VOLUME 2 OF 2

THE LADY LORETTA FORMATION: SEDIMENTOLOGY AND STRATIFORM SEDIMENT-HOSTED BASE METAL MINERALISATION

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Appendices
A-1. FIELD METHODS

A-1.1 REMOTE SENSING

Based on the interpretation of remote sensed data, key field sections were located over areas of best outcrop and to avoid structurally complex regions. Various scales of airphotos and enlargements ranging from ca. 1:1000 to 1:80 000 were used. The geology of the western flank of Kamarga Dome was interpreted at ca. 1:25 000 from colour airphotos. The bedding trends, confirmed by dip and strike measurements on the ground, are shown in the location maps for sections KD1 to 6. Black and white and colour airphotos and false colour Landsat and SPOT imagery were used in the interpretation of the Lady Loretta mine environs and the Redie Creek area. Key surfaces and facies identified in field sections were matched to detailed airphoto interpretations and traced laterally were possible.

A-1.2 FIELD SECTIONS AND MAPPING

Over a dozen field sections, totalling approximately 68.5 km on the ground, were measured in the field. The start and finish of each area of outcrop described were accurately located using a Global Positioning System (GPS) (see Appendix A.4). Detailed sections were measured using a Jacob's staff and Abney level, Brunton compass and tape, or measurements relative to a taut line. Ground sections were dip corrected manually using modal dips as the section was being measured. The measured sections were augmented by dozens of spot observations and detailed examination of other areas of outcropping Lady Loretta Formation. Where outcrop permitted, key surfaces and diagnostic facies were walked out and lateral variations noted. The immediate environs of the Lady Loretta mine and several areas at Kamarga Dome were mapped in detail (see Appendices A-15 and A-16). The locations of these areas and the types of data collected are summarised in Table 1-2, Section 1.6.

Emphasis was placed on recognition and description of:

- sedimentary structures
- pseudomorphed evaporites
- microbial fabrics
- ripple morphology using qualitative and quantitative methods
- palaeocurrent indicators
- cyclic sedimentation
- potential bounding surfaces that could be traced laterally.

Computer drafted sections of true stratigraphic thickness (tst) were generated at scales appropriate to the detail recorded and are included as Appendix A-15.
A-2. PALAEOCURRENT MEASUREMENT AND ANALYSIS

A wide variety of oriented sedimentary structures was used for palaeocurrent analysis (see Section 5.5). The majority of data were derived from the maximum dip of crossbeds and the trends of ripple crests. These have been treated separately. To avoid a bias introduced by better outcrop of individual bed forms, approximately equal numbers of measurements were taken from each bed exposed in any outcrop. Measurements made in the vicinity of the mine include proportionally more small bedforms such as ripple cross-lamination where these can be seen in section.

All measurements were corrected for tectonic dip using specialist software. Data from outcrop of the synclines at Lady Loretta mine have been corrected by unfolding the synclines. The palaeocurrent data are presented as 10% class size, equal area plots, in the conventional current-to sense. Vector data were plotted unidirectionally and the trends of ripples, channel orientations and the elongation of microbialites are shown bidirectionally. The number of measurements are shown next to the rose. The vector mean, vector magnitude and consistency ratio were calculated for all plots and are available on request. However, the software used does not treat bimodal data appropriately.

A-3. CORE LOGGING

Drillholes containing cored intersections of the Lady Loretta Formation described in detail are located in Figure 3-5 and summarised in Table 1-2, Volume 1. None are a complete intersection of the whole formation. The majority of core is HQ or NQ diameter. Some deeper holes stepped down to BQ.

Key intersections from the Lady Loretta mine were chosen to avoid structural complications and to complement other detailed work by Aheimer (1994), Carr (1981), McGoldrick (1993, 1994) and NABRE. In addition, dozens of other cores from the mine were examined to compile the palinspastic and sedimentological reconstructions.

Although there is extensive core of the ore body, it was not oriented during drilling, has been intensively sampled with consequent missing sections, and is in generally poor condition. Core from the surface drilling has been mechanically split and broken into short lengths (<3 cm), making it very difficult to work with. All core that intersected the Ore Sequence or Pyritic Unit, including some key intersections described by Carr (1981), has deteriorated during storage because of the presence of reactive pyrite (Figure A-3-1). Recourse to the original mine-site core descriptions, Carr's (1981) original data and colour photographs of the core immediately after drilling were advantageous.

In several instances, minor errors were detected on the depths marked on the core or there were mismatches between the core annotations, box labels and/or the driller's blocks marking the end of each core run. The annotated core was given precedence and errors were corrected by iteration over the interval of the core run.

Unless otherwise acknowledged, the core from angled and/or curved drillholes has been corrected to true stratigraphic thickness. Dip to core axis measurements were taken at
a spacing appropriate to their rate of change (nominally about every ten metres) and the calculations were performed on Geotrig software. Core descriptions at decimetre to metre scale were computer drafted at scales of 1:100 or 1:200 graphic logs (Appendix A-15) using AppleCore software.
Figure A-3-1: The good, the bad and the ugly. (a) A portion of a typical core from underground drilling at the Lady Loretta mine. Drillhole 2330WD55, 96.7 to 109.5 m. Photographed immediately after drilling in 1988. (b) The same core, after slabbing and storage. Photographed in 1996. Note the deterioration because of reactive pyrite. (c) Another example showing reactive pyrite from immediately below the Ore Sequence, drillhole 2250WD42. White ruler is 30 cm long.
LADY LORETTA
1983
U/G PROGRAM
4 LEVEL
DRILL HOLE
233 WD 55
INTERVAL
96.7 TO 109.5
A-4. NOTES ON LOCATION AND SAMPLE DATA

The field sample numbers are prefixed by an abbreviation of the location name. A key to the abbreviations is given at the start of volume one and in Table 1-2, Volume 1. The 1966 Australian Metric Map Grid has been used. The Universal Grid Zone Designation is 54K. Coordinates shown in bold in Appendix A-13 are GPS fixes. These are claimed to have a precision of ±12 m. Other locations are approximate, taken from airphotos, the published 1:100 000 topographic maps or the CEC 1:5000 map of the mine area.

In the vicinity of the Lady Loretta mine, the most recent of the plethora of mine map grids was used to locate samples on the 1:5000 scale maps (Appendix A-16). An algorithm to convert from one grid to another and to AMG was provided by Mark Duffet (CODES) and the AMG grid has been added to maps (Appendix A-16). Drillhole numbers have been prefixed by the drilling section. These are metres increasing in a northeast direction. Surface drillholes contain the letter P. For example, drillhole 2315P91 spudded at the surface on grid line 2315. The abbreviation MET in a drillhole name refers to core drilled for metallurgy. Several of these drillholes recovered 8 inch diameter core. Underground drilling has been undertaken along the plane of the drilling section as either east inclined or declined (EI and ED) or their western counterparts. The final numbers in the name of the underground drillhole are the angle relative to horizontal. Thus, 2420ED13 was drilled to the east, 13° below horizontal on section 2420. Depths refer to the distance from the top of the collar.

Catalogue numbers (in Appendix A-13) refer to samples held in the collection of the Geology Department, University of Tasmania. Arrows indicate stratigraphic-up and, in the case of underground drilling and overturned bedding, are not necessarily up hole. The core depths given for catalogued samples are driller's depths and do not correspond to the true stratigraphic thicknesses shown on the graphic logs in Appendix A-15.

Duplicates of many samples are held at the Lady Loretta mine office and some duplicate samples were collected by NABRE (AGSO).
A-5. PETROGRAPHY

A-5.1 PETROGRAPHIC NOMENCLATURE

Rocks containing more than 50% terrigenous material were classified according to the particle and grain sizes on the Wentworth (1922) scale as modified by Swanson (1981). Siliciclastic rocks are classified using Swanson's (1981) compositional classification. Carbonate descriptions follow Embry and Klovan's (1971) modification of Dunham's (1962) terminology. The current study follows Wright (1992a) who recommended a 62.5 μm boundary in defining carbonate "mud".

The grainsize shown on the graphic logs (Appendix A-15) is a compromise of clastic grainsize, carbonate texture and sedimentary profile produced by the software.

The term dolostone is used to distinguish the lithotype from dolomite the mineral, and the terminology for dolomite crystal forms is from Sibley and Gregg (1987).

Barite textures and cauliflower cherts are described using the anhydrite textural classification of Maiklem et al. (1969).

The terminology for quartz varieties follows the descriptive nomenclature as presented by Hesse (1990). This is based on optical properties and is not a mineralogical classification.

A-5.2 PETROGRAPHIC METHODS

Where appropriate, carbonates have been stained with Alizarin Red-S, either in thin section or slab. Potassium ferricyanide stain was used to distinguish ferrous carbonates. Siderite was stained using the potassium hydroxide - hydrogen peroxide method of Warne (1962).

Over 150 thin sections, including some from Aheimer (1994) and others loaned by AGSO and exploration companies, were examined using conventional plain and polarised light microscopy. Cathodoluminescence microscopy was of limited value because the majority of samples, including those with complex cement histories, had only a uniformly dull luminescence. Attempts to distinguish between detrital and authigenic feldspar using cathodoluminescence were also unsuccessful.
A-6. ANALYTICAL METHODS

A-6.1 XRD, ISOTOPE AND TRACE ELEMENT STUDIES OF DOLOMITIC ROCKS

The current study has used analytical data provided by several independent studies. In addition, XRD, isotope and trace element studies were undertaken as part of this study.

Seventeen whole-rock carbon and oxygen isotopic analyses of dolostones and dolomitic siltstones in core from drillhole Amoco 83-5 were undertaken as part of AMIRA/ARC project P384. The samples were run at 49°C on a SIRA mass spectrometer at the Central Science Laboratory, University of Tasmania, and the data have been corrected to 25°C using a factor of 0.04 per mil per degree C. The precision of these data, established with duplicate analyses for both O and C, is ± 0.1‰. Independent whole-rock sampling and analyses of the same core were undertaken as part of the NABRE project and their results were incorporated into the database.

More detailed sampling was undertaken specifically for the current study. Unweathered dolomite was sampled using a dental drill under a binocular microscope, avoiding diagenetic material such as veins. XRD analysis was used to confirm the mineralogy and to determine the degree of crystallinity. The samples were run on the X-ray diffractometer system at the Tasmanian Department of Mineral Resources. The qualitative mineralogy was determined by manual search-match methods. The eleven strongest peaks of the dolomites were used for cell dimension refinement by least-squares. The mean errors are: a₀ (∅) ±0.0015; c₀ (∅) ±0.008; d (104) ± 0.001. The mole percent Mg in dolomite was determined by the Goldsmith et al. (1961) method with an error of ± 0.01‰. Stoichiometry and degree of crystallinity are expressed relative to lattice constants for the dolomite-calcite series from Land (1985).

The powders were allowed to react with anhydrous phosphoric acid under vacuum for 24 hours. The evolved CO₂ from each sample was analysed for δ¹³C and δ¹⁸O using the Optima automated mass spectrometer at the Central Science Laboratory, University of Tasmania. The precision for δ¹⁸O varies between 0.003 and 0.014‰ and for δ¹³C is between 0.002 and 0.008‰. The δ¹⁸O values are expressed relative to VPDB and VSMOW.

Portions of the duplicate powders were dissolved in 1 M HCl for 2 hours and analysed for Ca, Mg, Na, Mn and Fe using a Techtron atomic absorption spectrophotometer. The detection limits are ± 1% for Ca and Mg and ± 5 ppm for Na, Mn and Fe (Robinson, 1980). Strontium was analysed using a Varian Spectra A800 AAS. The precision is ± 5 ppm. Several sample blanks and the GFS400 and NBS88b dolomite standards were used to monitor the precision. Similar trace element analyses from whole-rock samples of the Lady Loretta Formation by McGoldrick (1993) were also utilised in the current study.
Analytical and gravimetric factors used to convert results expressed as oxides or carbonates to proportional elemental composition, and vice versa, were taken from Németh (1975).
A-6.2 ANALYSIS OF ORGANIC CARBON

Samples (>400 mg dry weight) of carbonaceous rock were collected from core by drilling using either a 2 mm masonry bit or a dental drill. Obviously pyritic or mineralised material was rejected. A mineralogical sample of FeCO₃, analytical grade CaCO₃ and charcoal were also used to test the technique. Samples found to contain siderite were rejected after it was demonstrated that its presence could produce erroneously high TOC values. The standards Tas-Dolomite and NIST1c were used to monitor the precision. Duplicates of the latter gave a precision of ± 0.02 % TOC. Organic carbon was determined using a slight modification of the method of Krom and Berner (1983). In this method, one subsample is analysed for total (inorganic plus organic) carbon using a Carlo Erber Elemental Analyser and another is analysed for inorganic carbon after ashing for 24 hours at 400°C. The difference between the two equates to organic carbon as measured by combustion.

During the current study, drillholes 2240P142 and 740P148 at the Lady Loretta mine and Amoco 83-5 were sampled for organic petrology. The analyses were undertaken by NABRE (AGSO) and some results are presented by Crick (1997).
## A-7. ANALYTICAL RESULTS

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<th>H</th>
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<th>%TOC</th>
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*Table A-7-1: Results of TOC determinations. The colours refer to rock colour chart by Goddard et al. (1979).*
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**Table A-7-2:** XRD and isotope data for samples of ooid pisoid grainstone, Kamarga Dome (this study) and oxygen isotope data from the Lady Loretta ore body (from Large et al., 1995).
Table A-7-3: Major and trace element data for ooid pisoid grainstone, Kamarga Dome.

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<th>Fe %</th>
<th>Mn ppm</th>
<th>Mn %</th>
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<th>Na %</th>
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*Sample rejected
A-8. CARBONATE MINERALOGY IN THE LADY LORETTA FORMATION

The carbonate mineralogy of the Lady Loretta Formation has been analysed at several localities (core from drillhole Amoco 83-5, section KD4 Kamarga Dome, the Lady Loretta ore body, Johnson Creek and the Carrier area) that span the range of stratigraphic and lateral distribution of the formation. The last two locations were included as possible analogues for the Lady Loretta SSHBM mineralisation. In addition, spot samples from other drillholes have been analysed. Many of these data are unpublished analyses by other workers (Berg, 1986; Carr, 1981; Duhig, 1994; McGoldrick, 1993). Other spot analyses quoted in company reports demonstrated unusual carbonate mineralogy elsewhere in the Lady Loretta Formation (e.g. elevated Mn from 142-176 m driller's depth in drillhole CM35 in the Dayview Syncline).

Details of the analytical techniques used in this study are presented in Appendix A-6.1.

Complimentary carbon and oxygen isotopic studies have been undertaken at the Lady Loretta mine and from the KD4 section.

A-8.1 KAMARGA DOME

A-8.1.1 Carbonate Composition

Surface samples of least-weathered dolomite from the KD4 section at Kamarga Dome are well-ordered and close to stoichiometric. An ooid pisoid grainstone (see Section 6.3) was analysed in detail. The major element composition of the coated grains and cement are similar and plot close to pure dolomite (Figure A-8-1), although the insoluble residue contains a high proportion of quartz resulting from the preferential silicification/overgrowth of ooid nuclei.

A-8.1.2 Primary Aragonite, Dolomite or Calcite?

It has been suggested that most atypically large Proterozoic coated grains, such as those analysed here, were originally aragonitic in composition. These interpretations were based on the spalling of the ooid coats and the relatively high Sr content. Swett and Knoll (1989) considered values in excess of 2000 to 4000 ppm Sr diagnostic as an aragonite precursor. Spalling of coats was not observed in the Lady Loretta examples and Table A-8-1 compares the Sr content to other Proterozoic coated grains.

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<td>pisoid</td>
<td>&lt;100 - 7382</td>
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</tr>
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<td>ooid</td>
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<td>Tucker (1985)</td>
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<td>μ = 45.0, σ = 16.5</td>
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Table A-8-1: Comparison of Sr contents of various Proterozoic coated grains.
Even allowing for some loss during diagenesis, the Sr contents of the coated grains from the Lady Loretta Formation are 50 times lower than the other Proterozoic samples cited. Thus, it is unlikely that the Lady Loretta coated grains had an aragonite precursor.

It is not possible to differentiate between a dolomite or calcite precursor based on either textural evidence or geochemistry.

A-8.2 LADY LORETTA ORE BODY
A-8.2.1 Carbonate Composition
Studies by Taylor (1973), Carr (1981, 1984), Duhig (1994) and work undertaken for the current study have demonstrated the wide variation in composition of carbonates at the Lady Loretta mine. Several studies (e.g. Large and McGoldrick, 1993) documented a systematic change in carbonate composition associated with an alteration halo around the orebody. Siderite forms an envelope about 50 m wide surrounding the ore. This grades out through an ankerite zone to dolomite, some 150 m from the ore. The present examines the gross variations associated with the ore body so they can be compared with carbonate compositions from elsewhere.

The first set of data from the Lady Loretta ore body was taken from Carr's (1981) unpublished microprobe data after low totals were filtered out. It should also be pointed out that there is a discrepancy of about 3 wt% between Carr's (1981) microprobe and AAS analyses, especially from samples of the Ore Sequence. The microprobe analyses have spurious low Ca.

Forty five dolomites and 55 siderites are plotted on the carbonate composition tetrahedron shown unfolded in Figure A-8-2b. This demonstrates several important points:
• there is only minor variation in composition between the groundmass and vug-fill in either dolomites or siderites; sideritic veins are slightly higher in MnCO3
• the dolomites range through ferroan dolomite toward ankerite (Figure A-8-2c)
• the siderites are a diverse group, note the spread in MnCO3/MgCO3 and the two samples of groundmass and one vein that have unusual FeCO3/CaCO3.

Carr (1981) demonstrated that the siderite at Lady Loretta mine includes compositions more accurately described as sideroplesite and pistomesite. A more detailed microprobe analysis by Duhig (1994) included mineralised samples (with significant wt% ZnCO3) and is probably more reliable data than Carr's (1981) analyses from the Ore Sequence. Duhig’s (1994) study identified a complete spectrum of carbonate compositions from almost pure dolomite through ferroan-dolomite to ankerite and magnesian siderite, sideroplesite and pistomesite in association with high ZnCO3 siderite. This variation can occur over a very small scale. For example, a single thin section contained 2.8 -14wt% MnCO3, 5-30wt% MgCO3 and 0.7-14.4wt% ZnCO3. Duhig (1994) confirmed that the ankerite, not dolomite, is the dominant carbonate outside the zone of sideritic alteration.

Linear regression analyses of Carr's (1981) data was undertaken to study elemental relationships in more detail. Although crossplots and regression analyses of major and minor elements in carbonates are commonly undertaken in studies of diagenesis (e.g. Adabi,
1997; Adabi et al., 1996; Rao, 1990; Veizer, 1983), any inferred relationships between major elements may be statistical aberrations (McGoldrick pers. comm., 1996). Where only two or three elements account for the bulk of the composition, it is only to be expected that there will be an antithetic relationship between them. Furthermore, using the percentage of insoluble residue to adjust the analyses to a total of 100 percent will introduce additional complications to any statistical analysis. These compounded problems account for the highly questionable $r^2$ values (0.99, 0.91, 0.88) derived from Carr’s (1981) 20 AAS analyses of Ca, Mg and Fe in dolomites from the Lady Loretta mine.

Carr’s (1981) microprobe data appear more reliable (after low totals and dolomitic siltstones were excluded) since the major elements do not have a simple antithetic relationship (Table A-8-2).

<table>
<thead>
<tr>
<th>Lady Loretta Mine</th>
<th>+ / - Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca, Mg, Fe, Mn</td>
<td></td>
</tr>
<tr>
<td>n = 60</td>
<td></td>
</tr>
<tr>
<td>$r^2$</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>+</td>
</tr>
<tr>
<td>Mg</td>
<td>0.57</td>
</tr>
<tr>
<td>Fe</td>
<td>0.20</td>
</tr>
<tr>
<td>Mn</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table A-8-2: Results of regression analysis of Carr’s (1981) microprobe data from dolomites at the Lady Loretta mine. Significant correlations are shown in bold.

The most statistically valid trends in the microprobe data are positive correlations between Ca and Mg and a negative relationship between Mg and Fe. Dolomites should have a strong correlation between Ca and Mg, but this would normally be a negative relationship, as Mg replaces Ca. The positive relationship is interpreted as an alteration trend, involving at least one other element, by suggesting that both Mg and Ca are being substituted for (Adabi, pers. comm., 1996).

The significance of siderite is another important aspect of the carbonate chemistry at the Lady Loretta mine and is discussed more fully in Section 11.3.1. Several authors (e.g. Carr, 1981; Vaasjoki and Gulson, 1985) have stated that the presence of siderite at Lady Loretta contrasts to the prevalence of dolomite in other north Australian SSHBM ore bodies. Whereas siderite is relatively most abundant at Lady Loretta, it is also present at Hilton (Mount Isa), Mount Novit and Century. Comparison of the siderite at Lady Loretta with analyses from the Mount Isa sequence (reported in Neudert, 1983) show that, compositionally, they are similar.

At the Lady Loretta mine, Carr (1984) described two generations of siderite, distinguished by the relative amount of Zn. He also interpreted his 1981 data to show a general trend of increasing Zn content in siderite stratigraphically toward the Ore Sequence. Although this would be difficult to justify statistically (Figure 8-2a) based on his data, it was confirmed by independent analyses reported by Large and McGoldrick (pers. comm., 1997).
Taylor (1973) noted the complete absence of dolomite in siderite-bearing samples and Hancock and Purvis (1990) stated that siderite and dolomite were mutually exclusive on a microscopic scale. Carr (1984) found that the two carbonate phases do not occur together in unmineralised host rocks although they do co-exist within the ore and in veins throughout. It is true that the end members (dolomite and siderite) are rarely found together on a microscopic scale, but all the previous statements are contrary to the observed gradation through ferroan-dolomite that commonly occurs within individual beds over vertical distances of several centimetres. Siderite occurs where dolomite and pyrite are interbedded but is most abundant directly adjacent to the pyrite and on the side overlying, not underlying, the pyrite (as illustrated in Aheirer, 1994, his Plate 4.5). This can be interpreted to suggest a diagenetic origin of at least some of the siderite, with Fe leaching up from the pyrite. The diagenetic origin of the siderite is discussed more fully in Section 11.3.1.

Duhig (1994) found that Mn and Mg in siderite are positively correlated and inversely correlated to Zn and Fe. To test this, Carr’s (1981) microprobe data have been converted to proportional elemental compositions and statistically analysed using linear regression analysis (Table A-8-3).

<table>
<thead>
<tr>
<th>Lady Loretta Mine</th>
<th>+ / - Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ca    Mg  Fe  Mn  Zn</td>
</tr>
<tr>
<td></td>
<td>0.01  0.91 0.00 0.09</td>
</tr>
<tr>
<td>r²</td>
<td>0.06  0.09 0.25 0.00</td>
</tr>
<tr>
<td></td>
<td>0.00  0.20 0.05 0.00</td>
</tr>
</tbody>
</table>

Table A-8-3: Results of regression analysis of Carr’s (1981) microprobe data for siderite.

There is a strong negative correlation between Fe and Mg, as would be expected if Fe was substituting for Mg in the transformation of dolomite to siderite. None of the other relationships inferred by Duhig (1994) can be justified based on Carr’s (1981) data.

A-8.3 AMOCO 83-5
A-8.3.1 Carbonate Composition
Limited analyses of whole rock samples from impure dolomites and dolomitic siltstones in core range from 11% to 49% percent dolomite. A linear regression analysis (Table A-8-4) of the elemental composition of the nine most-dolomitic samples shows a strong positive trend between Ca and Mg similar to other dolomite samples discussed above. Nickel appears to have an antithetic relationship to Ca and Mg, possibly reflecting its greater abundance in the least pure dolomites. The lack of any correlation with Na may be because of low Na totals. Positive correlations between the other trace elements are normally associated with sediments enriched in organic matter, with reducing conditions, or both (Mongenot et al., 
1996). It is significant, therefore, that the majority of facies sampled here are both oxidised and of low TOC (<0.5 wt%). There is a positive correlation between V and Cr. The ratio of V/Cr for all the samples from Amoco 83-5 (including dolomitic siltstones and shales) averages 1.3 with a maximum of 2.0. Such values (V/Cr <2.0) in shales are interpreted as evidence of oxic conditions (Jones and Manning, 1994). The Zr values for the carbonates are significantly lower than from clastic rocks in the same core, but in both cases there is a strong positive correlation with TiO₂ (overall $r^2 = 0.92$). This is interpreted as the sedimentary concentration of detrital heavy minerals (zircon and rutile), as might be expected in a tidal environment.

<table>
<thead>
<tr>
<th>Amoco 83-5</th>
<th>+ / - Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 9</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>+ - + + - - - - -</td>
</tr>
<tr>
<td>Mg</td>
<td>0.99 - + + + - - - - -</td>
</tr>
<tr>
<td>Fe</td>
<td>0.33 0.36 + - - + + + + +</td>
</tr>
<tr>
<td>Mn</td>
<td>0.23 0.17 0.00 + - - - - -</td>
</tr>
<tr>
<td>Sr</td>
<td>0.43 0.37 0.11 0.18 - - - - - -</td>
</tr>
<tr>
<td>Na</td>
<td>0.00 0.01 0.22 0.05 0.23 - + - + + +</td>
</tr>
<tr>
<td>Cr</td>
<td>0.42 0.37 0.23 0.41 0.29 0.00 0.79 + + + +</td>
</tr>
<tr>
<td>Ni</td>
<td>0.62 0.49 0.25 0.47 0.39 0.00 0.23 + + + +</td>
</tr>
<tr>
<td>Rb</td>
<td>0.42 0.39 0.38 0.28 0.20 0.02 0.95 0.69 + +</td>
</tr>
<tr>
<td>V</td>
<td>0.44 0.48 0.44 0.22 0.40 0.00 0.89 0.70 0.93 + +</td>
</tr>
<tr>
<td>Zr</td>
<td>0.16 0.16 0.17 0.15 0.18 0.01 0.78 0.57 0.74 0.72</td>
</tr>
</tbody>
</table>

Table A-8-4: Results of linear regression analysis of dolomitic samples from Amoco 83-5 core. Raw data from McGoldrick (1993). Significant correlations are shown in bold.

A-8.4 JOHNSON CREEK

A-8.4.1 Carbonate Composition

Taylor (1973) described the mineralogy and geochemistry of sideritic ironstones from outcrop and carbonates from core intersections at Johnson Creek. This work was prior to the stratigraphic subdivision of the Paradise Creek Formation and his samples are now assigned to the lower-most Lady Loretta Formation.

The carbonate compositions, shown in Figure A-8-3, are similar to the Lady Loretta mine. They range from ferroan dolomite, through ankerite, to almost pure siderite. Note that there is also a wide spread in MgCO₃/ MnCO₃.

Analyses from pyritic facies in drillhole DDJ1 at Johnson Creek show the dolomite to be well-ordered and close to stoichiometric. Siderite, sideroplesite and pistomesite were also detected and Taylor (1973) considered their presence unusual in Australia. This is probably an overstatement, but it is significant that these minerals also occur in the Lady
Loretta Formation away from the mine and at a different lithostratigraphic position to the ore body. As these carbonate minerals have been used to indicate the alteration halo around the Lady Loretta Zn-Pb-Ag ore body, it may enhance the prospectivity of the Lady Loretta Formation in the Johnson Creek area. However, Taylor's (1973) analyses could be interpreted to show that Cu (average of 605 ppm, maximum 6000 ppm) may be a more likely target than Pb (average of 8.5 ppm, maximum 20 ppm) or Zn (< 60 ppm). Alternatively, it may indicate that these carbonate compositions are a common diagenetic feature of carbonates in highly pyritic facies and may not, in isolation, be vectors to mineralisation.

A linear regression analysis of major and minor elements (Table A-8-5) was compared to the data from the Lady Loretta mine. Fluorine was included because it is unusually, and consistently, high in all of Taylor's (1973) samples. Fluorine does not correlate to any other element analysed. As with the previous locations, the strongest positive correlation is between Ca and Mg and there is a negative correlation between Fe and Ca. Iron and Mn, however, have a positive correlation as do Cr and V. The ratio of V/Cr is significantly lower than for Amoco 83-5 and averages 0.6 with a maximum of 1.3. This may be interpreted to suggest more oxic conditions if the work of Jones and Manning (1994) can be extrapolated from shales to carbonates. However, since no details of the sample preparation were given, it is possible that a Cr steel mill was used.

<table>
<thead>
<tr>
<th>Johnson Ck</th>
<th>+ / - Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>+</td>
</tr>
<tr>
<td>Mg</td>
<td>0.62</td>
</tr>
<tr>
<td>Fe</td>
<td>0.49</td>
</tr>
<tr>
<td>Mn</td>
<td>0.09</td>
</tr>
<tr>
<td>Sr</td>
<td>0.06</td>
</tr>
<tr>
<td>Na</td>
<td>0.00</td>
</tr>
<tr>
<td>Cr</td>
<td>0.17</td>
</tr>
<tr>
<td>Ni</td>
<td>0.15</td>
</tr>
<tr>
<td>V</td>
<td>0.17</td>
</tr>
<tr>
<td>As</td>
<td>0.06</td>
</tr>
<tr>
<td>F</td>
<td>0.00</td>
</tr>
<tr>
<td>Cu</td>
<td>0.24</td>
</tr>
<tr>
<td>Pb</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table A-8-5: Results of linear regression analyses of Taylor's (1973) data from Johnson Creek. The most significant correlations are shown in bold.
A-8.5 CARRIER AREA
A-8.5.1 Carbonate Composition
Drillholes CRD1 to 5 in the Carrier area intersected Lady Loretta Formation and whole rock analyses of their cores are reported in Berg (1986). The compositions of carbonates are plotted in Figure A-8-5. A range of carbonates from slightly calcareous dolomite, through ferroan dolomite and ankerite to impure siderite are present. Proportionally fewer samples have the wide spread of MnCO₃/MgCO₃ seen elsewhere. The generally low MnCO₃ means that the data cluster on the FeCO₃ - MgCO₃ axis and that the top triangle in Figure A-8-5a and b are almost mirror images.

The results of a linear regression analysis of elemental compositions are shown in Table A-8-6. The only statistically valid correlation (using a cutoff of \( r^2 = 0.5 \)) is a negative relationship between Cu and Pb. Positive correlations between Ca and Mg and between Pb and Zn and a negative relationship between Fe and Ni are also suggested.

<table>
<thead>
<tr>
<th>Carrier n = 15</th>
<th>+ / - Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td>Ca</td>
<td>+</td>
</tr>
<tr>
<td>Mg</td>
<td>0.31</td>
</tr>
<tr>
<td>Fe</td>
<td>0.00</td>
</tr>
<tr>
<td>Mn</td>
<td>0.28</td>
</tr>
<tr>
<td>Na</td>
<td>0.08</td>
</tr>
<tr>
<td>K</td>
<td>0.09</td>
</tr>
<tr>
<td>Ni</td>
<td>0.01</td>
</tr>
<tr>
<td>Rb</td>
<td>0.00</td>
</tr>
<tr>
<td>As</td>
<td>0.04</td>
</tr>
<tr>
<td>Ba</td>
<td>0.05</td>
</tr>
<tr>
<td>Cu</td>
<td>0.00</td>
</tr>
<tr>
<td>Pb</td>
<td>0.04</td>
</tr>
<tr>
<td>Zn</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table A-8-6: Results of linear regression analyses of Berg’s (1986) data from carbonates in the Carrier area. The most significant correlation is shown in bold.

A-8.6 SUMMARY
This study of the carbonate chemistry has demonstrated a marked contrast between the "least-altered" dolomite in an ooid/pisoid grainstone and the Fe, Mn, and Mg enriched carbonates associated with carbonaceous pyritic shales at various stratigraphic levels including the host rocks to the Lady Loretta ore body. The data presented can be interpreted to suggest that normal diagenetic alteration is responsible for the ankerite, siderite and various Mn and Mg carbonates at the ore body and that the carbonate alteration halo may be a function of the host facies rather than a vector to mineralisation.
Figure A-8-1: Composition of an ooid pisoid grainstone from outcrop at Kamarga Dome. Twenty eight analyses of coated grains, cement and bulk samples all plot close to the composition of pure dolomite labelled D.
Figure A-8-2: Composition of carbonates at the Lady Loretta mine. (a) The relative abundance of ZnCO$_3$ in siderite plotted stratigraphically. (b) Carbonate composition tetrahedron (unfolded). Solid symbols are dolomite (45 analyses), open symbols are siderite (55 analyses). Circles represent groundmass and diamonds symbolise veins or vug-fill. (c) Both AAS and microprobe analyses of dolomite. Circles represent groundmass and diamonds symbolise veins or vug-fill. Pure dolomite (D) and ankerite (A) are indicated. All analyses from Carr (1981).
Figure A-8-3: Composition of carbonates in the Lady Loretta Formation at Johnson Creek. (a) Carbonate composition tetrahedron (unfolded) showing the range from ferroan dolomite to siderite (23 analyses). (b) Composition shown in relation to pure dolomite (D) and ankerite (A). All analyses from Taylor (1973).
Figure A-8-4: Composition of carbonates from cored drillholes in the Lady Loretta Formation in the Carrier area. (a) Carbonate composition tetrahedron (unfolded) showing the range from slightly calcareous dolomite, through ferroan dolomite and ankerite towards siderite (15 analyses). (b) Composition shown in relation to pure dolomite (D) and ankerite (A.) All analyses from Berg (1983).
A-9. OXYGEN AND CARBON ISOTOPIC STUDIES

A-9.1 DOLOMITE AWAY FROM THE LADY LORETTA MINE

The samples included in the current study consisted of whole rock powders of dolomites from drillhole Amoco 83-5, microbial material and carbonate cement from near the contact of the Esperanza and Lady Loretta Formations in drillhole CM35 and ooids and cement from outcrop of an ooid pisoid grainstone in the KD4 section at Kamarga Dome. The ooid pisoid grainstone was chosen for detailed study because it is:

- the purest dolomite sampled (49.1 - 50.4 mol% Mg)
- the least diagenetically altered (based on textural preservation and trace element composition)
- not associated with an evaporitic overprint
- low in S and/or organic C that might interfere with $\delta^{18}O$ and $\delta^{13}C$ determinations (Spangenberg et al., 1995)
- possible to treat clasts and matrix separately
- suitable for complementary trace element studies
- from a reasonably well constrained environment of deposition.

The results are listed in Appendix A-7, summarised in Table A-9-1 and plotted on Figure A-9-1. Note there is little spread in the data compared to many other similar studies and the low $r^2$ value for the correlation between $\delta^{13}C$ and $\delta^{18}O_{VPDB}$. The overall results are biased by the extreme negative (most depleted) $\delta^{18}O$ values from the microbial samples at the Esperanza/Lady Loretta Formation contact. There is no significant difference between the isotopic analyses of the ooids and the bulk composition. The most positive (most enriched) $\delta^{18}O_{VPDB}$ of -7.850%o is from the Amoco 83-5 core.

If this is accepted as the least-altered dolomite, it is possible to calculate a palaeo-temperature for the time of deposition using the methodology advocated by Rao (pers. comm., Departmental Seminar, 1996), Adabi (1997) and Adabi et al. (in press). This has been modelled for a number of scenarios (Tables A-9-1 and A-9-2), using different equations and assuming different isotopic compositions for Palaeoproterozoic seawater (-8 ± 1‰) consistent with contemporaneous formations in the McArthur Basin (Veizer et al., 1992). Similar results are obtained if the maximum $\delta^{18}O_{VPDB}$ (-8.111‰) from the ooid pisoid grainstone is used. For comparison, the most depleted value of -13.107‰ from the Esperanza / Lady Loretta Formation contact has also been modelled, this gives an unrealistically high depositional temperature (>58°C). Similarly high palaeo-temperatures were calculated when the present $\delta^{18}O_{VPDB}$ seawater of 0.0 was used. If the seawater value of -4.9‰ originally advocated by Irwin (1980) is used, temperatures of about 50°C are obtained.

The results summarised in Tables A-9-1 and A-9-2 show that the palaeo-temperatures from the most enriched $\delta^{18}O_{VPDB}$ analyses, range between 29°C and 39°C. The most plausible cases correspond to 31°C to 35°C. This would indicate a shallow-
water tropical setting to proponents of this technique. In comparison, modern shallow equatorial waters are consistently above 30°C; Persian Gulf lagoons and tidal flats fluctuate seasonally between 15°C and 40°C; Flemming (1977) recorded temperatures of 30°C in a lagoon compared to 16°C in the nearby open ocean; the waters of Shark Bay range from 19°C to 29°C (Rao, 1996); and temperatures of between 60°C and 70°C have been recorded in shallow stratified brine pools (Stewart, 1963).

<table>
<thead>
<tr>
<th>Sample Suite</th>
<th>n</th>
<th>Stats</th>
<th>$\delta^{18}C$ VPDB‰</th>
<th>$\delta^{18}O$ VPDB‰</th>
<th>$\delta^{18}O$ VSMOW‰</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ooid pisoid grainstone</td>
<td>17</td>
<td>Max</td>
<td>0.798</td>
<td>-8.111</td>
<td>22.499</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>-0.018</td>
<td>-10.094</td>
<td>20.455</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu$</td>
<td>0.327</td>
<td>-8.875</td>
<td>21.711</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma$</td>
<td>0.247</td>
<td>0.554</td>
<td>0.571</td>
<td></td>
</tr>
<tr>
<td>All analyses</td>
<td>36</td>
<td>Max</td>
<td>0.798</td>
<td>-7.850</td>
<td>22.741</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>-2.534</td>
<td>-13.107</td>
<td>17.349</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\mu$</td>
<td>0.071</td>
<td>-9.168</td>
<td>21.396</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma$</td>
<td>0.683</td>
<td>1.110</td>
<td>1.143</td>
<td></td>
</tr>
</tbody>
</table>

Table A-9-1: Summary of carbon and oxygen isotope analyses from the Lady Loretta Formation away from the mine.

Irwin (1980) Equation: $T(°C) = 31.9 - 5.55(\delta^{18}O_{PDB\,dol} - \delta^{18}O_{PDB\,water}) - 0.17(\delta^{18}O_{PDB\,dol} - \delta^{18}O_{PDB\,water})^2$

<table>
<thead>
<tr>
<th>Sample used in Scenario</th>
<th>$\delta^{18}O_{PDB,dol}$ VPDB‰</th>
<th>Assumed $\delta^{18}O_{PDB}$ for Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most enriched dolomite</td>
<td>-7.850</td>
<td>-7‰ 31‰ 26‰</td>
</tr>
<tr>
<td>Most enriched ooid pisoid grainstone</td>
<td>-8.111</td>
<td>-8‰ 33‰ 27‰</td>
</tr>
<tr>
<td>Overall dolomite average</td>
<td>-9.168</td>
<td>-9‰ 39‰ 33‰</td>
</tr>
<tr>
<td>Most depleted dolomite</td>
<td>-13.107</td>
<td>-9‰ 65‰ 58‰</td>
</tr>
</tbody>
</table>

Table A-9-2: Palaeo-temperatures in degrees Celsius calculated assuming different scenarios and using the Irwin (1980) equation. The most plausible cases, corresponding to the least-altered dolomite, are stippled.
Land (1985) Eq: \( T(\degree C) = 16.4 - 4.3((\delta^{18}O_{PDB} \text{ dol} - 3.8) - \delta^{18}O_{PDB \text{ water}}) + 0.14((\delta^{18}O_{PDB} \text{ dol} - 3.8) - \delta^{18}O_{PDB \text{ water}})^2 \)

<table>
<thead>
<tr>
<th>Sample used in Scenario</th>
<th>( \delta^{18}O_{PDB} %)</th>
<th>(-7)%</th>
<th>(-8)%</th>
<th>(-9)%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most enriched dolomite</td>
<td>-7.850</td>
<td>39</td>
<td>34</td>
<td>29</td>
</tr>
<tr>
<td>Most enriched ooid pisoid grainstone</td>
<td>-8.111</td>
<td>41</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Overall dolomite average</td>
<td>-9.168</td>
<td>47</td>
<td>41</td>
<td>36</td>
</tr>
<tr>
<td>Most depleted dolomite</td>
<td>-13.107</td>
<td>73</td>
<td>66</td>
<td>59</td>
</tr>
</tbody>
</table>

Table A-9-3: Palaeo-temperatures in degrees Celsius calculated assuming different scenarios and using the Land (1985) equation. The most plausible cases are stippled.
Figure A-9-1: Crossplot of oxygen and carbon isotopes from the Lady Loretta Formation away from the mine.
A-9.1.1 Comments on Palaeo-Temperatures Derived From Oxygen Isotopes

The validity of this technique may be open to challenge on the basis of simplistic assumptions and inappropriate mathematical methods. The logic acknowledges that, at any one time, variations in $\delta^{18}O$ can arise in either, or any combination, of several ways:

(i) different primary carbonate mineralogy (high or low-Mg calcite, dolomite, aragonite) will affect the $\delta^{18}O$,

(ii) varying the composition of the fluid that precipitated the mineral,

(iii) varying the temperature at which the mineral is precipitated.

Application of the technique infers the first and the second in order to calculate the third.

When examined in more detail, the major assumptions and the logic, in this case, are that:

- that the primary mineralogy was dolomite, not a high or low-Mg calcite or aragonite precursor; this is highly controversial and can be impossible to prove in Palaeoproterozoic rocks (although, in this case, aragonite is least likely; see Section 4.2)
- the rate of precipitation did not significantly affect the isotopic composition; such kinetic effects can be significant in modern skeletal tropical carbonates (Rao, 1996), but may be less of a problem for chemical sediments
- all diagenetic, metamorphic and weathering processes will deplete $\delta^{18}O$ so the most enriched $\delta^{18}O$ corresponds to the "least-altered" dolomite; ideally, the lack of alteration can be verified using textural studies and other isotopic and trace element studies
- as the term "least-altered" implies, at least some depletion in $\delta^{18}O$ will have occurred and thus the calculated palaeo-temperature will be a little higher than reality
- the calculated palaeo-temperature is an average of the material in any one sample; even small samples (e.g. an ooid) take decades or more to form, and bulk samples will include diurnal, seasonal and possibly longer term secular variation
- the palaeo-water temperature can be related to palaeo-latitude; unfortunately temperature is also a function of water depth; so how does one isotopically distinguish between very deep tropical water and polar conditions in the absence of fossils?
- the sample and the "seawater" value are of identical ages to avoid the secular variation in $\delta^{18}O$; there is a dearth of reliable age dates for the Palaeoproterozoic and secular variation in $\delta^{18}O$ is very poorly understood
- a fluid of identical chemical composition ("seawater") was involved in all cases and this remained unchanged throughout the precipitation of the sample; even fairly subtle salinity differences will affect the isotopes and, in this case, both the sample and "seawater" were from sequences containing evaporite pseudomorphs
- a "seawater" value can be derived from analyses of contemporaneous samples and that variations from this reflect different depositional temperatures in the same fluid composition; this is close to circular logic as explained below:
The equations can be reduced to: if $\delta^{18}O_{\text{VPDB, dol}} < \delta^{18}O_{\text{VPDB, seawater}}$, the calculated palaeo-temperature will be proportionally greater than 32°C (Irwin Equation) or 35°C (Land Equation). As the difference between the assumed seawater value and the sample decreases, the calculated palaeo-temperatures will approach these values. As, in this case, the $\delta^{18}O_{\text{VPDB, dol}}$ and $\delta^{18}O_{\text{VPDB, seawater}}$ were both derived from “least-altered” carbonates, they will be essentially the same (in fact, theoretically identical after the correction for fractionation) and it is only to be expected that "tropical" values will result.

"Seawater" values would be better determined from primary fluid inclusions. For this technique to be valid, the $\delta^{18}O$ of primary fluid inclusions and the unaltered host carbonates should differ by a constant amount that equates to the fractionation factor. This has yet to be determined for Palaeoproterozoic carbonates.

The over-riding flaw in this technique is mathematical. The equations imply that by using two independent variables, it is possible to solve for a third. However, temperature, fluid composition and carbonate mineralogy are not independent variables. Studies of modern environments clearly show that, although modern seawater has relatively little variation in $\delta^{18}O$, water chemistry varies with temperature, as does the composition of carbonate precipitated (Rao, 1996). Thus, it is mathematically inappropriate to solve simple equations of the type presented here to determine a palaeo-temperature.

A-9.2 STABLE ISOTOPE STUDIES IN THE LADY LORETTA ORE BODY

Studies by Large et al. (1995) documented a systematic variation in the stable isotopes in carbonates within the alteration halo around the Lady Loretta ore body. The inner zone siderite has more enriched oxygen isotopes and depleted carbon isotopes relative to the outer zone dolomite. Dolomite from the mine has more depleted oxygen and carbon isotopes than away from the vicinity of the mine.

A-9.2.1 Dolomite

Dolomites from the vicinity of the ore body have $\delta^{18}O_{\text{VPDB}}$ values of -13.9 to -12.3%0 (16.5 to 18.2‰ $\delta^{18}O_{\text{VSMOW}}$) and $\delta^{13}C$ of -0.9 to -1.5‰. Modeling, assuming a bicarbonate fluid composition, indicates that these dolomites were formed from a fluid of about 50°C, $\delta^{18}O_{\text{VPDB}}$ of -40.6‰ (+6 $\delta^{18}O_{\text{VSMOW}}$), -5‰ $\delta^{13}C$, and can be interpreted to suggest either a meteoric or evaporated seawater source (Large et al., 1995).

A-9.2.2 Siderite and Ankerite

Siderites have $\delta^{18}O_{\text{VPDB}}$ values of -7.4 to -2.5‰ (23.2 to 28.3‰ $\delta^{18}O_{\text{VSMOW}}$) and $\delta^{13}C$ of -1.9 to -3.2‰. Modeling indicates that the siderite and ankerite could both have formed from a single fluid with a $\delta^{18}O_{\text{VPDB}}$ of -23.9‰ (+6 $\delta^{18}O_{\text{VSMOW}}$), -6 $\delta^{13}C$, suggesting a meteoric source at temperatures of near 100°C (Large et al., 1995). Siderite could not have precipitated from the same fluid that formed the dolomite.

Alternatively, if the siderite is accepted as primary (Section 11.3.1 argues against this), the isotopic data may be interpreted using the fields developed by Mozley and
Wersin (1992) to indicate a depositional environment. The siderite from the ore body plots in the area of overlap between continental and marine settings.

**A-9.2.3 Carbon and Oxygen Isotopes as Vectors to a Mineralisation - a Caveat**

The work by Large *et al.* (1995) demonstrated that systematic variation in stable isotopes can be used as a vector to mineralisation at Lady Loretta mine. Although not stressed in their work, there is a strong mineralogical control on the oxygen isotopes. Depletion in oxygen isotopes toward the ore body applies only to the dolomite, not the siderite. Siderite is enriched relative to both the outer carbonate halo and to dolomites from elsewhere in the formation.
A-10. QUANTITATIVE STRATIGRAPHY AND SEDIMENTOLOGY

A-10.1 INTRODUCTION

Quantitative stratigraphy and sedimentology is directed towards:

- determining if the observed vertical sequence is random or ordered and in which way it is spatially ordered (by Markov chain analysis)
- detecting, statistically verifying and interpreting non-random arrangements of bed or cycle thickness using Fischer plots
- determination of cycle periodicity, duration and sediment accumulation rates using various techniques of spectral analysis.

The latter technique is part of the emerging field of “cyclostratigraphy” and is controversial because it is based on the assumptions of a complete sedimentary record, objective description of stratigraphic elements, uniform thickness-time relationships (see Yang et al., 1995) and a hierarchy of different order cycles that some authors (e.g. Drummond and Wilkinson, 1996) argue are artefacts. It is unsuitable for environments with erosional features, where cyclic stratigraphy is produced by “sealevel fluctuations or where significant detrital or reefal sedimentation disturbs the record of cycles” (Cotillion, 1995). This technique is inappropriate for broad-scale studies of the Lady Loretta Formation and has only been applied to specific local examples in an effort to demonstrate a tidal periodicity. The results, however, will add fuel to the debate about Proterozoic global dynamics.

The current study concentrated on the first two, longer-established, techniques to confirm non-random depositional patterns. The interpretation of such patterns, using various models of cyclic or episodic sedimentation that can be related to causes such as relative sealevel rise and fall, are also controversial. This section deals with the mathematical aspects; the sedimentary interpretation is discussed in Sections 10.2.2, 10.5.2 and 15.2.

A-10.2 MARKOV CHAIN ANALYSIS

A-10.2.1 Terminology and Methodology

Two types of oscillatory repetitions are commonly recognised empirically; rhythmic (ABCABCA) and cyclic (ABCBA), but there is no clear definition of either term in the geological literature (Einsele et al., 1991). Terms such as “tidal rhythmites” (see Sections 5.4 and A-10.4), “Lofer cycles”, “cyclothems” and “Milankovitch cycles” are well entrenched in the geological literature but are not mathematically-correct terms. Indeed, many sequences (including textbook examples of cyclothems) can be interpreted as either cyclic or rhythmic depending on selection of the starting point of each repeat unit and it is ironic that tidal rhythmites are closest to mathematical cycles. Further confusion can arise when relating non-random sedimentation to stratigraphic forcing and Milankovitch cycles that imply periodicity. Besides the misuse of “cycle” to imply order in both time and space, Drummond and Wilkinson (1993a, 1996) argued that many well-documented examples of sedimentary stratigraphic repetition (including the Proterozoic peritidal carbonate cycles of Grotzinger, 1986b) cannot be attributed to any deterministic periodic process. To avoid the problems of terminology between so-called cyclic and rhythmic sequences, the term “preferred
sequence" has been used to describe the stratigraphic repeat unit and the word "cyclic" has been used in the broadest sense.

Markov chain analysis is a statistical technique used to test for a non-random vertical arrangement in a sedimentary succession. This technique enables the rejection of random sedimentation with a stated degree of confidence; it does not prove cyclicity and says nothing about periodicity. Furthermore, no sedimentary sequence is truly random (such a sequence would invalidate Walther’s Law) and only very small contributions (with probabilities of about 0.1 to 0.2) in which one unit depends on its predecessor can produce the effect of great order, both statistically and visually (Powers, 1984). Even random data, if inappropriately analysed and interpreted, can give the visual effect of cyclicity. The latter was cunningly demonstrated by the Zeller (1964) experiment.

The initial step of Markov chain analysis is to break the sedimentary sequence into a number of units (usually as defined facies) and record the upward transitions from one to the next. All contacts between facies can be logged or, alternatively, the succession can be sampled at regular intervals. In both cases the results are recorded in a transition count matrix. The former technique, as used in the current study, has the advantage of not missing any thin beds that may be critical to the evaluation of the sequence, but it ignores the possibility of two units of the same type overlying one another (thus, making it impossible to distinguish between ABC ABC and ABCA ABCA). It produces a diagonal of embedded structural zeros in the transition count matrix, which complicates statistical analysis. If transitions are logged over a continuous section, the row and column totals of the transition count matrix must be the same or differ by a maximum of one. Only zero or two row totals cannot equal their corresponding column totals (Powers and Easterling, 1982). Published examples that fail these preliminary tests (e.g. Driese and Dott, 1984) must have included gaps or faults in the sequence. Other workers have simply ignored breaks in the sequence to preserve row and column totals. During the current study, each part of discontinuous sections has been analysed separately.

The next step is to convert the transition count matrix to a transition probability matrix. That is then compared to a probability matrix generated by assuming random sedimentation. The comparison is by means of a $\chi^2$ test. There are two ways of calculating the matrix that assumes random sedimentation. The methodology used by Gingerich (1969) and Selley (1970) honours row, not column, totals and so is not entirely justifiable statistically nor strictly independent. Goodman (1968), Carr (1982) and Powers and Easterling (1982) developed the more meaningful quasi-independence technique that iteratively calculates each element of the matrix. The current study utilised two computer programs based on the latter method. The first program is custom-written using the normalised probability difference technique of Powers and Easterling (1982) and works with probabilities. The second is from

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*Geologists unwittingly generated cycles from a series of numerical "stratigraphic" data and then correlated them. The data were, in fact, random numbers taken out of the Lawrence, Kansas, telephone book.*
Wells (1989) and uses absolute values. It tests for asymmetry and uses both transition \( \chi^2 \) values and binomial probability to select the statistically most significant transitions. The two programs produce identical \( \chi^2 \) values for matrices that pass the row and column sum tests, but treat mis-matches in row and column sums differently. Printouts of the matrix transformations have not been included, but are available on request.

Subtraction of the expected random matrix from the observed matrix produces the difference matrix. The greatest positive elements of the difference matrix are usually used to construct the preferred sequence (the so-called modal cycle), but the relative weightings of each transition can be largely subjective and statistically significant negative differences are commonly ignored. For instance, Allen (1970) recommended a probability cutoff of \( +0.15 \) and more recent workers such as Okhravi and Lahijani (1994) ignored significant negative differences. Often these interpretations suggest more organisation (longer "cycles") than is justifiable from the data (Graham, 1988). The current study used two statistical methods to overcome this problem. The Powers and Easterling (1982) normalised probability differences technique evaluates both positive and negative departures from expected transition values and thus identifies "extreme" difference cells. Those values of \( >2.0 \) or \( <2.0 \) (i.e. outside of ca. 98% of the standard normal distribution) will make the greatest contribution to non-randomness. The Wells (1989) method determines the preferred sequence based on both transition \( \chi^2 >2.71 \) and binomial probability \( >0.2 \). It also highlights "disfavoured" transitions from the other extreme of the statistical distribution. As pointed out by Carr (1982), it is possible to statistically reject random sedimentation and yet not be able to justify a cycle incorporating all facies.

Finally, the overall sequence and individual transitions were tested for asymmetry (i.e. are A→B transitions as common as B→A).

**A-10.2.2 Markov Chain Analysis of Amoco 83-5**

Four lithofacies have been recognised in the lower portion of the Lady Loretta Formation intersected in drillhole Amoco 83-5. The interval from 430.0 m to 483.2 m consists entirely of alternations of two lithofacies (CDCD). Empirical observation suggested that the underlying sequence was a regular arrangement of all four lithofacies. This interval, from 483.2 to 582.2 m, was analysed using Markov chain analysis. The normalised probability difference matrix highlights the importance of the D→E1 and C→A upward transitions. With only 20 facies to facies transitions, any statistical analysis of the logging method must be treated with caution. However, non-random sedimentation is indicated with a confidence level of \( >99\% \).

The calculated \( \chi^2 \) values and the most likely transitions based on both the normalised probability differences and the Wells (1989) method are summarised in Table A-10-1.
A-10.2.3 Application of Markov Chain Analysis to the Lady Loretta Host Rocks

G. Carr (1981) studied the cyclicity of the hanging wall sequence (including the so-called "Cyclic Unit") in drillholes 2300P129 and 2315P91. Working before the publication of the methods of his namesake (T. Carr, 1982) and Powers and Easterling (1982), Carr's (1981) study logged over 1900 transitions but simply converted observed transitions to probabilities from which he inferred the most probable cycles; he did not statistically test the frequency of the observed transitions against those expected had sedimentation been random. The current study has more rigorously processed his original data, also taking into account the significant faults and gaps in the section.

The facies defined by Carr (1981), and prefixed by D in this study, are summarised in Section 10.2.2. The results of Markov chain analysis are summarised in Tables A-10-2 to A-10-5.

<table>
<thead>
<tr>
<th>Absolute Normalised Probability Difference &gt; 20</th>
<th>n</th>
<th>Sequence Randomness</th>
<th>Asymmetry</th>
<th>Preferred Sequence</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>$\chi^2$</td>
<td>df.</td>
<td>%Chance</td>
</tr>
<tr>
<td>D→B $^2.07$</td>
<td>20</td>
<td>15.9</td>
<td>5</td>
<td>99×&lt;99.9</td>
</tr>
<tr>
<td>C→A $^2.02$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[\begin{array}{cccc}
D→B & 20 & 15.9 & 5 & 99×<99.9 \\
C→A & 20 & 15.2 & 4 & 90×<95 \\
\end{array}\]

Table A-10-1: Results of Markov chain analysis of drillhole Amoco 83-5.
<table>
<thead>
<tr>
<th>SU</th>
<th>Compress. m above Ore</th>
<th>Carr's &quot;Cycles&quot;</th>
<th>Carr (1981)</th>
<th>n</th>
<th>Uncorrected m above ore</th>
<th>Sequence Randomness</th>
<th>Asymmetry</th>
<th>Preferred Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>140-110</td>
<td>DC-DB-DB-DA-DC</td>
<td>310</td>
<td>86.38-70.61</td>
<td>97</td>
<td>5</td>
<td>&gt;99.99</td>
<td>78</td>
</tr>
<tr>
<td>4</td>
<td>110-85</td>
<td>non-cyclic</td>
<td>32</td>
<td>70.51-57.46</td>
<td>19.5</td>
<td>5</td>
<td>99&lt;chi</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>85-56</td>
<td>DC-DB-DA-DC</td>
<td>169</td>
<td>56.00-49.49</td>
<td>204</td>
<td>11</td>
<td>&gt;99.99</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DC-DB-DA-DC</td>
<td></td>
<td>49.49-47.11</td>
<td>53.5</td>
<td>11</td>
<td>&gt;99.99</td>
<td>49</td>
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<tr>
<td></td>
<td></td>
<td>DC-DB-DA-DC</td>
<td></td>
<td>47.04-43.51</td>
<td>92.6</td>
<td>19</td>
<td>&gt;99.99</td>
<td>82</td>
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<td></td>
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<td>DC-DB-DA-DC</td>
<td></td>
<td>43.51-40.26</td>
<td>93.5</td>
<td>19</td>
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<td></td>
<td></td>
<td>DC-DB-DA-DC</td>
<td></td>
<td>20.87-00.00</td>
<td>205</td>
<td>19</td>
<td>&gt;99.99</td>
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<td>1</td>
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<td>245</td>
<td>137.43-000.00</td>
<td>1245</td>
<td>19</td>
<td>&gt;99.99</td>
<td>1245</td>
</tr>
</tbody>
</table>

Table A-10-2: Results of Markov chain analysis of the Cyclic Unit in drillhole 2300P129, comparing Carr's (1981) empirical "cycles" to statistically preferred sequences.
<table>
<thead>
<tr>
<th>SU</th>
<th>Corrected n above are</th>
<th>Uncorrected n above are</th>
<th>Powers &amp; Exceeding Normalized Prob. Differences Method</th>
<th>Preferred Transitions</th>
<th>Disallowed Transitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>140-119</td>
<td>85</td>
<td>DA-DC: 3.92 DA-DC: 3.81 DC-DC: 3.41</td>
<td>DA&lt;DB</td>
<td>DA&gt;DB</td>
</tr>
<tr>
<td>4</td>
<td>110-85</td>
<td>18</td>
<td>DB-DA: 1.91 DB-DA: 1.89 DB-DA: 1.89</td>
<td>DA&lt;DB</td>
<td>DA&gt;DB</td>
</tr>
<tr>
<td>2</td>
<td>65-55</td>
<td>52</td>
<td>DA-DC: 2.64 DA-DC: 2.25 DB-DC: 2.22 DB-DA: 2.18 DC-DC: 2.18</td>
<td>DA&lt;DB</td>
<td>DA&gt;DB</td>
</tr>
<tr>
<td>1</td>
<td>55-55</td>
<td>96</td>
<td>DA-DC: 3.28 DA-DC: 3.26 DC-DC: 3.00 DA-DC: 2.90 DA-DC: 2.90 DC-DC: 2.77 DC-DC: 2.59</td>
<td>DA&lt;DB</td>
<td>DA&gt;DB</td>
</tr>
<tr>
<td>105-105</td>
<td>122</td>
<td>DA-DC: 4.05 DA-DC: 3.44 DB-DC: 3.20 DB-DC: 3.04 DB-DC: 2.97 DB-DC: 2.81 DC-DC: 2.81</td>
<td>DA&lt;DB</td>
<td>DA&gt;DB</td>
<td></td>
</tr>
</tbody>
</table>

Table A.10-3: Statistically preferred upward transitions in the Cyclic Unit of drillhole 2300P129.
Table A-10-4: Statistically preferred upward transitions in drillhole 2315P91.

<table>
<thead>
<tr>
<th>Uncorrected m above Ore</th>
<th>n</th>
<th>Powers &amp; Easterling Normalised Prob. Difference Method</th>
<th>Wells Binomial Prob. &amp; Transition ( \chi^2 ) Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Preferred Transitions</td>
<td>Disfavoured Transitions</td>
</tr>
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<td>10.015 - 5.965</td>
<td>87</td>
<td>DBc-&gt;DB 4.83</td>
<td>DA-&gt;DC 2.87</td>
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<td></td>
<td></td>
<td>DBc-&gt;DA 3.61</td>
<td>DB-&gt;DC 2.86</td>
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<td>DB-&gt;DB 2.23</td>
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<td>DB-&gt;DB 2.23</td>
</tr>
<tr>
<td>5.485 - 3.505</td>
<td>62</td>
<td>DBc-&gt;DB 3.10</td>
<td>DA-&gt;DC 2.11</td>
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<td>DB-&gt;DC 2.18</td>
<td>NC</td>
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<td>3.505 - 00.950 incl. gaps</td>
<td>17</td>
<td>DBC-&gt;DB 2.77</td>
<td>DA-&gt;DC 2.11</td>
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<td>00.950 - 00.000</td>
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<td>DBc-&gt;DB 3.10</td>
<td>DC-&gt;DA 2.10</td>
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</table>

Table A-10-5: Results of Markov chain analysis of a 10 m interval of the hanging lower Cyclic Unit intersected in drillhole 2315P91 and described in detail by Carr (1981).
A-10.2.4 Interpretation of the Markov Chain Analysis at the Lady Loretta Mine

In nine of the ten intervals analysed in 2300P129, sedimentation is non-random with a >99.99% level of confidence and even those intervals described by Carr (1981) as "essentially non-cyclic" or "non-cyclic" are clearly non-random. The sequence of transitions in each unit is highly asymmetric. The transitions DB→DA and DA→DC dominate throughout the entire interval analysed. There is only a single transition interval (DC→DB, 180-160 m, 2300P129) in which Carr empirically recognised a significant transition that cannot be statistically justified by either the Powers and Easterling (1982) normalised probability technique or the Wells (1989) method. Note that the normalised probability technique is the only method to favour the DA→DB transition.

Drillhole 2315P91 has similarly high $\chi^2$ values for sequence order and asymmetry as 2300P129. The same statistically preferred sequences as 2300P129 can be inferred (Table A-10-5).

Overall, a conventional interpretation of the "modal cycle" for the Cyclic Unit, based on both the normalised probability differences and the Wells (1989) method, would be DC→DBv→DA→DC, where DBv includes DB and the laminated, "slumped" and carbonate variants recognised by Carr (1981). This is illustrated in Figure 10-1, Volume 1. The implications of the preferred sequence for both the sedimentological and mineralisation models are discussed in their respective Chapters.
A-10.3 FISCHER PLOTS
A-10.3.1 Theory of Fischer Plots

Fischer plots are graphic displays of cumulative deviations from the mean unit thickness throughout a stratigraphic interval. They have their greatest application in the study of cyclic shallow-water carbonates, in which each preferred sequence (cycle) is plotted as a unit. Observed cycle thickness in excess of subsidence has been interpreted to represent depositional accommodation space formed by eustatic sealevel rise. A positive slope on the plot is interpreted as having formed under conditions of increased accommodation space provided by relative sealevel rise and peaks on the curve correspond to maximum flooding surfaces.

Osleger and Read (1993) gave details on the interpretation of Fischer plots in peritidal, tidal and shallow water storm-dominated environments. However, Pratt et al. (1992) cautioned against using Fischer plots in subtidal or peritidal sequences that formed as prograding wedges. Other comparable studies include Elrick (1995) who used Fischer plots to correlate a series of sections in a ramp to ramp-margin transition and found that the plots failed to identify sealevel oscillations in some exposure-capped peritidal and subtidal cycles.

At the time of writing, opinions as to the worth of Fischer plots fell into two diametrically opposed camps. On one hand, the proponents followed Read and Goldhammer (1988), Crevello (1991) and Read et al. (1991). Grotsch (1996) is probably an extremist in that he used Fischer plots to correlate Cretaceous peritidal shallowing-up cycles between Greece and Mexico despite the enormous palaeo-geographic separation and different rates of subsidence in the two areas. The other school of thought disputes the usefulness of Fischer plots to identify long-term changes in the rate of accommodation and hence their applicability as a correlation tool or to interpret relative changes in sealevel (Algeo and Wilkinson, 1988; Drummond and Wilkinson, 1993a,b,c, 1996 and discussion in Bond and Kominz, 1991). Boss and Rasmussen (1995a) tested the assumption, implicit in Fischer plots, that preserved cycle thickness is a measure of accommodation space. Their study of the Bahama Bank carbonate sediments deposited during the Holocene post-glacial sealevel rise concluded that cycle thickness and accommodation are not statistically correlated ($r^2=0.03$). This was challenged by Diecchio (1995) on three counts. Boss and Rasmussen (1995a,b) had used subtidal sediments and most workers agree that Fischer plots cannot be used to infer eustasy in a subtidal setting. Secondly, Diecchio (1995) challenged their method of plot construction as incorrect and, finally, he pointed out that the Holocene cycle they were trying to model is still undergoing a sealevel rise and therefore incomplete.

Given this disparity of views regarding Fischer plots, I have been circumspect in interpreting them as de-facto sealevel curves. However, as an objective statistical technique, they can be a useful adjunct to Markov analysis in providing an independent test of non-random sedimentation.
A-10.3.2 Terminology and Methodology

The details of plot construction are given in Sadler et al. (1993). Cycle number (not depth or time) is plotted as the horizontal axis and the resulting plot should always form a roller-coaster starting and ending at the same datum. Groups of adjacent units that are consistently thicker or thinner than the mean are termed runs. A run of units thicker than the mean plots as a positive slope on the Fischer plot. The \( Z \) score is used to test for randomness in the size and, therefore, frequency of runs. It is calculated from the following equation:

\[
Z = \frac{r - \left\{ \frac{2n_1n_2}{n_1 + n_2} + 1 \right\}}{\sqrt{\left( \frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1 + n_2)^2(n_1 + n_2 - 1)} \right)}}
\]

where:
- \( r \) is the total number of runs
- \( n_1 \) is the number of units thicker than the mean
- \( n_2 \) is the number of units thinner than the mean.

For example, a \( Z \) score of -2 means an \( r \) value two standard deviations below the expectation for random stacks; standard tables of area under the normal curve reveal that there is a greater than 97.7\% chance that, compared to random stacking patterns, the data have significantly fewer and, thus, longer runs (Sadler et al., 1993). Documented examples of peritidal Fischer plots have predominantly negative \( Z \)-scores. An additional check for non-randomness, which is independent of the statistical distribution of \( r \), was devised for the current study. It is performed by using a computer algorithm to pseudo-randomly rearrange the observed thicknesses (herein termed randomised) and recalculating the \( Z \) score. A non-random sedimentary sequence will have a significantly higher absolute \( Z \) score than its randomised counterpart. A completely random stack would have a \( Z \) score of 0.0, \( n_1 / n_2 \) of 1.0 and \( r / (n_1 + n_2) \) of 0.5.

The Fischer plots presented in the current study have been generated by a custom-written spreadsheet that plots both a conventional Fischer plot and a bar graph of unit thickness. To stress that the plots are relative to the mean, it has been used as datum. \( Z \) scores have been calculated for the raw data, the randomised raw data and after decreasing ten fold those values above the 95 percentile (herein referred to as filtered data).

A-10.3.3 Application to Drillhole Amoco 83-5

The entire core from drillhole Amoco 83-5 was logged at decimetre to metre scale (detailed log available on request) and a Fischer plot generated (Figure A-10-1a,b).

As a test of reproducibility, the interval from 287.4 m to 582.2 m that corresponds to the descending portion of Figure A-10-1a was reanalysed separately. There was no significant difference in any of the statistical parameters, as shown in Table A-10-6. The
interval from 482.2 m to 582.2 m (TD) used for Markov analysis was also plotted and analysed separately. Plots were generated for the units as logged and using the preferred sequences recognised by Markov chain analysis (Appendix A-10.2). Both plots were similar and the interval shows the same character as the corresponding portion of Figure A-10-6a.

Workers such as Osceger and Read (1991, 1993) would interpret this plot as suggesting maximum flooding surfaces at either end of the cored interval with a low stand at about cycle 220 (290 m). However, such an interpretation may be misleading in the light of work of Boss and Rasmussen (1995a) and would have to be corroborated by other sedimentological evidence. The Z score and other statistical parameters shown in Table A-10-6 demonstrate that there is an 87% chance that such a plot is non-random and that the plot is not being unduly affected by any abnormally large thicknesses.

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Amoco 83-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval (m)</td>
<td>6.00 - 582.2</td>
</tr>
<tr>
<td>Number of Units</td>
<td>376</td>
</tr>
<tr>
<td>Treatment</td>
<td>as logged</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>1.56</td>
</tr>
<tr>
<td>σ</td>
<td>1.34</td>
</tr>
<tr>
<td>max</td>
<td>10.1</td>
</tr>
<tr>
<td>n1 / n2</td>
<td>1.78</td>
</tr>
<tr>
<td>r / n1 + n2</td>
<td>0.44</td>
</tr>
<tr>
<td>Z</td>
<td>1.12</td>
</tr>
<tr>
<td>%Chance Non-random</td>
<td>86.9</td>
</tr>
</tbody>
</table>

Table A-10-6: Statistical analysis of the Fischer plot for drillhole Amoco 83-5.

A-10.3.4 Fischer Plots from the Vicinity of the Lady Loretta Mine

Application of Fischer plots to the host stratigraphy at the mine is complicated by folding and faulting and the need to correct bed thickness in curved drillholes inclined relative to bedding. Fischer plots have been generated for the faulted Cyclic Unit sequence intersected in drillhole 2300P129. Table A-10-7 gives relative depths before and after correction. The DC-based "cycles" recognised empirically by Carr (1981) and statistically verified by Markov chain analysis were plotted (Figure A-10-2a,b). Alternative plots using different starting points for the preferred sequence were also generated. These plots were almost identical, demonstrating that the choice of the start and finish of each repeat unit has virtually no effect on the distribution of unit thicknesses, and confirming that the Fischer plot was not being biased by selection of preferred sequences. Wherever statistically valid, individual fault blocks in 2300P129 were analysed separately and compared to the overall plot. Only the fault block between cycles 385 and 499 is spurious. Thus, little credence can be put on that section of the Fischer plot, other than to say that it
can be interpreted as evidence of non-random sedimentation. The data for 2300P129 (Table A-10-7) contain several anomalously large values that were filtered out in a separate analysis. Both the raw and filtered data have large $Z$ scores, showing that there is a $<0.01\%$ chance of random sedimentation even when faults are included.

A 10 m interval at the base of the Cyclic Unit in drillhole 2315P91 was also logged in detail by Carr (1981) and has been analysed using the same criteria for 2300P129. There is a 93.2\% chance that the raw data are non-random. However, filtering shows that with only 54 units, the plot is sensitive to the exclusion of the top 95 percentile (Table A-10-7).

Given the relatively short stratigraphic interval analysed and the reservations about the interpretation of Fisher plots, these data from the Lady Loretta mine are not interpreted as sealevel curves.

<table>
<thead>
<tr>
<th>Drillhole</th>
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<th>2315P91</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>above Ore</td>
<td>137.42</td>
<td>10.015</td>
</tr>
<tr>
<td>Number of Units</td>
<td>574</td>
<td>54</td>
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<td>Treatment</td>
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<tr>
<td>sequences</td>
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<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>23.99</td>
<td>21.75</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>55.56</td>
<td>28.78</td>
</tr>
<tr>
<td>max</td>
<td>1093.00</td>
<td>368.00</td>
</tr>
<tr>
<td>$n_1 / n_2$</td>
<td>2.15</td>
<td>2.05</td>
</tr>
<tr>
<td>$r / n_1 + n_2$</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td>$Z$</td>
<td>9.03</td>
<td>8.14</td>
</tr>
<tr>
<td>%Chance Non-</td>
<td>&gt;99.99</td>
<td>&gt;99.99</td>
</tr>
<tr>
<td>random</td>
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Table A-10-7: Statistical analysis of the hanging Cyclic Unit intersected in drillholes 2300P129 and 2315P91.
Figure A-10-1a: Portion of Fischer plot for drillhole Amoco 83-5.
Figure A-10-1b: Continuation of Fischer plot for drillhole Amoco 83-5.
Figure A-10-2a: Portion of Fischer plot for drillhole 2300P129.

The letter F indicates a fault.
Figure A-10-2b: Continuation of Fischer plot for drillhole 2300P129. The letter F indicates a fault.
A-10.4 INTERPRETATION OF PERIODICITY BY PATTERN RECOGNITION AND SPECTRAL ANALYSIS

A-10.4.1 Introduction

Nearly identical varve-like, normally graded layers can be deposited in environments ranging from deep marine, through estuarine and tidal, to shallow lagoons and fresh water lakes. However, unlike deposits formed by storms, turbidites or lacustrine varves; tidal deposits may exhibit a distinctive periodicity of bed or laminae thickness that can be related to diurnal inequality and/or the lunar cycle of neap-spring deposition (Feldman et al., 1993). Studies of this periodicity have been undertaken in either of a number of ways, or various combinations of them:

- purely theoretical studies based on mathematical models to simulate tidal deposition
- statistical analysis of modern tidal station data
- studies of the bed thicknesses in modern tidal sediments
- studies of the bed thicknesses in ancient sedimentary analogues
- studies of vertical variations in mineralogy, geochemistry or isotope data.

Most studies have focused on either tidal rhythmites (vertically stacked beds that show cyclic changes in layer thickness) or tidal bundles within the foresets of crossbedding (see Sections 5.3 and 5.4). The literature includes examples from Archaean to Recent and includes a variety of depositional environments (delta front, abandoned tidal channel, tidal flat, and estuary). Table A-10-8 presents a summary of such studies from the literature.

Early studies generally presented their data simply as variation plotted against bed or lamina number and periodicity was established empirically. The last few years have seen increasingly complex mathematical algorithms applied to the analysis of the data. Various techniques of spectral analysis, often used to construct modern predictive tide tables or to study Milankovitch cycles in the ancient rock record (e.g. ten Kate and Sprenger, 1992; Yang et al., 1995), have also been used to test for periodicity in tidalites. Techniques are discussed in Pardo et al. (1994), Sprenger and ten Kate (in press) and Weedon and Read (1995).

Studies of tidal periodicity from ancient rocks have implications beyond establishing an environment of deposition. Once tidal deposition has been established it is possible to calculate the rate of deposition, albeit over a small interval. Rates measured in modern tidal environments show considerable variation but are typically very high; in the order of centimetres per week. Ancient examples are comparable (see examples given by Enos, 1991). However, measurements over such short time periods should not be extrapolated as they may not be representative of long term preservation.

Several workers have also attempted to quantify the variations in tidal frequency through geological time and infer the temporal changes to the Earth-Moon-Sun system as the Moon retreats from Earth (see Section 2.2). Such work is beyond the scope of the current study.
<table>
<thead>
<tr>
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<th>FORMATION/SETTING</th>
<th>FACIES</th>
<th>ENVIRON.</th>
<th>C</th>
<th>PS</th>
<th>NEAP to NEAP</th>
<th>μ</th>
<th>LUNAR PERIOD</th>
<th>SOLAR DAY/yr</th>
<th>DEP. RATE</th>
<th>REFERENCE</th>
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<tr>
<td>Modern</td>
<td>tidal station data - Townsville, Australia</td>
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<td></td>
<td></td>
<td>-</td>
<td>12.5</td>
<td>24.4</td>
<td></td>
<td></td>
<td>Shi (1991)</td>
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<tr>
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<td>Bengal shelf</td>
<td>stacked couplets</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>16.6</td>
<td>16.6</td>
<td>5.2</td>
<td></td>
<td>Segall and Kuehl (1994)</td>
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<tr>
<td>Modern</td>
<td>salmon R.</td>
<td>stacked couplets</td>
<td>estuary</td>
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<td>-</td>
<td>25-23</td>
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<td>stacked sand/mud layers</td>
<td>estuary</td>
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<td>10-12</td>
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<tr>
<td>Recent</td>
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<td>stacked couplets</td>
<td>estuary</td>
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<td>-</td>
<td>25-26</td>
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<td>26,28</td>
<td>9.7</td>
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<td>tidal</td>
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<td>Shi (1991)</td>
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<td>-</td>
<td>12,11</td>
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<td></td>
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<td>Dalrymple (1992)</td>
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<td>Lower Pennsylvanian (305±5 Ma)</td>
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<td>-</td>
<td>25,29,23</td>
<td>25.7</td>
<td>28.3±0.1</td>
<td>(5.2X10^5)</td>
<td></td>
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<td>Lower Pennsylvanian (312±5 Ma)</td>
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<td></td>
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<td>-</td>
<td>11-25, 25-27</td>
<td>-</td>
<td>28.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pennsylvanian Mississippian</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>23.25,30</td>
<td>26</td>
<td>35cm/yr</td>
<td>(3.5X10^5)</td>
<td></td>
</tr>
<tr>
<td>Cambrian</td>
<td>several</td>
<td>graded rhythms</td>
<td>barrier island to tidal shelf</td>
<td></td>
<td></td>
<td>-</td>
<td>21,10,12</td>
<td>14.3</td>
<td>400±7</td>
<td></td>
<td>Sonett et al. (1996), Williams (1991)</td>
</tr>
<tr>
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<td>Elatina</td>
<td>graded rhythms</td>
<td>delta front</td>
<td></td>
<td></td>
<td>-</td>
<td>14,32</td>
<td>-</td>
<td>30±0.5</td>
<td></td>
<td>Basumallick et al. (1996)</td>
</tr>
<tr>
<td>Neoproterozoic</td>
<td>Bhandar Sst</td>
<td>graded rhythms</td>
<td>tidal-flat, lagoon</td>
<td></td>
<td></td>
<td>-</td>
<td>14,32</td>
<td>-</td>
<td>25±0.3</td>
<td></td>
<td>Sonett et al. (1996)</td>
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<td>-</td>
<td>14,32</td>
<td>-</td>
<td>45±6</td>
<td></td>
<td>Basumallick et al. (1996)</td>
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</table>

Table A-10-8: Summary of data on tidalites from the literature. The columns labelled C and PS indicate studies based on empirical counts and power spectra to determine periodicity. The number of units between successive neap tides (minima on chart plots) were counted and averaged. Those data shown with a stippled background were derived by the original authors. Sedimentation rates shown in brackets are in Bubnoff units (m/10^6 yr) for comparison with other literature (e.g. Enos, 1991).
Data from the Lady Loretta Formation

Rare, but highly distinctive, regular arrangements of bed thickness or changes to the lithology within individual beds are commonly observed in exposures of the Lady Loretta Formation. Data from several localities are summarised in Tables A-10-9 and A-10-10. Stacked fining-up couplets were described from the KD1C section at Kamarga Dome and in core from drillhole 2420ED62, 41m (Figure 5-2, Chapter 5). Although the former sample comes from a demonstrably marine sedimentary package, neither of the other examples have corroborating tidal sedimentary features. Core from Amoco 83-5 that contains bipolar ripple cross-lamination was also analysed because the percent of sandstone in individual couplets appeared to be non-randomly distributed.

Apparently non-random arrangements of thicknesses were noted in foresets of sandstone crossbeds from Russell Creek and Gundaria Bore. Silty carbonate foreset thicknesses were measured in a much smaller crossbed set from the KD1A section. All these examples contain reactivation surfaces and come from units containing other sedimentary features interpreted as indicative of tidal deposition. The statistical distributions of dip angle and foreset thickness of these examples are discussed in Section 5.3.3.

Data Collection and Correction

Thicknesses of individual laminae, beds or fining-up couplets were measured in the field or from photograph mosaics. Core samples were slabbed and polished and measured under a binocular microscope. Where necessary, measurements were corrected to true stratigraphic thickness.

Thickness Charts

The thickness charts are shown in Figures A-10-3 to A-10-7. These charts are similar to those of tidal deposits (both ancient and modern) presented in the literature cited in Table A-10-8. Non-random arrangements of bed or foreset thicknesses and some periodicity are evident empirically in most of the Lady Loretta data. Whereas, the Amoco 83-5 thickness data are random (many beds have rippled tops making measurement difficult), the percent sandstone does appear to peak at a similar periodicity to some of the other charts (Figure A-10-3b). The Gundaria Bore foreset data have a distinctive thick-thin alternation (Figure A-10-7) that is more pronounced at greater foreset thicknesses. Simple counts of the number of units between successive minima and the mean number of units in each cycle are shown in Table A-10-9. The majority of the data have repetitions of about 13-15 or 26-27 units per cycle. The possible exception is the data from the mine, but only one cycle is preserved.
A-10.4.4 Spectral Analysis of the Lady Loretta Data

This technique objectively highlights those frequencies that repeat periodically in the data by plotting a power spectrum of power versus frequency. It analyses the entire waveform instead of focusing on peak-to-peak or trough-to-trough relations used in empirical techniques. Spectral analysis of bed thickness data has the implicit assumptions that each bed was deposited during a uniform time interval and that the stratigraphic record is continuous. The data from the Lady Loretta Formation, although comparable to most other studies, have too few measurements in any one section for a rigorous statistical evaluation.

The technique applied here is a minimalist approach, without pre-filtering, and no test for randomness has been applied. The mean has been subtracted from the data and zeros added to bring the total number of readings to an increment of 2". Spectral analysis was undertaken using a Fast Fourier transform in specialist software and the resulting power spectra are shown with the accompanying thickness charts (Figures A-10-3 to A-10-7). The spectra are an accurate representation of the power only at those frequencies plotted (indicated by a dot on the curve). The period is the inverse of the frequency (x axis) corresponding to the highest peak power (y axis) and, although shown here to one decimal place, is strictly an integer.

The results (rounded to one decimal place for comparison with means) are summarised in Table A-10-11.
<table>
<thead>
<tr>
<th>Location</th>
<th>Mean Period from Empirical Observation</th>
<th>Period from Spectral Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>KD1-C</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>2420ED62, 41m</td>
<td>10, ?12</td>
<td>27.4</td>
</tr>
<tr>
<td>KD1-A</td>
<td>13.25</td>
<td>12.5</td>
</tr>
<tr>
<td>Russell Creek</td>
<td>26</td>
<td>20.8</td>
</tr>
<tr>
<td>Gundaria Bore (couplets)</td>
<td>13.25</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Table A-10-11: Frequencies determined by spectral analysis compared to means of cycles determined empirically.

The power spectra do not always detect the same periods as determined by empirical observation. In the cases of the core from the mine and outcrop at Russell Creek, spectral analysis focussed on a single cycle, produced a poorly defined peak and so is dubious. However, in the other examples, there does seem to be a recurrence of periods in the 12.5 to 13.3 range and at approximately twice that.
Figure A-10-3a: Thickness chart and power spectrum for vertically stacked carbonate/claystone couplets over a ca. 20 cm interval, n=47.

Figure A-10-3b: Percent sandstone in vertically stacked fine grained sandstone/claystone couplets over ca. 10 cm in core from drillhole Amoco 83-5, 536 m, n=37.
Figure A-10-4: Thickness chart and power spectrum for vertically stacked silty carbonate/carbonaceous shale couplets in core from drillhole 2420ED62, 41m at the Lady Loretta mine. The sample represents ca. 7 cm of tst and contains 37 units. The power peak is poorly defined.
Figure A-10-5: Thickness chart and power spectrum for silty carbonate laminae in a crossbed in the KD1 field section. The 57 laminae constitute only ca. 3 cm tst.
Figure A-10-6: Thickness chart and power spectrum for foreset beds in a medium grained sandstone at Russell Creek. The 40 beds constitute ca. 45 cm tst.
Figure A-10-7: Thickness charts and power spectrum for foreset couplets defined by
alternations of fine to coarse grained sandstone in a crossbed at Gundaria Bore. There
are 115 alternations over a ca. 5.8 m interval. Note the thick-thin alternation evident within
each couplet at higher total thicknesses. The lower thickness chart and the power
spectrum are based on couplet thicknesses. The power peak is poorly defined because it
honours the subsidiary troughs evident on the left flanks of the two central peaks in the
thickness chart.
A-10.4.5 Interpretation and Discussion

Tidal Rhythms and the Rock Record

The Earth presently experiences lunar tides twice in a lunar day of 24hr 54min. The two tides, called semi-diurnal, are not equal because of the Earth's declination. The pattern can range from an extreme of semi-diurnal change to one that is essentially daily (see the comparison of modern tropical tidal data presented in Archer, 1991). The tropical month, related to lunar declination relative to Earth's equator, has a period of 27.32 days (13.66 days per half-month). Such systems are usually produced by diurnal tides and the deposition of a single bed per tide. Every 14.77 days, when the Sun, Moon and Earth are close to being in conjunction, a spring tide occurs. Neap tides result from the Sun and Moon being in quadrature with the Earth. Every 29.53 days (the lunar month) a greater amplitude spring tide coincides with the full Moon. Where spring tides are unequal and a half-month inequality is observed, the period is 27.55 days. These familiar rhythms are well documented in tidal records and typically result in the deposition of a series of couplets corresponding to the semidiurnal cycle. There are also longer-term cycles, not discussed here, but described in Archer (1991) and House (1995).

Although sedimentologists had long recognised non-random thickness variations from a variety of environments, it has only been since the 1980s that such variations were studied systematically and comparisons made between modern and ancient tidal deposits. Not surprisingly, many modern and Holocene tidal sediments show semi-diurnal, diurnal and/or neap-spring cycles. However, it is important to note that average number of units preserved from neap to neap varies considerably from the theoretical ca. 14 and 28 (Table A-10-8).

There are also numerous examples of periodic fluctuations in bed thickness from the ancient rock record (Table A-10-8) but these are often difficult to interpret where the environment of deposition is not well constrained. For example, the much-cited work of Williams (1981 et seq.) detected periods of 14 and 25-27 between minima. He originally interpreted this as sunspot periods in annual glacial varves. The same cycles were subsequently reinterpreted as tidalites (Sonett et al., 1996: Williams, 1989, 1991).

Fluctuations from the theoretical average per bundle in tidalites can arise in several ways. Spring tides may erode previous deposits or neap tides may not be sufficiently strong or may not reach the site of deposition. Storms and changes to the amount of runoff will also cause variations.

Interpretation of the Lady Loretta Data

The apparent periodicity in the rhythmites from the Lady Loretta Formation has frequencies within the range of values from both modern and ancient tidalites. A ca. 14 unit cyclicity in bed/lamina thickness is interpreted as reflecting diurnal deposition within a neap-spring tidal cycle. Maxima correspond to spring tides and minima to neap tides. Stronger spring tides presumably carried a proportionally high sand content in the Amoco 83-5 example. The thick-thin alternations seen in coset thickness are similar to those described by Dalrymple (1992), Nio and Yang (1991), Richards (1986) and Williams
(1991). These are interpreted as semi-diurnal, reflecting diurnal inequality of tides. The one example from the mine is problematic, although clearly non-random and superficially similar to other tidalites, there are too few data for satisfactory analysis.

There is a paucity of reliable data from the Lady Loretta Formation and seemingly large fluctuations in the data available. Consequently, it is not prudent to attempt to calculate the length of the year or to speculate about global dynamics other than to say that, contrary to Merifield and Lamar (1968) and Olson (1972), Palaeoproterozoic tidal deposits do not appear to be remarkably different from their modern counterparts (see Section 2.2) and contrast to some of the Neoproterozoic examples from the literature.
A-11. RIPPLE ANALYSIS

A-11.1 INTRODUCTION

Ripples can potentially be useful indicators of sedimentary environment and, in some exceptional cases, of palaeocurrent direction (see Section 5.5.2) and water depth. However, the old and persistent myth that asymmetric ripples are exclusively the product of unidirectional flow, and therefore non-marine, is a misleading generalisation and was acknowledged as such as early as the 1940s (Evans, 1949). Furthermore, the distinction between symmetric and asymmetric is too often a subjective field assessment.

The current study has used both qualitative and quantitative approaches to ripple description and interpretation. The objectives of this ripple analysis of the Lady Loretta Formation were to:

- provide objectivity in description of ripple morphologies
- compare ripple morphologies from the vicinity of the Lady Loretta mine with those in the formation regionally
- determine if the majority of ripples formed under current, wave or combined flow
- apply the Clifton and Dingler (1984) method to estimate palaeo- water depth and wave height.

A-11.2 TERMINOLOGY

The three fold classification of ripples into current, wave and combined-flow is partly descriptive, partly interpretative, often subjective and varies between authors (Table A-11-1). The main differences in terminology concern asymmetric ripples produced by non-unidirectional flow. Tanner (1967) and Reineck and Singh (1980) differentiated between asymmetric wave ripples and combined-flow ripples of variable symmetry. For simplicity, the current study follows Harms (1969) and Allen (1984) and groups these types together.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>current ripples</td>
<td>I. current-formed ripple marks</td>
<td>current ripples (transverse)</td>
<td>current ripples</td>
<td>unidirectional flow ripples</td>
<td>current ripples</td>
</tr>
<tr>
<td>wave ripples</td>
<td>II. symmetric wave-formed ripple marks and swash zone ripples</td>
<td>symmetrical wave ripples</td>
<td>wave ripples</td>
<td>wave ripples (Reineck et al., 1971)</td>
<td>wave ripples</td>
</tr>
<tr>
<td>combined-flow ripples</td>
<td>asymmetric wave-formed ripple marks</td>
<td>asymmetrical wave ripples</td>
<td>wave ripples</td>
<td>asymmetric oscillation ripples (Evans, 1941; Reineck &amp; Wunderlich, 1968)</td>
<td>combined-flow ripples</td>
</tr>
<tr>
<td>modifications and special cases</td>
<td>transverse current/wave ripples</td>
<td>longitudinal current/wave ripples</td>
<td>not recognised</td>
<td>longitudinal ripples (van Straaten, 1951)</td>
<td>not observed</td>
</tr>
</tbody>
</table>

Table A-11-1: Synonymy of terms used to classify ripples.
A-11.3 TECHNIQUES OF RIPPLE ANALYSIS

A-11.3.1 Ripple Indices

Ripple indices that ratio the various dimensions of ripples can be used to provide an objective, quantitative, means of description. Such indices have been measured from ripples generated in laboratory experiments and from modern examples in a variety of environments. Within certain constraints, it is possible to use the indices of ancient examples to postulate a depositional setting. The most commonly used indices are:

- Ripple Index \( (RI = \lambda / \eta) \), also called the Vertical Form Index
- Symmetry Index \( (RSI = Ls / LI, \text{such that } s > l) \)
- Straightness Index \( (SI = Cc / d) \)

These indices have been developed, revised and reviewed by Tanner (1967), Allen (1979), Collinson and Thompson (1989) and Lindholm (1987). Comparable ripple analyses have been undertaken in a late Proterozoic intertidal sandstone (Sarkar, 1981), sandstones in a wave-dominated early Proterozoic braided delta (Eriksson et al., 1995), argillaceous Cambrian epeiric-sea sediments (Moore, 1982) and an early Proterozoic shallow freshwater lake (Aspler et al., 1994).

In the current study, the conventional two-dimensional plots of Tanner (1967) and a three-dimensional crossplot of the indices have been used. The latter presentation focuses on the area nearest the origin in the original Tanner plots. Using the published cut-offs discussed below, pure wave ripples will plot near the lower back corner of the cube. Data that satisfy the criteria for a wave origin on all three crossplots are shown as a square. Current and combined-flow ripples will, in general, plot towards the outside of the cube. Swash and wind ripples would plot above the cube.

A-11.3.2 Equations to Estimate Palaeo-Wave Height and Water Depth

There have been several attempts to develop equations to quantify wave height and water depth based on the Airy wave theory using measurements of ripple morphology and grainsize. Tanner (1971), Komar (1974), Allen (1981), Clifton and Dingler (1984), and Diem (1985) developed and refined these empirically-derived equations; of which, the following is appropriate to the current study:

\[
H = 38.52 + 1.89\lambda - 7.111n \ln D \\
\ln h = 22.74 + 0.97\lambda - 3.72\ln D - 0.41H
\]

where \( H \) is wave height in centimetres, \( h \) is water depth in centimetres, \( \lambda \) is ripple spacing in centimetres and \( D \) is grainsize in microns. To apply this technique, the ripples must meet the following criteria: \( RSI < 1.5, LI / \lambda = 0.4 - 0.6, \eta / \lambda > 0.1 \) and \( \lambda / D < 400 \) (see Aspler et al. (1994) for explanation of these cutoffs).

This approach has been used in studies of ancient ripples by Sundquist (1982), Moore (1982), Aspler et al. (1994) and Dyson (1995a). While acknowledging the theoretical validity of this technique, it would appear that the equations presently used are gross simplifications. Dyson (1995b) pointed out that palaeobathymetric calculations from ripples
capping tempestites were likely to be underestimates. Commonly, the results are not borne out by even casual observations of ripples in modern settings and I regard the results as order-of-magnitude estimates at best.

A-11.3.3 Study of Internal Structures and Relationships Between Ripples
The internal geometry of ripples can be a useful adjunct in ripple analysis. Newton (1968) compared the internal structures of nearshore wave-formed ripples from modern tideless and tidal settings. He concluded that such ripples (both symmetric and asymmetric) exhibit a unidirectional internal lamination dipping toward shore. The net sediment transport direction, however, may be other than in the foreset dip direction. De Raaf et al. (1977) documented a number of internal structural features (e.g. opposed unidirectional crosslamination and chevron up-building) as indicative of wave action.

Climbing ripple lamination (also known as ripple drift) is the internal structure formed from the migration and simultaneous upward growth of ripples produced by either currents, waves or combined flow. Ripples may climb in-phase or in-drift. Climbing ripple lamination forms in a variety of marine, fluvial and aeolian environments during periodic rapid accumulation of sediment (see Reineck and Singh, 1980 and de Boer et al., 1988 for specific examples). Climbing ripples are sometimes associated with combined-flow or normal current ripples and hummocky cross-stratification in tempestites. They also occur in fine grained turbidites and in tidal flat deposits.

A-11.3.4 Wave Ripples
Symmetrical wave ripples are relatively straight crested and "tuning-fork" crest bifurcation is common; the crests range from smoothly rounded to peaked but the troughs are usually gently rounded. In plan view, wave ripples are usually more regular than current ripples. However, the degree, as well as directions, of ripple symmetry may vary considerably along the length of a train of wave ripples.

The ripple index varies from 4 to 13 but is generally around 3 to 8 (Allen, 1984) or 6 to 7 (Reineck and Singh, 1980). Symmetric wave ripples are internally variable and may have chevron or bundled upbuilding, or unidirectional cross lamination. Ripple crests can be modified because of changing current strength or water depth, leading to the development of truncated or double crests and stepped sides. The latter are usually interpreted as indicative of shallowing or emergence.

Wave ripples occur in a wide range of modern environments: river channels and floodplains, inshore lake waters, and a variety of marine settings ranging from intertidal flats to deep sea (Allen, 1984). An interference pattern of relatively short wavelength wave ripples is typical of a tidal flat, barrier shoreface or subtidal environment. Swash zone ripples have a higher ripple index than other forms of wave ripples. In modern examples, wave ripples become more asymmetric shorewards with the lee side directed onshore. Wave ripple cross-lamination is a characteristic structure of shoreface to foreshore buildup-zone sediments.
A-11.3.5 Current Ripples

Current ripples produced by unidirectional currents tend to be strongly asymmetrical with a steep downstream lee side (often 30° to 35°). They are restricted to grainsizes less than 0.6 mm. Typical wavelengths (10 to 60 cm) are longer than wave ripples. This gives a higher ripple index; generally 8 to 20, but ranging as high as 40. Allen (1984) and Reineck and Singh (1980), amongst others, postulated a trend from straight crested to linguoid or lunate with increasing current velocity and decreasing water depth. Work by Oost and Bass (1994) demonstrated that this trend could be independent of flow strength and was a function of the time allowed to reach an equilibrium state.

Ripples associated with turbidites and contourites are a special case of current ripples. They are commonly associated with convolute laminae and are commonly bounded by, and often pass laterally into, parallel laminae. In more distal facies, the ripples often occur as thin lenses. Contourite ripples typically have ripple indices of 9 to 18 (Cook and Mullins, 1983).

A-11.3.6 Combined-Flow Wave Ripples and Asymmetric Wave Ripples

Combined-flow ripples are superficially similar to current ripples but tend to be more internally variable along their length. They may have a characteristic internal form-discordance with an irregular lower bounding surface, bundle-wise arrangement of foreset laminae, and foreset laminae with offshoots.

The smallest asymmetric ripples (<4.5 mm height) are almost invariably of wave, rather than current, origin (Reineck and Singh, 1980). Asymmetric wave ripples either lack spurs and stoss-side ridges altogether; or have fewer of these features in a less regular arrangement, compared to current ripples (Allen, 1884). Furthermore, asymmetric wave ripples tend to occur in contiguous domains bordered by discontinuities in the ripple pattern. In other cases, they can best be differentiated using the ripple index (ranges 5 to 16, mostly 6 to 8) and other indices based on their geometric properties.

As the terms wave-current and combined-flow ripples imply, they are formed by the interaction of both unidirectional and oscillatory (wave) currents. Such ripples are often associated with storm beds (Arnott and Southard, 1990; Myrow and Southard, 1991). Asymmetric wave ripples with wavelengths between about 0.1 m and 1 m abound on modern intertidal flats, as well as in rocks of subtidal to intertidal origin. Such ripples occur on marine shelves and in lakes, commonly in shallower water than their symmetrical counterparts (Allen, 1984 and references therein).

A-11.4 Ripples in the Lady Loretta Formation Regionally

Well-exposed ripple pavements are a prominent feature of the Lady Loretta Formation regionally. They occur sporadically throughout the stratigraphy but are most common in the transition to Shady Bore Quartzite.
A-11.4.1 Description
A wide variety of different ripple morphologies are present. Interference ripples are ubiquitous. Using the terminology of Allen (1984), the latter vary from subtle modification of the dominant trend, through "brick-" and "tile-patterns" to "egg-crate patterns". These forms can vary along strike of a single ripple pavement. Figure A-11-1b shows an asymmetric "egg-crate pattern". Ladder-back ripples (characterised by spurs projecting in the downstream direction - Figure A-11-1c) commonly occur associated with, or grade laterally to, interference ripples.

Tuning-fork bifurcation is common in both symmetric and asymmetric ripples (Figure A-11-1e). Modifications to ripple crests are also very common. Double-crested and planed ripples are particularly abundant in the transition to Shady Bore Quartzite. These forms have been excluded from measurements of ripple indices in accordance with Tanner (1967) and may result in the abundance of current ripples being under-estimated in that part of the stratigraphy. Lunate, linguoid and catenary-swept ripples were observed at the Russell Creek and Brenda Creek sections.

A-11.4.2 Qualitative Interpretation
Interference ripples are clear evidence of the interplay of different oscillatory hydraulic regimes. The examples in the Lady Loretta Formation are interpreted to indicate that such regimes varied from unequal and out of phase ("brick-pattern"), through equal in phase ("tile-pattern") to nearly equant hexagonal ("egg-crate pattern") (Allen, 1984); sometimes during the deposition of a single bed or between successive beds (Figure A-11-1f). Orthogonal or opposed currents produced symmetric patterns; asymmetric patterns result from the interplay of currents at other angles. Interference ripples are the dominant ripple form on modern tidal flats, but have also been reported from estuaries and lakes in as much as 15 m of water (Komar, 1973; Allen, 1984). The formation of interference ripples as part of a spectrum of tidal bed forms associated with emergence is described by Klein (1977). Examples from the Lady Loretta Formation associated with planed or double-crested ripples, scour pits and washout rills (see Section 5.7) are good evidence of intertidal deposition.

Ladder-back ripples, sometimes thought to be diagnostic of a tidal flat, also occur in a range of peritidal environments from back-barrier estuary to shallow marine (Reddering, 1987). Tuning-fork bifurcation is found almost exclusively in wave (and wind) ripples but not current ripples (Tanner, 1967).

Modifications to ripple crests, such as planed and double-crested ripples, are interpreted as evidence of shallowing, possibly to a few centimetres of water (Klein, 1977). Collectively, these ripples are most likely to have been deposited in a very shallow marine to tidal flat environment with evidence of intertidal conditions locally.

A-11.4.3 Application of Ripple Indices
The ripple measurements from the Lady Loretta Formation regionally, have been subdivided into a carbonate-dominated northern group and a clastic-dominated southern group. The northern group is plotted in Figures A-11-2, A-11-3 and the southern group in Figures A-11-4, A-11-5. Each data point represents the mean values from between 5 and 30
measurements of a single wave train. The lack of tectonic deformation can be demonstrated by reliable strain indicators, such as ooids, in the outcrops of Lady Loretta Formation used.

The majority of the data from both north and south plot as either wave ripples or of indeterminate origin. Few points plot in the current field, although many of these ripples appear asymmetric. This is consistent with the findings of Tanner (1967) and references therein, who also concluded that very shallow wave-formed ripple marks are commonly asymmetric. Some points with higher RSI values plot in the wind field in Figures A-11-2b and A-11-4b, but the same ripples plot in the wave field in Figures A-11-2a and A-11-4a.
Figure A-11-1: Ripples. (a) Slabbed section showing internal structure of ripples in sandstone, BCC177. (b) Interference ripples in an asymmetric "egg-crate" pattern, Greater Loretta Syncline. (c) Lunate ripples with ladderback spurs. (d) A ripple pavement exposed in outcrop in the Big Syncline. (e) Parallelism and tuning fork bifurcation in ripples, Kamarga Dome. (f) Stacked ripple pavements, Ploughed Mountain. Note the change in orientation upsection visible to the right of the geology pick. (g) Asymmetric interference ripples with cubic moulds after halite, Kamarga Dome.

Coin is 3 cm d and bar scale is 1 cm.
Figure A-11-2: (a) and (b) Tanner plots of 103 ripple analyses from outcrop of the carbonate-dominated northern Lady Loretta Formation. Each of the points plotted represents the mean of a ripple train.
Figure A-11-3: Three-dimensional plot focussed near the origin of the previous Tanner plots. Data from outcrop of the carbonate-dominated northern Lady Loretta Formation. Wave generated ripples will plot towards the lower back corner of the cube. Data that fulfil the wave-origin criteria on all three crossplots are shown as squares.
Figure A-11-4: (a) and (b) Tanner plots of 60 ripple analyses from outcrop of the clastic-dominated southern Lady Loretta Formation. Each of the points plotted represents the mean of a ripple train.
Figure A-11-5: Three-dimensional plot focussed near the origin of the previous Tanner plots. Data from outcrop of the clastic-dominated southern Lady Loretta Formation. Wave generated ripples will plot towards the lower back corner of the cube. Data that fulfil the wave-origin criteria on all three crossplots are shown as squares.
A-11.4.4 Estimates of Palaeo-Wave Height and Water Depth

Results of application of the Clifton-Dingler equations to suitably filtered data are given in Table A-11-2. Water depths of a few metres at the most and, in most cases, considerably less are interpreted.

<table>
<thead>
<tr>
<th>Location</th>
<th>n</th>
<th>X cm</th>
<th>D (est.) cm</th>
<th>WAVE HEIGHT cm</th>
<th>WATER DEPTH cm</th>
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Table A-11-2: Application of the Clifton-Dingler equations to suitably filtered ripple measurements from the Lady Loretta Formation regionally.
**A-11.4.5 Study of the Internal Structures**

**Description**

Examples of observed internal structures are shown in Figures A-11-6 and A-11-1a. Opposed vergence in the same bedding surface, commonly on adjacent ripples, was observed at several outcrops. In one case, it was associated with small climbing ripples. Detailed study of serially-sectioned core from Amoco 83-5 shows repeated very nearly opposed palaeocurrent directions at a very small scale. Mud drapes are common in the coarser grained facies in the transition to Shady Bore Quartzite.

**Interpretation**

The repeated opposed vergence is considered to be of tidal origin. The climbing ripples observed are more likely to be associated with flood tide. Mud drapes within ripple sets form during alternating periods of bedload transport from oscillatory flow and deposition from suspension (de Raaf et al., 1977) and are typical of a tidal flat.

**A-11.4.6 Summary of Ripple Analysis of the Formation Regionally**

Both the qualitative field observations and the quantitative analysis can be interpreted to indicate a shallow marine to intertidal setting. This is consistent with inferences made from other sedimentological data from the same beds.

**A-11.5 RIPPLES IN THE VICINITY OF THE LADY LORETTA MINE**

Ripple pavements are not well exposed near the Lady Loretta mine (Figure A-11-1d shows an exception) and there is evidence of slight tectonic deformation of some ripples as a result of folding. Whereas small-scale ripples are common in core, only unoriented two-dimensional measurements are possible. Consequently, there are less reliable data and individual measurements (rather than the means of a ripple train) have been used.

**A-11.5.1 Description and Qualitative Interpretation**

There are generally fewer ripples present in the Lady Loretta Formation exposed near the mine than in other facies in the formation regionally. Those present tend to be smaller (in accordance with a finer grainsize) and of variable symmetry. Interference ripples are commonest in the coarser-grained facies exposed in the core of the Big Syncline but also occur immediately below the Ore Sequence on the eastern flank of both synclines.

The interference ripples are interpreted as indicative of opposed oscillatory flow regimes but the other ripple morphologies are not diagnostic of a particular environment.

**A-11.5.2 Application of Ripple Indices**

Fifteen examples from core, for which only RI can be calculated, range from 6 to 10 and could be of wave or contourite origin. The majority of points derived from outcrop measurements plot within the wave fields on the Tanner plots (Figure A-11-7) and cluster towards the wave corner of the three dimensional crossplot (Figure A-11-8). The higher RSI values, possibly indicative of wind in Figure A-11-7b, are not corroborated by Figure A-11-7a.
Figure A-11-6: Sketches of the internal geometries of ripples from the Lady Loretta Formation. Sample numbers are given on the left. Bar scale is 1 cm.
clay drapes

TRE114

bundled lenses

opposed bidirectional
bundled lenses

BCC177

finer-grained
draped lens

offshooting and
draping foreset

opposed bidirectional
lenses

BCC197A

asymmetric chevron
up-building

subsidiary
crest

opposed bidirectional
lenses of different sizes

BCC197B

separate development
of subsidiary crest

undulating
erosional top

flat lamination
passing to low-angle
cross-lamination

clay drapes, mud flakes,
wisps of organic matter

TRE121B

chevron up-building
of bundled lenses

offshooting and
draping foresets

clay drapes

irregular undulating
set boundary

asymmetric chevron
up-building

association with
planar lamination

CCC131
Figure A-11-7: (a) and (b) Tanner plots of 46 ripple analyses from outcrop in the vicinity of the Lady Loretta mine. Each of the points plotted represents an individual set of measurements.
Figure A-11-8: Three-dimensional plot focussed near the origin of the previous Tanner plots. Data from the vicinity of the Lady Loretta mine. Wave generated ripples will plot towards the lower back corner of the cube. Data that fulfil the wave-origin criteria on all three crossplots are shown as squares.
A-11.5.3 Estimates of Palaeo-Wave Height and Water Depth

Application of the Clifton-Dingier equations determine the estimated palaeo-wave heights and water depths shown in Table A-11-3. Accepting these as order-of-magnitude estimates, the data indicate quite shallow conditions, of perhaps less than a metre.

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<th>$\eta$ (cm)</th>
<th>D ($\mu$m)</th>
<th>$\eta/\lambda$</th>
<th>$\lambda/D$</th>
<th>LI/\lambda</th>
<th>RI</th>
<th>RSI</th>
<th>SI</th>
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<th>WATER DEPTH (cm)</th>
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Table A-11-3: Application of the Clifton-Dingier equations to suitably filtered ripple measurements from the vicinity of the Lady Loretta mine.

A-11.5.4 Studies of the Internal Structures

Description

Some, but not all, of the Lady Loretta Formation at the mine contains repeated opposed vergence within ripples. This is demonstrable within the same piece of core. Rare examples from interference ripple pavements in the Pyritic Unit show opposed unidirectional cross-lamination between adjacent ripples.

Interpretation

Repeatedly opposed vergence is most consistent with a wave-dominated tidal influence.

A-11.5.5 Summary of the Ripple Analysis in the Vicinity of the Lady Loretta Mine

The current study includes data from the sequence previous interpreted as turbidites (Neudert, 1987) deposited in deep water (typically envisaged as hundreds of metres)
(Amade, 1986). However, it would appear that a much shallower setting may be more plausible. Wave-influence is interpreted, at least in part.
A-12. SEQUENCE STRATIGRAPHIC TERMINOLOGY AND SEQUENCE STRATIGRAPHIC INTERPRETATION OF GAMMA LOGS

A-12.1 SEQUENCE STRATIGRAPHIC TERMINOLOGY

The emergence of sequence stratigraphy as a discipline in its own right has been accompanied by "a certain volume of contradictory literature, a proliferation of confusing jargon and the emergence of different 'schools', each with its own set of terms and definitions" (Allen, 1995). In particular, there is, as yet, little consensus on some of the basic definitions of the genetic terminology and there is no formal code of nomenclature (Posamentier and James, 1993; Trendall, 1996). Much of the original Exxon terminology was published by Van Wagoner et al. (1988) and the following discussion has been amended from that work and from Allen (1995) and Krapez (1996, 1997). This thesis is only presenting the very basics and is by no means a comprehensive treatment of the subject. The reader is referred to the afore-mentioned publications for more detail.

"Accommodation" is the potential volume in which a sediment can accumulate and is not necessarily the same as the palaeo-bathymetry in a marine setting (Allen, 1995).

The fundamental unit of sequence stratigraphy is the "sequence", which consists of genetically-related strata bounded by unconformities and their correlative conformities (Van Wagoner et al., 1988). Each sequence can be subdivided into "system tracts" that are defined by their position within the sequence and by the stacking patterns of "parasequences". Allen (1995) described a parasequence as those sediments between two consecutive maximum surfaces. In practical terms, each parasequence may equate to upward-coarsening regressive shelf and coastal deposits of the order of several metres or tens of metres thick. Posamentier and James (1993) pointed out that the terms parasequence and sequence commonly have been used inconsistently and interchangeably.

A "depositional system" is a three-dimensional assemblage of lithofacies and a "system tract" is a linkage of contemporaneous depositional systems. The two-dimensional vertical arrangement of system tracts is termed the "depositional complex" on the graphic logs in Appendix A-15. Three main types of system tracts are recognised: lowstand (LST), transgressive (TST) and highstand (HST). The theoretical stacking geometry of these systems tracts is, in ascending order, lowstand, transgressive and highstand.

The LST forms a regressive succession that comprises the sediments deposited during falling RSL, the ensuing still stand and the interval of slowly rising RSL during which shoreline regression is maintained (Allen, 1995). Thus, a LST represents the four-dimensional geometry of the deposits that accumulate during the lowest rates of accommodation creation (Krapez, 1996). On a carbonate ramp with a pronounced shelf-break, relatively small volumes of carbonate (compared with siliciclastics), are deposited...
during the LST since the area for carbonate production is considerably reduced (Wright, 1993). During falling sealevel, small perched lagoons can be produced on the tidal flats of a gently sloping unrimmed ramp. Much larger lagoons will be produced on a rimmed shelf as the barrier is exposed during the RSL fall.

A TST comprises the sediments deposited when RSL rises faster than the rate of sediment supply. It constitutes an overall transgressive succession characterised by landward-stepping parasequences and commonly forms an upward-fining and upward-thinning section on well-logs of siliciclastic sedimentary rocks. Carbonate sedimentation rates, however, keep up with and even exceed the rate of RSL rise. Thus, aggradation and even progradation of shelfal/inner ramp facies can take place during a TST (Wright, 1993). On a rimmed shelf, reefs may keep up with the increasing RSL and create large lagoons.

A HST constitutes an overall regressive succession deposited when the rate of RSL rise decreases to less than the rate of sediment supply (Allen, 1995). The early phase of the highstand corresponds to period of gradual sealevel rise, whereas the late highstand corresponds to a period of sealevel fall (Krapez, 1997). Compared to siliciclastics, much greater amounts of carbonate sediment are deposited during a HST (Wright, 1993). A short term fall in RSL during a HST may result in large hypersaline lagoons or shelves on which subtidal evaporites form.

Sequences are separated by various types of surface. A "sequence boundary", as originally defined by the Exxon group, is a regionally extensive surface (at a basin-wide scale) that is characterised, in part, by stratal discontinuity surfaces in the form of onlap, downlap and toplap. It may occur as an unconformity or its correlative conformity, depending on the position within the basin, with an unconformity likely to be landward of its correlative conformity (Allen, 1995). The facies above a sequence boundary are a basinward shift from those below. For example, such a relationship can be produced by a marine regression.

This geometry of sequence boundaries was originally interpreted from seismic data, but the definition has now been extended to rock stratigraphic relationships. Cartwright et al. (1993) argue that, in doing so, the original basin-wide context implicit in the Exxon terminology is no longer valid. Thus, "the long-distance correlation of sequence boundaries determined by means other than seismic geometry may be artefacts" (Cartwright et al., 1993).

The "maximum flooding surface" (MFS) is characterised by a stratal downlap and constitutes the surface of maximum transgression and water depth which separates transgressive and regressive parasequences (i.e. the base of the HST, top of TST). It is also the surface on which coastal deposits prograde and commonly is interpreted on the basis of highest gamma count shales (see next section). Outer shelf sedimentation associated with this surface is often referred to as a "condensed sequence" and can include highly carbonaceous shales, phosphatic precipitates, hardgrounds and glauconite.
An "emergence surface" (in Allen’s 1995 terminology) is the summit of a prograding coastal succession and can also be marked by carbonaceous shales or sabkha sediments deposited at this point of minimum palaeo-bathymetry. The junction between the top of a LST and the base of overlying TST is termed the “transgressive surface” or “flooding surface”.

### A-12.2 GAMMA LOGS AND THEIR USE IN SEQUENCE STRATIGRAPHY

Gamma ray logs have been recorded over portions of core and outcrop of the Lady Loretta Formation, as summarised in Table A-12-1.

<table>
<thead>
<tr>
<th>Section/Drillhole</th>
<th>References</th>
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<tbody>
<tr>
<td>Wangunda field section</td>
<td>Zeilinger (1995), this study</td>
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<tr>
<td>L3C Costean</td>
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<td>Amoco 83-5</td>
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<td>CRD 2,3,4</td>
<td>Berg (1986)</td>
</tr>
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<td>LA64</td>
<td>unpublished NABRE log, this study</td>
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<tr>
<td>0740P148</td>
<td>Zeilinger (1995), this study</td>
</tr>
<tr>
<td>2240P142</td>
<td>Zeilinger (1995), this study</td>
</tr>
<tr>
<td>various P and MET series drillholes</td>
<td>Placer and CEC files at Lady Loretta mine</td>
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</tbody>
</table>

Table A-12-1: Gamma ray data recorded from the Lady Loretta Formation.

Existing hardcopies of downhole gamma ray logs were available for three of the CRD drillholes in the Carrier area (Berg, 1986) and from several surface (P and MET) drillholes at the Lady Loretta mine. Unfortunately matching core from the MET holes had been destroyed for analysis.

Additional gamma recordings were made as part of the NABRE project. Total gamma counts were recorded at 0.5 m intervals in outcrop using a hand-held instrument and spectral U/Th/K recordings were made at 0.5 m or 1.0 m intervals over core using a shielded dual-detector instrument. Different rock volumes in core were compensated for by using standards for each diameter of core. The logs over outcrop are qualitative and vary from one instrument to another. Further details of the methodology are given in Krassay (1996) and Krassay and McConachie (1996). NABRE gamma logs and accompanying measured sections and core descriptions are presented in Zeilinger (1995).

Correction of the core to true stratigraphic thickness results in a non-regular, but closer, spacing of the gamma readings. These corrections have been included on the graphic logs in Appendix A-15 but not in Zeilinger (1995). The gamma data in this thesis
have not been averaged, filtered or smoothed. To avoid the problem of comparing logs with different horizontal scales, the gamma logs in this thesis are displayed with the measured range of data scaled linearly across a standard width column.

The gamma log is most easily interpreted in clastic facies where the total count gamma trace is interpreted as a grain size log. Parasequences are recognised on the basis of repetitive lithological patterns and correlation of major key surfaces (sequence boundaries) that correspond to base line shifts or inflections in the gamma curve. Peaks in the gamma ray curve are commonly related to organic-rich shale which are interpreted as records of maximum transgression and flooding. This approach was refined by Creaney and Passey (1993) who utilised both gamma and resistivity logs to predict TOC. Use of the gamma log alone to infer maximum flooding surfaces is not always a valid interpretation. As discussed by Posamentier and James (1993), not every “hot” shale will correspond to a MFS and vice versa.

In several instances noted during this study, the total gamma counts seemed to be spuriously low over some areas of obviously high organic carbon content. This was the case for outcrop at Wangunda (cf. 143 - 148 m and 24 - 26 m), but is of most significance in cores of the Ore Sequence and Ore Sequence Equivalent. Despite the demonstrably high TOC (Section 4.8) and the presence of radioactive minerals that produce thucholite (Section 11.2.2), this interval can be correlated across both synclines and to drillhole LA64 as a gamma low. This is possibly attributable to the abundance of pyrite.

Gamma logs are of less value in carbonate-dominated peritidal sequences where there are few clay-rich interbeds and, as Aigner et al. (1995) demonstrated, it is impossible to use gamma logs alone to interpret the depositional environments within, or correlate between, lagoonal and ramp facies. Additionally, the 0.5 m and 1.0 m spacing used by AGSO could not resolve the ca. 1.0 m “cycles” (or parasequences) that typify many peritidal environments (see discussion of “cycles” in Section 10.2.2 and Appendix A-10).

Multi-element gamma ray logs have been used as indicators of the depositional environment or palaeo-redox conditions. Adams and Weaver (1958) advocated the interpretation of low Th/U ratios (below 2) as indicative of anoxic and/or reduced marine deposition. Ratios above 7 were recorded from the oxidised and/or subaerial continental sedimentary rocks. Jones and Manning (1994) evaluated a number of geochemical ratios in argillaceous rocks as potential indicators of palaeo-oxygen concentration. The UTTh index and authigenic uranium content correlated well with the degree of pyritisation and were therefore considered reliable indicators of palaeo-redox conditions. The Th/U ratio was calculated for selected intersections of the Lady Loretta Formation. However, there was little variation in the ratio from a mean of about 2.0, even between clearly oxidised and reduced sedimentary rocks.

The K data are also of relevance to the current study. The authigenic K feldspar-cherts documented from the Lady Loretta Formation should be identifiable using this
technique, as documented from the McArthur Basin by Davidson (1995). Alteration halos related to the passage of mineralising brines may be manifest as anomalously high or low K contents in the multi-element gamma logs (Krassay and McConachie, 1996). In practice, the total counts from K feldspar cherts were commonly less than from organic shales and fault zones. This is particularly evident on the downhole logs from the P and MET series drillholes. There were insufficient multi-element gamma measurements of the K feldspar-cherts to convincingly demonstrate a proportionally higher K count.

Several of the key gamma ray logs presented in this thesis warrant qualifications not expressed in Zeilinger (1996). The following comments are the opinion of the author and expressed in deference to any forthcoming from NABRE.

The gamma ray logs through Zn-Pb-Ag mineralised intervals (particularly the Ore Sequence in drillhole 2240P142) will be significantly attenuated by the amount of Pb (locally up to 35 wt%) in the core. The gamma log of 2240P142 was also plagued by instrument problems and the data presented in Zeilinger (1995) resulted from the adjustment and splicing of sections recorded with either one or two detectors operational. To avoid the duplication of readings and negative total gamma counts shown in Zeilinger (1995), the data shown in this thesis honours the highest reading and has been bulk shifted by +16 cpm.

The upper 42 m of core from drillhole 740P148 is highly weathered. This, and the wider sample spacing, accounts for the attenuation and loss of resolution of the gamma log over that interval. This also provides some indication of the relationship to be expected between weathered outcrop of these lithologies and fresh rock. Core from immediately below the Ore Sequence Equivalent in 740P148 is highly oxidised and this can be interpreted as evidence of faulting. There are also apparent structural complications in the lower-most ca. 20 m of core suggestive of parasitic folding (Grant, pers. comm., 1997).

The coincidence of high Fe analyses and the relatively low gamma readings from the Ore Sequence Equivalent probably means that the low gamma response is attributable to the abundance of pyrite. This has import for sequence stratigraphic interpretation since at least one genetic model for the Lady Loretta ore body maintains that most of the pyrite is epigenetic and, thus, may not be a valid sequence stratigraphic unit.

The gamma ray recordings from drillhole CM35 are responding to the pervasive silicification and quartz veining in that core.

NABRE also recorded gamma data over very poor outcrop and highly weathered costean exposures in the Contractors Costean in the footwall of the Small Syncline. Although this was the best available site, the costean was dug to map major faults such as Spider and Max's Fault and numerous smaller faults and fault zones. Subsequent ground-truthing by the author demonstrated that many of the gamma spikes were coincident with fault zones. Other zones of brecciation produced gamma lows. These
gamma data are given in Zeilinger (1995) as BCC1 DQ5869 but have not been included in this thesis.

The gamma log for the Wangunda field section as presented in Zeilinger (1995) does not tie to the author's lithological log of the measured section because of the duplication of gamma readings on dip slopes. The graphic log presented in this thesis rectifies the problem.
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A-14. SUPPORTING PUBLICATIONS


These publications have been removed for copyright or proprietary reasons.
A-15. MAPS AND GRAPHIC LOGS

Location maps of field sections follow. Detailed maps of the mine are provided only in the Buka copy.

See pocket for the following graphic logs.

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KEY TO LOCATION MAPS FOR FIELD SECTIONS

Sample location / data point

Measured section

Pms  Shady Bore Quartzite

Pml  Lady Loretta Formation

Pmz  Esperanza Formation

Bedding trace from airphoto interpretation

Fault

Syncline

Anticline

Quartz veins

Creek
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