platform within a tectonically quiescent geosyncline has a number of global analogies, with similarities further suggested by the dominance of manganese derivation from older cratonic weathered material.

Accumulation of the giant sedimentary manganese deposits of Nikopol and Chiatura (U.S.S.R.) reflect both these relationships - the Nikopol manganese mineralisation resting on stable shield, while the manganese ore of the Chiatura deposit is found within the stable median part of a geosyncline (Roy, 1981). Sapozhnikov (1970) suggests upwelling of manganese-rich waters from a large reservoir of concentrated manganese possibly resulting in precipitation of manganese near the shore. This interpretation indicates another analogous concept relative to the Boolcunda, Etna, and Muttabee deposits, represented in the proposed existence of a manganese enriched hydrologic regime supplying manganese for possible precipitation.

The location of the ore bodies within the littoral to sublittoral zone of a shallow-marine shelf has similarities with these Oligocene Soviet Union accumulations, and also with the largest manganese accumulation in Australia, the Cretaceous Groote Eylandt deposit. The development of concentrated manganese in anoxic waters of an intracratonic basin, and precipitation in nearshore favourable zones during regressive phase eustasy (Frakes and Bolton, 1984) are features directly analogous to proposed genesis parameters of deposition at Boolcunda, Etna, and Muttabee.

However, the association of the Etna and Muttabee deposits to carbonate facies must also be considered, as this association and the paragenesis considered for their accumulation suggest a different deposit form than those considered thus far. The differentiation by Roy (1981) here is relevant whereby the deposits of Etna and Muttabee show a limestone-dolomite type association, reflecting sharp, localised, isolated mineralisation forming variable-sized lenses and pods. Similar features, particularly the association with carbonate rocks are reflected in the deposits at Imini, Morocco (Force et al., 1986) and Karadzhal, U.S.S.R. (Roy, 1981).

Overall, indications from these comparisons reflect a common trend for accumulation of many sedimentary manganese deposits. The basic parameters include the littoral to meridional position of the accumulation on a stable continental shelf, with concentration and possible metallogenesis a result of the interactive processes between eustasy, manganese geochemical response, and the prevailing hydrologic system.

5. CONCLUSIONS

The nature and origin of the sedimentary manganese accumulations at Boolcunda, Etna and Muttabee has been discussed, indicating the sedimentological character of enclosing sediments plus proposed source derivation and modes of manganese concentration. The regional Proterozoic rock sequence mapped and ore facies observed were differentiated, along with geochemical and mineralogic profiling of the host and ore facies, establishing the framework of geological informations from which the interpretative genesis models were produced.

As the deposits studied comprise the accumulation of a sedimentary metallic body, an emphasis has been placed on the palaeoenvironmental characteristics existing during ore formation, deduced from analysis of sedimentological features observed during field mapping, and the regional geological history of enclosing Adelaide Geosyncline.

The environment under which accumulation developed can be interpreted as a shallow-marine sedimentary regime, situated on a stable platform. The geographic location of the deposits, relative to the palaeoenviroment determined, vary from the high energy carbonate platform sedimentation at Etna and Muttabee to nearshore paralic-marine deposition at Boolcunda.

Interaction of these sedimentary settings with manganese-rich fluids and the larger hydrodynamic system is interpreted as the main cause for mineralisation. The positioning of the accumulations on the shallow-marine shelf accentuated possible interference between water-sediment boundaries, interference seen as a result of eustatic fluctuations and contemporaneous circulation pattern changes.

Weathering of a source region to the west and pre-existing hydrologic concentrations are interpreted for manganese derivation. The build-up of appreciable concentrations to form a possible ore accumulation is envisaged to result from eustatic fluctuations recorded by the sediment characteristics and causing concentration during transgressive phases, followed by precipitation and accumulation under regressive conditions. Geochemical and mineralogic analyses essentially support the sedimentary nature of the accumulations mineralising in an aqueous environment, aided further by their close comparisons with global values for MnO and constituent mineralogic features.

The ultimate genesis of the sedimentary manganese deposits at Boolcunda, Etna and Mutabee required existence of a specific localised geologic setting producing retention and accumulation of the precipitated manganese. Thus, at Etna and Muttabee the proposal is for an interactive genesis model, involving migration of manganese-rich fluids at a mixing boundary between the sediment surface and an oxic-anoxic water interface. Percolation was preferentially along more permeable calcarenite-sandstone horizons within a carbonate sequence.

The Boolcunda accumulation resulted fron oxidation and precipitation of Mn^{2+} in a nearshore setting dominated by redbed sedimentation. This oxygenated high energy regime effectively concentrated the dominantly particulate manganese within the local palaeoslope depressions forming an isolated accumulation of manganiferous mud. Unstable slope sediments resulted in debris/slurry flows into this mud, producing the observed sedimentary breccia supported by a manganese matrix. Interspersed oxic sedimentation aided retention of the manganese.

The modes of formation suggested here reflect specific localised mineralisation, but nonetheless may be used to support further research and exploration of such sedimentary manganese accumulations within the Adelaide Geosyncline or other similar tectonic-sedimentologic settings.

ACKNOWLEDGEMENTS

I wish to thank the following people because of their particular attributes which make them individual and of great importance to me. I thank you with great gratitude for your support, encouragement, and faith in me over the last few years - and my life thus far:

Mum and Dad - I don't need to say anymore, do I ?!

Dean, Steven, Tim, and of course Samantha

Christine

Tania, David, Andrew, Peter, James - my cohorts in insanity

Marius

Professor L.A. Frakes and Mr. B.R. Bolton

Mr. P. McDuie   Mr. J. Stanley   Mr. G. Trevelyn

Mrs. C. Badcock   Mrs. S. Proferes   Mr. R. Barrett

Sophi and Browyn

Karen - a special person in anyones book

and to many friends to mention - I care no less for you !

REFERENCES

ARMSTRONG, A.T. (1938) : *Mining Review # 69* , p: 59
" " (1941) : *Mining Review # 74* , p: 46-47

BATURIN, G.N. (1988) : *The geochemistry of Manganese and Manganese-nodules in the ocean.* Reidel Publ. Co.

BINKS, P.J. (1971) : The geology of the Orroroo 1:250,000 Map Area. SI 54-1 *Rep. Invest., # 36.* Dept. Mines of S.A.

BROWNS, H.Y.L. (1908) : *Mining Records of South Australia*

CORNELIUS, H.S. (1940) : *Mining Review # 73* , p: 65-66

CRERAR, D.A., CORMICK,R.K., and BARNES, H.L. (1978a) : Geochemistry of manganese: an overview, *in* Varentsov, I.M. and G.Y. Grasselly (eds), Geology and Geochemistry of Manganese, Vol. 1 : Stuttgart, E. Schweizerbert'sche.

EVANS, A.M. (1987) : *An Introduction to Ore Geology.* Blackwell Scientific Publ.

FORCE, E.R., BACK, W, SPIKER, E.C. and L.P. KNAUTH (1986) : A ground-water mixing model for the origin of the Imini manganese deposit (Cretaceous) of Morocco. *Economic Geology,* Vol. 81, p: 65-79.

FORD, W.G. (ed) (1932) : *Dana's Textbook of Mineralogy,* Fourth Ed. John Wiley & Sons, New York-Chichester-Brisbane-Toronto

FRAKES, L.A. and BOLTON, B.R. (1984) : Origin of Mn giants : sea-level change and anoxic-oxic history. *Geology,* Vol. 12, p: 83-86.

FRENZEL, G. (1980) : The manganese ore minerals, *in* Varentsov, I.M. and G.Y. Grasselly (eds), *Geology and Geochemistry of Manganese,* Vol. 1 : Stuttgart, E. Schweizerbert'sche.

GILES, C.W., and TEALE, G.S. (1987) : A comparison of the geochemistry of the Roopena Volcanics and the Beda Volcanics. *Geol. Surv. S. Aust., Q. Geol. Notes, # 71,* p: 7-13.

GLASBY,G.P. (ed) (1977) : *Marine Manganese Deposits.* Elsevier Oceanography Series. Elsevier Scientific Publ. Co.

HEWETT, D.F. (1966) : Stratified deposits of the oxides and carbonates of manganese. *Economic Geology,* Vol. 61.

KNUTSON, J., DONNELLY, T.H., and TONKIN, D.G. (1983) : Geochemical constraints of the genesis of copper mineralisation in the Mount Gunson area, South Australia. *Economic Geology,* Vol. 78, p: 250-274.

LeLONG, F., TARDY, Y., GRANDIN, G., TRESCASES, J.J., and B. BOULANGE (1976), *in* K.H. Wolf (ed) : *Handbook of Strata-Bound and Strataform Ore Deposits,* Vol 1, No. 3 : Pedogenesis, chemical weathering and processes of formation of some supergene ore deposits. Elsevier Publ. Co., Amsterdam-Oxford-New York, p: 93-173.

LEWIS, D.W. (1984) : *Practical Sedimentology.* Hutchinson Ross Publ. Co., Straudburg, Pennsylvania.

MANSFIELD, L.L. (1949) : *Mining Review # 91* , p: 202-203.

PARKIN, L.W. (ed) (1969) : *Handbook of South Australian Geology.*

PLUMMER, S.P. (1974) : The stratigraphy, sedimentation and palaeoenvironment of the Late Precambrian Umberatana Group in the Mount Remarkable-Alligator Gorge area, South Australia. University of Adelaide Ph.D Thesis (unpubl.).

PREISS, W.V. (1973) : Palaeoecological interpretations of South Australia's Precambrian stromatolites. *Journ. geol. Soc. Aust., # 19,* p: 501-532.

PREISS, W.V. (1985) : Stratigraphy and tectonics of the Worumba Anticline and associated intrusive breccia's. *Bulletin # 52, Geol. Surv. South Australia.*

PREISS, W.V., (compiler) (1987) : The Adelaide Geosyncline: Later Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. *Bull #53, Geol. Surv. S. Aust.*

PREISS, W.V. and B.G. FORBES (1981) : Stratigraphy, correlation and sedimentary history of Adelaidean (Late Proterozoic) basins in Australia. *Precambrian Research,* Vol 15, p: 255-304. Elsevier Scientific Publ. Co., Amsterdam.

PREISS, W.V., and KINSMAN, J.E. (1978) : Stratigraphy and palaeoenvironmental interpretation of the Brighton Limestone south of Adelaide and its equivalents in the Orroroo region. *Rep. Invest., Geol. Surv. S.Aust., # 49.*
RANKAMA, K, and SAHAMA, T.G. (1950) : *Geochemistry.* Uni. of Chicago Press, Chicago, pp: 912.

RIDGWAY, J.E. (1951) : *Mining Review # 93* , p: 102-107.

ROY, S. (1981) : *Manganese Deposits.* Academic Press Inc., London.

RUTLAND, R.W.R., A.J. PARKER, G.M. PITT, W.V. PREISS, and B. MURRELL (1981) : The Precambrian of South Australia, *in* Hunter, D.R.(ed) *Precambrian of the Southern Hemisphere.* Elsevier Scientific Publ. Co., Amsterdam.

SHEPHERD, R.G., and THATCHER, D (1959) : The geology of the Quorn Military Sheet. *Rep. Invest. #13*, Dept. Mines of S. Aust.

STANTON, R.L. (1972) : *Ore Petrology.* McGraw-Hill, Inc.

SMIRNOV, V.I. (1968) : The source of ore-forming material. *Economic Geology,* Vol. 63, p: 380-389.

SUNDBY, B., and SILVERBERG, N (1980) : Pathways of manganese in an open estuarine system. *Geochimica et Cosmochimica Acta*, Vol 45,
p: 293-307

THOMSON, B.P., COATS, R.P., MIRAMS, R.C., FORBES, B.G., DALGARNO, C.R. and JOHNSON, J.E. (1964) : Precambrian rock groups in the Adelaide Geosyncline: a new subdivision. *Q. geol. Notes, geol. Surv. S. Aust., # 9*: p: 1-19

VARENTSOV,I.M. and G.Y. GRASSELLY (eds) (1980) : *Geology and Geochemistry of Manganese, Vol. 1-3* Stuttgart, E. Schweizerbert'sche

VEIZER, J. (1976), *in* K.H. Wolf (ed) : *Handbook of Strata-Bound and Stratiform Ore Deposits,* Vol 1, # 3 : Supergene and surficial ore deposits; textures and fabrics. Elsevier Publ. Co., Amsterdam-Oxford-New York, p:1-37.

von der BORCH, C.C. (1980) : Evolution of Late Proterozoic to early Palaeozoic Adelaide Fold Belt, Australia : comparisons with Post-Permian rifts and passive margins. *Tectonophysics, # 70,* pp: 115

WEDEPOHL, K.H. (ed) (1969) : *Manganese: Handbook of Geochemistry, Vol 2-3.* Springer-Verlag Berlin.

WEDEPOHL, K.H. (1980) : Geochemical behavior of manganese, *in* Varentsov, I.M. and G.Y. Grasselly (eds), *Geology and Geochemistry of Manganese, Vol. 1* : Stuttgart, E. Schweizerbert'sche.

WILLIAMSON, G. (1987) : The geology and origin of manganese deposits at Pernatty Lagoon, Sotuth.Australia. B.Sc. Hons. Thesis (unpubl.)

WHITE, D.E. (1968) : Environments of generation of some ore-deposits.

WOPFNER, H. and M. SCHWARZBACH (1976), in K.H. Wolf (ed) : *Handbook of Strata-Bound and Strataform Ore Deposits*, Vol 1, No 3 : Ore deposits in light of the palaeoclimatology. Elsevier Publ. Co., Amsterdam-Oxford-New York, p: 43-87.

ERRATA

REFERENCES

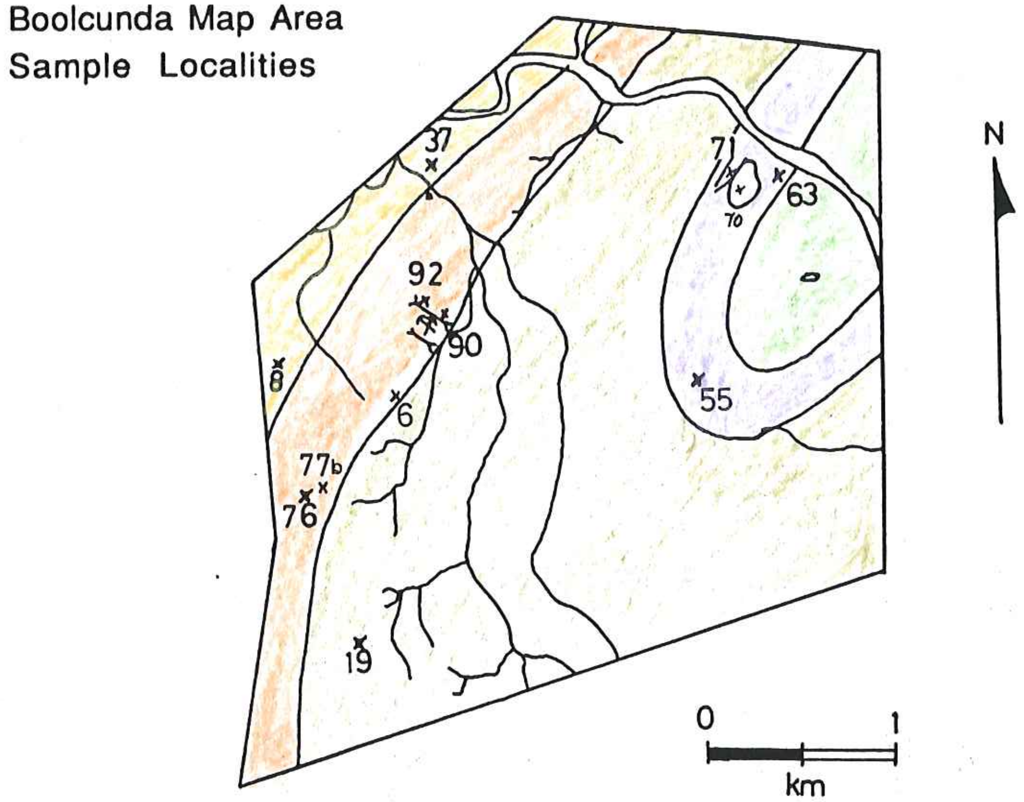
WHITE, D.E. (1968): Environments of generation of some base-metal ore deposits. *ECONOMIC GEOLOGY*, Vol # 63, p: 301-336.

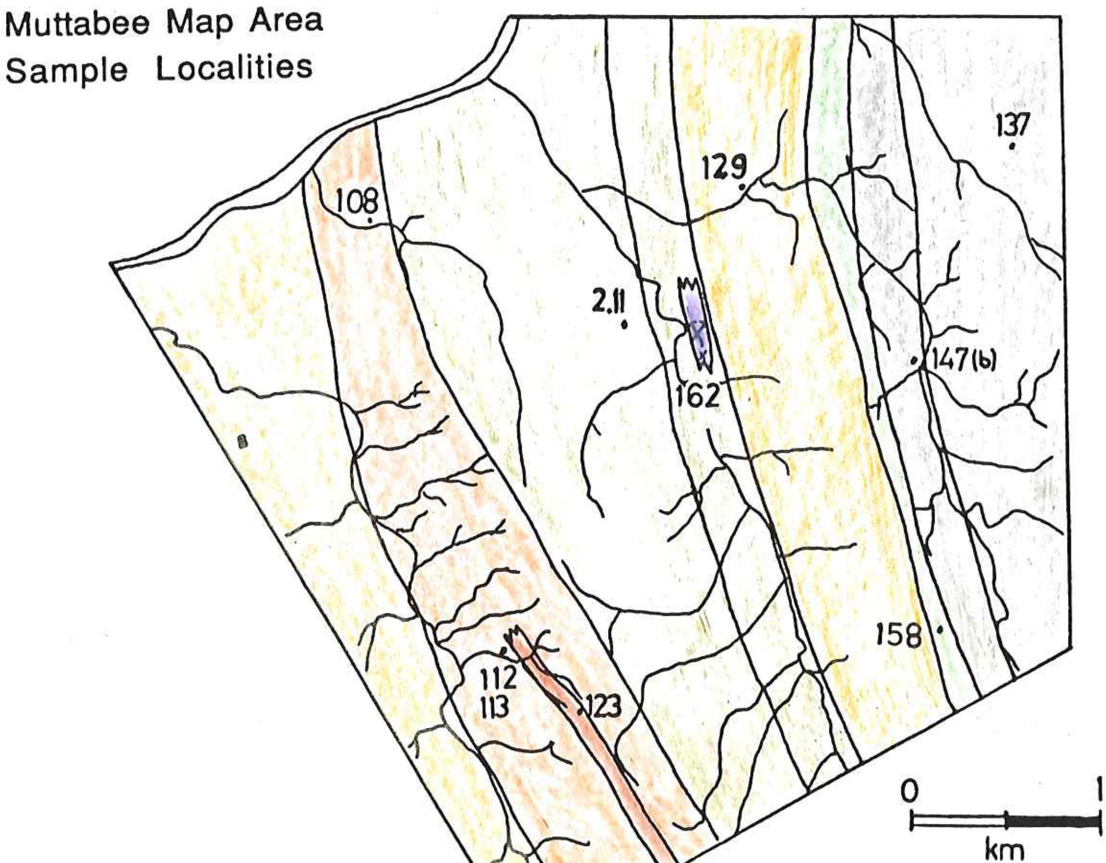
SAPOZHNIKOV, D.G. (1970): Geological conditions for the formation of manganese deposits of the Soviet Union. In Roy, S (1981), *Manganese Deposits*. Academic Press.

APPENDIX B.1

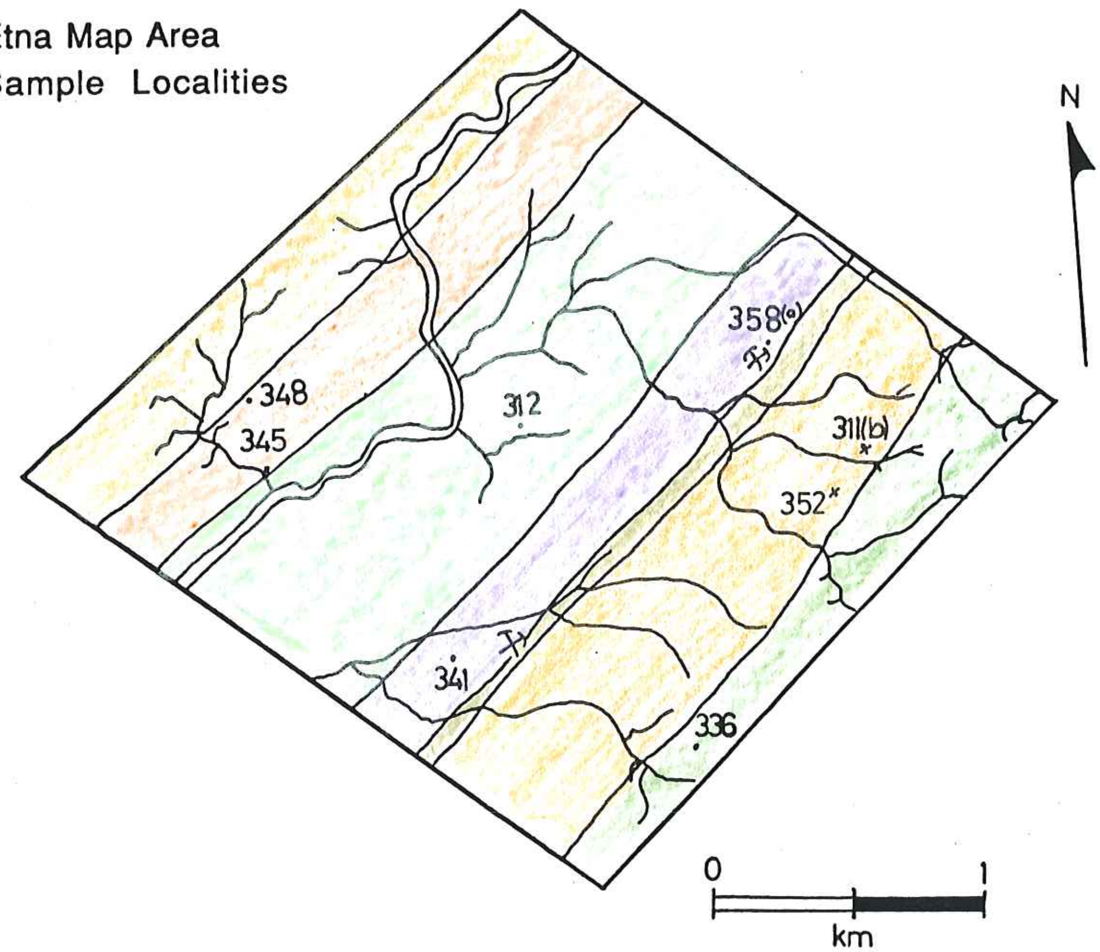
PETROGRAPHIC DESCRIPTIONS

(Whole Rock Anaysis)

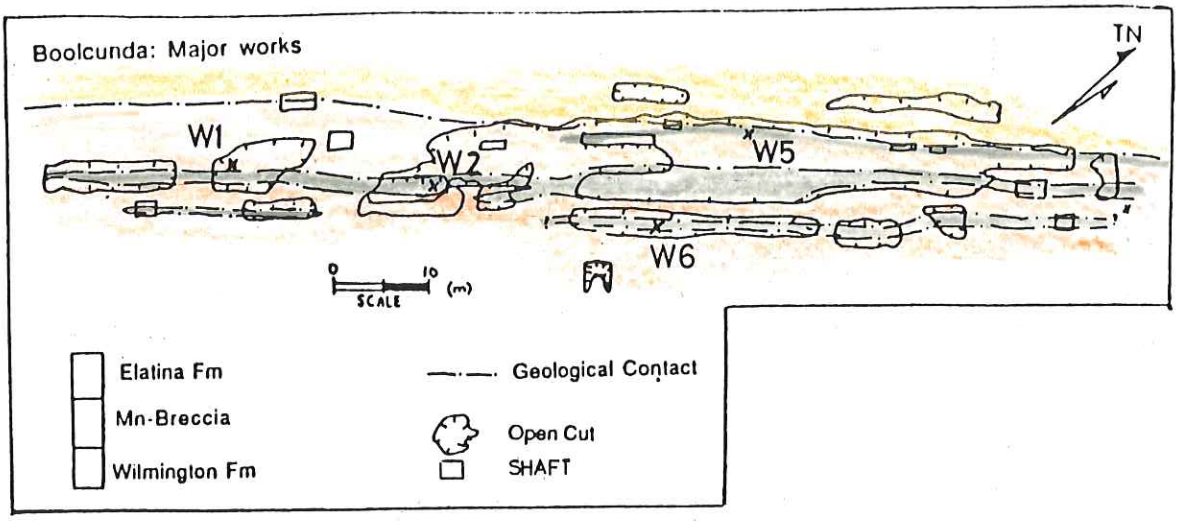

Boolcunda Map Area
Sample Localities
N
37
71
63
70
92
90
8
6
55
77b
76
19
0
1
km


Muttabee Map Area
Sample Localities
137
129
108
2.11
162
147(b)
158
112
113
123
0
1
km

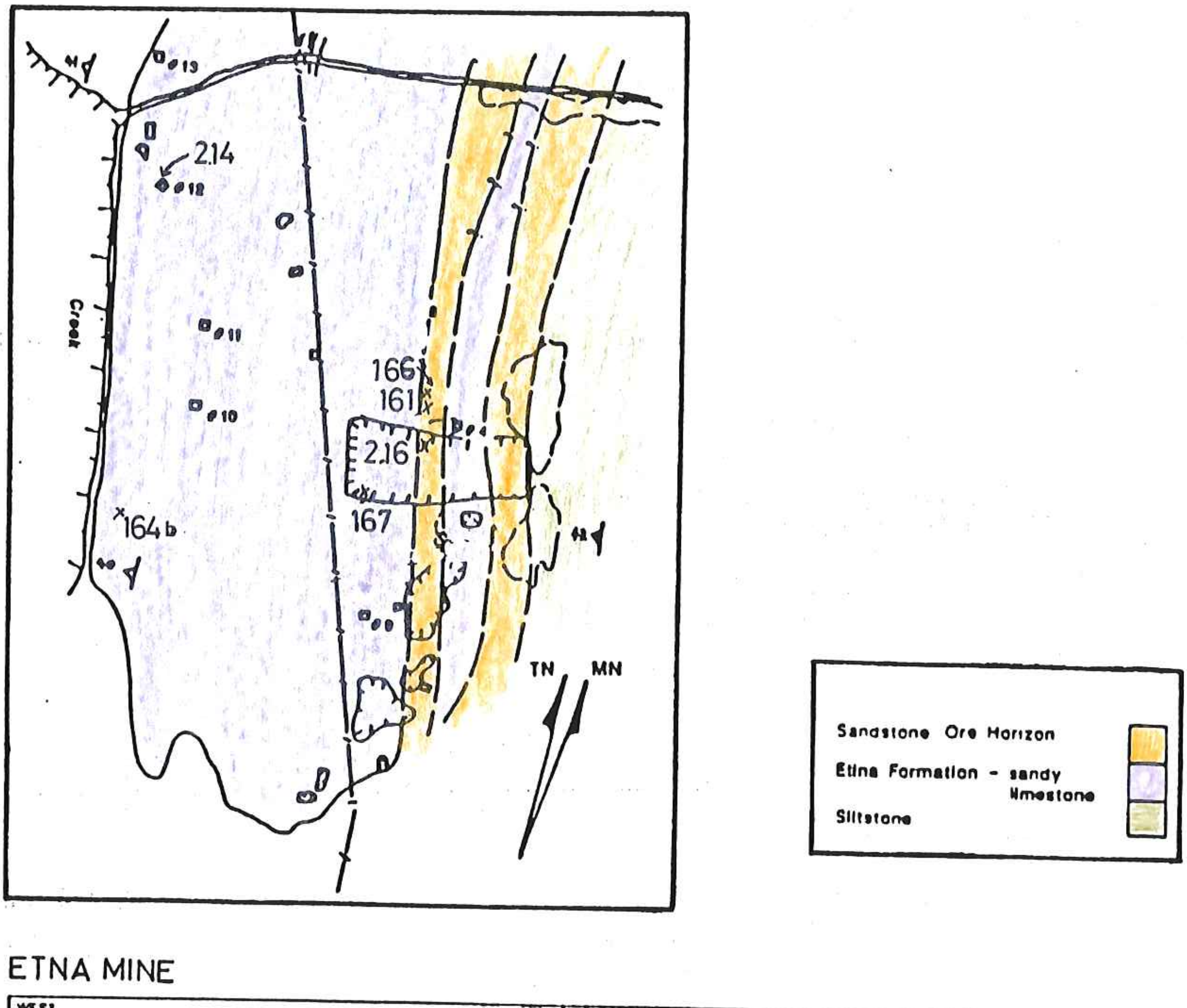
Etna Map Area
Sample Localities



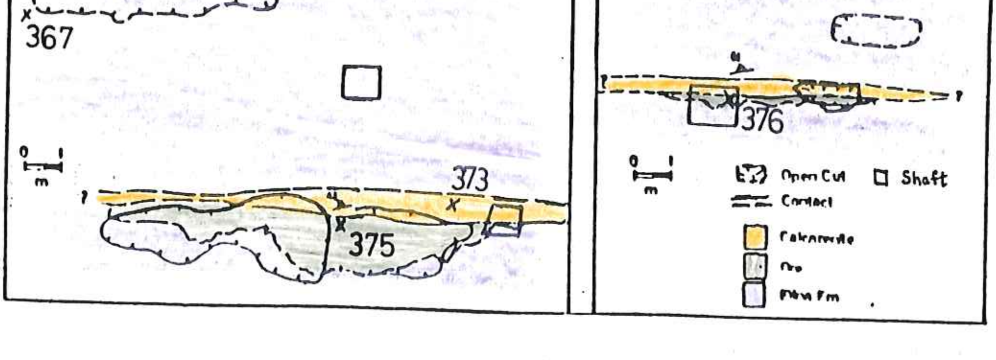
BOOLCUNDA MINE



MUTTABEE MINE



ETNA MINE



1 SAMPLE IDENTIFICATION

895-070 Boolcunda: Post-Triassic Cover

2 FIELD RELATIONSHIPS

Forms low hilly outcrop of the central eastern map area. Consisting of flat-lying large scale planar cross-bedded quartzite with basal conglomerate lag beds, unconformably overlying the Etina Formation limestone and sandstone.

3 HAND SPECIMEN DESCRIPTION

A noncalcareous clean mature coarse to conglomeratic quartzite. Maturity is reflected in the clean, well rounded and sorted character of this dusty cream-white internally massive crystalline siliceous cemented rock. Composed of >90% vein quartz, < 3% opaques and kaolinized feldspar, minor chert fragments, and a siliceous cement. See plate 2g.

4 THIN SECTION DESCRIPTION

Compact equant quartz grains with straight facet boundaries form 99% of this rock in thin section. The grains all show undulose extinction but have a bimodal character: dominantly holocrystalline grains 0.5-1.0 mm in size; interspersed with minor polycrystalline aggregate grains.

Siliceous recrystallisation is minor, observed as a few thin quartz overgrowths. Accessory mineralogy composes the rest of the rock, and includes: chloritised and very minor fresh biotite: subhedral hematitic opaques < 0.2 mm in size; and ?rutile

5 INTERPRETATION

Represents sedimentation from the local pervading palaeo-river systems and drainage pattern, thus forming a recent fluvial deposit. Channel filling has formed large-scale planar cross-bedding, often with basal conglomeratic lag bands, along with a dominantly clean thick planar bedded quartzite. N to NNE palaeocurrent direction agrees with the prevailing drainage direction of the influencing creek.

BRACHINA FORMATION/ULUPA SILTSTONE **895-008**
895-037

1 SAMPLE IDENTIFICATION

895-008 Boolcunda: Brachina Formation siltstone

2 FIELD RELATIONSHIPS

Forms youngest outcrop of the Adelaidean sequence mapped, with subdued relief physiography along NW map margin. Variable lithological appearance between a grey flaggy shale interbedded within the more dominant red-brown well indurated and poor to thinly bedded fine siltstone. Contacts range from sharp to fining upwards. Planar uniform bedding predominates the sedimentary structures, but small-scale trough cross bedding in the more coarse beds existed, showing a NE-NNE depositional current direction.

3 HAND SPECIMEN DESCRIPTION

A well cemented and excellently thinly planar bedded siltstone, incorporating a pale olive fine silt and greyish olive coarse silt as interbeds within the dominant red-brown fine to sandy siltstone. Internal structures include planar and minor wavy laminae, minor fining upward contacts, and minor cross bedding principally confined to the coarser beds.

4 THIN SECTION DESCRIPTION

A very fine grained planar laminated siltstone, grains all <0.1 mm. Dominated by a phyllosilicate matrix - clay, chlorite, sericite - and silt-sized subangular quartz grains (30%). Interspersed with these minerals are muscovite and a little biotite, as flakes forming approximately 15% of the rock. Opaques are subangular and subhedral, dispersed within the matrix, but also outlining the planar laminations. Overall a quartzose fissile siltstone, grainsize increases and quartz percentage increases defining layering.

5 INTERPRETATION

Represents shallow water subtidal deposition of fine clastic material in a region transitional between marginal redbeds and deeper water reducing conditions (Brachina Formation and Ulupa Siltstone). Planar bedding, minor fining upward, and minor sand interbeds indicate continued influence of seafloor traction currents or higher energy transporting episodes in an otherwise quiet energy environment.

1 SAMPLE IDENTIFICATION

895-037 Boolcunda: Ulupa Siltstone

2 FIELD RELATIONSHIPS

This sample, from the NE map margin reflects the upper lithology of this unit - a very well planar bedded internally planar laminated fine grained siltstone. Stratigraphically lower relative to 895-008, this siltstone is a grey thicker bedded non-calcareous lithology, indicative of the Ulupa Siltstone.

3 HAND SPECIMEN DESCRIPTION

Fine-grained thick to massively bedded grey siltstone, internally massive to vague planar laminated character. Very uniform siltstone, difficult study without petrographic analysis.

4 INTERPRETATION

Basinal equivalent of the Brachina Formation siltstone, formed under very quiet reducing conditions below effective wave base. Planar laminations plausibly formed from seafloor traction currents or storm activity, the only processes strong enough to produce such structures in the deep marine setting envisaged for this lithology's development.

WILMINGTON FORMATION **895-090**
895-108
895-123
895-112
895-345

1 SAMPLE IDENTIFICATION

895-090 Boolcunda: Wilmington Formation siltstone interbed

2 FIELD RELATIONSHIPS

Forms one the series of siltstone interbeds between the sandstones of the Wilmington Formation, taken from upper zone of the main costean bounding the main Boolcunda Manganese mine workings.

3 HAND SPECIMEN DESCRIPTION

Pale yellowish brown uniform massive to planar bedded coarse siltstone. Moderate to thickly bedded (0.5 - 40 cm), internally planar parallel laminated with variable intercalations of a yellowish orange fine sand.

4 THIN SECTION DESCRIPTION

A thinly bedded quartzose siltstone, composed of monocrystalline subangular to angular fine quartz grains (< 0.1mm) set in a very fine clay-chlorite-sericite matrix, slightly more abundant that the quartz. Appreciable (< 15%) muscovite plates exist, 0.1-0.3 mm in size, generally forming a preferred orientation parallel to the planar laminations. Opaques form the remaining accessories, comprising subangular Mn and Fe grains, both outlining bedding but also as disseminated material.

5 INTERPRETATION

Forms one a number of conformable siltstone interbeds within the Wilmington Formation, and thus represents an interval of finer clastic sedimentation between sandstone accumulation. The generally massive nature of the lithology implies still high energy conditions and/or rapid deposition of the unit as time was not allowed for reworking into a structured sedimentary rock. Both high energy conditions and rapid sediment influx agree with the overall character of the formation, situated within a marginal subtidal regime undergoing rapid paralic and source variations.

1 SAMPLE IDENTIFICATION

895-108 Muttabee: Wilmington Formation sandstone

2 FIELD RELATIONSHIPS

Part of major linear ridge system dissecting the Muttabee field area to the west. Specimen found in the lower part of this ridge system.

3 HAND SPECIMEN DESCRIPTION

Pale greyish-pink coarse sandstone. Mostly massive but with minor thick bedding. Composed of subangular to angular coarse quartz grains and minor weathered feldspar grains. Minor granular trains of quartz, feldspar, chert, and other minor resistant accessories exist.

4 THIN SECTION DESCRIPTION

This thin section indicates an arkosic sandstone - over 90% is composed of an aggregate of monocrystalline euhedral to subrounded quartz grains (0.1-0.3mm) with a minor ?kaolinized clay-sericite matrix and altered feldspathic content. Accessories include euhedral to subangular < 0.1 mm dispersed opaque grains, fresh feldspar, and amphibole.

5 INTERPRETATION

Rapid sedimentation within a marginal marine subtidal shelf environment. Coarse clastic input was rapid giving the massive nature of the lithology. The inference is also for a relatively high energy environment, influenced by changes in the paralic-eustatic conditions, as the unit has a pervasive redbed character, supported by postulated palaogeographical interpretations (Preiss, 1987).

1 SAMPLE IDENTIFICATION

895-123 Muttabee: Lower Wilmington Formation

2 FIELD RELATIONSHIPS

Occurs within the lower reaches of the major ridge system composed of the more resistant sandstones of the Wilmington and Elatina Formations, trending N-S along the western margin of the Muttabee map area.

3 HAND SPECIMEN DESCRIPTION

Similar to 895-108, composed of medium to coarse subangular to subrounded clastic grains, dominated by quartz, although the pink-red colour highlight the feldspathic nature of this lithology. Massive the minor thick bedding form the structures observed in this arkosic sandstone.

4 THIN SECTION DESCRIPTION

Euhedral quartz grains set in a very fine clay-sericite groundmass characterise this rock under the microscope. The quartz grains have a bimodal distribution size: < 0.2 mm; and grains < 0.03 mm, generally as part of the fine matrix.

Aside from this matrix material (65%) and the quartz particles (30%), the rock is composed of rounded to subrounded opaques (Mn and hematite); muscovite flakes with no preferred orientation; and accessory plagioclase, rarely fresh.

5 INTERPRETATION

This is essentially a greywacke, forming silty portion of the sandstone unit forming the Wilmington Formation. Deposition is seen to have occurred in a marginal marine setting but with relatively quiet energy condition, and a steady sediment influx thus accounting for the massive nature of this medium-coarse clastic lithology.

1 SAMPLE IDENTIFICATION

895-112 Muttabee: Wilmington Formation siltstone interbed

2 FIELD RELATIONSHIPS

Encountered in all three map areas this siltstone horizon within the sandstone of the Wilmington Formation forms a conformable interbedded unit. It ranges from a maximum thickness and best outcrop at Muttabee of some 30-40 m, to a thin < 5 m enigmatic horizon at Etna. Its conformable nature and similar outcrop character to the enclosing sandstones make it a difficult horizon to differentiate, particularly where it pinches out into the surrounding sandstones.

Exists within the upper reaches of the Wilmington Formation, part of the aforementioned ridge system comprising these sandstones.

3 HAND SPECIMEN DESCRIPTION

A fine grained well-sorted quartzose reddish-brown indurated siltstone. Internally massive, its exposure too has a poorly bedded character. A fine lithology, with the appearance of subrounded to subangular quartz grains predominating set in a clay-sericite matrix.

4 INTERPRETATION

The uniform but strike-discontinuous nature of this horizon implies two basic facts: that sedimentation was continuous, attested by the conformable character of the interbed; and that the episode of sedimentation forming this unit was short-lived, with accumulation in possibly isolated depressions condusive to silt deposition. Also in a similar a manner to those already discussed, the rate of sedimentation is envisaged to be rapid, accounting for the massive nature of this lithology.

1 SAMPLE IDENTIFICATION

895-345 Etna: Basal Wilmington Formation sandstone

2 FIELD RELATIONSHIPS

Taken from the medium-relief rounded ridge morphology forming the more resistant sandstones of this formation, striking NE-SW, from the Etna map area.

3 HAND SPECIMEN DESCRIPTION

The hand specimen shows a pale brown medium-grained sandstone. It is dominated by subangular quartz grains with a minimal proportion of kaolinized cement. Internally massive this lithology crops out as massive to thickly planar bedded unit.

4 INTERPRETATION

Rapid sedimentation in relatively quiet energy conditions appear to have prevailed during formation of this sandstone, although episodic turbulent conditions too seem to have affected its depositional history (very minor cross-bedding - large scale). As before, a marginal marine regime influenced its formation, prior to eustatic rise with a corresponding shallowing and higher energy conditions found in the overlying Elatina Formation sandstones (see below).

ELATINA FORMATION 895-076 895-092 895-348

1 SAMPLE IDENTIFICATION

895-076 Boolcunda: Elatina Formation sandstone, overlying Wilmington Formation and mineralised horizon. Main mine site.

2 FIELD RELATIONSHIPS

Forms the hanging wall sandstone bounding the ore accumulation. It is a uniform and competent outcrop surrounding the mine, and elsewhere is represented by the pink and red sandstone, mostly massive but occassionally trough cross-bedded, producing the major ridge physiography of the area.

3 HAND SPECIMEN DESCRIPTION

Greyish red to blackish red subangular moderately sorted medium grained sandstone. Contains mostly quartz particles, with dispersed white micaceous flakes and a somewhat kaolinized binding cement forms the remaining constituents. A competent lithology with moderate sized planar bedding and generally internally massive morphology.

4 INTERPRETATION

Forms a mostly massive sandstone lithology proposed to have been part of the sequence of sedimentation following a localised depositional hiatus between the Wilmington and Elatina Formations. Renewed clastic influx from the west and northwest is indicated from ripple mark current directions, with its palaeogeographical location also supporting the proposed marginal shallow marine depositional environment, with corresponding high energy subtidal conditions.

1 SAMPLE IDENTIFICATION

895-092 Boolcunda: Elatina Formation structured sandstone.

2 FIELD RELATIONSHIPS

Basal stratigraphic Elatina Formation sandstone,this horizon ranging from < 1m to up to 20 m represents a good marker bed in the field area. It generally occupies a position near the apex of the ridge system formed by the sandstones of the Elatina Formation, and overlies the siltstone interbeds of the same formation.

3 HAND SPECIMEN DESCRIPTION

A porous medium to coarse grained subrounded and well sorted pink to pale red feldspathic sandstone. Dense small-scale rapidly bifurcating heavy mineral outlined trough cross-bedding is spectacularly evident. Opaque minerals are disseminated throughout this grain supported lithology (Plate 2d).

4 INTERPRETATION

The scale and nature of the festoon trough cross-bedding indicate deposition in a rapidly fluctuating current affected aqueous system. The envisaged regime is one with high energy conditions but still within the lower flow regime of the hydrologic system (Lewis, 1984). Accompanying this rapidly changing current direction is rapid deposition of sand sized particles and heavy minerals, outlining the bedding. These features imply a very shallow submerged subtidal regime, strongly affected by tidal and wave activated sediment motion.

1 SAMPLE IDENTIFICATION

895-348 Etna: Elatina Formation sandstone

2 FIELD RELATIONSHIPS

Forms silty portion of the upper Elatina Formation sandstone. Part of northeastery trending linear ridge system of high relief rolling hills, similar outcrop morphology as seen at Boolcunda and Muttabee.

3 HAND SPECIMEN DESCRIPTION

Greyish-red to pale reddish coloured planar thinly bedded silty sandstone. Dominated by subangular to subrounded fine quartzose sand particles, set in a minor kaolinized matrix.

4 INTERPRETATION

A regime similar to that already discussed, although this particular sample indicates the existence of the influx of finer sedimentary material to the high energy shallow subtidal setting under which the lithology formed.

1 SAMPLE IDENTIFICATION

895-312 Etna: Enorama Shale limestone interbed

2 FIELD RELATIONSHIPS

Found only within the Etna map area, and further only as two thin < 3 metre limestone interbeds. These two beds are much more resistant than the surrounding calcareous shale, and thus form two distinct layers, well rounded in outcrop.

3 HAND SPECIMEN DESCRIPTION

An olive grey sandy limestone lithology, dominated by subangular to minor subrounded quartz grains, set in a micritic to very fine sparry calcite cement. The sandy portion gives a sugary weathered exposure character.

4 INTERPRETATION

The transitional deposition model envisaged for this unit (Preiss, 1987) can account for these sandy limestone interbeds within the fine laminated calcareous Enorama Shale. The transition from the Etina Formation of shallow marine conditions to this somewhat deeper water sedimentary setting implies some form of eustatic-paralic variation, and as such could have undergone a change to a shallow marine setting conducive for sandy carbonate precipitation.

TARCOWIE SILTSTONE 895-019
895-2.11

1 SAMPLE IDENTIFICATION

895-019 Boolcunda: Tarcowie Siltstone

2 FIELD RELATIONSHIPS

This unit composes the thickest mappable unit forming much of the central portion of the map area. It has a characteristic flaser bedded morphology, due to grainsize variations producing a diagnostic ribboned weathered profile. Approximate differentiation into two units, a lower well structured and bedded siltstone and an upper more massive indurated siltstone, the Tarcowic Siltstone forms both low-relief rolling hills and shallow valleys plus an isolated ridge morphology bounding the map area to the south. It underlies the ridge-forming Elatina Formation sands and silts. Other features include both minor trough cross bedding and occasional fining upward horizons.

3 HAND SPECIMEN DESCRIPTION

Ranges from slightly calcareous to non-calcareous light olive grey uniform indurated fine to medium siltstone. Small-scale (1-3 cm) flaser thin wavy bedding predominates but both planar bedding, laminae, and bed-parting do occur. Upper unit (this sample) has discontinuous thin dark yellowish brown sandy silt intercalated seams. Lower unit is more structured and typical of this regionally extensive lithology (Binks, 1971).

4 INTERPRETATION

Flaser bedding and the fine grained nature imply, along with postulated palaeogoegraphical positioning, a shallow subtidal shelf environment - generally quiet but quite shallow to allow for the lower energy structures observed.

1 SAMPLE IDENTIFICATION

895-2.11 Muttabee: Tarcowie Siltstone

2 FIELD RELATIONSHIPS

Part of upper thick uniform siltstone lithology. This sample is better cemented and forms more indurated resistant higher relief outcrop relative to a more sandy Tarcowie siltstone stratigraphically below this unit. Physiographic nature varies from minor ridges to dominant rolling hills with a pervasive NNE-SSW trend.

3 HAND SPECIMEN DESCRIPTION

Consisting of intercalated thin layers of a very fine light grey siltstone and a dusky yellow to olive grey very fine sandy siltstone - the former dominating. Characteristic ribboned weathered surfaces were observed, due to the flaser bedded nature of the rock, a consequence of grainsize variations. Overall a well indurated lithology, noncalcareous, weathering grey or a reddish brown.

4 THIN SECTION DESCRIPTION

Dominated by fine subangular to angular quartz grains 0.05 mm average size, along with minor plagioclase feldspar, both set in a quite abundant sericitic-chloritic matrix.

The flaser bedding is easily discernible, reflected by increase in matrix silt content and decrease in coarse clastic content.

Muscovite is the dominant accessory forming dispersed laths and flakes, while the remaining constituents are represented by subhedral opaque minerals.

5 INTERPRETATION

The flaser structure of this lithology tends to support a shallow marine shelf environment, affected by wave base conditions in a low energy subtidal regime.

COX SANDSTONE MEMBER

895-129
895-158
895-311(b)

1 SAMPLE IDENTIFICATION

895-129 Muttabee: Cox Sandstone - upper stratigraphic position

2 FIELD RELATIONSHIPS

Part of lower relief hills backing the Muttabee mine site. Sample taken from the upper part of this sandstone to silty sandstone horizon, representing basal Tarcowie Siltstone.

3 HAND SPECIMEN DESCRIPTION

Pale greyish-pink subangular to subrounded medium-grained sandstone. Internal structure ranges from dominantly massive lithology to minor trough cross-bedded outcrop, and very minor granular trains.

1 SAMPLE IDENTIFICATION

895-158 Muttabee: Cox Sandstone Member

2 FIELD RELATIONSHIPS

Situated within the NNE-SSW trending low hill system before the topography falls to form the low lying area of the sandy Tarcowie Siltstone. Generally forms poor rounded exposure, difficult to determine any definite diagnostic characteristics.

3 HAND SPECIMEN DESCRIPTION

Well thinly bedded medium-fine feldspathic sandstone. Internally massive with only minor internal planar laminae in this reddish-brown well-sorted subangular grained sand.

1 SAMPLE IDENTIFICATION

895-311(B) Etna: Cox Sandstone Member

2 FIELD RELATIONSHIPS

Stratigraphically part of the upper sandstone unit forming a major W-E trending ridge system from the central Etna map area, overlain by a sandy silt equivalent to the Tarcowie Siltstone. Out of all the Cox Sandstone samples and field outcrop this sample of the unit from Etna best exemplifies true Cox Sandstone, the others somewhat more analogous to a very sandy Tarcowie Siltstone.

3 HAND SPECIMEN DESCRIPTION

Coarse, thick to massive bedded outcrop is typical of this coarse massive sandstone. Pale orange to greyish-pink in colour, the sandstone is feldspathic composed mostly of subangular quartz grains.

4 INTERPRETATION

The dominantly massive nature is indicative of rapid sedimentation of coarse clastic material, as a single continuous event. The more structured elements, basically confined to the Muttabee region representing a closer Tarcowie Siltstone analogy, reflect a lower energy regime where reworking has produced previously absent sedimentary structures (planar bedding; very minor trough cross-bedding). All these features are diagnostic of a nearshore shallow marine shelf setting affected by tidal and wave activity. Thus, unlike the postulated slurry-debris flow formation process envisaged by Preiss (1987, p:175-176), the unit mapped tended to reflect a uniform coarse to fine clastic classic sedimentation mode, rapidly changing from sand to silty sand to sandy silt to the final silt of the Tarcowie.

UROONDA SILTSTONE MEMBER 895-336

1 SAMPLE IDENTIFICATION

895-336 Etna: Uroonda Siltstone Member

2 FIELD RELATIONSHIPS

Bounds the Etna field area to the south, forming major high relief rolling hills, incised by erosional valleys. Not encountered within the Muttabee field area, while within the Boolcunda precinct it is a strongly weathered poorly exposed alluvium-covered unit.

3 HAND SPECIMEN DESCRIPTION

Massive olive-green indurated siltstone. Slightly coarser than the overlying Tarcowie Siltstone but with a very poor massive outcrop. Internally, however, fine planar laminae are observed along with minor wavy bedding to this uniform fine well-sorted silt.

4 INTERPRETATION

Differentiation from the encompassing Tarcowie Siltstone was done relative to the diagnostic poor massive and rounded outcrop of the Uroonda Siltstone. This unit represents diachronous deposition, before and during Tarcowie Siltstone formation, in a more distal and/or deeper water setting compared to the Tarcowie.Siltstone. (Refer back to Figure 5 for sediment distribution).

ETINA FORMATION - SANDSTONE 895-055 895-2.16

1 SAMPLE IDENTIFICATION

895-055 Boolcunda: Etina Formation silty sandstone facies

2 FIELD RELATIONSHIPS

Minimal poor outcrop of small low-lying hills in the central eastern map region form this unit, folded about the shallowly southward plunging Uroonda Syncline. It is appears to have a diachronous nature in that it occurs stratigraphically adjacent to and below the tongue of Etina Formation sandy limestone. Correlation as a silty sandstone to siltstone of the Etina Formation is favoured. The extension of this unit on the eastern limb of the governing anticline is of a dark grey massive fine to silty sandstone with flesh-coloured ?feldspathic blebs.

3 HAND SPECIMEN DESCRIPTION

Orange-brown weathering grey-dark olive green coarse siltstone to fine sandstone. The coarser silty sand variety predominates with a moderate bedded internally massive character, while the finer sandstone has good thin bedding, planar parallel internal laminae and minor dark green coarse drape-like intercalations (?flaser bedding).

4 INTERPRETATION

This sandstone unit is the lateral equivalent of the Etina Formation limestone. The limestone facies forms a thin laterally discontinuous isolated tongue within this sandstone. High energy conditions appear to have prevailed, producing the dominantly massive to thickly planar bedded outcrop observed. No subaerial exposure is envisaged reflected in the uniform nature of the sedimentary structures indicating a shallow marine shelf environment dominated by clastic input but with minor carbonate precipitation - again supporting the oxygenated high energy regime implied.

1 SAMPLE IDENTIFICATION

895-2.16 Muttabee: Etina Formation sandstone

2 FIELD RELATIONSHIPS

Taken from a thin sandstone layer immediately overlying the mineralised horizon from the Muttabee map area. This sandstone forms part of a small isolated lense of Etina Formation limestone, sandy limestone, and calcarenite surrounded by the Tarcowie Siltstone.

3 HAND SPECIMEN DESCRIPTION

Highly weathered pale brown angular to subangular coarse slightly calcareous sandstone. Moderately sorted, with a preponderance of quartz grains, held together by a kaolinized ?carbonate cement. Generally a massive rock, although a discrete layer of very faint small-scale trough cross-bedding was observed immediately overlain by a single seam of flat-lying pale brown mud rip-up clasts.

4 INTERPRETATION

Forming a thin conformable unit within the dominantly sandy limestone of the Etina Formation, some process is required which inhibited carbonate precipitation and allowed clastic sandstone accumulation. The most plausible model is for a sudden influx of coarse clastic detritus, rapidly deposited within the high energy carbonate platform environment - deposited and lithified before this environment could effectively rework the sand combining it into the surrounding sand limestone

ETINA FORMATION - OOLITIC AND/OR SANDY LIMESTONE

895-063
895-341
895-358(a)

1 SAMPLE IDENTIFICATION

895-063 Boolcunda: Etina Formation - Oolitic sandy limestone

2 FIELD RELATIONSHIPS

This rock forms a weathered profile as a cream-pink calcareous outcrop, irregularly and poorly exposed within the keel of the anticline from the Boolcunda map locality. It overlies minimal outcrop of Uroonda Siltstone.

3 HAND SPECIMEN DESCRIPTION

Pale pink to moderate red, pink-cream weathered form is the most common outcrop form. The hand sample shows a well sorted fine subangular to subrounded sandy portion within the micritic partly dolomitized calcitic cement of this limestone.

4 THIN SECTION DESCRIPTION

Composed of spherical and ellipsoidal carbonate micritic ooids set in a micritic to sparru calcite cement. Dispersed throughout are subangular holocrystalline quartz grains, bimodal in grainsize: from 0.5-1.0 mm ; to those less than 0.1 mm. Minor polycrystalline metamorphic-derived quartz grains were observed, supporting the westerly provenance of this lithology - from the Gawler Block units.

Plate 1g shows the altered indistinct boundaries of the 1-1.5 mm ooids constituting this rock. Cementation rings are poorly preserved, often with only the central nucleating particle visible - generally a fine quartz grain. Accessory plagioclase, microcline and very minor perthitic microcline exist.

Ooids	50%
Quartz	30%
Cement	20%
Feldspar	< 1%

5 INTERPRETATION

The oolitic and sandy nature of this lithology suggests a high energy carbonate platform, where strong water currents aided carbonate precipitation as ooids but also incorporated concomitant nearshore sand deposition. Permanent submergence is further implied with an overall environment strong in carbonate and sedimentary reworking processes.

1 SAMPLE IDENTIFICATION

895-341 Etna: Oolitic and sandy Etina Formation limestone

2 FIELD RELATIONSHIPS

Upper horizon of the thick Etina Formation limestone unit, forming very low hill topography surrounded by low-lying plain morphology. Represents the thickest Etina Formation encountered from all of the field areas.

3 HAND SPECIMEN DESCRIPTION

Light yellow olive oolitic limestone. Sand content < 30%, with the yellow olive ooids having an elongate character. The quartz grains are subrounded to rounded, medium to coarse grained, and irregularly dispersed throughout the rock.

1 SAMPLE IDENTIFICATION

895-358(a) Etna: Etina Formation limestone conglomerate horizon

2 FIELD RELATIONSHIPS

This unit forms a very thin < 2 metre limestone horizon between classic oolitic and sandy limestone of the Etina Formation. It occurs in the upper portion of the limestone unit, conformable in character, and only found within the environs of the Etna field area.

3 HAND SPECIMEN DESCRIPTION

Buff weathering, calcareous intraformational conglomeratic limestone. Composed of fine flakes and fragments of yellowish-orange carbonate material, along with appreciable background subrounded quartz sand portion.

4 THIN SECTION DESCRIPTION

Dominated by mosaic carbonate cement, mainly of sparry calcite. This cement is primary and secondary, replacing plagioclase feldspar or as mineralisation along fractures. Quartz grains are sparse, subrounded and holocrystalline forming a similar proportion as the carlsbad twinned fresh plagioclase (≈10%). Very minor opaques as fine subhedral grains are dispersed within the rock, as is biotite.

5 INTERPRETATION

The interpretation of 895-341 and 895-358(a) differ. 341 is similar to the genesis proposed for 895-063. However the limestone conglomerate represented by 358(a) has a totally different mode of origin.

Still within the high energy shallow marine environment dominated by carbonate precipitation, the formation of this conglomerate is attributed to the process of channel development along the floor of this carbonate platform with the prevailing currents effectively ripping up and reworking the already established limestone into the observed limestone composed of carbonate fragments. Essentially can be pictured as channel-fill thin horizon, supported by its thin lens-like field character.

TAPLEY HILL FORMATION 895-137 895-147(b)

1 SAMPLE IDENTIFICATION

895-137 Muttabee: Tapley Hill Formation

2 FIELD RELATIONSHIPS

Forms part of the lower Tapley Hill Formation representing the classic lithological form, exposed only within the Muttabee field area. Outcrop form is of low lying rolling hills, bounding the map area to the east.

3 HAND SPECIMEN DESCRIPTION

This is a dark bluish-grey finely laminated siltstone. Slightly calcareous, this fine grained lithology has a very uniform appearance often with symmetric ripple-marked bedding surfaces. Although fine grained, the rock shows a well-sorted character dominated by subangular silt-sized quartz grains.

4 INTERPRETATION

The uniformity and regional persistence of this unit, along with its slightly calcareous, pyritic, and fine grained nature allude to a quiet deep marine basinal sedimentation environment. The very fine laminations support this low energy regime, although noting that the packets of ripple-marked units observed in the field imply at least some, plausibly episodic, increase in the energy of the aqueous system. These ripple features are effectively isolated to the upper portion of this unit,and can therefore be seen as representing a shallowing of the marine environment, as highlighted below and in the text (Chapter 2).

1 SAMPLE IDENTIFICATION

895-147(b) Muttabee: Upper sandy and calcareous Tapley Hill Formation

2 FIELD RELATIONSHIPS

Constitutes the upper horizon of the Tapley Hill Formation, forming again low relief rolling hills trending NNE-SSW, often with a rib-like weathered profile due to protrusion of thicker coarser sandy interbeds within the sandy silt lithology.

3 HAND SPECIMEN DESCRIPTION

Greyish-red to pale yellowish-brown coarse siltstone. Characteristic of this rock are conformable interbeds (5-50 cm) of thick massive sandstone, often calcareous, interspersed between bluish-grey to purple-blue sandy silt to fine silt of the Tapley Hill Formation. Sand portion is mediun to fine grained, well-sorted, and subangular.

4 INTERPRETATION

This upper horizon is coarser and thicker bedded and laminated than its lower counterpart. The inference is for a shallowing of the depositional environment, caused by eustatic shallowing effectively moving the system into a distal nearshore setting influenced by a greater sedimentation rate of coarser clastic material and also variable carbonate precipitation.

MANGANESE ORE DESCRIPTIONS
BOOLCUNDA

1 SAMPLE IDENTIFICATION

895-W1 Boolcunda: Siltstone interbed within WilmingtonFormation.

2 FIELD RELATIONSHIPS

Outcropping within the environs of the main mine workings, this unit forms part of the cycle of interbedded silts and sands of the middle and upper Wilmington Formation, as rounded ridge outcrop.

3 HAND SPECIMEN DESCRIPTION

Greyish red moderately sized planar bedded coarse siltstone. Internally variability exists, from dominantly planar laminated to massive. Minor discontinuous drapes of dark yellow orange fine sand also typify this rock.

4 INTERPRETATION

A fine grained lithology representing a phase of fine clastic accumulation, interbedded with coarser sandstone deposition. Boundaries are mostly erosional implying numerous nondepositional hiatuses between the facies changes. This suggests a region which is easily influenced by rapid eustatic-paralic variations, therefore implying a nearshore shallow marine environment with high energy conditions and probably rapid sediment influx.

The importance of this unit is its high background iron and manganese content, indicating that there has been post-genetic enrichment of surrounding rocks principally in response to percolating groundwaters. As discussed in the text the high iron content of this silt alludes to a possible iron sink hypothesis further aiding manganese accumulation.

1 SAMPLE IDENTIFICATION

895-W2	Boolcunda: Main breccia-ore horizon
895-W6	" "

2 FIELD RELATIONSHIPS

Comprises one of four parallel breccia-ore horizons within the central part of the Wilmington Formation sandstones and siltstones. Strike parallel occurring on a low ridge on the western limb of the anticlinal structure deforming the rocks.

3 HAND SPECIMEN DESCRIPTION

Comprises a sedimentary breccia of lithified sedimentary clasts set in a manganiferous cementing matrix. The clasts are all angular and mostly weathered, ranging from 0-1 cm and 2-10 cm, plus minor blocks up to 80 cm in size. They show no imbrication or preferred orientation.

These clasts can be differentiated into

1. fissile pale brown fine siltstone
2. weathered pale grey massive coarse siltstone
3. massive dark yellowish-brown fine sandstone - subangular and moderately-sorted
4. coarse dark blackish-red subangular well-sorted sandstone - forms the dominant clast type. Planar bedded to massive
5. very minor Mn clasts < 1cm in size

The breccia matrix is an agglomeration of:

1. detrital matrix replaced by a manganese cement - replacing a silty sand matrix material
2. botryoidal and nodular cavity filling manganese as a primary constituent
3. secondary massive rubbly manganese mineralisation along thin seams and fractures.

4 POLISHED SLAB DESCRIPTION

895-W2

The polished section indicates an irregular impure ore, containing approximately equal proportions of gangue material and small voids, and manganese mineralisation. This manganese mineralisation ranges from a morphology as a cement supporting the gangue material to well defined clasts within the dominant detrital portions of the ore zone. The clasts are of pyrolusite and psilomelane.

The manganese phases form a complex intergrowth of fine to medium grains of pale yellow pyrolusite, and bluish-grey psilomelane. The pyrolusite displays classic shrinkage laminae (Varentsov and Grasselly, 1980), while the psilomelane phase occurs as a massive crystalline textured primary ore. However, the psilomelane also exists as a fibrous growth feature postulated as a wad (hydroxide) phase, and also a very minor clasts of colloform material. Pyrolusite occurs in less abundance, existing as primary ore and secondary ore replacing psilomelane.

Indicating minor association of iron mineralisation is represented in the occurrence of a few specks of fine pyrite. The gangue too reflects concomitant iron mineralisation as much of it has a distinctive orang-brown tinge.

895-W6

Another sample representing the impure aggregate nature of the mineralisation at Boolcunda. The sample has 60% ore and 40% gangue and voids. The texture of the pyrolusite mineralisation is dominantly massive and crystalline. Minor dispersed grains of a tablet-equant texture were also observed. Overall the mineralisation is uniform and primary in character, supporting the gangue material. Further noted was manganese both wrapped around and infiltrating and replacing the gangue material and, supporting the primary and replacement genesis model proposed for this accumulation.

Further observed were a few fine grains of strongly bireflectant pyrite with a golden hue, and along with the ornage-brown tint to most of the gangue material, again suggesting concomitant iron mineralisation.

5 INTERPRETATION

As described from the text, the mineralisation is suggested to be as primary form nucleating within cavities and forming a dominant manganese mud. This interpretation is supported by the impure nature of the ore indicated from the polished slab, with contemporaneous pyrolusite and psilomelane mineralisation occurring as primary manganese mud, primary cavity filling, and as secondary detrital replacement and ore enrichment (wad).

1 SAMPLE IDENTIFICATION

895-W5 Boolcunda: Cavity-fill/replacement ore forming part of ore-matrix cementing the breccia-ore horizons.

2 FIELD RELATIONSHIPS

Taken from near the ore horizon - hanging wall boundary from the main workings. Comprises a thin, irregular but pervasive ore morphology as part of the breccia-ore horizon within the Wilmington Formation sandstones and siltstones.

3 HAND SPECIMEN DESCRIPTION

Distorted thin (3-20mm) seam of strongly massive mineralized ore. The botryoidal form of this sample gives it a pisolitic texture in section, composed of internal growth rings - initially appearing detrital contaminated but with a purely mineralized cortex. Interstitial spaces between these pisolites is filled with both secondary calcite and detritus from the surrounding host rocks, namely medium to coarse subangular to subrounded quartz particles.

4 POLISHED SLAB DESCRIPTION

This sample represents the minor botryoidal nature of the primary ore mineralisation observed. The ore is essentially a wad, composed of manganese hydroxide-phases, represented by a loose fibrous psilomelane texture in an otherwise amorphous crytalline mass.

The boundaries between the spherical botryoids is composed of an aggregate of fine grained gangue and amorphous and fine grained creamy-white pyrolusite showing the typical shrinkage laminae described by Varentsov and Grasselly (1980), set dominantly within free space. Pyrolusite dominates toward the edges of the botryoids, reflecting later-stage paragenesis and secondary replacement of the psilomelane phase.

5 INTERPRETATION

The origin of this sedimentary breccia cemented by manganese appears to be related to a localised hiatus in the sedimentary history of the Wilmington Formation. This hiatus effectively allowed the concentration and trapment of manganese in what was plausibly a local topographic depression or erosional depression. Slumping of adjacent sands and silts into this depression with an existing manganese concentration produced the breccia, with the clasts already lithified.

MANGANESE ORE DESCRIPTION
MUTTABEE

1 SAMPLE IDENTIFICATION

895-113 Muttabee: Ore pod within Elatina Formation sandstone

2 FIELD RELATIONSHIPS

Forms a small 2 by 6 metre shallow dipping glory box on the western decline of the major high relief ridge system bounding the Muttabee map area to the west. The mineralisation is hosted within a silt interbed within the Elatina Formation medium to coarse red-brown sandstone. This silt is a grey massive thin lens within the surrounding sands.

3 HAND SPECIMEN DESCRIPTION

The manganese mineralisation is a classic botryoidal morphology, nucleated upon a thin flat venear of silty impure manganese bedding. The ore is hard and mostly nodular, although a rubbly massive character was also observed. Very minor small (< 1-2mm) fragments of the surrounding siltstone host lens are seen, indicating at least some form of contemporaneous development of sedimentation and mineralisation.

4 POLISHED SLAB DESCRIPTION

The polished section here represents beautiful reniform structured cryptomelane. Composed of continuous growth layers subdivided into three textural forms:

(1) massive very fine crystalline material
(2) loose fibrous character
(3) minor spicular-needle texure along void contacts

Also evident were thin layers of pyrolusite - impure containing dispersed fine detrital material. Secondary cryptomelane was seen in minor amounts, as vein-fill within veins cross-cutting primary layering, sugesting a second phase of paragenesis.

5 INTERPRETATION

A localised pocket of manganese mineralisation is envisaged for this pod-sized deposit associated with a thin manganiferous fine massive siltstone lens. Plausible interpretation is for a small localised depression - whether topographical or erosional is still unclear - in which both silt deposition and manganese concentration was occurring simultaneously within a reducing environment. The vughy nature of the ore reflects nucleation of the manganese within an open aqueous system.

1 SAMPLE IDENTIFICATION

895-161	Muttabee:	Wedge of high grade ore from main sand-ore horizon
895-167	Muttabee:	Massive ore constituting main observed outcrop
895-2.14	Muttabee:	Massive ore constituting main observed outcrop

2 FIELD RELATIONSHIPS

All samples taken from the mine locality, specifically from the calcarenite lithology forming the host to the manganese mineralisation. The high-grade wedge is only 3 by 1.5 metres in size and very distinct from the remaining massively outcropping mineralisation.

3 HAND SPECIMEN DESCRIPTION

All three samples highlight the bimodal morphology of the mineralisation at Muttabee. Most dominant is the massive ore which is generally very vughy in appearance too. The other form of ore is as a cavity-fill form appearing as a nodular and botryoidal mineralised masses. Both these lithologies reflect the replacement and primary void fill character of the manganese mineralisation found.

4 POLISHED SLAB DESCRIPTION

895-161

This polished section reflects a two-stage paragenetic response of the mineralisation at Muttabee. There exists approximately equal proportions of fine to medium grained equant crystals and minor aggregate grains of creamy-white pyrolusite, and psilomelane, overprinting replacing the pyrolusite as massive, colloform, and spicular textured pale to deep bluish-grey psilomelane.

The strong secondary nature of the psilomelane is represented in the replacement of pyrolusite; and its spicular and needle growth into voids and spaces dispersed within the ore. As stated the pyrolusite is dominantly fine grained, but does have minor large grains which appear to have been fractured and infiltrated by secondary gangue material and psilomelane. Some of this primary pyrolusite also reflects a druse-tablet texture.

895-167

Another relatively impure ore, having irregular masses of very fine siliceous gangue and numerous voids and spaces. Many of the original voids have been infilled by manganese mineralisation, essentially taking three forms:

(1) reniform texture as primary nodular growth into voids

(2) spicular thin and fine needles growing perpendicular into voids

(3) very minor coarse granoblastic massive grains.

The void infilling material is all composed of dark bluish-white psilomelane. However the dominant ore phase is as an impure replacement pyrolusite, showing typical shrinkage cracks (Varentsov and Grasselly, 1980), and minor pseudomorphs after manganite. The mineralisation is represented as as equal amounts of isotropic fine grained gangue dispersed with uniform equant fine grains of pale cream-white pyrolusite. The texture is irregular, apart from the fine grains, and shows no perferred orientation. Some larger grains appear to be aggregates of finer pyrolusite particles. Psilomelane replacing this pyrolusite is as a massive pale bluish-white material.

Finally, at major contacts with larger voids or with gangue material, the pyrolusite changes from a massive to digitate texture, and then followed by fine grained psilomelane and ?manganite needles protruding into the void.

5 INTERPRETATION

Again mainly a massive manganese ore, with a lithological character reflecting replacement and minor cavity-filling of a pre-existing calcarenite host rock. The dissolution and replacement means a secondary mineralisation process, with the manganese accumulating from percolating groundwaters directly from the prevailing aqueous system. Much of the replacement is almost all-pervasive although overall the ore is rather impure due to clastic material contamination.

MANGANESE ORE DESCRIPTION
ETNA

1 SAMPLE IDENTIFICATION

895-375	Etna: small lens mineralisation
895-376	Etna : small lens mineralisation

2 FIELD RELATIONSHIPS

Both these samples are taken from the main western workings found within the Etna map area. They therefore exist within the thin < 2 metre zone of mineralisation bound by the low-lying Etina Formation limestone.

3 HAND SPECIMEN DESCRIPTION

The ore consists of a rubbly replacement of a medium-grained subrounded well-sorted calcarenite to calcareous sandstone. The general outcrop of the calcarenite is highly weathered with the maganese disseminated as rubbly blebs, thin broken clasts representing original thin bedding, and as minor botryoidal-nodular cavity-filling mineralisation. This variable nature of the ore is a response to its variable replacement character but also to the influence of secondary supergene processes.

4 THIN SECTION DESCRIPTION

895-375

A polished thin section of 895-376 was made. It showed the dominance of the calcareous sandstone host relative to overall mineralisation. Composed of subrounded quartz grains, mostly corroded or embayed set is a supporting sparry calcite to micritic cement. A number of the fine to medium grained quartz grains had carbonate inclusions and alteration features.

The quartz grains show a bimodal distribution - 0.2-0.4 mm grains and those less than 0.01 mm in size. Microcline and dominantly carlsbad twinned plagioclase also is found, occurring as small euhedral grains.

Recrystallisation rims are observed, as rings of carbonate cement and as calcareous inclusions disseminated within the coarser quartz and feldspar grains but also outlining original grain boundaries.

The manganese mineralised zones contain impurities of fragmental quartz, feldspar, and carbonate cement. Cross-cutting this mineralisation are fine calcite-filled fracture veins. Also noted was some hematite staining decreasing in intensity from the manganese mineralisation, and minor disseminated subrounded opaques.

4 POLISHED SLAB DESCRIPTION

Similar to the minralisation at Muttabee, the ore at Etna too is rather impure, represented in this slide by approximately 30% gangue and void spaces. The mineralogy is dominated by strongly bireflectant white to bluish-white psilomelane. It has two basic textures - dominantly as a fine grained material with a fibrous crystalline appearance, but also as a massive to nodular zoned texture along boundaries with gangue material and within vein dilatational spaces.

Massive and minor zoned textures represent secondary mineralisation as psilomelane and pyrolusite. In association with the primary psilomelane is hollandite as minor replacement, diagnosed by strong bireflectance and its yellowish hue under oil. The secondary replacement pyrolusite occurs as fine grains, and diagnosed by its characteristic creamy-white colour and moderate anisotropy.

5 INTERPRETATION

The ore accumulation here is similar to that seen at Muttabee. To this end then the replacement and minor cavity-filling mineralisation reflects processes of secondary enrichment - hypothesised to be due to direct input from an adjacent aqueous system concentrated in manganese. The basic requirement is for enough time for mineralisation to be effective and not necessarily a response to the conditions affecting the sedimentary regime.

APPENDIX B.2

PETROGRAPHIC DESCRIPTIONS

(no Whole Rock Anaysis)

SAMPLE IDENTIFICATION

895-107(a) Muttabee: Elatina Formation Sandstone

This unit sample forms part of the major N-S trending high-relief ridge of sandstones parallel to the western Muttabee map boundary. The hand specimen is a fine to medium grained light brown porous sandstone. Dominated by subangular quartz grains, followed by heavy minerals outlining dense fine-scale trough cross-bedding. Manganese was observed as disseminated material, as minor vein material associated with quartz veining, and as dendritic coatings.

THIN SECTION DESCRIPTION

The overall constituents as shown in the table below indicate a quartzose sandstone with strong heavy mineral proportion as material outlining trough cross-bedding.

Quartz	45%
Opaques	40%
Feldspar	3%
Accessories	2%

The quartz grains show a subangular aggregate character, as holocrystalline particles with both straight and undulose extinction angles. Dominantly with straight contacts these grains also have numerous fluid inclusions and a bimodal distribution: those < 0.2mm, and grains of silt-sized nature.

Minor altered fine plagioclase feldspar (< 0.5mm) grains were irregularly dispersed throughout the rock, as was accessory muscovite plates and laths. Aside from these accessory features and the quartz content, the sample had a preponderance of subangular to subrounded opaque grains, of both hematitic and manganiferous material, the former predominating. Minor limonite alteration as a secondary replacement feature was also observed.

SAMPLE IDENTIFICATION

895-006 Boolcunda: Trezona Formation

Occurring as a thin 2 - 5 metre marker horizon at contact between the Tarcowie Siltstone and Wilmington Formation sandstone. Irregular exposure as two thin discontinuous lenses only delineated within the Boolcunda map area.

Hand specimen description is just as distinctive as the "hieroglyphic outcrop form, as it shows a deep red-brown intraclastic calcareous shale. Composed of thin wavy red shale flakes within a red carbonate cement.

THIN SECTION DESCRIPTION

Microscope analysis indicates a lithology dominated by curled elongate re mudflakes of shale, composed of translucent clays, silt-sized to micritic calcite. Disseminated within this material is polycrystalline and holocrystalline fine subhedral quartz grains (< 0.5 mm), with undulose extinction features. Also interspersed are carlsbad twinned plagioclase feldspar, nearly all altered to a sparry and micritic calcite cemented material. Accessory material in reflected in muscovite and minor biotite flakes averaging 0.2 mm in size.

The cementing material is bimodal, including clay-silt very fine material and mostly by high birefringent sparry and micritic calcite.

Carbonate - cement	70%
- flakes	
Quartz	25%
Plagioclase	< 3%
Micas	1%
Opaques	< 1%
Accessories	< 1%

SAMPLE IDENTIFICATION

895-071 Boolcunda : Etina Formation oolitic limestone

Upper lithology of the thin Etina Formation outcrop in eastern part of the Boolcunda map area. This sample represents a sandy-oolitic facies within the isolated lens exposure of the Etina Formation. Hand specimen indicates oolites averaging 0.1-0.4 mm, along with well-rounded coarse grains of quartz, both residing within a medium-grey coloured carbonate cement. Also a feature is the existence of thin 1-3 mm stylolites.

THIN SECTION DESCRIPTION

Thin section features differ considerably from the macro-hand specimen description, particularly related to the oolitic nature of this sample. Dominating is the quartz content forming ≈70% of the rock, of subhedral and subrounded grains set in a carbonate cement highlighting minimal grain contact. Grain faces are mostly jagged/irregular with a preponderance for straight extinction features. Very minor polycrystalline quartz grains exist, supporting input from metamorphic-derived material.

Second in constituent importance is the carbonate cement. It is a coarse sparry calcite mosaic, irregular grains < 2mm in size, forming 25% of this sample. Apart from minor appearance of fresh and altered plagioclase feldspar (< 5%), the rock contains accessory muscovite flakes and subhedral hematitic opaques.

SAMPLE IDENTIFICATION

895-162 Muttabee : Etina Formation calcarenite

Part of the hanging-wall calcarenite lithology bounding the lower of the two mineralised calcarenite horizons from the Muttabee manganese deposit. It is fine-grained lithology, well sorted and ?rounded, consisting of a calcarenite.

THIN SECTION DESCRIPTION

Angular immature quartz grains dominate this thin section. They have a bimodal character, from 0.5mm to those < 0.1 mm, all with straight extinction and set in a sparry calcite cement. The carbonate cement forms much of the matrix material but also forms alteration features along grain boundaries and within grains of both quartz and feldspar. This feldspar is plagioclase and possibly microcline. Opaques form the remainder of the lithology, subrounded grains and hematitic-limonitic staining.

Calcite cement	68%
Quartz	30%
Plagioclase	1%
Opaques	1%

SAMPLE IDENTIFICATION

895-166 Muttabee ; Etina Formation calcarenite with mud rip-up clasts

Exposed within costean-trenches from the main lode horizon of the Muttabee manganese works. This unit is a very thin 10-50 cm. discontinuous layer immediately overlying the mineralised horizon, and ranges from massive to vaguely flaser bedded fine to coarse calcarenite. Analysed here because of a thin single seam of pale tan mud rip-up clasts intercalated in the calcarenite.

The hand specimen indicates a poorly to moderately sorted calcilutite, dominated by fine quartz grains and a carbonate cement, flesh-coloured feldspar, and minor disseminated opaques.

THIN SECTION DESCRIPTION

Like the hand sample, analysis under the microscope indicates a rock dominated by quartz grains set in a carbonate cement. The quartz grains are rounded to subrounded 0.3-0.5 mm in diameter and those < 0.05 mm. The cement is a mosaic of micritic and sparry calcite, often seen replacing the carlsbad twinned plagioclase feldspar grains. Opaques are minor, dispersed as subrounded grains sometimes parallel to minor bedding planes.

The clay-mud flakes form drapes as well as rip-up clasts, infilling irregularities in the quartz material. Chlorite blebs and hematitic staining characterise the accessory features of this fine sandy limestone lithology.

Quartz	65%
CaCO3 cement	30%
Plagioclase	1%
Opaques	< 2%
Mud clasts	2%
Accessories	< 1%

SAMPLE IDENTIFICATION

895-164(B) Muttabee : Etina Formation sandy limestone

This litholgy forms another part of the bounding unit of the manganese mineralised zone. Its variation is difficult to discern because of the irregular nature of the boundary, but is seen to be a sandy limestone composed of well rounded and sorted coarse quartz grains set in a carbonate cement.

THIN SECTION DESCRIPTION

The major feature in thin section is the mosaic sparry calcite material cementing this rock, with grains < 0.02 mm in size. Angular quartz grains also feature, irregularly dispersed with straight and undulose extinction of holocrystalline 1 mm grains and particles < 0.5 mm.

Secondary calcification seen as rings of and cores of calcite replacing quartz grains. Observed too was accessory material, differentiated into plagioclase feldspar and minor microcline, plus negligible opaques.

CaCo3 cement	65%
Quartz	30%
Plagioclase	5%
Opaques	< 1%

SAMPLE IDENTIFICATION

895-367 Etna : Etina Formation oolitic limestone

Oolitic limestone horizon either side of the thin calcarenite mineralised unit from the Etna accumulation of manganese. Situated in the middle section of the Etina Formation, represented by a medium-grey oolitic limestone, oolites < 0.2mm in diameter, set in carbonate cement, along with minor coarse subrounded quartz grains.

THIN SECTION DESCRIPTION

Dominated by a carbonate mosaic sparry calcite cement, with grains exhibiting well defined parallel twinning. The quartz grains are mature 0.3mm particles, mostly with straight extinction and holocrystalline character, although example of undulose extinction and polycrystalline grains were seen. Minor plagioclase grains were also observed, composed of equant carlsbad twinned and minor albite twinned particles. All show secondary carbonate alteration.

Unlike the hand specimen the thin section interpretation is for limestone lithology, only partly sandy with no oolitic features.

The thin section has the following constituent percentages:

CaCO3 Cement	90%
Plagioclase	< 5%
Quartz	5%%
Opaques	1%
Accessories	< 1%

SAMPLE IDENTIFICATION

895-352 Etna : Tarcowie Siltstone

This sample represents the most sandy Tarcowie Siltstone lithology encountered, and formed a thin 40-50 m horizon within low-lying relief at Etna, separating the Etina Formation carbonates from the underlying Cox Sandstone Member. Dominantly a coarse siltstone to very fine sandstone, this unit show a markedly variable lithologic character, from a common massive appearance to fine wavy bedding rock represented in exposure by a light olive-grey and dark olive-grey slightly calcareous lithology.

THIN SECTION DESCRIPTION

The thins section analysis suggests a lithology very similar to the classic Tarcowie Siltstone. This is observed in the uniform flaser bedded fine silt character found, with banding a result of (1) grainsize variations - coarser and finer layers, and (2) quartz percentage increase and chlorite-sericite matrix percentage decrease. The rock is dominated by this chlorite-sericite very fine matrix material (55%) and quartz material (40%).

This quartz content has a bimodal distribution, from grains < 0.1mm to silt-sized material < 0.01mm forming part of the matrix. The grains are dominated by straight extinction features.

Opaques form the remaining major material, dispersed a subrounded fine grains , < 0.1mm in size, and also represented as minor limonitic staining. Accessory material is represented by very minor mature euhedral amphibole, muscovite flakes 0.05mm in length, and euhedral zircon grains.

SAMPLE INDENTIFICATION

895-373 Etna : Cross-bedded sandstone forming upper boundary of ore horizon

This unit occurs as a 10-40cm strike continuous medium to fine grained sandstone, between calcareous sediments of the Etina Formation. It is a moderate olive-brown well sorted sandstone, with a vague outline of dense small-scale (< 2cm) trough cross-bedding. It is slightly calcareous.

THIN SECTION DESCRIPTION

Overall the rock has a fine grained nature, with subrounded euhedral quartz grains averaging 0.2mm in size set in a sericitic-chlorite matrix. The quartz material is euhedral, with a dominance of straight extinction over undulose features. Grains have straight boundaries, and nearly all a rimmed by a thin sericitic coating.

The matrix material is microcrystalline, dominantly of sericite with lesser chlorite. Opaques conclude the rest of the major constituents observed, comprising subangular fine grains sometimes outlining the vague bedding. Accessory material is dominated by plagioclase feldspar, multiple-twinned and euhedral in form. Muscovite, euhedral amphibole, and possibly rutile were also encountered.

APPENDIX C

GEOCHEMICAL ANALYSES

METHODS AND RESULTS

ANALYSIS OF MAJOR ROCK LITHOLOGIES AND MANGANESE SAMPLES

A WHOLE ROCK GEOCHEMICAL ANALYSIS

1 Fresh samples were obtained by removal of weathered material.

Large samples were then crushed in a jaw crusher, enabling further finer grinding using a Siebtechnik tungsten-carbide mill.

2 Using 3-4 grams of this finely milled material, the percentage loss of volatiles was determined via overnight heating of the samples at 960^{o}C.

3 280 grams of ingnited sample, 20 milligrams of Sodium nitrate and 1.5 grams of flux (lithium tetraborate) were weighed out and mixed, and then heated in a platinium crucible by Mr. P. McDuie to produce a fused disc.

4 The fused disk was then used for geochemical elemental analysis, determined by Mr. J Stanley using the Siesmans SRS X-Ray Spectrometer.

5 Na_2O determination for each sample was performed by taking approximately 30 milligrams of the unignited powdered sample and digesting it within teflon beakers, in an acidic solution of 50% H_2SO_4 and 50% 0.1MHF. The disgested solution was then made up to 100ml volume, using volumetric flasks.

6 Na_2O concentrations were subsequently analysed using the Atomic Absorption Spectrometer (AAS), calibrated against known standards.

B DIGESTION PROCEDURE

1 Weigh out 500 mg of unignited sample into clean dry 50 ml teflon beaker. Wet sample with small amount of deionised water, then add 5 ml of concentrated HCl acid.

2 Beakers are then covered and placed on a hot plate at 180^{o}C for approximately 1 hr. Following their removal the residual material is rinsed off covering lids, and the solution is again heated to reduce volume.

3 Remove from hotplate and add 2 ml concentrated HCl, then 10 ml of (conc) HF, reheating at 180^{o}C until evaporated.

4 Again (!) take beakers from the hotplate, now adding 10 ml of conc HCl, and to each 10 ml of La/Zr solution (20000 ppm La/10000 ppm Zr).

5 The solution is now ready to be made up to volume. This is done by transferring solutions to a 100 ml volumetric flask, adding 2 ml of 6% w/v K solution, before making the solution up to 100 ml volume.

6 Transfer solutions to 100 ml plastic bottles, ready for analysis using the AAS.

7 A number of solutions, particularly those of the manganese samples, were diluted tenfold to allow for high trace concentrations envisaged. This allowed for later accurate trace element analysis with all samples within the sensitivity range calibrated for each element on the AAS.

8 The trace element results made following the above procedure had readings which correlated well with the USGS-STANDARD used as the control and comparison geochemical sample in this analysis.

C OPERATION OF VARIAN AA-6 ATOMIC ABSORPTION SPECTROMETER

1 Following instruction from Mr. P. McDuie, the analysis of trace elements was performed using the above named AAS, with the following operating conditions:

Element	Lamp Current (mA)	λ (nm)	SBP (nm)	Flame	Background Correction
Cu	3	324.8	0.5	Air/Acet	Y
Co	8	240.7	0.5	"	Y
Na	7	232	0.5	"	Y
Ni	10	217	1	"	Y
Pb	5	357.9	0.2	"	N
Cr	5	213.9	0.5	"	Y
Zn	8	589	0.2	"	N

SAMPLE NUMBER LOCALITIES (895 PREFIX)

BOOLCUNDA	8 19 37 55 63 70 76 90 92 W1 W2 W5
ETNA	311(b) 312 336 341 345 348 358(a) 375 376
MUTTABEE	108 112 123 129 137 147(b) 158 2.11 113
	161 2.14 2.16

POST-TRIASSIC COVER - BOOLCUNDA

SAMPLE # 895-070

Major Elements %		Trace Elements (ppm)	
SiO2	99.11	Cu	10
Al2O3	0.2	Co	124
Fe2O3	0.1	Ni	<2
MnO	0.01	Pb	<7
MgO	0.04	Cr	<6
CaO	0.03	Zn	<4
Na2O	0.01	Sr	-
K2O	0.04	Ba	-
TiO2	0.39		
P2O5	0.02		
SO3	0.02		
LOSS	0.22		
TOTAL	100.2		

BRACHINA FORMATION

SAMPL # 895-008

Major Elements %		Trace Elements ppm	
SiO2	64.99	Cu	6
Al2O3	14.91	Co	42
Fe2O3	7.97	Ni	37
MnO	0.05	Pb	<3
MgO	2.58	Cr	81
CaO	0.37	Zn	112
Na2O	1.72	Sr	30
K2O	2.52	Ba	388
TiO2	1.21		
P2O5	0.23		
SO3	0.01		
LOSS	3.11		
TOTAL	99.68		

ULUPA SILTSTONE

895-037

Major Elements %		Trace Elements ppm	
SiO2	63.38	Cu	23
Al2O3	15.04	Co	60
Fe2O3	8.42	Ni	59
MnO	0.05	Pb	<9
MgO	2.68	Cr	91
CaO	0.45	Zn	132
Na2O	1.81	Sr	43
K2O	2.9	Ba	517
TiO2	1.43		
P2O5	0.27		
SO3	0.01		
LOSS	3.23		
TOTAL	99.68		

ELATINA FORMATION

SAMPLE #	895-076	895-092	895-348
Major Elements (%)			
SiO2	73.39	82.53	61.15
Al2O3	8.85	8.51	15.54
Fe2O3	7.67	3.44	7.38
MnO	0.03	0.02	0.09
MgO	1.59	0.36	2.73
CaO	0.63	0.13	1.73
Na2O	2.21	0.09	1.4
K2O	2.35	0.43	3.64
TiO2	0.46	1.06	1.07
P2O5	0.29	0.02	0.2
SO3	0.02	0.02	0.01
LOSS	1.9	3.42	4.43
TOTAL	99.39	100.02	99.37
Trace Elements (ppm)			
Cu	38	13	33
Co	62	36	34
Ni	85	<7	49
Pb	21	<7	<5
Cr	41	50	-
Zn	169	11	94
Sr	67	22	-
Ba	245	60	-

WILMINGTON FORMATION

SAMPLE #	895-090	895-108	895-123	895-112 (silt interbed)	895-345
Major Elements (%)					
SiO2	64.44	88.99	60.86	53.68	67.22
Al2O3	15.31	5.89	9.22	21	12.52
Fe2O3	6.46	1.31	3.63	9.79	6.54
MnO	0.07	0	0.13	0.03	0.03
MgO	2.5	0.6	4.21	2.41	3.31
CaO	0.42	0.12	7.19	0.1	0.52
Na2O	1.14	0.07	1.34	0.09	1.27
K2O	4.8	0.81	2.67	7.15	2.95
TiO2	0.88	0.33	0.6	1.3	1.04
P2O5	0.24	0.01	0.14	0.09	0.21
SO3	0.01	0.01	0.01	0	0.02
LOSS	3.51	1.85	9.82	4.02	3.84
TOTAL	99.78	99.99	99.82	99.64	99.46
Trace Elements (ppm)					
Cu	58	13	11	64	19
Co	30	75	36	19	40
Ni	49	34	64	27	32
Pb	-	<7	<7	12	-
Cr	97	28	47	75	75
Zn	81	11	53	38	78
Sr	44	-	-	-	-
Ba	338	-	-	-	-

ENORAMA SHALE

SAMPLE #	895-312 (limestone interbed)
Major Elements (%)	
SiO_2	33.78
Al_2O_3	4.58
Fe_2O_3	1.93
MnO	0.05
MgO	1.68
CaO	30.83
Na_2O	1.15
K_2O	0.77
TiO_2	0.47
P_2O_5	0.08
SO_3	0.07
LOSS	25.1
TOTAL	100.49
Trace Elements (ppm)	
Cu	38
Co	28
Ni	<7
Pb	<3
Cr	28
Zn	29
Sr	-
Ba	-

TARCOWIE SILTSTONE

SAMPLE #	895-019	895-2.11
Major Elements (%)		
SiO_2	67.44	69.82
Al_2O_3	10.78	9.7
Fe_2O_3	4.63	5.13
MnO	0.1	0.05
MgO	3	3.14
CaO	3.29	2.46
Na_2O	2.05	1.59
K_2O	2.13	2.26
TiO_2	0.73	1.23
P_2O_5	0.18	0.13
SO_3	0.02	0.02
LOSS	4.98	4.02
TOTAL	99.33	99.54
Trace Elements (ppm)		
Cu	24	<4
Co	62	54
Ni	29	24
Pb	14	14
Cr	66	75
Zn	74	72
Sr	-	-
Ba	-	-

COX SANDSTONE MEMBER

SAMPLE #	895-129	895-311(b)	895-158 (silty sand unit)
Major Elements (%)			
SiO2	81.41	94.18	79.5
Al2O3	7.89	2.4	8.72
Fe2O3	3.2	0.74	3.48
MnO	0.02	0.04	0.02
MgO	0.85	0.25	1.23
CaO	0.25	0.11	0.26
Na2O	1.92	0.05	1.8
K2O	1.95	0.92	1.9
TiO2	0.92	0.04	0.69
P2O5	0.1	0.04	0.11
SO3	0.01	0	0
LOSS	1.37	0.83	1.85
TOTAL	99.88	99.6	99.55
Trace Elements (ppm)			
Cu	13	<5	18
Co	49	151	163
Ni	12	<5	47
Pb	<3	-	<5
Cr	41	<6	56
Zn	25	11	128
Sr	33	12.3	-
Ba	271	175	-

UROONDA SILTSTONE MEMBER

SAMPLE# 895-336

Major Elements	(%)	Trace Elements	(ppm)
SiO2	70.83	Cu	31
Al2O3	10.28	Co	66
Fe2O3	4.52	Ni	27
MnO	0.06	Pb	-
MgO	3.2	Cr	59
CaO	1.28	Zn	60
Na2O	2.03	Sr	-
K2O	2.77	Ba	-
TiO2	1.02		
P2O5	0.16		
SO3	0.02		
LOSS	3		
TOTAL	99.17		

ETINA FORMATION - CALCARENITE/SANDSTONE

SAMPLE #	895-055	895-2.16
Major Elements (%)		
SiO2	53	79.2
Al2O3	11.89	8.49
Fe2O3	5.94	3.02
MnO	0.11	0.02
MgO	4.27	2.15
CaO	9.04	0.22
Na2O	0.87	0.64
K2O	2.92	3.33
TiO2	0.79	0.44
P2O5	0.19	0.1
SO3	0	0.01
LOSS	10.45	2.02
TOTAL	99.46	99.63
Trace Elements (ppm)		
Cu	16	6
Co	30	56
Ni	37	12
Pb	<3	-
Cr	75	<6
Zn	78	11
Sr	79	100
Ba	306	227

ETINA FORMATION - LIMESTONE

SAMPLE #	895-063	895-341	895-358(a)
Major Elements (%)			
SiO2	18.16	26.45	5.96
Al2O3	1.64	4.22	1.32
Fe2O3	0.83	4.34	0.56
MnO	0.05	0.18	0.08
MgO	17.21	14.24	0.7
CaO	24.17	20.01	49.58
Na2O	0.31	0.25	0.52
K2O	0.61	0.57	0.23
TiO2	0.06	0.28	0.13
P2O5	0.02	0.08	0.03
SO3	0.03	0.05	0.1
LOSS	36.82	29.45	40.19
TOTAL	99.92	100.11	99.4
Trace Elements (ppm)			
Cu	11	<3	49
Co	17	40	23
Ni	<2	15	12
Pb	<3	-	<7
Cr	<6	31	31
Zn	11	68	19
Sr	52	-	254
Ba	72	-	27

TAPLEY HILL FORMATION

SAMPLE #	895-137	895-147(b)
Major Elements (%)		
SiO_2	24.41	61.17
Al_2O_3	4.45	7.94
Fe_2O_3	1.98	3.11
MnO	0.13	0.11
MgO	1.44	2.04
CaO	35.67	10.86
Na_2O	1.1	1.82
K_2O	0.73	1.68
TiO_2	0.32	0.64
P_2O_5	0.15	0.16
SO_3	0.12	0.11
LOSS	29.68	10.5
TOTAL	100.18	100.13
Trace Elements (ppm)		
Cu	13	14
Co	49	34
Ni	12	17
Pb	<3	<9
Cr	41	56
Zn	25	38
Sr	-	-
Ba	-	-

MANGANESE ORE - BOOLCUNDA

SAMPLE #	895-W1 (Elatina Fm silt)	895-W2	895-W5
Major Elements (%)			
SiO2	72.53	2.61	0.23
Al2O3	5.71	1.09	0.75
Fe2O3	12.73	0.71	0.26
MnO	1.93	63.6	64.69
MgO	1.22	0.5	0.69
CaO	0.27	0.44	4
Na2O	1.27	3.51	0.62
K2O	1.77	0.01	1.46
TiO2	0.37	0.05	0.02
P2O5	0.17	0.4	0.3
SO3	0.02	0.41	0.1
LOSS	1.63	19.78	11.96
TOTAL	99.61	93.1	85.06
Trace Elements (ppm)			
Cu	6	96	1503
Co	163	113	113
Ni	69	105	64
Pb	<7	-	-
Cr	25	12	12
Zn	122	319	222
Sr	177	2018	6394
Ba	1311	14205	47802

MANGANESE ORE - ETNA

SAMPLE #	895-375	895-376
Major Elements (%)		
SiO2	10.68	18.46
Al2O3	2.21	2.67
Fe2O3	0.8	1.58
MnO	45.49	48.19
MgO	0.68	0.91
CaO	10.57	1.24
Na2O	0.22	0.26
K2O	0.76	0.81
TiO2	0.16	0.14
P2O5	0.34	0.41
SO3	0.06	0.09
LOSS	16.01	10.05
TOTAL	87.98	84.82
Trace Elements (ppm)		
Cu	87	42
Co	174	194
Ni	77	52
Pb	-	-
Cr	19	25
Zn	344	378
Sr	1887	1551
Ba	38684	65945

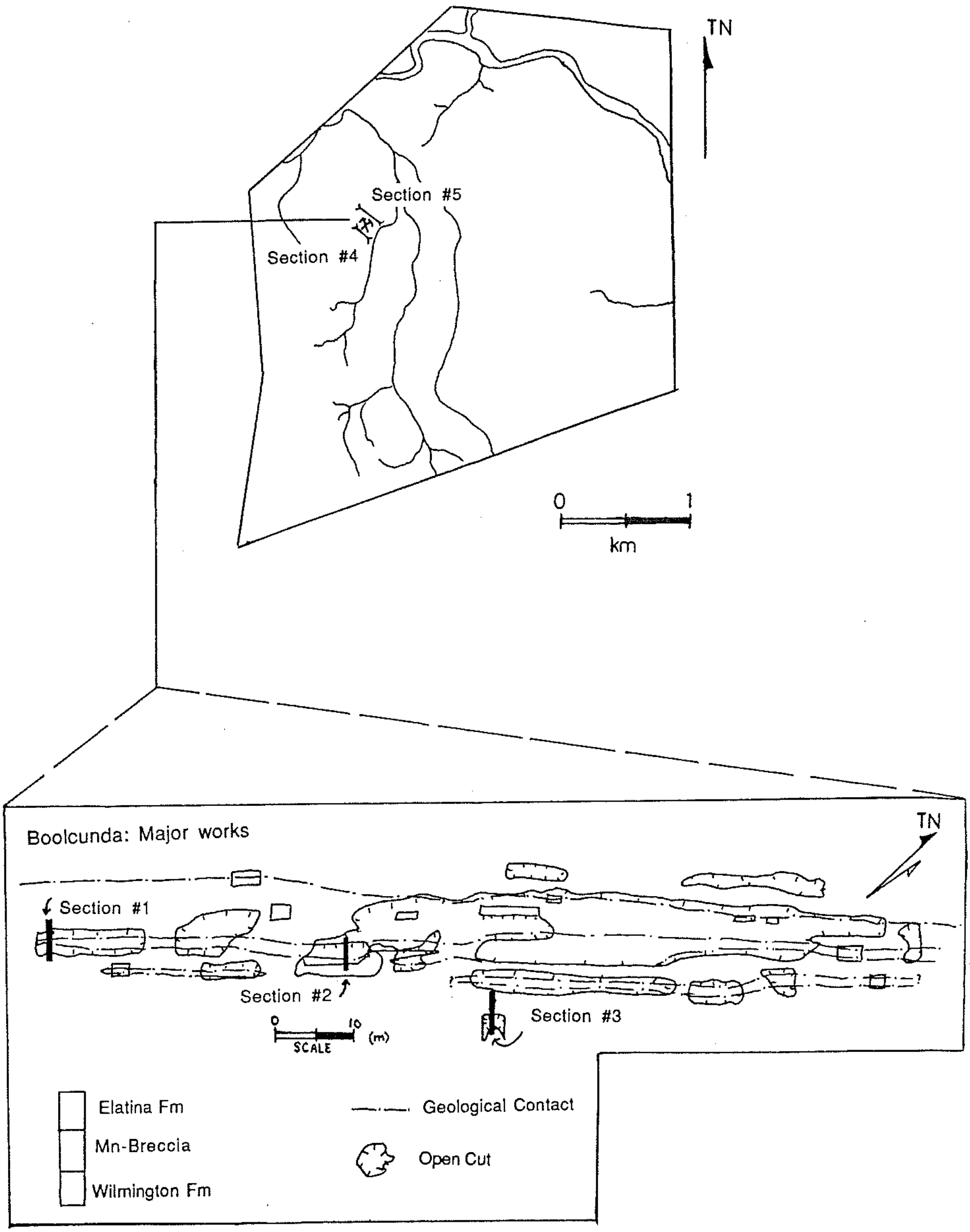
MANGANESE ORE - MUTTABEE

SAMPLE #	895-113 (Elatina Fm)	895-161	895-2.14
Major Elements (%)			
SiO2	2.56	0.8	5.64
Al2O3	2.9	0.78	1.35
Fe2O3	0.69	0.36	0.58
MnO	69.49	75.47	68.07
MgO	0.39	0.32	0.4
CaO	0.41	0.39	1.24
Na2O	0.7	0.58	0.17
K2O	3.48	0.77	1.08
TiO2	0.06	0.03	0.08
P2O5	0.6	0.26	0.36
SO3	0.05	0.16	0.05
LOSS	11.71	11.86	11.76
TOTAL	93.05	91.78	90.78
Trace Elements (ppm)			
Cu	3539	120	117
Co	8626	74	411
Ni	159	15	15
Pb	<3	-	-
Cr	<9	<9	12
Zn	2134	98	95
Sr	2315	3177	2623
Ba	14145	30617	25374

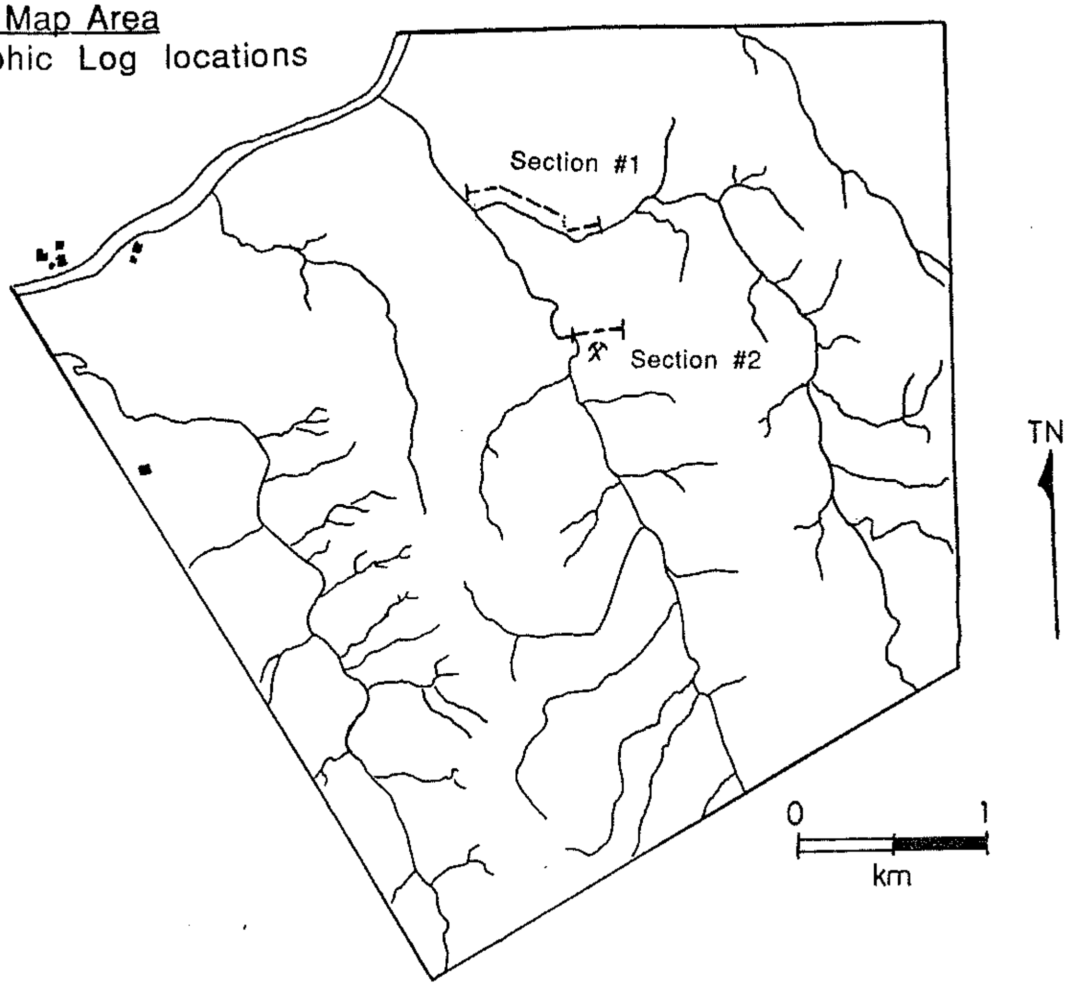
APPENDIX D

STRATIGRAPHIC LOGS

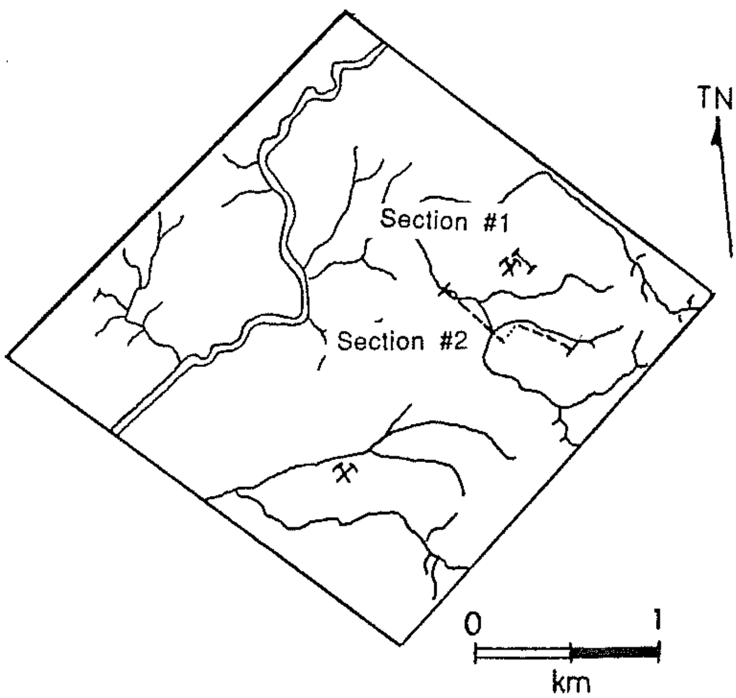
<u>Boolcunda Map Area</u>
Stratigraphic Log locations



Muttabee Map Area
Stratigraphic Log locations



Etna Map Area
Stratigraphic Log locations



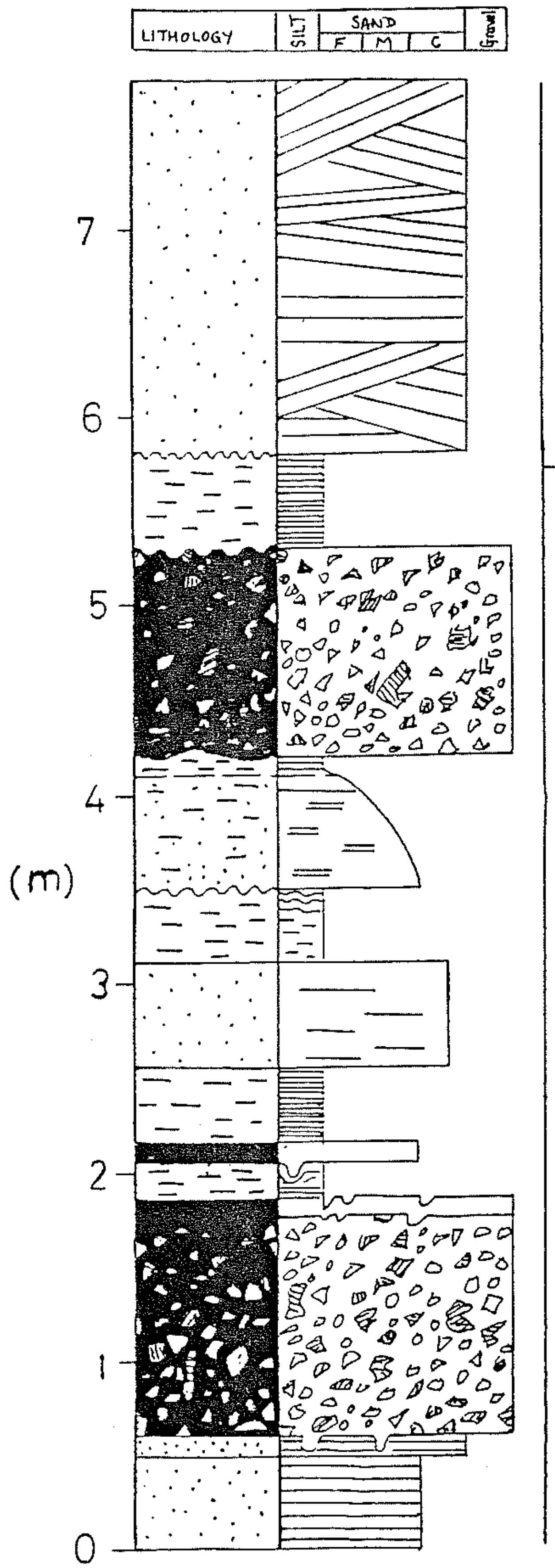
Stratigraphic Log Nomenclature

LEGEND

- Sandstone
- Siltstone
- Silty Sandstone
- Mn Sedimentary Breccia
- Massive Mn-ore
- Limestone
- Oolitic Limestone
- Sandy Limestone
- Intraformational Limestone Congl.

- planar lamination
- planar bedding
- planar cross-bedding
- trough cross-bedding
- wavy/flaser bedding
- sandy starved ripples
- sedimentary slump
- erosional contact
- vague bedding
- continuous sequence
- calcareous
- stylolite

Boolcunda: Main Works: Section #1
C Gregory 1988



coarse subangular blackish-red micaceous and manganiferous sandstone
large-scale cross bedding showing easterly current direction
basal erosional contact

Wilmington Fm

light grey finely planar laminated fine siltstone
erosional-drape basal contact

weathered breccia-ore horizon
rubbly, botryoidal, nodular and massive Mn matrix
angular 1-6 cm fissile siltstone and coarse sandstone clasts form this sedimentary breccia

fining upward pale yellowish-brown sandstone
planar bedding corresponds to finer grainsizes with coarser units being more massive
erosional base

fine bluish-grey siltstone, internally massive

blackish-red manganiferous and micaceous coarse poorly sorted subangular sandstone

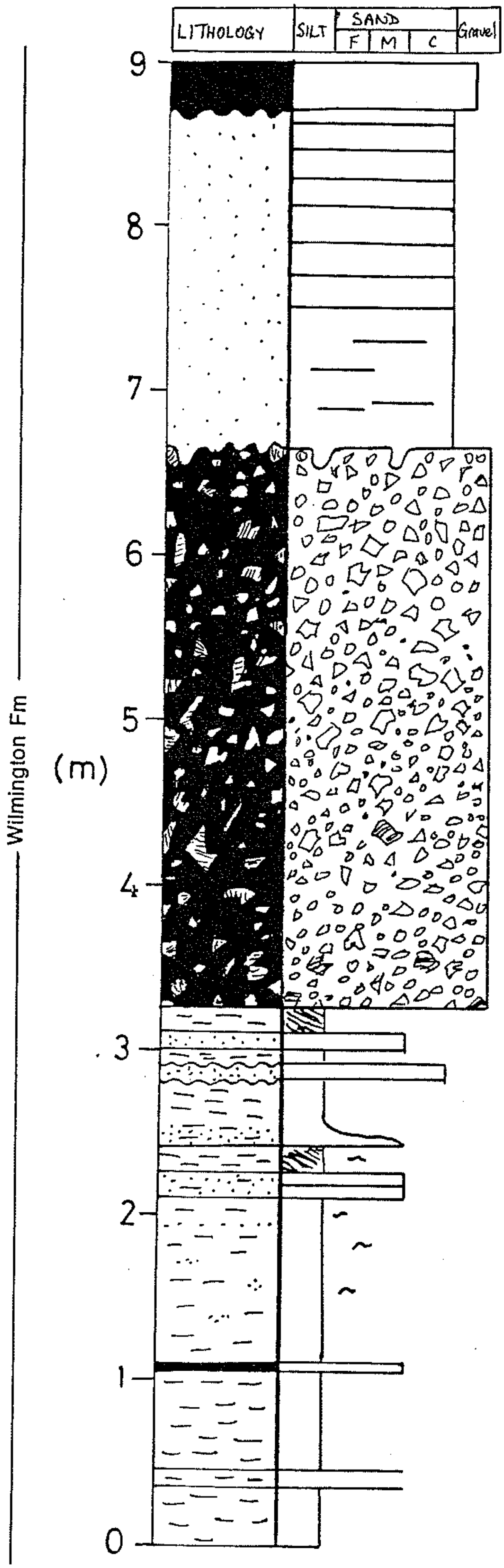
very fine planar laminated light grey to pale yellow-brown silstone
rubbly weathered Mn-horizon - cavity filling
distorted laminated fine yellowish siltstone

Mn-matrix supported breccia-ore horizon
lithified angular clasts of fine siltstone and coarse sandstone dominate - no grading or imbrication

blackish-red coarse manganiferous and micaceous sandstone
pale yellowish-brown to greyish-red siltstone
planar bedded and laminated with minor greyish silt intercalated layers

Boolcunda: Main Works: Section #2

C Gregory 1988



rubbly to massive Mn-mineralisation
thin distorted band

blackish-red manganiferous and micaceous medium-grained sandstone
initially massive, grading into a planar bedded unit

Breccia - Ore horizon
Mn-matrix
lithified sedimentary clasts 1-6 cm ave. but up to 80 cm.
irregular orientation to these angular clasts, composed of weathered pale brown siltstone, massive brown siltstone, pale grey siltstone, and yellowish and blackish-red coarse sandstone

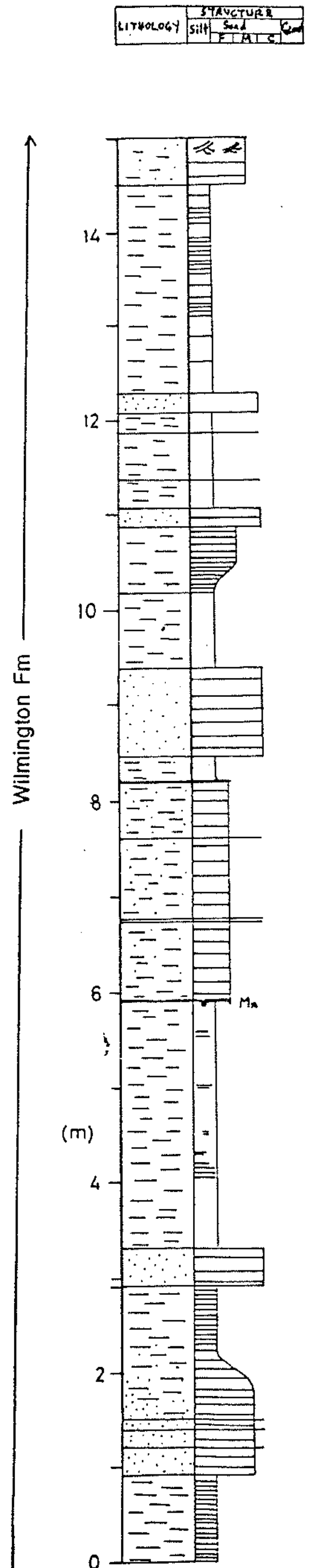
pale brown massive thin medium-grained sand interbedded with a greyish-red fine massive siltstone

repeat of above except with small thin sandy drape-like intercalations

cyclic grey planar bedded siltstone; ranges from a fine pale purple-grey silt, to a coarse yellow-grey lense-like silt

greyish-red planar bedded internally massive fine siltstone with thin orange-grey intercalated sandy silt layers
minor Mn-filled thin fracture planes

Boolcunda: Main Works: Section #3
C Gregory



manganese works

Blackish-red manganiferous and micaceous coarse sandstone
upper sole-marked bedding plane

dusky-red fine massive siltstone - minor internal planar laminae

purplish dusky-red fine fissile siltstone
appears sheared with fissility at 30° to bedding contacts

pale red thickly planar bedded coarse siltstone

grey to blackish-red fissile siltstone: same as fissile silt seem above

pale red thickly planar bedded fine-medium silt

purple grey fissile siltstone with minor coarse sandy seams

dusky-red coarse planar bedded siltstone
basal distorted layer with thin manganiferous "buffer" layer

greyish-red massive to moderately planar thick bedded fine siltstone

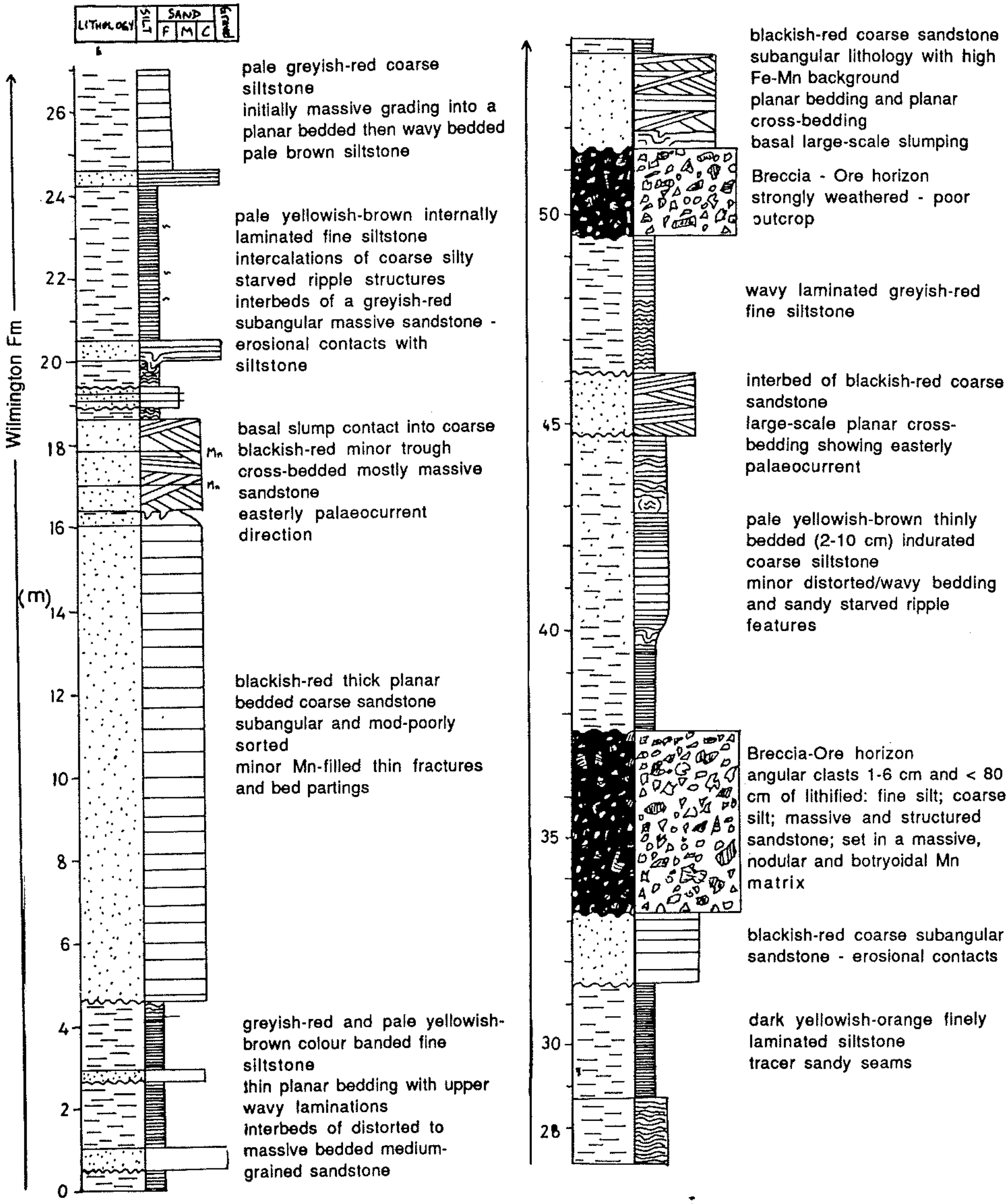
greyish-red planar bedded medium-grained sand

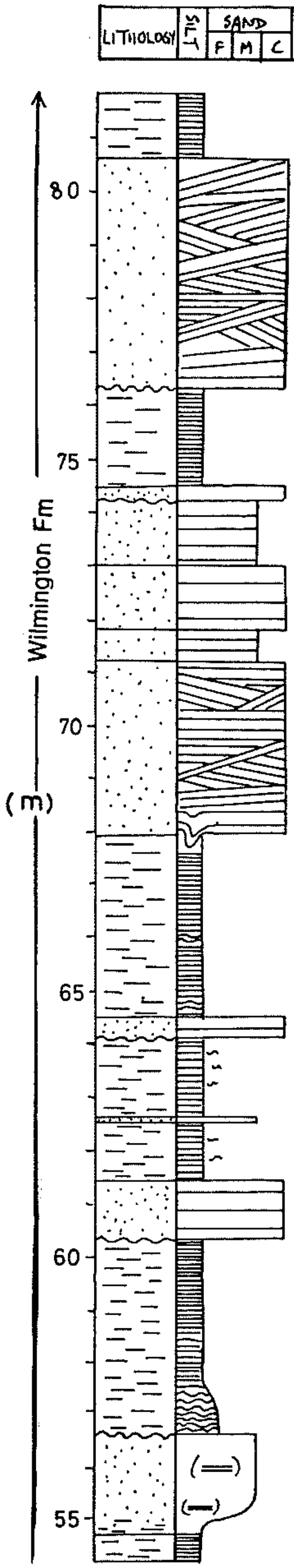
blackish-red to very dark-red planar bedded (.5-2 cm.) medium-fine sandstone
secondary Mn-mineralisationalong thin bed partings

grades into a flaggy, weathered greyish-red laminated coarse siltstone

greyish-red laminated fine siltstone
flaggy weathered outcrop

Boolcunda: Main Works: Section #4 (Small Costean)
C Gregory 1988



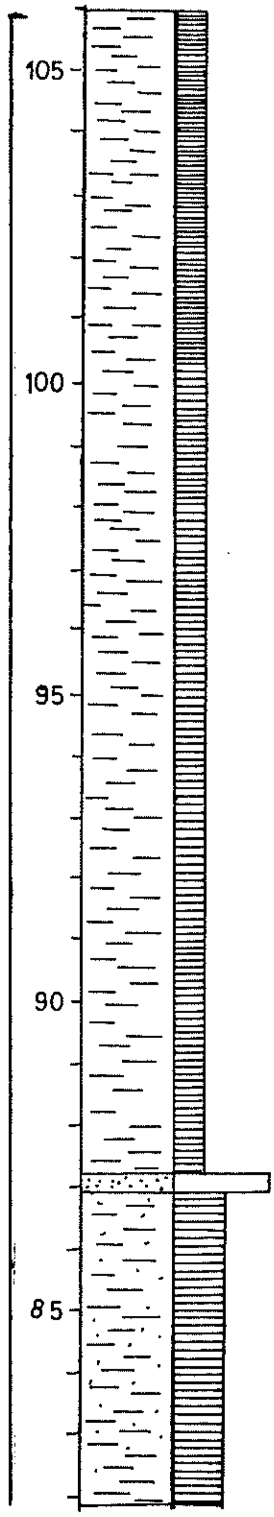


blackish-red coarse subangular sandstone, high in background Fe and Mn
planar bedding and cross-bedding

greyish-red planar laminated fine siltstone interbed

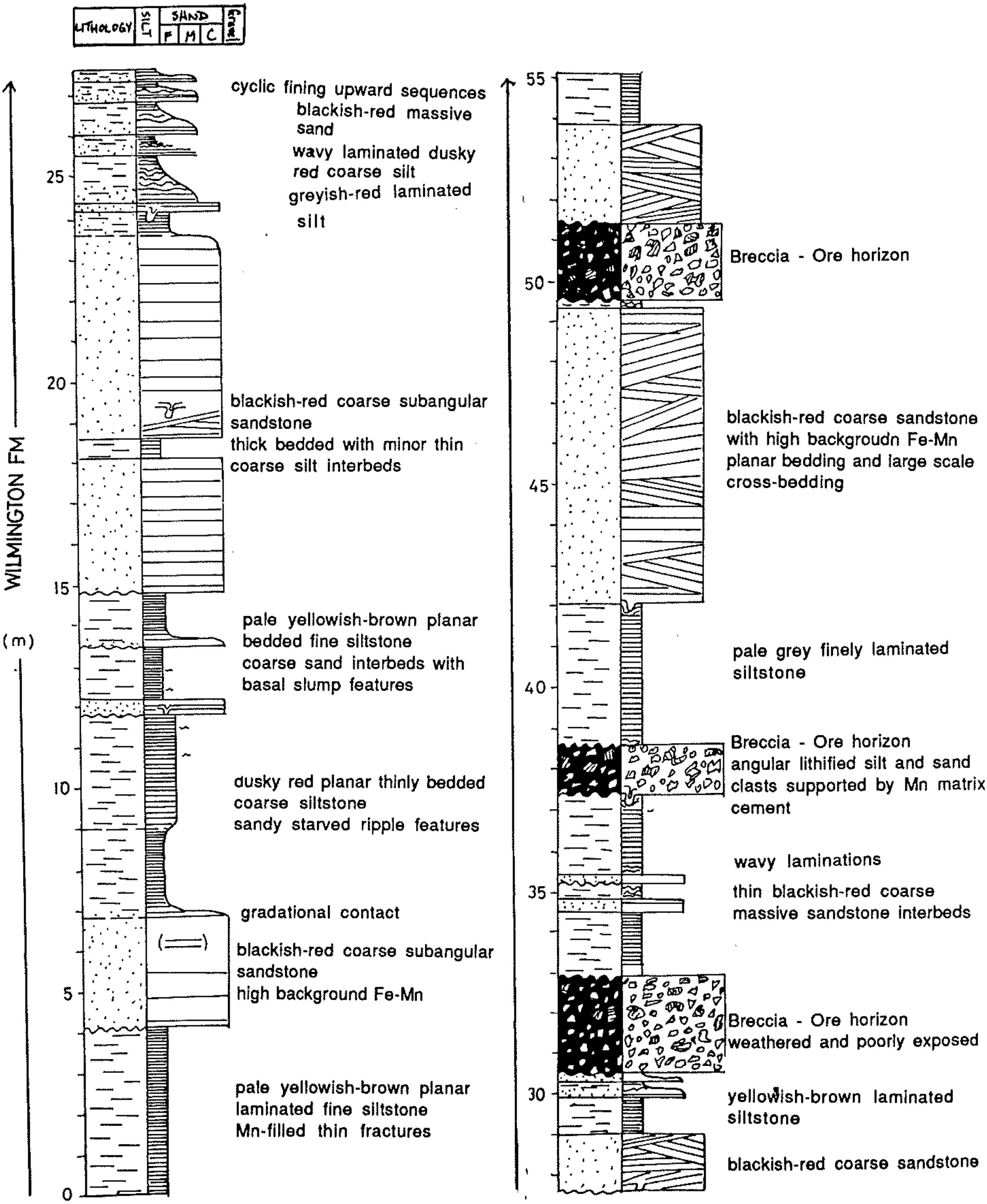
intially planar cross-bedded blackish-red coarse sandstone, grading into a thick bedded silty sandstone

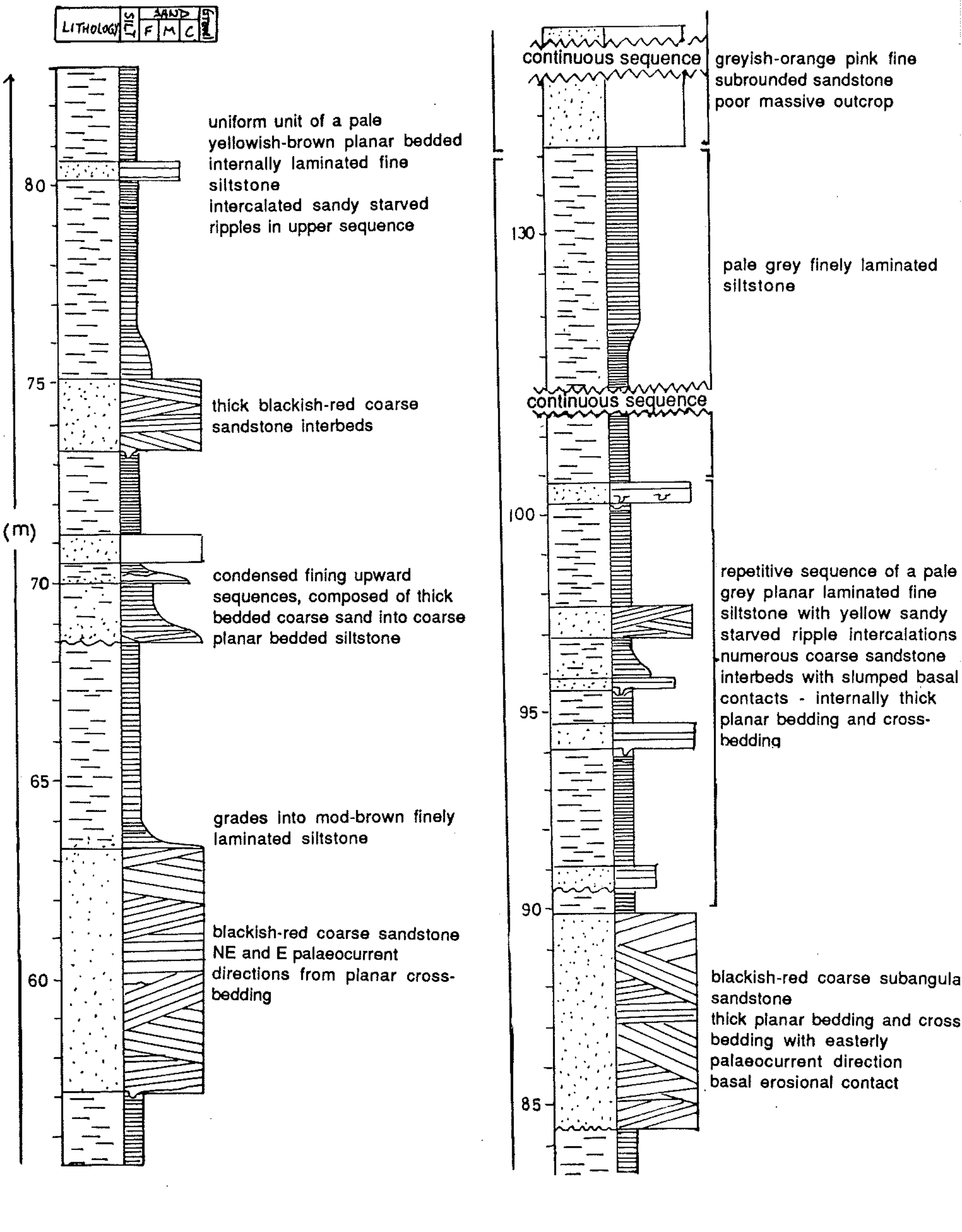
thick cyclic sequence of a wavy to planar laminated greyish-red to pale yellowish-brown fine siltstone, with erosional contacts into blackish-red coarse massive to thickly bedded sandstone
minor starved ripple features

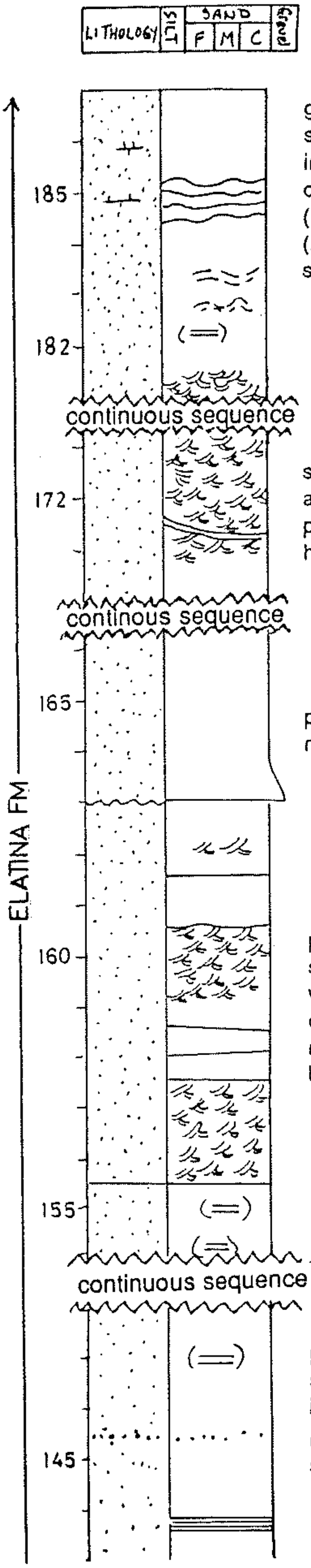


dusky-red planar laminated to well thickly bedded fine siltstone
blackish-red coarse sandstone interbed

Boolcunda: Main Works: Section #5 (Large Costean)
C Gregory 1988




LITHOLOGY
SILT
SAND
F
M
C
(m)
80
75
70
65
60
uniform unit of a pale yellowish-brown planar bedded internally laminated fine siltstone
intercalated sandy starved ripples in upper sequence
thick blackish-red coarse sandstone interbeds
condensed fining upward sequences, composed of thick bedded coarse sand into coarse planar bedded siltstone
grades into mod-brown finely laminated siltstone
blackish-red coarse sandstone NE and E palaeocurrent directions from planar cross-bedding
continuous sequence
greyish-orange pink fine subrounded sandstone poor massive outcrop
130
pale grey finely laminated siltstone
continuous sequence
100
95
90
85
repetitive sequence of a pale grey planar laminated fine siltstone with yellow sandy starved ripple intercalations numerous coarse sandstone interbeds with slumped basal contacts - internally thick planar bedding and cross-bedding
blackish-red coarse subangula sandstone
thick planar bedding and cross bedding with easterly palaeocurrent direction
basal erosional contact



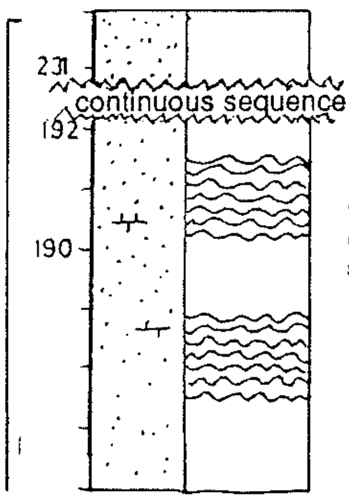
grades into coarse to granular sandstone
initially massive it has cycles of
(1) massive coarse sandstone
(2) wavy bedded coarse sandstone
slightly calcerous

sudden conformable change into a densely trough cross-bedded pale red sandstone, outlined by heavy minerals

pale red to greyish-pink massive sandstone

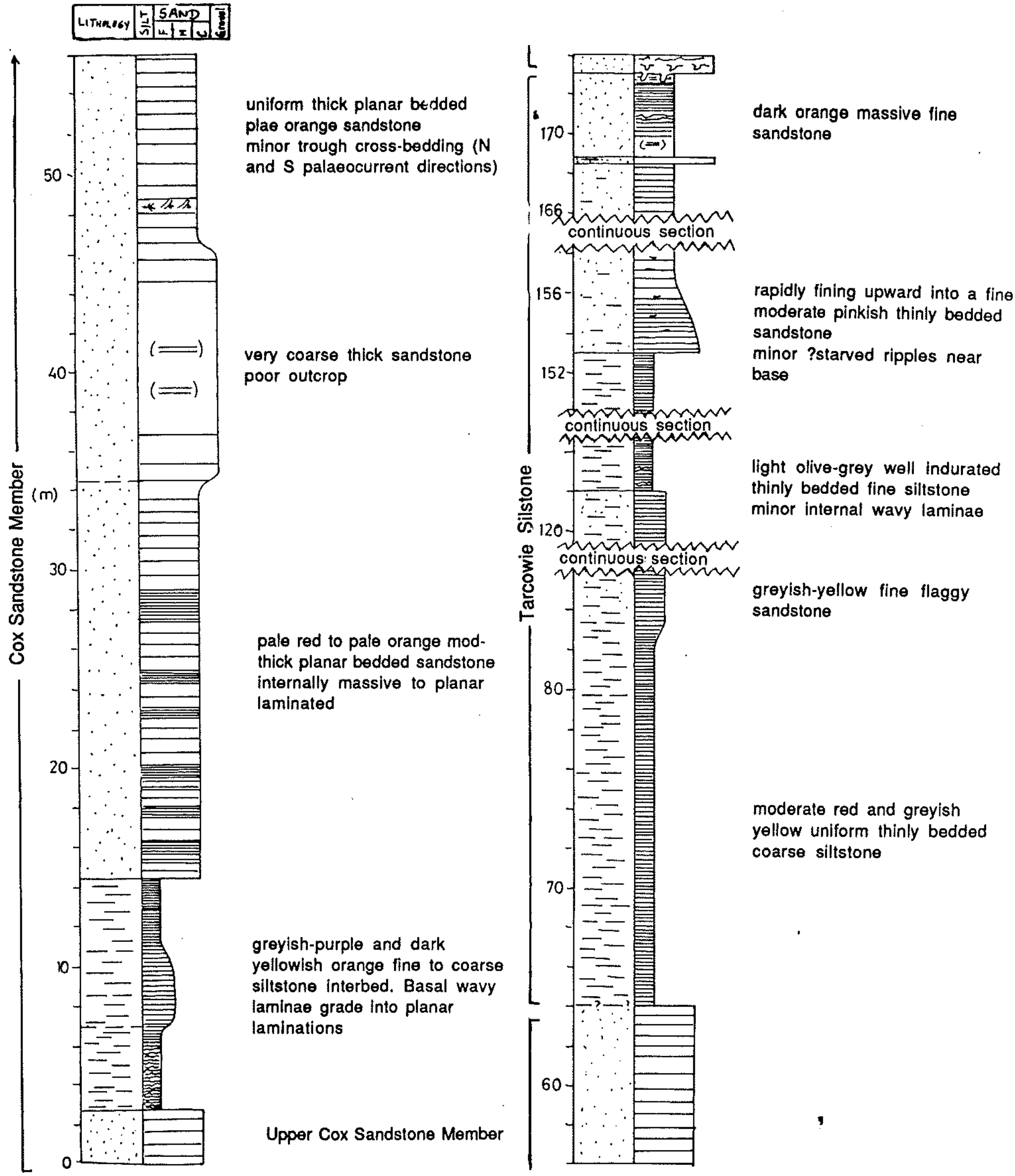
pale red to dusky brown coarse sandstone
varies from massive rounded outcrop to densely heavy mineral outlined trough cross-bedded rock

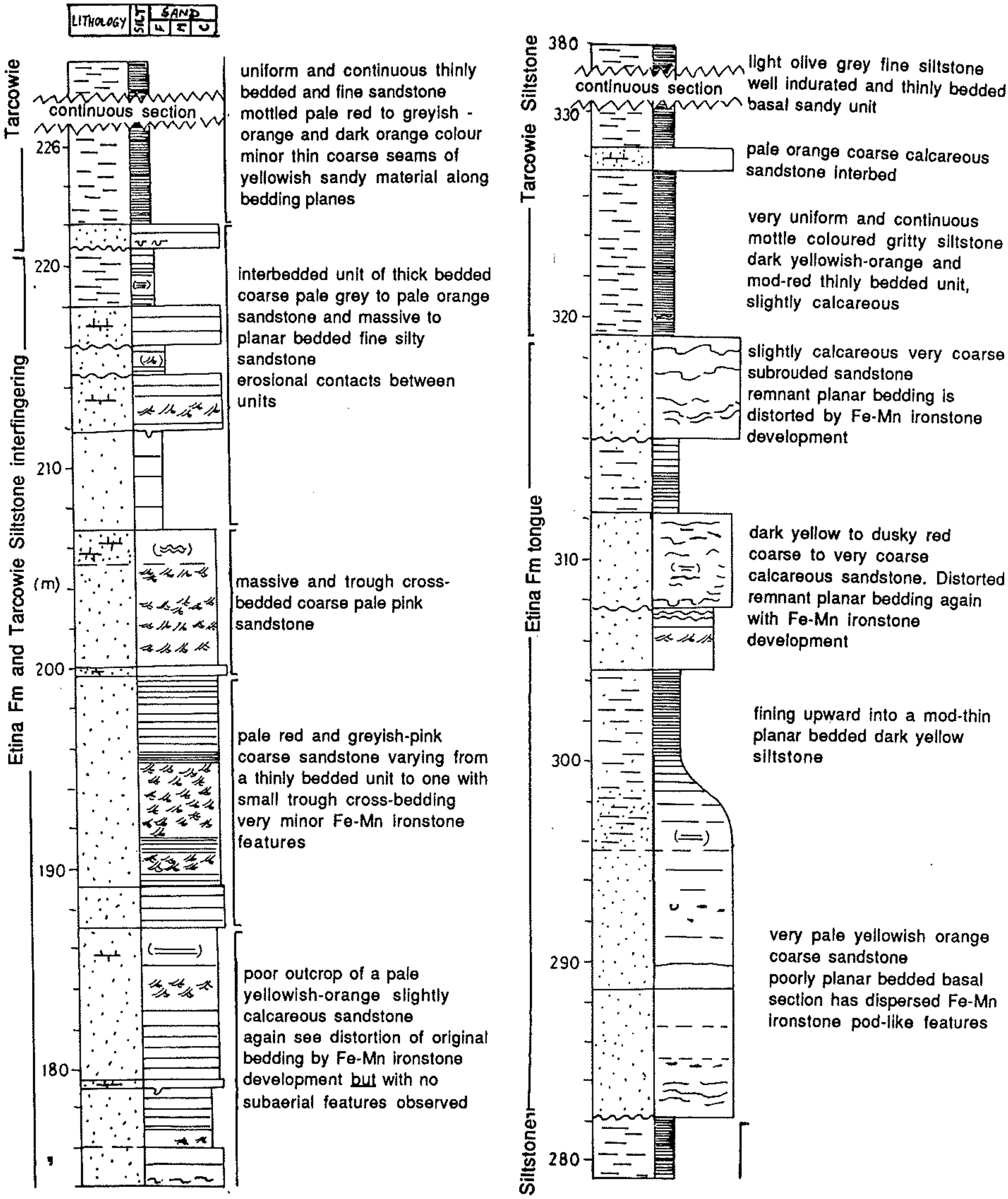
pale red massive coarse sandstone
isolated thick bedding
minor granular trains with a subangular quartzose lithology



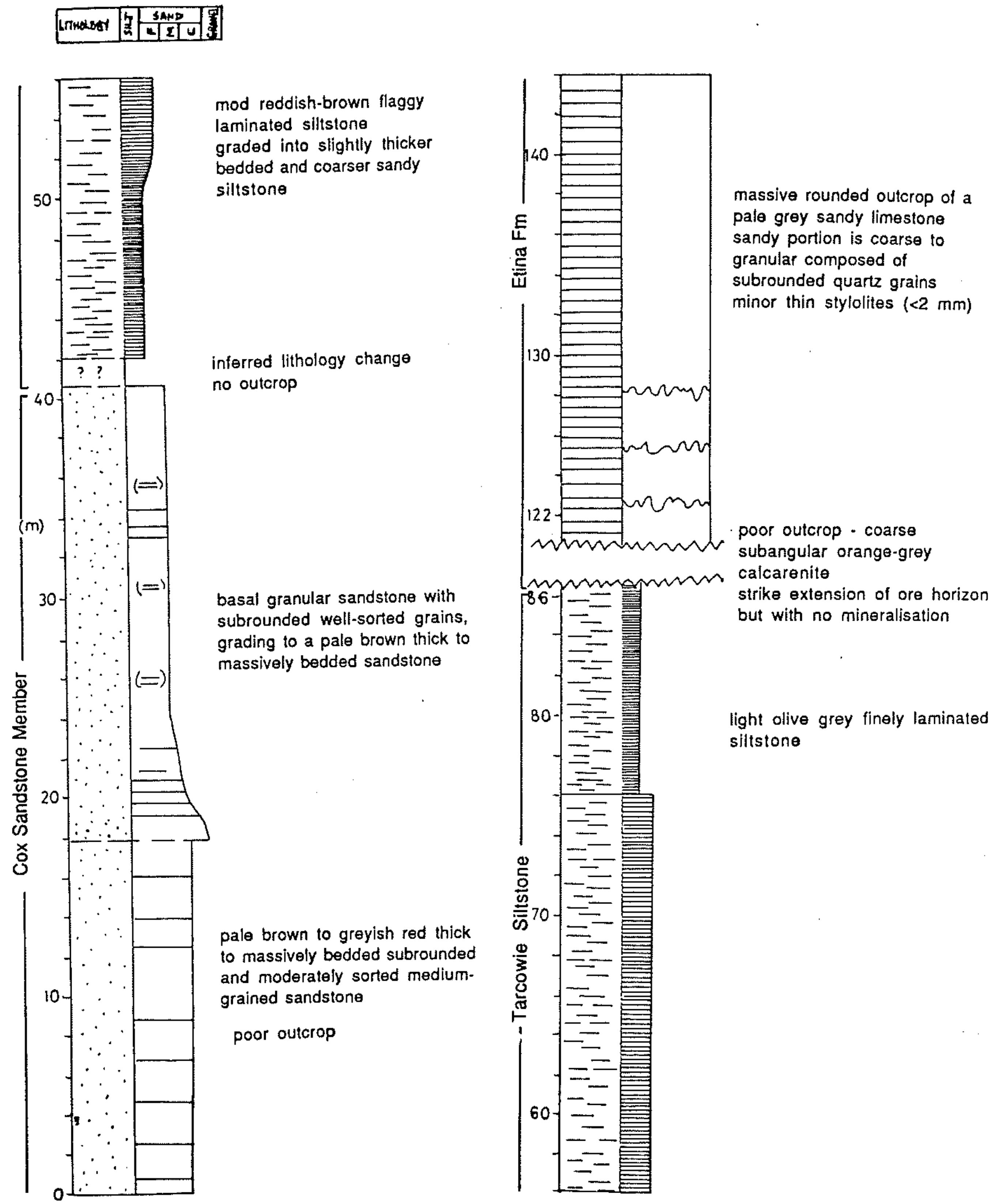
continuous sequence of a greyish-pink alternating massive to wavy bedded sandstone

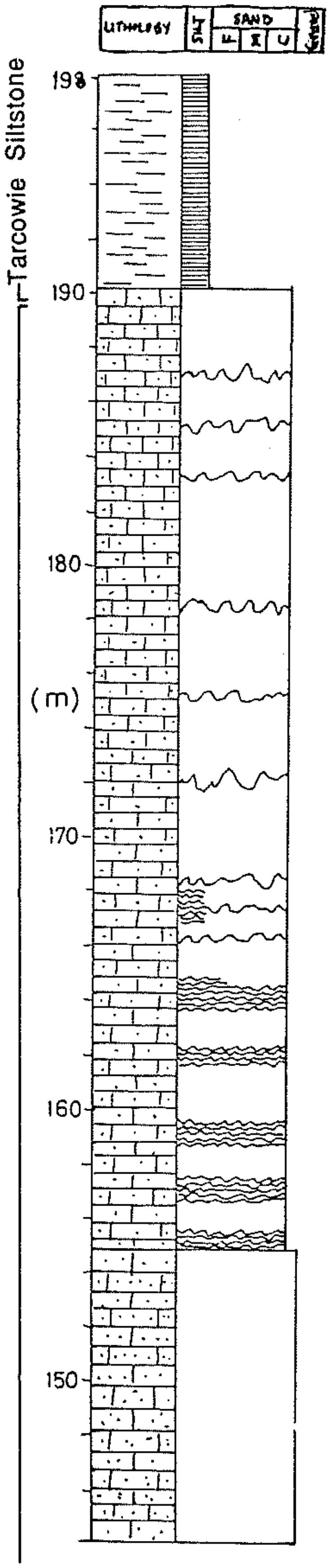
Muttabee: Stratigraphic Section #1
C Gregory 1988




LITHOLOGY
SILT
SAND
F
M
C
Tarcowie
continuous section
Etina Fm and Tarcowie Siltstone interfingering
226
220
210
(m)
200
190
180
uniform and continuous thinly bedded and fine sandstone
mottled pale red to greyish - orange and dark orange colour
minor thin coarse seams of yellowish sandy material along bedding planes
interbedded unit of thick bedded coarse pale grey to pale orange sandstone and massive to planar bedded fine silty sandstone
erosional contacts between units
massive and trough cross-bedded coarse pale pink sandstone
pale red and greyish-pink coarse sandstone varying from a thinly bedded unit to one with small trough cross-bedding
very minor Fe-Mn ironstone features
poor outcrop of a pale yellowish-orange slightly calcareous sandstone
again see distortion of original bedding by Fe-Mn ironstone development but with no subaerial features observed
Tarcowie Siltstone
Etina Fm tongue
Siltstone
380
330
320
310
300
290
280
continuous section
light olive grey fine siltstone
well indurated and thinly bedded
basal sandy unit
pale orange coarse calcareous sandstone interbed
very uniform and continuous mottle coloured gritty siltstone
dark yellowish-orange and mod-red thinly bedded unit,
slightly calcareous
slightly calcareous very coarse subrouded sandstone
remnant planar bedding is distorted by Fe-Mn ironstone development
dark yellow to dusky red coarse to very coarse calcareous sandstone. Distorted remnant planar bedding again with Fe-Mn ironstone development
fining upward into a mod-thin planar bedded dark yellow siltstone
very pale yellowish orange coarse sandstone
poorly planar bedded basal section has dispersed Fe-Mn ironstone pod-like features

Muttabee: Stratigraphic Section #2
C Gregory 1988



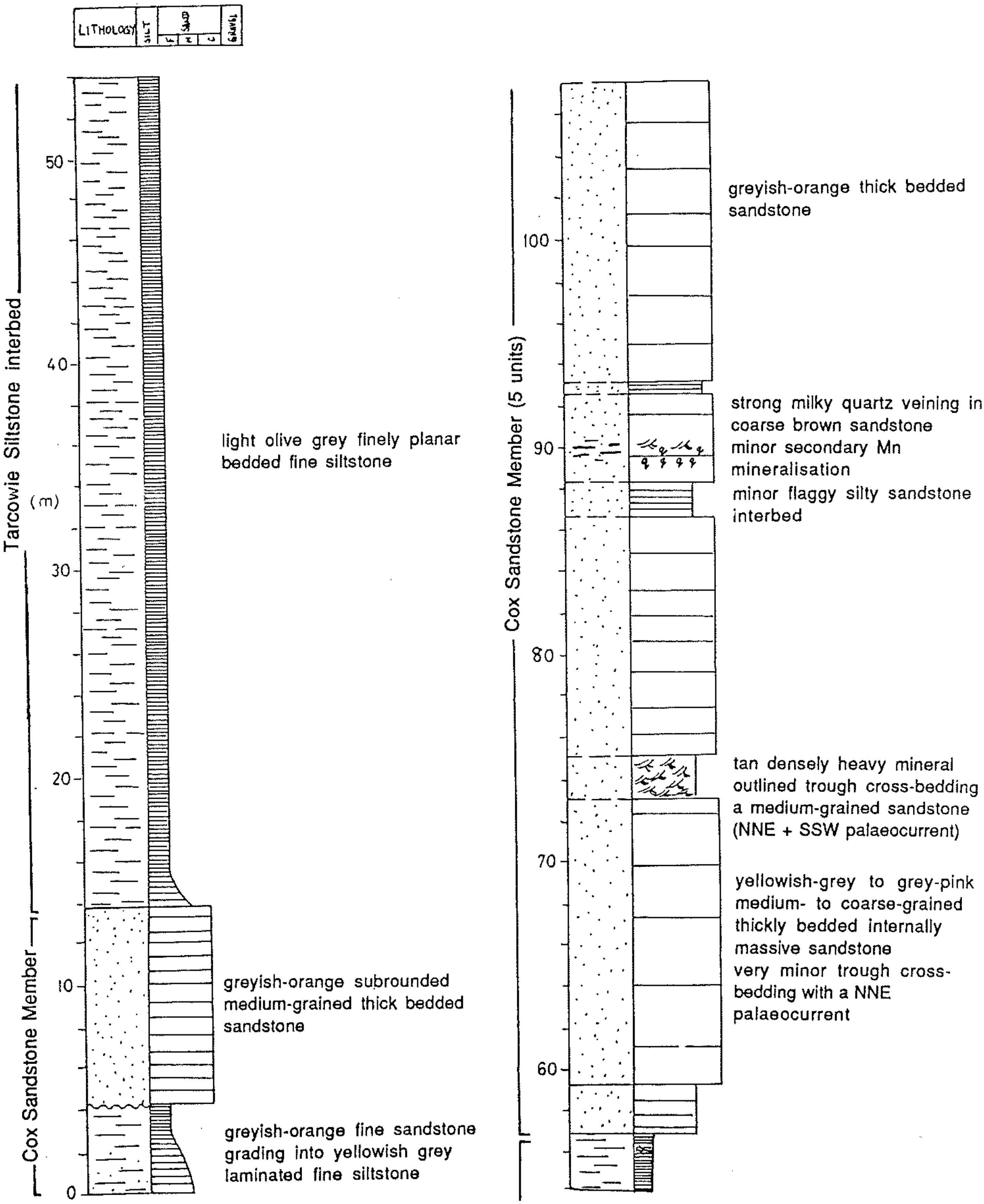


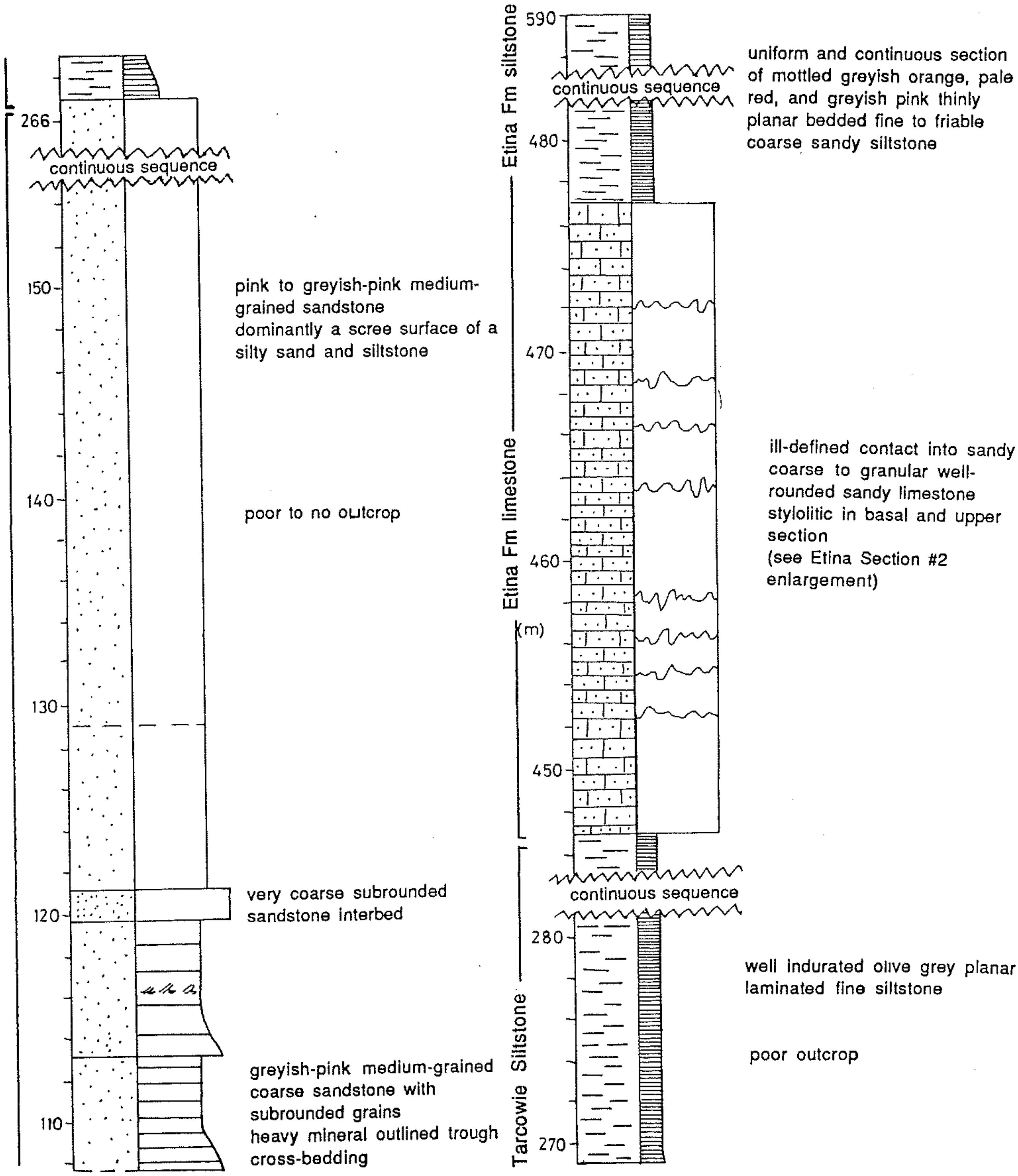
light olive grey laminatd fine indurated siltstone

stylolites dominate in upper sequence

yellowish grey fine sandy limestone
specific zones of yellow-grey fine muddy interbeds, wavy in form

Etina: Stratigraphic Section #1




266
continuous sequence
150
pink to greyish-pink medium-grained sandstone
dominantly a scree surface of a silty sand and siltstone
140
poor to no outcrop
130
very coarse subrounded sandstone interbed
120
greyish-pink medium-grained coarse sandstone with subrounded grains
heavy mineral outlined trough cross-bedding
110
Etina Fm siltstone
590
continuous sequence
480
uniform and continuous section of mottled greyish orange, pale red, and greyish pink thinly planar bedded fine to friable coarse sandy siltstone
Etina Fm limestone
470
460
450
(m)
ill-defined contact into sandy coarse to granular well-rounded sandy limestone stylolitic in basal and upper section
(see Etina Section #2 enlargement)
continuous sequence
Tarcowie Siltstone
280
270
well indurated olive grey planar laminated fine siltstone
poor outcrop

Etna: Stratigraphic Section #2
C Gregory 1988