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CRA EXPLORATION PTY. LIMITED
ACN 000 057 125

Eighth Annual Report
For The Period Ending 9 November 1996
EL 34/88 Zeehan No. 2, Tasmania

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SAJ Russell

Date: November 1996

Licence Holder: CRA Exploration Pty. Limited

Submitted to: Chief Geologist, South East District

Copies to: Mineral Resources Tasmania
CRAE - South East District
CRAE - Zeehan
CRAE - ETIG
Allegiance Mining NL

Submitted by:

Accepted by:

CRAE Report No. 22209

Abstract

Exploration has continued on EL 34/88 (Zeehan 2) for carbonate hosted base-metal deposits within the Gordon Limestone of the Zeehan area, West Tasmania. . Analogies with Irish-style carbonate hosted Zn/Pb deposits are being used to guide exploration.

Work undertaken in the 12 month period to 9 November 1996 consisted of diamond drilling at King Billy prospect (1 hole for 113.7m); reconnaissance wacker bedrock sampling at Rose Valley (14 holes for 37m) and reconnaissance soil and stream geochemistry southwest of King Billy.

Diamond drilling at King Billy failed to intersect significant base-metal mineralisation. However, siderite alteration and ferruginous clays with elevated zinc values were intersected at the base of the limestone, in contact with the underlying Moina Sandstone. Major faulting is associated the sandstone contact.

Results from the detailed helimag survey were received. They highlighted complex but discernible geology and zones of siderite alteration.

One major north-south linear magnetic anomaly at the southern margin of the King Billy prospect, hosted by Cambrian sediments, was subjected to a reconnaissance geochemical programme. No significant results were obtained.

A basin analysis study was completed using Geosea Consultants (Dr Clive Burrett). Three formations have been recognised in the Gordon Limestone corresponding to differing carbonate depositional environments.

Recommendations are:-

- Continued interpretation of the helimag data for the King Billy and Firewood Siding areas.
- Diamond drill test a gravity anomaly and silicic breccias south of the Firewood Siding Fault.
- Further diamond drilling of the lower limestone contact in the west of King Billy, near an area with major dolomitisation and inferences of syn-sedimentary faulting.

Rehabilitation consisted of replacing vegetation removed for the drill-site, ripping of compacted ground around drill-sites and the removal of rubbish and cuttings.

Expenditure for the 12 month period was $117,128.

Total expenditure for this licence to 31st October 1996 is $749,791.

This licence is currently being offered for Joint Venture.

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Plans

Plan No.	Title	Scale
✓ Tv 1025	EL 34/88 Zeehan 2 Location Plan	1:100 000
✓ Tv 1022	Zeehan Project Target Plan	1:50,000
✓ Tv 998	EL 34/88 Zeehan 2 & EL 45/92 Mt Dundas Amber Creek and King Billy Prospects Geological Interpretation	1:5,000
✓ Tv 1155	EL 34/88 Zeehan 2 Zeehan Carbonate, King Billy Prospect Section 71200E : DD96ZK123	1:1,000
✓ Tv 1156	EL 34/88 Zeehan 2 Zeehan Carbonate, Rose Valley Prospect Bedrock Sampling Sites	1:25,000

Appendices

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Appendix III	Analytical Methods for Drillcore and Bedrock Wacker Sampling
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1. Conclusions and Recommendations

Two carbonate-hosted Zn-Pb targets were tested: King Billy and Firewood Siding/Rose Valley. Activities included diamond drilling, geochemical sampling (including bedrock wacker, soil, rock and stream sediment sampling), and a contract basin analysis study by Dr Clive Burrett of Geosea Consultants.

No significant base metal mineralisation was intersected at King Billy. However, important geological information was gathered, in particular the presence of siderite alteration at the Moina Sandstone / Gordon Limestone contact.

Silicified breccias within the Gordon Limestone near the Firewood Siding Fault are highly significant. They are of special interest as the breccias envelope a small gravity high (EZ data) on the downthrow side of the Fault.

Results from the helimag survey were received and highlighted significant anomalies within limestone at Firewood Siding, Professor Range and King Billy. A 1.5 km x 200m north-south linear magnetic anomaly is hosted in Cambrian sediments at the south western extent of King Billy. This is known as the King Billy magnetic anomaly, centred on 368350E 5350900N (AMG). Initial geochemical reconnaissance indicates a mafic, volcanic breccia unit.

The basin analysis study indicates that the Firewood Siding area was near the basin margin during Ordovician carbonate deposition.

The collection and compilation of data over the past two years has greatly increased the understanding of the geology of the Ordovician/Silurian sequence. Prior to further drilling or surface work, greater effort should be put into the three dimensional geometry of the limestone and the unique pattern of carbonate deposition.

Recommendations for 1997 include:-

- Diamond drilling to test a coincident gravity anomaly and silicified decalcified breccia unit at Firewood Siding.
- Diamond drilling to test the lower sandstone/limestone contact at the western end of King Billy.
- Further processing of the detailed helimag data to better delineate further drill targets, particularly the basal limestone contact at Firewood Siding and Professor Range.

2. Introduction

Zeehan 2, EL 34/88 covers 34 km^2 located near Zeehan on the Tasmanian W coast (plan Tv 1025). EL 34/88 was granted to "His Grace, The Most Noble, The Duke of Avram" on 9th December 1988, and transferred to Major Mining Ltd on the 23rd November 1989. CRA Exploration Pty. Limited entered into a joint venture agreement with Major to explore EL 34/88, commencing on 23rd April 1991. Major Mining Ltd divested its interest in the joint venture to Allegiance Mining NL, with the exploration tenements transferred to CRAE (90%) and Allegiance (10%) as tenants in common on 22nd January 1994.

During the period under review, the eighth year of tenure, CRAE has a statutory obligation to spend a minimum of $68,000 in exploration. This report details all exploration activities conducted within EL 34/88 by CRAE for the twelve month period 9/11/95 to 9/11/96.

CRAE's principal focus in the Zeehan area is zinc mineralisation within the Ordovician Gordon Limestone, considered prospective for Irish-style carbonate-hosted Zn-Pb deposits.

Prospect targets which have undergone exploration include King Billy, Firewood Siding and Rose Valley (Plan Tv 1022).

Sub-divisions of the Gordon Limestone have been made on a lithologic/lithostratigraphic basis for utilisation in drillhole logging. Explanation of formation codes is in Appendix I.

See Parkinson (1992, 1993 and 1994) and Tear (1995) for regional setting, prospect geology and mineralisation.

3. Review of Previous Work

See Appendix II.

4. Exploration Completed in the 12 Month Period Ending 9/11/96

Diamond Drilling Summary

DDH	Prospect	East AMG	North AMG	AMG Zone	Elev (m ASL)	T Depth (m)	Azim (AMG)	Dip	Date Drilled	Details Appendix
DD96ZK123	King Billy	371212	5351970	55	145m	113.7	180	60	20/3/96	III
					Total	113.7m				

For a description of the analytical method see Appendix III.

Wacker Bedrock Sampling Summary

Prospect	No. of Samples	Depth		Zinc		Lead	
		Range (m)	Average (m)	Max. (ppm)	Mean (ppm)	Max. (ppm)	Mean (ppm)
Rose Valley	14	0.8-9.5	2.7	242	73	533	52

For a description of the analytical method see Appendix III.

4.1 King Billy

King Billy is 3 km east of Amber Creek, in the eastward continuation of the Gordon Limestone from Professor Range. King Billy is divided by the EL 34/88 - 45/92 boundary (Plan Tv 998).

Work on this prospect consisted of two diamond drill holes. One hole however, is located on EL 45/92 and is reported in CRAE report number 22159.

4.1.1 Diamond Drilling

DD96ZK123 60° to 180° (AMG) TD 113.7m Drillrig: LY38 - Helirig
(Diamond Drilling of Tasmania Pty. Ltd.)

Aim of hole

Diamond drill test of elevated surface geochemistry (up to 1.35% Zn) at the lower limestone/ sandstone contact and down-dip test of helimag surface anomaly.

Results

This hole tested a potential sulphide target at the Moina Sandstone / Gordon Limestone contact (Plan Tv 1155). Shear zones, inconsistent bedding angles and poor correlation with wacker bedrock sampling data confirms the presence of faulting. Siderite alteration zones intermixed with sandy ferruginous clays occur immediately above the Moina Sandstone. A maximum zinc value of 950 ppm (375 ppm Pb) occurs within the ferruginous clays. The Oolite Unit of the Ugbrook Formation is only partly represented in the hole. Minor dolomitisation is present. (Appendix IV).

4.1.2 King Billy Magnetic Anomaly

The King Billy magnetic anomaly is centred on 368350E, 5350900N (AMG) at the south western extent of King Billy. It is approximately 1.5 km long by 200m wide, striking in a north-south direction. The vertical derivative magnetic signature of the anomaly is >7 nT.

The magnetic anomaly was followed up with reconnaissance stream sediment sampling, rock chip sampling and a single soil sampling line (Plan Tv 998) (Appendix V).

Stream sediment assays returned high iron values (up to 5%) with slightly elevated copper (51 ppm), gold (16 ppb) and platinum (6.8 ppb). Major element analysis indicated the stream drained a mafic lithology. The rock sampling identified an unrecognisable mafic unit with 2.4 ppb Pt and 5.6 ppb Pd plus elevated values for other mafic related elements.

The soil sampling help to define a mafic unit coincident with the magnetic high. Copper values at the centre of the anomaly yielded up to 1610 ppm with iron values up to 12%, gold up to 12 ppb, platinum up to 1.3 ppb and palladium up to 4.1 ppb.

4.2 Firewood Siding / Rose Valley

Field inspection of Gordon Limestone outcrops south of the Zeehan - Strahan Highway showed some small hummocks to be silicified breccias, possibly carbonate breccias (although there was no reaction with dilute hydrochloric acid).

A single reconnaissance wacker bedrock sample line was completed south of the Firewood Siding area, within the Rose Valley prospect. This line confirms the presence of limestone in that area, and provides some geological control for the detailed helimag data (Plan Tv 1156). (Appendix VI).

4.3 Detailed Helimag Survey

The Gordon Limestone of the Zeehan area was flown over as part of a detailed sub-regional helicopter-borne magnetic survey. Line spacing was approximately 60m with an average flight height of 30m and sampling intervals were approximately every 3-4m. A feature of this innovative survey was that the flight lines were aimed at being perpendicular to the strike of the limestone which resulted in time consuming and complex processing.

Relevant parts of the initial report (CRAE report 22222) are included in Appendix VII. This report was written just after CRAE decided to seek a joint venture partner for EL 34/88. Minimal interpretation was made and none has been transferred to geological maps.

Areas requiring further interpretation and follow up include a number of magnetic highs within the limestone at Professor Range, the series of magnetic highs at the lower contact of the limestone at King Billy and the large elevated zone at South Firewood Siding /Baura.

4.4 Basin Analysis Study

Dr Clive Burrett of Geosea Consultants was contracted to provide a stratigraphic study of the Zeehan carbonate drill holes to establish:-

- a stratigraphic column for the Zeehan carbonate sub-basin including identification of formational boundaries.
- a measure of the variability of carbonate depositional environments and the positional inference of syn-sedimentary faults.

This was achieved very successfully with one hole from the Firewood Siding area indicating proximity to a basin margin and hence potential sites for base metal mineralisation.

A copy of the report is included in Appendix VIII. Holes examined from within EL 34/88 included DD95ZR103.

5. Discussion of Results

5.1 King Billy

- Diamond drill hole DD96ZK123 intersected sideritic alteration, which is the most distal known occurrence (in the horizontal plane) of siderite away from the Heemskirk Granite. This may imply that siderite alteration is not related to the Devonian intrusion.
- Significantly, the lack of dolomitisation at the basal contact in DD96ZK123 is accompanied by low zinc values.
- The unpredicted shallow depth of Moina Sandstone in hole DD96ZK123 highlights the structural complexity of the King Billy area.
- No explanation was found for the 1.35% Zn surface bedrock wacker anomaly.
- More widespread alteration, in particular dolomitisation, occurs at the western margin of King Billy. This is coincident with limestone thickness variation along strike from the King Billy magnetic anomaly. Galena, minor sphalerite and pyrite are found in aircore samples in this western area.
- The limestone's eastern margin has not been defined by CRAE work.
- Further interpretation of the helimag data will assist geological delineation.

5.2 Firewood Siding / Rose Valley

- The gravity anomaly associated with the silicified (carbonate) breccias is important. If it can be proved that the breccias occur at the point of maximum downthrow on the Firewood Siding Fault (a key Irish concept), then this is a very strong target.
- Some of those breccias bear resemblance to the black matrix breccias intimately associated with Zn/Pb orebodies of the Irish carbonates.

6. Environment and Rehabilitation

A number of activities conducted during 1996 have impacted on the environment. These include:

- diamond drilling at King Billy (helicopter supported)
- wacker sampling at Rose Valley

Rehabilitation of surface disturbance included:-

- capping of diamond drill hole collars
- raking of drill sites
- recovering drill sites with cleared vegetation
- removal of rubbish and cuttings

All exploration work is discussed on site with Department of Industry Safety and Mines personnel prior to it being undertaken. Their advice allows for environmental impact of the proposed work to be kept to a minimum.

The drill site and grid line will naturally revegetate. No permanent new access tracks were created. Where possible, low-impact technologies were employed in exploration.

The King Billy diamond drillhole required helicopter support and several trees needed to be felled. Clearance of the drill site for the helicopter was kept to a minimum.

7. References

Kratochvil, M.	1991	EL 34/88 Henty, Tasmania. Statutory Progress Report for the Period Ending 9th November 1991. CRAE Report No. 17635.
Parkinson, R.G.	1992	Zeehan No. 2 EL 34/88. Report on Exploration for the Fourth Year of Tenure, 9/11/91 to 9/10/92. CRAE Report No. 18359.
Parkinson, R.G.	1993	Zeehan No. 2 EL 34/88. Report on Exploration for the Fifth Year of Tenure, 9/10/92 to 9/11/93. CRAE Report No. 19285.
Parkinson, R.G.	1994	Zeehan No. 2 EL 34/88. Report on Exploration for the Sixth Year of Tenure 9/11/93 to 9/11/94. CRAE Report No. 20458.
Tear, S J	1995	Zeehan No. 2 EL 34/88. Report on Exploration for the Seventh Year of Tenure 9/11/94 to 9/11/95. CRAE Report No. 21151

8. Location

Queenstown	SK55-5	1:250,000
Pieman	7914	1:100,000
Zeehan	7914-S	1:50,000

9. Keywords

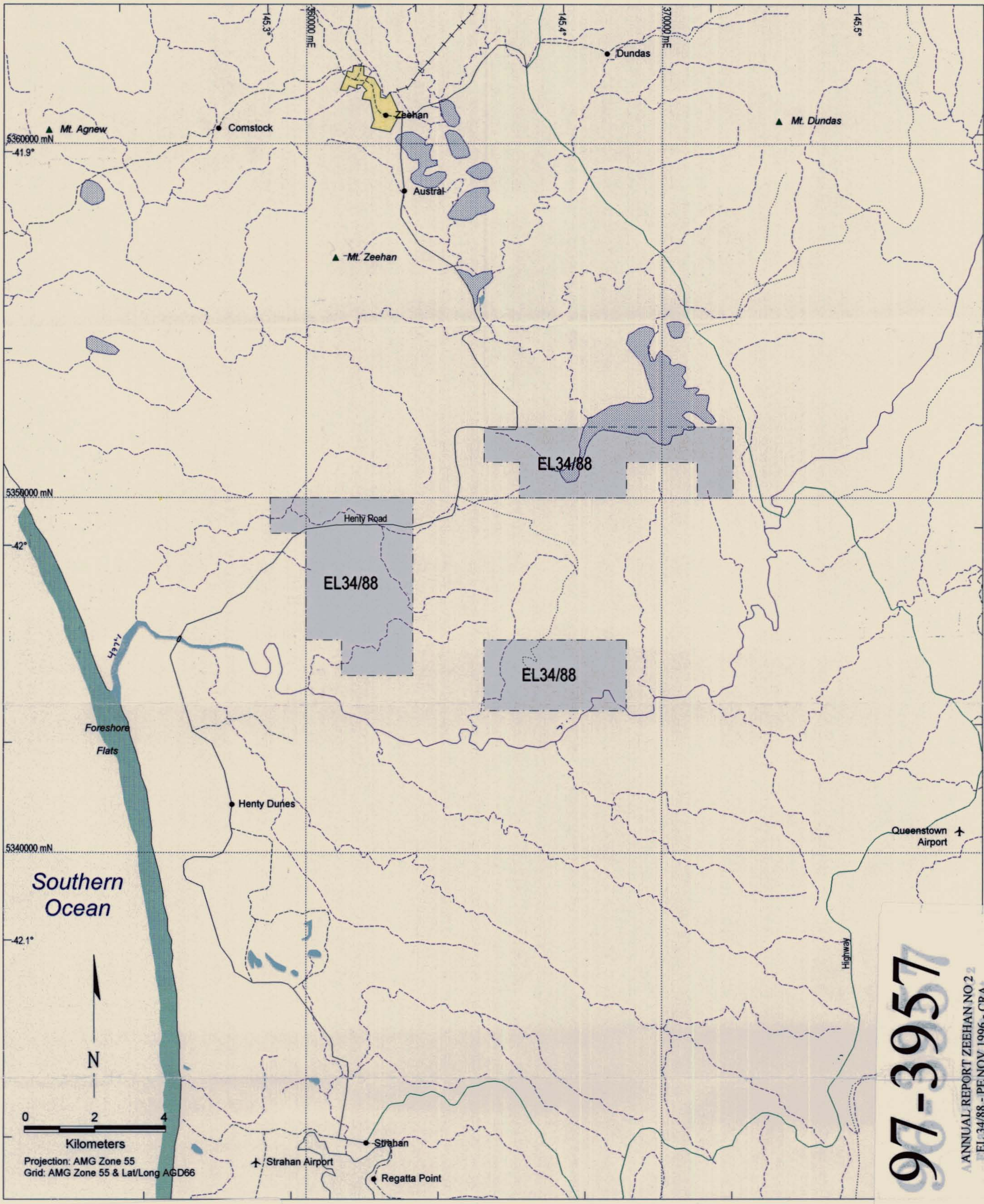
Tasmania, Ordovician, Gordon Limestone, Wacker Bedrock Sampling, Diamond drilling, Zinc, Helicopter-borne Magnetics, Basin Analysis, Syn-sedimentary faulting, Siderite,. Dolomite.

10. DPO Register

CRA Exploration Pty Limited
DPO Register

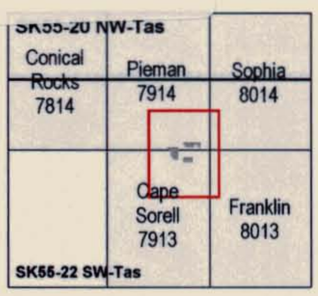
EL 34/88 Zeehan 2

DPO Number	LAB Batch Number	Lab Name	DPO Location	Office Date	Geologist	Tenement Number	Tenement Name	Sample Type	Number of Samples	250,000 Map Sheet	100,000 Map Sheet
77399	11633	Analabs	Zeehan	17/2/96	S. Tear	34/88	Baura	Rock	6	SKSS-5	7914
77397	11589	Analabs	Zeehan	30/1/96	S. Tear	34/88	King Billy	Rock/Soil/SS	28	SKSS-5	7914
82156	11833	Analabs	Zeehan	18/4/96	S. Tear	34/88	Rose Valley	Bedrock	14	SKSS-5	7914
82157	11831	Analabs	Zeehan	18/4/96	S. Tear	34/88	King Billy	Half DD/HQ/NQ	40	SKSS-5	7914



5 cm

Location Diagram



Mapsheet Reference

Legend

- Town
- Mountain
- EL Boundary
- Perennial Drainage
- Non-Perennial Drainage
- Highway
- Secondary Road
- Minor Road
- Track
- Railway
- Lake
- Swamp
- Urban

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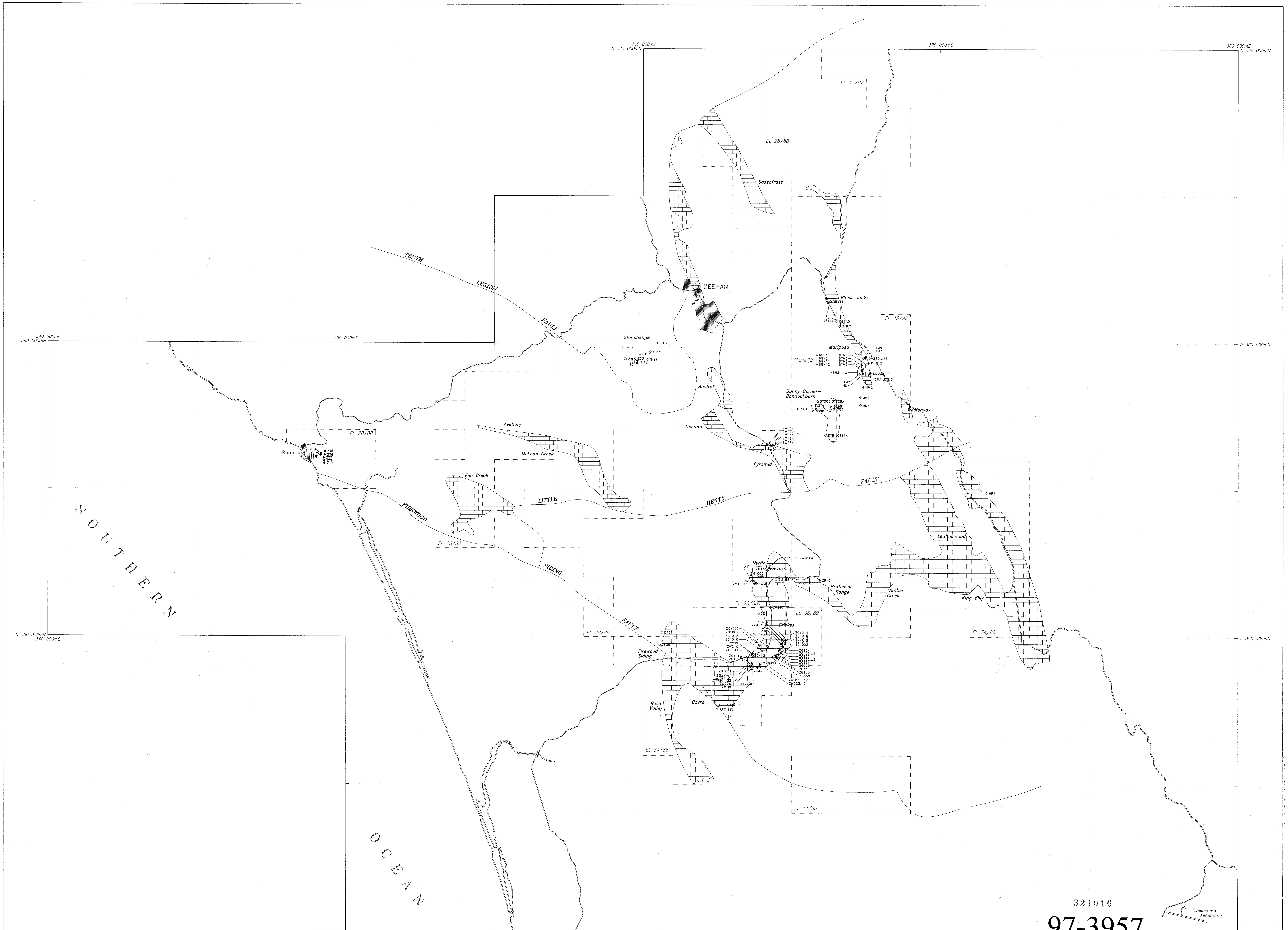
321015

EL34/88 Zeehan 2

Location Plan

Author: Simon Tear	Reference: SW Tasmania SK55-22
Drawn: Tony Sargeant	File Name: Tv1025.wor
Date: December 1996	Report No: 22209
Scale: 1:100,000	Plan No: Tv1025



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S TEAR - S RUSSELL

Diamond Drillhole – CRAE 1995

Diamond Drillhole – CRAE Pre 1995

Diamond Drillhole – Other

Major Faults

CRAE Tenement Boundaries

Ordovician Gordon Limestone
(usually covered by peat and gravels)

0 1 2 3 4kilometres

6cm

North

CRA EXPLORATION PTY. LIMITED

ZEEHAN PROJECT
Target Plan

Ref.:	SK55 – 5	File:	Tv1022.dwg
Scale:	1 : 50000	Date:	November 1995
Author:	Simon Tear	Report No.:	22209
Drawn:	T. Sargeant	Plan No.:	Tv 1022


LEATHERWOOD
AMBER CREEK
KING BILLY
To Professor Range
EL 45/92 Mt. Dundas (CRAE)
EL 34/88 Zeehan 2 (CRAE JV)
5353000 mN
5352000 mN
5352000
5351000
5350000
367000 mE
368000 mE
369000 mE
370000 mE
371000 mE
DD96ZK124/5
DD96ZK123
Argillaceous
LEGEND
Soil Sample (1996)
Rock Chip Sample (1996)
Stream Sed. & Panning (1996)
Aircore Drillhole (1995)
Wacker Drillhole (1995)
Proposed Drillhole
EL Boundary
Drainage
- Perennial
- Non-Perennial
Fault
- Approximate
- Inferred
Thrust Fault
- Approximate
- Inferred
Geological Boundary
- Approximate
- Inferred
500ppm Zinc Contour
Lead Linear
Magnetic Anomalies (helimag)
Sc Crotty Quartzite
Ogud Upper Dolomite Unit
Ogsi Siltstone Unit
Ogul Undifferentiated Limestone
Ogdl Undifferentiated Dolomite
Ogmu Laminated Micrite Unit
Ogoo Oolite Unit
Ogsd Siderite Unit
Ogdc Dark Grey / Black Clay Unit
Ogfc Ferruginous Clay Unit
Ogms Massive Sulphide Unit
Ogst Silty Transition Unit
Ogfz Fault Zone
Ogbr Carbonate Breccia
Om Moina Sandstone
Oo Owen Conglomerate
Cd Dundas Group (Undifferentiated) Cambrian
Silurian
Gordon Limestone
Ordovician
5 cm
300 200 100 50 0 100m
Scale 1:5000
Datum: Australian Geodetic Datum 1966 (AGD66)
Grid: Australian Map Grid Zone 55 (AMG55)
Geological information interpreted from deep overburden sampling (wacker and aircore drilling)
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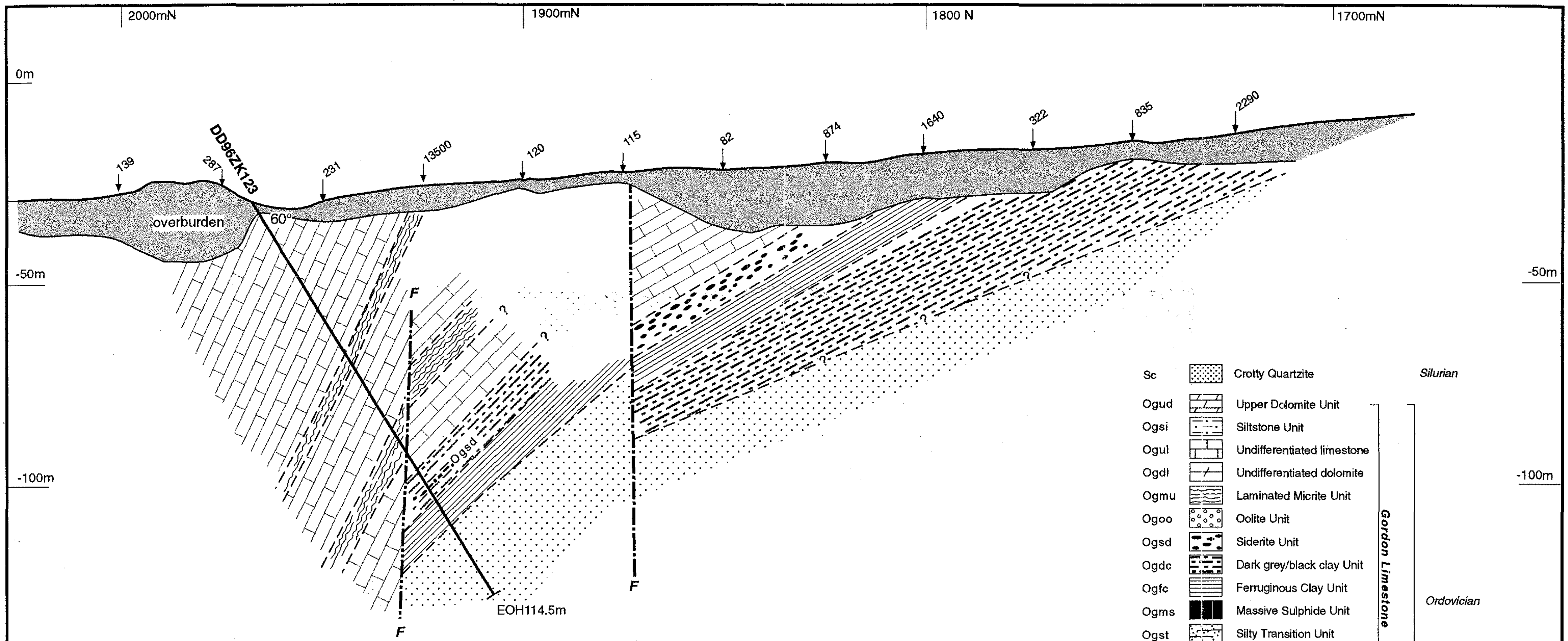
97-3957
ANNUAL REPORT ZEEHAN NO 2
EL 34/88 - PE NOV 1996 - CRA
S TEAR - S RUSSELL
CRA EXPLORATION PTY. LIMITED
EL34/88 Zeehan 2 & EL45/92 Mt. Dundas
Amber Creek &
King Billy Prospects
Geological Interpretation
Author: Simon Tear
Drawn: Tony Sargeant
Date: November 1995
Scale: 1:5000
Mapsheet Ref: SK55-20
File Name: Tv998.dwg
Report No: 22209
Plan No: Tv998



Sc	Crotty Quartzite		Silurian
Ogud	Upper Dolomite Unit	Gordon Limestone	Ordovician
Ogsi	Siltstone Unit		
Ogul	Undifferentiated limestone		
Ogdl	Undifferentiated dolomite		
Ogmu	Laminated Micrite Unit		
Ogoo	Oolite Unit		
Ogsd	Siderite Unit		
Ogdc	Dark grey/black clay Unit		
Ogfc	Ferruginous Clay Unit		
Ogms	Massive Sulphide Unit		
Ogst	Silty Transition Unit		
Ogfz	Fault zone		
Ogbr	Carbonate breccia		
Om	Moina Sandstone		
Oo	Owen Conglomerate		
Ed	Dundas Group (undifferentiated)		Cambrian

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EL 34/88 - PE NOV 1996 - CRA
S TEAR - S RUSSELL

5 cm

ZP37 20ppm — Bedrock sampling (aircore EOH / wacker) Hole no / Zn : ppm

Strong siderite in aircore holes

Moderate siderite in aircore holes

Elevated Zn in aircore holes

Drillhole Intercept Mineralisation Styles

Zinc as Sphalerite

Zinc as mixed sphalerite, zinc rich siderite and zinc silicates (+carbonates)

Zinc as zinc rich siderite

0 10 20 30 40 50 60m

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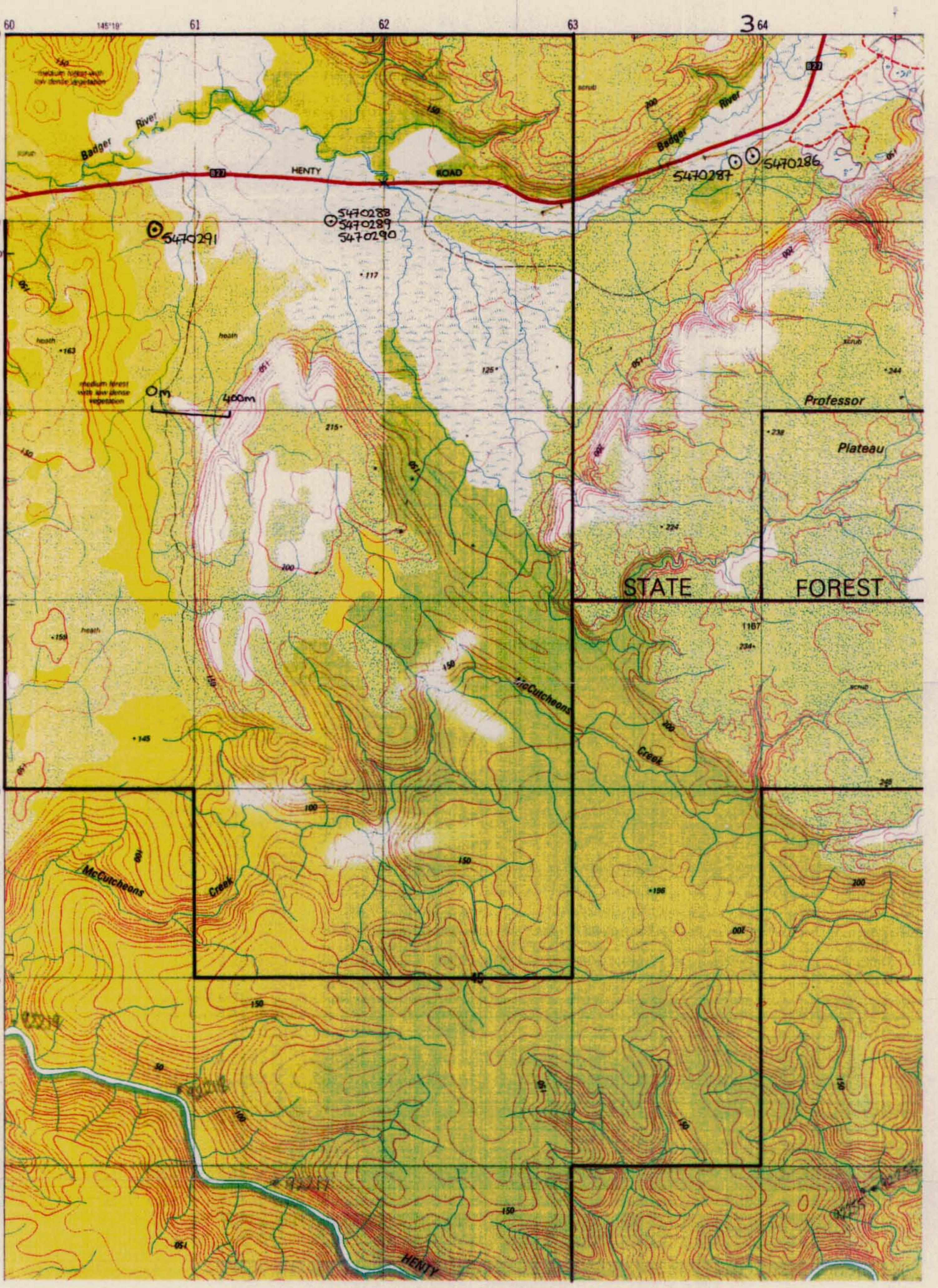
EL34/88 Zeehan 2
KING BILLY PROSPECT
Section : 71200 E
DD96ZK123

Author:	S J Tear, S Russell	Reference:	SK5505 Queenstown
Drawn :	D Oliver	File Name :	Tv1155
Date :	June 1996	Report No:	22209
Scale :	1:1000	Plan No :	Tv1155

TASMANIA 1:25 000 SERIES



5 cm

5470291 Rock Sample Site

0m 400m Wacker Bedrock Sample Line

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EL 34/88 - PE NOV 1996 - CRA
S TEAR - S RUSSELL

321019

CRA EXPLORATION PTY. LIMITED	
EL 34/88 ZEEHAN 2 ZEEHAN CARBONATE FIREWOOD SIDING/ROSE VALLEY BEDROCK SAMPLING SITES	
Ref.:	Scale: 1:25000
Author: SJ TEAR	Report No.: 22209
Drawn: SJ TEAR	Plan No.: Tv 1156

321020

Appendix I

The Gordon Limestone Lithostratigraphy

Zeehan Carbonate Project

In the Zeehan sub-basin the Gordon Limestone has a thickness of 500m (DDH ZB1007). Drilling by CRAE has subdivided this formation into lithologic and lithostratigraphic units. These subdivisions have been utilised in the drillhole logging and are displayed below.

Drill Hole Logging Formation / Lithology Codes

Sc	=	Crotty Quartzite		**SILURIAN**
Ogud	=	Upper Dolomite	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogsi	=	Siltstone Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogul	=	Undifferentiated limestone	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogdl	=	Undifferentiated dolomite	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogmu	=	Laminated Micrite Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogoo	=	Oolite Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogsd	=	Siderite Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogdc	=	Dark Grey / Black Clay Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogfc	=	Ferruginous Clay Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogms	=	Massive Sulphide Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Ogst	=	Silty Transition Unit	**GORDON LIMESTONE**	**ORDOVICIAN**
Om	=	Moina Sandstone		**ORDOVICIAN**
Oo	=	Owen Conglomerate		**ORDOVICIAN**
Ed	=	Dundas Group (undifferentiated)		**CAMBRIAN**

An explanation for the sub-divisions is given below.

1) The Crotty Quartzite

This formation is a sequence of deltaic quartzites of Silurian age. However in drillcore there appears to be no consistency in lithologies at its base which is perhaps to be expected. The question of a faulted contact is brought to mind and thus the unit has not been subdivided. In DD95ZM190 the sequence passes from white massively bedded sandstone into interbedded/interlaminated sands, shales and silts before finally passing into dark shales (fissile) and clays (possible fault gauge). This is possibly matched in DD95DS98 but there are considerable thickness variations.

2) The Upper Dolomite Unit (Ogud)

This is a dolomitised limestone unit that always occurs beneath the Crotty Quartzite contact. Its thickness is variable, up to 100m in DD95ZR104 and down to 25m in DD95ZM190. It is possible that the dolomitisation is fault related, the fault being the Crotty Quartzite/Gordon Limestone Contact.

3) The Siltstone Unit (Ogsi)

This is an argillaceous calcsiltite with bands of bioclastic calcarenite and nodular calcsiltite. Locally it is unreactive to dilute HCL. It generally occurs at the base of the top third of the stratigraphic column and has an average thickness of 15m.

There is a transitional upper and lower sequence to the main Siltstone Unit.

4) Undifferentiated Limestone (Ogul)

This is a bucket term to fit all limestones that do not separate out into any distinctive lithology subdivision

5) Undifferentiated Dolomite (Ogdl)

Localised zones of dolomitised limestone occur within various parts of the stratigraphic column. Unless it is part of the Upper Dolomite, it is referred to as undifferentiated dolomite. The dolomitisation is attributable to faults and/or due to mineralisation as Ogdl units often have elevated base metal values.

6) Laminated Micrite Unit (Ogmu)

This is a distinctive lithofacies comprising of banded and stylolitic fine grained calcarenites and micrites. Sometimes the laminae consist of argillaceous material. The units have an upper thickness limit of generally <3m except in specific circumstances (DD95ZP63). Birds eye micrite units are often associated with the laminated zones. The unit is not a marker horizon but occurs with sufficiently regularity in drillcore as to be able to assist stratigraphic correlations.

7) Oolite Unit (Ogoo)

This unit occurs in outcrop at Grieves Prospect as a dolomitised equigranular calcarenite unit - believed to be an oolite. It is believed that this well sorted, clean, medium grained bioclastic calcarenite unit, locally oolitic, is really part of a package of well sorted calcarenites seen towards the base of the limestone sequence.

8) Siderite Unit (Ogsd)

The Siderite Unit is an alteration facies imposed on and replacing limestone (?dolomitised) at the base of the Gordon Limestone. It is regarded as being part of the alteration associated with the replacement Zn/Pb mineralisation.

Siderite alteration also occurs at Grieves in the middle of the limestone sequence.

Siderite is also present at the upper sandstone/limestone contact at Blackjacks (DD95DB110) and Myrtle (DD95ZM190).

9) Dark Grey/Black Clay Unit (Ogdc)

These clays are encountered at surface and in drill core above 300m vertical depth. They generally are to be found at the base of the limestone, although they can occur at the top contact (DD95DB110). Dark clays can also be found in the top of drillholes where surficial weathering of the limestones has produced a black pug - depths of 45 vertical metres have been recorded (DD95ZR103). The exact nature of the clays at the basal part of the limestone is unclear. They always underlie the Oolite Unit, often can be intermixed with siderite zones of the Siderite Unit and can be part of the underlying Silty Transition Unit. Whether they are products of deep surface weathering, palaeo-weathering, fault zones or mineral-related alteration remains to be resolved.

10) Ferruginous Clay Unit.

These are light grey, orange, yellow, brown and red coloured clays, often banded. They generally occur beneath the Dark Clay Unit, although at Grieves they can be intermixed with the Dark Clays. In some instances they are sericitic, in others they can be sandy (fine grained quartz grains). They are heavily limonitic and their exact nature is unsure. It is possible that the clays are part of the Silty Transition Unit or even the underlying Moina Sandstone. Alternatively they could be weathering products of mineralisation associated with the dark clay unit.

11) Silty Transition Unit

This is the basal unit of the Gordon Limestone. It comprises of a series of partly dolomitised limestones and fine grained arenaceous units with black siltstones. It appears to have a well defined thickness of between 12-16m and in some instances overlies the Moina Sandstone conformably. Mineralisation would appear to lie immediately above the top contact of the Silty Transition Unit.

12) Moina Sandstone

This sandstone formation is characterised by a silicic quartzite with localised conglomerate bands, often becoming a pink silicic quartzite.

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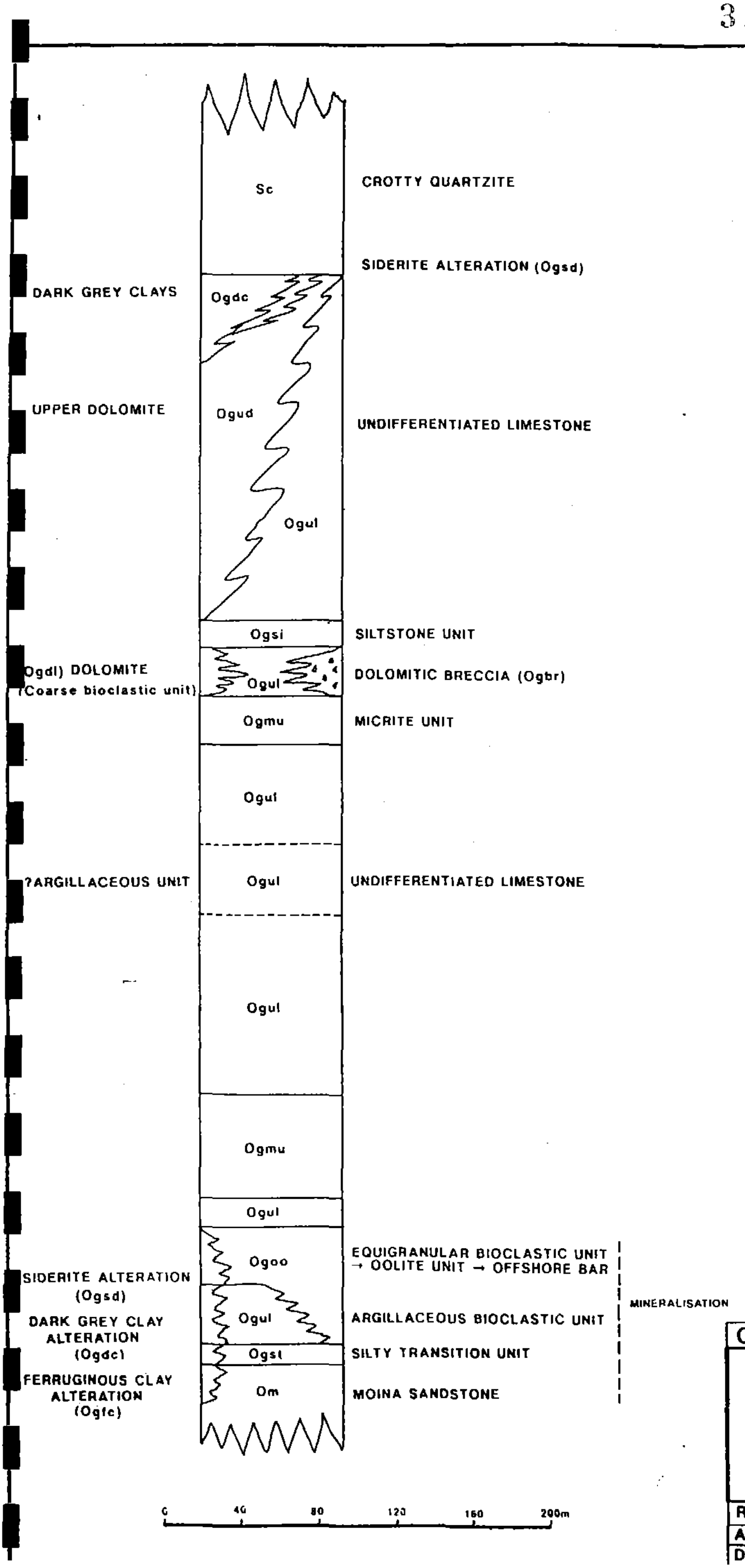

CRA EXPLORATION PTY. LIMITED

SEMI-SCHEMATIC

GORDON LIMESTONE STRATIGRAPHY

Ref.:	Scale:
Author: S.J.TEAR	Report No.:
Drawn: A JELEN	Plan No.:

321026

Appendix II

Summary of Previous Exploration

Competitor and CRAE

Exploration by Major Mining Ltd / CRAE Prior to 9/11/95

Year 1 & 2

Activities by Major Mining prior to CRAE's involvement are detailed in the relevant statutory reports. Field activities included a gradient array IP survey covering a small part of the Firewood Siding area.

Year 3

Exploration by CRAE on EL 34/88 prior to 9/11/91 focused on a compilation and review of existing open-file data (Kratochvil, 1991). Emphasis was placed on identifying areas of limestone not explored in detail by Amoco-EZ. CRAE's initial exploration strategy aimed to test two under-explored blocks of Ordovician limestone, the Fen Creek and McLean Creek areas. This approach was abandoned when it was realised there were more prospective targets with considerably easier access in the Badger River Valley.

Year 4

CRAE's exploration strategy in 1992 aimed to test for primary carbonate mineralisation in Gordon Limestone where the unit was cut by the Firewood Siding Fault (Parkinson, 1992). Incomplete Amoco-EZ bedrock sampling returned up to 1.45% Zn in this area. The Firewood Siding Fault may have been a conduit for metal-rich fluids passing into the limestone, and as such the areas of the fault/limestone contact is a prime focus for exploration.

Bedrock wacker sampling, dipole-dipole IP surveys, ground magnetometer traverses and reinterpretation of existing gravity data were completed. Line 9600E, between 5225N and 5400N showed over 0.1% Zn, up to 0.47% Pb and 0.32% Zn. Amoco-EZ produced 1.45% Zn from sampling in this vicinity. IP surveys identified several anomalies but it is unclear how they relate to known structure and stratigraphy. A circular gravity feature remains unexplained.

Year 5

CRAE continued to test for primary carbonate mineralisation in Gordon Limestone in the Firewood Siding area (Parkinson, 1993). Bedrock wacker sampling returned significantly elevated Zn-Pb up to 1.39% Zn and 1.09% Pb at or near the Gordon Limestone - Crotty Quartzite contact on the N side of the Firewood Siding Fault over a distance of 800m. Arsenic and Fe values were also enhanced coincident with the high Zn-Pb, suggesting a geochemical alteration halo may be developed around underlying mineralisation.

Wacker sample depths were commonly over 10m, and locally over 20m, suggesting thick development of potentially mineralised decomposed carbonate.

At the end of year 5, EL 34/88 was reduced from 68 km^2 to 34 km^2.

Year 6

Aircore drilling and end-of-hole sampling was completed at Firewood Siding. A total of 35 holes were drilled.

At Professor Range 102 aircore drillholes totalling 1578m were drilled. End-of-hole samples were collected and geochemically interpreted.

At Baura 30 wacker samples on a 200m x 25 grid were taken, mainly across the Moina Sandstone/Gordon Limestone contact.

Year 7

(Tear 1996) One diamond drill hole (TD 218m) was drilled at Firewood Siding, following up aircore drilling from the previous year. Elevated zinc values were found in association with the sandstone/limestone upper contact.

Two reconnaissance lines of deep overburden sampling were completed at the south east end of the Professor Range prospect. Maximum values of 5800 ppm Zn and 655 ppm Pb were returned. Two diamond drill holes (total 522m) were designed to test the upper and lower sandstone/limestone contact. Best result was 0.3m @ 0.8% Zn from 217.8m in DD95ZR104

At Baura, two diamond drill holes (total 105m) were targeted at the intersection of the Firewood Siding Fault and the lower limestone/sandstone contact. Best zinc values were 0.37% associated with a 2m siderite dark grey clay in DD95ZB1.

132 deep overburden samples were completed at the Amber Creek prospect. Results show that the lower sandstone/limestone contact contains anomalous concentrations of base metals and siderite.

Deep overburden sampling at King Billy (55 samples) highlighted anomalous base metals (6700 ppm Zn and 3750 ppm Pb) associated with the lower limestone/sandstone contact. 23 reverse circulation air core drill holes totalling 782m were completed. Best recorded value was in hole AC95ZK39; 3m @ 2.64% Zn and 1.3% Pb from 9m. Zinc and lead assays for the bottom of hole sampling were relatively low (maximum zinc value of 850 ppm, maximum lead value of 4840 ppm). Relative to other areas, the King Billy prospect contains higher concentrations of lead.

The Gordon Limestone in the Zeehan area was flown over as part of a sub-regional helicopter magnetic survey. Line spacing was approximately 60m with an average flight height of 30m. Sampling intervals were approximately every 3-4m. A feature of the survey was that the flight lines were aimed at being perpendicular to the strike of the limestone.

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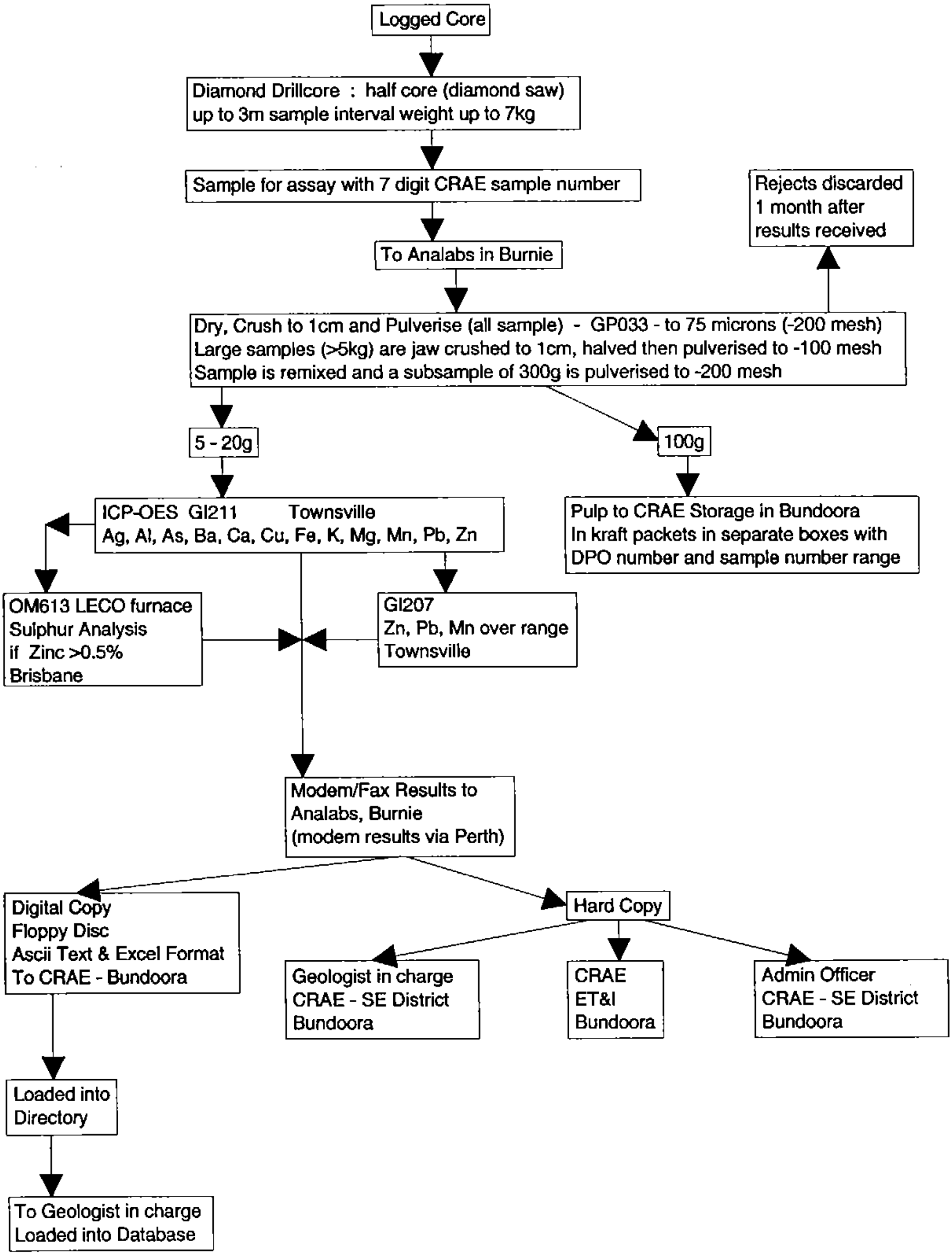
Appendix III

Analytical Methods for Drillcore and Bedrock Wacker Sampling

Diamond Drillcore Sampling Flowsheet



GI211 - Aqua Regia/Perchloric/hydrofluoric acid : acid digest
GI207 - Aqua Regia/Perchloric/hydrofluoric acid : acid digest

S.J.Tear August 1996

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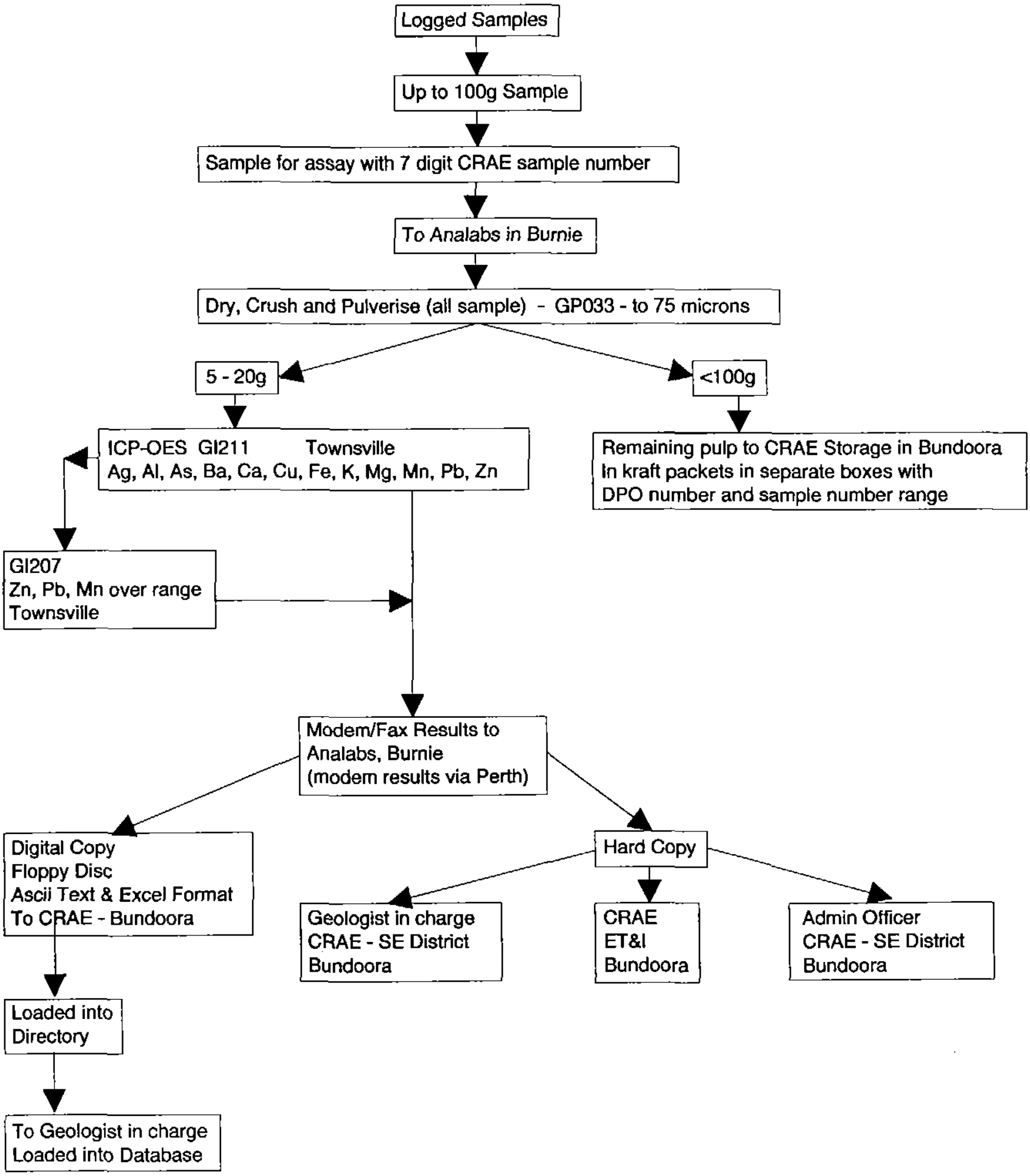
Bedrock Wacker Sampling Flowsheet



GI211 - Aqua Regia/Perchloric/hydrofluoric acid : acid digest
GI207 - Aqua Regia/Perchloric/hydrofluoric acid : acid digest

S.J.Tear August 1996

321033

Appendix IV

King Billy - DD96ZK123 - Diamond Drill Logs and Assay Results

CRA EXPLORATION PTY. LIMITED

DRILL-HOLE SUMMARY LOG

321034

HOLE NAME:	DD96ZK123	AMG	EAST 371212	NORTH	5351970
PROSPECT:	KING BILLY	GRID	EAST 71212	NORTH	1970
EL:	ZEEHAN 2 EL34/88	RL	145m.	DEPTH	113.7m

DATE DRILLED: 20/3/96

LOGGED BY: S.A.J. RUSSELL

DRILLING CO.: DD TAS

DRILL TYPE: DIAMOND

DRILL RIG: LY38 - Helicopter

LOC DRILL CORE: ZEEHAN

SURVEYS:

DEPTH	AZIM (AMG)	DIP	DEPTH	AZIM (AMG)	DIP
0m	180°	60°			
60m	180°	62°			
105m	182°	62°			

OBJECTIVES OF HOLE:

Diamond drilltest of elevated surface geochemistry and also lower limestone/sandstone contact. Possible down dip test of, helimag anomaly at lower limestone/sandstone contact.

LITHOGICAL SUMMARY:

FROM	TO	FORM CODE	COMMENTS
0	1.5	Qha.	No Recovery. - overburden.
1.5	24.7	Ogul.	Cavitatious + variably argillaceous calcarenite
24.7	27.0	Ogoo	Channel - equigranular bioclastic unit.
27.0	44.6	Ogul	variably argillaceous calcarenites. Minor pyrite on fractures
44.6	46.5	Ogmu.	Laminated micrite + minor bioclasts
46.5	66.1	Ogul	Calcarenite + local micrites + various pale grey clay horizons.
66.1	71.8	Ogmu	Dismicrite. Faint laminations @ 60° to C/A. Some burrows.
71.8	74.7	Ogfz.	Faulted argillaceous calcarenite.
74.8	78.8	Ogul.	Grey calcareous clays
78.8	82.4	Ogdc	Dominantly clays + minor competent calcarenite.
82.4	83.4	Ogsd.	Sideritic alteration zone.
83.4	94.5	Ogfc.	Dominantly ferruginous clays (+ some dk grey/black clays)
94.5	101.0	Om.	Dark red coarse grained arkosic sandstone
101.0	101.6	Om	Fissile ferruginous siltstone.
101.6	113.7	Om	Red coarse grained arkose sandstone.

MINERALISATION SUMMARY:

FROM TO COMMENTS

Zinc values < 1000ppm

Elevated zinc zone from 75 to 107m.

CONCLUSIONS:

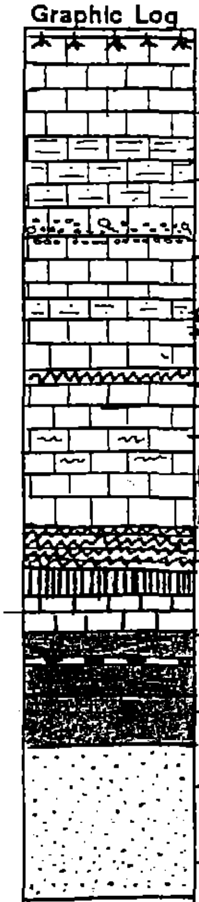
Hole finished >100m than expected because Moina sandstone was intersected

Cleavage = 80° to C/A @ 15m; 10° to C/A @ 34m;

Bedding = 35° to C/A @ 38m; 55° to C/A @ 43m; 55° to C/A @ 50m; 60° to C/A @ 70m

Bedding = 70-75° to C/A @ 101.6m,

Graphic Log



SHEET No. 1/4

C.R.A. EXPLORATION PTY. LIMITED

DRILL CORE LOG

TENEMENT NAME KING BILLY No. 34/88

PLAN – MAP REFERENCE Zeehan 2

AMG: 371212E

CO-ORDINATES 5351970N AZIMUTH 168° (Mag) DRILLERS DDTAS COMMENCED 20/3/1996 DEPTH 113.7m HOLE No. DD96ZK123

RL COLLAR 145m INCLINATION 60° DRILL TYPE LY 38 COMPLETED 26/3/1996 CASING LEFT DPO No(s) 82157

DEPTH From (M)	DEPTH To (M)	Core Rec. %	RQD	Graphic Log	CORE DESCRIPTION	SPECIAL FEATURES Weath, Alteration, Fracturing, Veining, Mineralization	Sample No.	From (M)	To (M)	Rec (M)	Mag sus Depth	Value	Depth	Value			Depth From	To	Rec (m)	%
																	0	1.5	0	0
0	1.5	0	–	Qha	No recovery	–					0.5	c/L	16.0	4			1.5	8.0	0.6	9
1.5	14.8	40	3F	Ogul	Cavitatious calcarenite (grey)	Variable iron (limonite)	5852501	12.4	13.7		1.0	c/L	16.5	2			8.0	9.0	0.9	90
					with local micritic units.	staining.					1.5	8	17.0	0			9.0	10.5	1.2	80
					Cavities are sand filled (brown)	Abundant calcite veining					2.0	C/L	17.5	0			10.5	12.0	0.7	47
					Occasional bioclasts.						2.5	C/L	18.0	0			12.0	13.7	1.1	65
14.8	15.2	100	3F	Ogul	Argillaceous/silty calcarenite	Possible cleavage @ 80° to					3.0	C/L	18.5	0			13.7	14.7	1.0	100
					unit, dark grey in colour	C/A.					3.5	C/L	19.0	5			14.7	16.8	1.6	76
15.2	16.8		2F	Ogul	Grey calcarenite, with ≈15%	Numerous calcite veins					4.0	CL	19.5	0			16.8	18.0	1.1	92
					argillaceous material + numerous						4.5	C/L	20.0	0			18.0	21.0	2.4	80
					bioclasts <0.5cm in diameter						5.0	C/L	20.5	2			21.0	24.0	2.8	93
16.8	18.5	70	3X	Ogf2	Broken up grey calcarenite	Calcite veining.					5.5	c/L	21.0	0			24.0	27.0	2.0	66
					+ argillaceous calcarenite.						6.0	C/L	21.5	0			27.0	30.0	1.5	50
					Medium grained sandy						6.5	C/L	22.0	0			30.0	33.0	2.5	83
					texture.						7.0	C/L	22.5	5			33.0	36.0	3.0	100
18.5	23.0	80	2F	Ogul	Grey-dark grey calcarenite	20-21m - possible fault					7.5	c/L	23.0	0			36.0	39.0	2.4	80
					fine grained with	zone (Ogf2) (broken core)					8.0	5	23.5	5			39.0	42.0	2.8	93
					significant argillaceous						8.5	5	24.0	2			42.0	44.5	2.5	100
					component (20-25%)						9.0	0	24.5	0			44.5	46.0	1.5	100
				Ogul	Intensely calcite veined	Pyrite occurs in fine	5852502	23.0	24.0		9.5	c/L	25.0	c/L			46.0	47.7	0.6	35
23.0	24.7	80	2F		grey calcarenite, locally	cracks + within the	03	24.0	26.0		10.0	2	25.5	c/L			47.7	51.0	2.2	96
					micritic, with ≈5%	calcarenite at the edge of					10.5	0	26.0	0			51.0	53.6	1.3	50
					argillaceous material	calcite veins.					11.0	CL	26.5	0			53.6	57.0	1.6	47
					Rare bioclasts.						11.5	0	27.0	0			57.0	60.0	2.0	66
24.7	27.0	66	3F	Ogoo	Pale grey equigranular	Calcite veining, + minor					12.0	0	27.5	0			60.0	63.0	1.9	63
					bioclastic unit, medium	py. along fracture surfaces					12.5	2	28.0	c/L			63.0	66.0	2.2	73
					grained - channel deposit.	+ edges of calcite veins					13.0	C/L	28.5	0			66.0	69.0	1.7	57
27.0	32.4	65	2F	Ogul	Grey-pale grey calcarenite	Abundant pyrite, often					13.5	2	29.0	c/L			69.0	72.0	2.7	90
					with intercalated dark	with calcite pressure	5852504	30.5	31.2		14.0	0	29.5	c/L			72.0	75.0	2.2	73
					brown clays (20-30cm	shadows around the py					14.5	5	30.0	0			75.0	78.0	2.0	66
					horizons) Argillaceous	aggregates.					15.0	0	30.5	0			78.0	81.0	3.0	100
					stylolites occur frequently	Possible fault zone @ base of section.					15.5	c/L	31.0	0			81.0	84.0	3.0	100

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C.R.A. EXPLORATION PTY. LIMITED

DRILL CORE LOG

SHEET No. 2/4

TENEMENT NAME KING BILLY No. 34/88

PLAN – MAP REFERENCE

CO-ORDINATES AMG 371212E 5351970N AZIMUTH 168° (Mag) DRILLERS DDTAS COMMENCED 20/3/1996 DEPTH 113.7m HOLE No. DD96ZK123

RL COLLAR 145m INCLINATION 60° DRILL TYPE LY 38 COMPLETED 26/3/1996 CASING LEFT DPO No(s) 82157

DEPTH From (M)	DEPTH To (M)	Core Rec. %	RQD	Graphic Log	CORE DESCRIPTION	SPECIAL FEATURES Weath, Alteration, Fracturing, Veining, Mineralization	Sample No.	From (M)	To (M)	Rec (M)	Mag Sus Depth	Value	Depth	Value
32.4	37.0	90	2F	Ogul	Grey uniform calcarenite	Pyrite common on					31.5	0	47.0	cl
					with ±30% argillaceous	fracture surfaces.					32.0	cl	47.5	4
					component. Minor bioclast	Minor calcite veining.					32.5	0	48.0	18
					occurrence <0.5cm	Cleavage 10° to C/A.					33.0	5	48.5	5
					(tetradium?)						33.5	10	49.0	cl
37.0	39.5	90	4X	Ogfz	As above, slightly coarser	Minor fault zone.	5852505	39.0	40.1		34.0	8	49.5	8
					+ core very broken up.	Minor pyrite.					34.5	10	50.0	cl
					with a 20cm zone of	Some synsed. deformation					35.0	5	50.5	0
					dark brown sandy clays	of bedding features @					35.5	20	51.0	0
						35° angle to C/A.					36.0	0	51.5	22
39.5	42.0	85	2F	Ogul	Grey fine grained calcarenite	Abundant calcite veining					36.5	8	52.0	cl
					+ argillaceous bands up	+ regions of pyrite					37.0	cl	52.5	cl
					to 5cm + argillaceous	occuring along fractures/veins.					37.5	3	53.0	cl
					stylolites.	Areas of broken core fracturing					38.0	cl	53.5	10
42.0	44.6	100	3F	Ogul	Grey calcarenite with	Clean calcite veining					38.5	6	54.0	2
					relatively high silt content.	B/Ps @ ≈ 55° to C/A.					39.0	5	54.5	cl
					+ fine grained	Minor pyrite content					39.5	10	55.0	cl
44.6	46.5	30	1F	Ogmu	Laminated pale grey	Significant calcite veins	5852506	46.0	47.7		40.0	cl	55.5	0
					micritic horizon containing	Minor pyrite.					40.5	9	56.0	cl
					minor bioclasts (bivalves)						41.0	10	56.5	cl
46.5	53.0	75	4X	Ogul	Grey calcarenite with	Calcite veining					41.5	15	57.0	0
					minor shear zones +	B/Ps @ 55° to C/A.					42.0	5	57.5	5
					sand filled cavities.	Broken core towards base	8852507	47.7	51.0		42.5	5	58.0	cl
53.0	66.1	62	5X	Ogul	Grey calcarenite, locally	Fault zone.	08	51.0	53.6		43.0	6	58.5	0
				(Ogfz)	micritic, with common	Minor calcite veining	09	53.6	57.0		43.5	10	59.0	cl
					argillaceous bands & stylolites	Minor pyrite occurrence.	10	57.0	60.0		44.0	10	59.5	cl
					Possible tetradium?		11	60.0	63.0		44.5	5	60.0	0
					Various pale grey clay		12	63.0	66.0		45.0	0	60.5	0
					horizons occur.						45.5	5	61.0	cl
											46.0	4	61.5	cl
											46.5	cl	62.0	cl

ASSAY VALUES (Analysed by RECOVERY)

From	To	m	%
84.0	87.0	3.0	100
87.0	90.0	3.0	100
90.0	93.0	3.0	100
93.0	96.0	1.8	60
96.0	99.0	0.8	2
99.0	101.6	2.6	100
101.6	104.5	2.9	100
104.5	108.0	3.0	86
108.0	111.0	3.0	100
111.0	113.7	2.7	100

C.R.A. EXPLORATION PTY. LIMITED
DRILL CORE LOG

SHEET No. 3/4
TENEMENT NAME KING BILLY No.
PLAN – MAP REFERENCE EL 34/88

AMG 371212E

CO-ORDINATES 5351970N AZIMUTH 168° (Mag) DRILLERS DDTAS COMMENCED 20/3/1996 DEPTH 113.7 m. HOLE No. DD96 2K123

RL COLLAR 145 m INCLINATION 60° DRILL TYPE LY38 COMPLETED 26/3/1996 CASING LEFT DPO No(s). 82157

DEPTH From (M)	DEPTH To (M)	Core Rec. %	RQD	Graphic Log	CORE DESCRIPTION	SPECIAL FEATURES Weath, Alteration, Fracturing, Veining, Mineralization	Sample No.	From (M)	To (M)	Rec (M)	ASSAY VALUES (Analysed by ....) Mag Sus Depth	Value	Depth	Value
66.1	69.0	57	2F	Ogmu	Dismicrite horizon. Pale	Significant calcite	5852513	66.0	69.0		62.5	5	78	6
					grey clay rich lacking the	veining					63.0	0	78.5	c/L
					distinct micrite laminations						63.5	5	79	0
					Minor argillaceous stylolites,						64.0	c/L	79.5	c/L
					+ burrows? (or anhydrite						64.5	5	80	0
					after gypsum) oriented						65	c/L	80.5	0
					parallel to the core axis.						65.5	5	81	25
69.0	71.8	90	3X	Ogmu	Pale grey/grey micrite	Minor pyrite within	14	69.0	71.7.		66	0	81.5	150
					with feint lamination	calcite veins present.					66.5	5	82	160
					@ 60° to C/A						67	c/L	82.5	0
71.8	74.7	73	4X	Ogfz	Dark grey calcarenite	Pyrite occurs on fracture	15	71.7	75.0		67.5	c/L	83	300
					with high (~60%)	surfaces in small					68	c/L	83.5	0
					argillaceous content. Core	quantities.					68.5	0	84	0
					is very broken.						69	0	84.5	0
74.7	78.8	70	5X	Ogul	Grey/dark grey clay		16	75.0	77.0		69.5	6	85	0
					zone, still calcareous.		17	77.0	78.8.		70	10	85.5	0
					Increasing iron content						70.5	c/L	86	0
					towards base (brown						71	0	86.5	0.
					colouration)						71.5	10	87	0
78.8	82.4	100	5X	Ogdc	Variably coloured clays	Sideritic zone from	18	78.8	80.9		72	10	87.5	10
					with regions of competent	80.9m → 81.3m	19	80.9	81.3		72.5	c/L	88	0
					calcarenite (30cm) +		20	81.3	82.4		73	4	88.5	0.
					remnants of original quartz/						73.5	c/L	89	5
					calcite veins. Competent						74	c/L	89.5	c/L
					calcarenite is relatively						74.5	6	90	12
					dense + may have undergone						75	0	90.5	10
					some sideritic alteration						75.5	0	91	10
82.4	83.4	100	2F	Ogsd	Zone of sideritic alteration		21	82.4	83.4		76	0	91.5	8
					Dense altered limestone						76.5	c/L	92	2
					grey/brown in colour						77	0	92.5	0
											77.5	c/L	93	0

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C.R.A. EXPLORATION PTY. LIMITED

DRILL CORE LOG

SHEET No. 4/4

TENEMENT NAME KING BILLY No. 34/88

PLAN – MAP REFERENCE

CO-ORDINATES AMG 371212E 5351970N AZIMUTH 168 (Mag) DRILLERS DDTAS COMMENCED 20/3/1996 DEPTH 113.7m HOLE No. DD96ZK123

RL COLLAR 145m INCLINATION 60° DRILL TYPE LY38 COMPLETED 26/3/1996 CASING LEFT DPO No(s) 82157

DEPTH From (M)	DEPTH To (M)	Core Rec. (%)	RQD	Graphic Log	CORE DESCRIPTION	SPECIAL FEATURES Weath, Alteration, Fracturing, Veining, Mineralization	Sample No.	From (M)	To (M)	Rec (M)	Mag Sus Depth	Value	Depth	Value
83.4	87.6	100	5X	Ogfc	Alternating brown ferruginous		5552522	83.4	84.7		93.5	0	109	20
					clays and dark grey/		23	84.7	85.5		94	CL	109.5	18
					black non calcareous		24	85.5	87.0		94.5	CL	110	5
					rotted limestones.		25	87.0	87.6		95	CL	110.5	25
					Increasing amounts of						95.5	CL	111	10
					ferruginous material						96	0	111.5	5
					towards base.						96.5	CL	112	0
87.6	94.5	90	5X	Ogfc	Ferruginous/limonitic		26	87.6	88.6		97	CL	112.5	2
					sandy clays/siltstones +		27	88.6	90.0		97.5	CL	113	CL
					fine grained sandstones	A zone of	28	90.0	91.9		98	CL	113.5	0
94.5	99.5	50	3F	OM	First unit of cohesive sst.	V. broken core + poor	29	91.9	93.0		98.5	0	114	0
					Orange brown coloured, coarse	core recovery (exist) towards.	30	93.0	94.5		99	0		
					grained sandstone.	base.	31	94.5	96.0		99.5	30		
99.5	101.0	100	2F	Om	Dark Red coarse grained		32	96.0	99.5		100	27		
					sandstone (arkosic in		33	99.5	101.0		100.5	25		
					nature) Contains grains		34	101.0	101.6		101	30		
					of sub rounded/sub angular						101.5	0		
					quartz < 0.5cm ø.						102	6		
101.0	101.6	100	5X	Om	Fissile ferruginous	Minor quartz veins					102.5	0		
					siltstone zone Dominant						103	0		
					limonite + phyllitic						103.5	0		
					material.						104	CL		
101.6	113.7	92	3F	Om	Red sandstone medium	B/Ps @ 70-75° to C/A.	35	101.6	103.8		104.5	CL		
					-coarse grained arkosic	Fault zone filled with	36	103.8	104.6		105	15		
					in nature Minor intercalated	fault gouge ≈105-106m.	37	104.6	107.0		105.5	CL		
					siltstones towards top	^of fault contacts =	38	107.0	109.0		106	CL		
					of section	top contact -70° to C/A.	39	109.0	111.0		106.5	10		
						bottom contact - 70 to 75° to C/A	40	111.0	113.7		107	5		
											107.5	CL		
											108	19		
											108.5	0		

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bhole	fullddh	DPO	smpno	Prospect	EL	afrom	ato	aag	aal	aas	aba	aca	acu	afe	ak	amg	amn	apb	azn	as	MRTLith
bhole	fullddh	DPO	smpno	Prospect	EL	afrom	ato	aag	aal	aas	aba	aca	acu	afe	ak	amg	amn	apb	azn	as	MRTLith
ZK123	DD96ZK123			King Billy	34/88	0	1.5														Qha
ZK123	DD96ZK123			King Billy	34/88	1.5	12.4														Ogul
ZK123	DD96ZK123	82157	5852501	King Billy	34/88	12.4	13.7	1.4	0.56	-5	110	32.4	-5	0.79	0.3	1.49	416	648	123		Ogul
ZK123	DD96ZK123			King Billy	34/88	13.7	23														Ogul
ZK123	DD96ZK123	82157	5852502	King Billy	34/88	23	24	1	0.23	-5	32	30.4	-5	1.55	0.12	1.22	439	35	39		Ogul
ZK123	DD96ZK123	82157	5852503	King Billy	34/88	24	26	0.9	0.14	-5	21	32.1	-5	1.34	0.07	0.68	365	69	70		Ogul/Ogoo
ZK123	DD96ZK123			King Billy	34/88	26	30.5														Ogoo/Ogu
ZK123	DD96ZK123	82157	5852504	King Billy	34/88	30.5	31.2	0.8	0.13	-5	10	34.5	-5	1.64	0.09	0.62	427	52	60		Ogul
ZK123	DD96ZK123			King Billy	34/88	31.2	39														Ogul
ZK123	DD96ZK123	82157	5852505	King Billy	34/88	39	40.1	0.6	0.6	-5	40	32.3	-5	1.24	0.32	1.44	507	37	61		Ogul
ZK123	DD96ZK123			King Billy	34/88	40.1	46														Ogul/Ogmu
ZK123	DD96ZK123	82157	5852506	King Billy	34/88	46	47.7	-0.5	2.18	-5	141	25.5	-5	1	1	2.33	340	22	34		Ogmu/Ogu
ZK123	DD96ZK123	82157	5852507	King Billy	34/88	47.7	51	-0.5	1.29	-5	84	28.2	-5	1.8	0.67	1.45	622	38	60		Ogul
ZK123	DD96ZK123	82157	5852508	King Billy	34/88	51	53.6	-0.5	1.3	-5	75	23.4	-5	2.06	0.68	1.76	503	43	297		Ogul
ZK123	DD96ZK123	82157	5852509	King Billy	34/88	53.6	57	-0.5	1.62	-5	91	32.7	-5	1.31	0.89	1.06	391	23	53		Ogul
ZK123	DD96ZK123	82157	5852510	King Billy	34/88	57	60	0.8	0.64	-5	44	31.6	-5	0.78	0.36	0.77	297	39	303		Ogul
ZK123	DD96ZK123	82157	5852511	King Billy	34/88	60	63	0.7	0.68	-5	49	32.4	-5	0.67	0.39	0.7	252	22	117		Ogul
ZK123	DD96ZK123	82157	5852512	King Billy	34/88	63	66	0.9	0.95	-5	60	32.2	-5	0.84	0.52	1.01	358	31	53		Ogul
ZK123	DD96ZK123	82157	5852513	King Billy	34/88	66	69	0.6	0.77	-5	57	31.7	-5	0.65	0.43	0.86	322	34	48		Ogmu
ZK123	DD96ZK123	82157	5852514	King Billy	34/88	69	71.7	-0.6	0.89	-5	59	28.8	-5	0.75	0.48	1.04	317	25	43		Ogmu
ZK123	DD96ZK123	82157	5852515	King Billy	34/88	71.7	75	-0.5	2.08	-5	117	23.1	-5	0.96	1.12	1.6	377	37	94		Oglz
ZK123	DD96ZK123	82157	5852516	King Billy	34/88	75	77	-0.5	1.99	-5	107	19.6	-5	0.82	1.09	1.19	262	38	144		Ogul
ZK123	DD96ZK123	82157	5852517	King Billy	34/88	77	78.8	-0.5	6.09	15	314	10.7	12	1.95	3.22	0.93	361	93	287		Ogul
ZK123	DD96ZK123	82157	5852518	King Billy	34/88	78.8	80.9	-0.5	8.72	-5	418	0.42	24	3.02	4.42	0.93	506	187	475		Ogdc
ZK123	DD96ZK123	82157	5852519	King Billy	34/88	80.9	81.3	-0.5	1.82	13	145	1.73	-5	33.1	0.99	0.76	10200	59	80		Ogsd
ZK123	DD96ZK123	82157	5852520	King Billy	34/88	81.3	82.4	-0.5	6.75	-5	350	1.18	13	1.77	3.56	0.28	397	142	377		Ogdc
ZK123	DD96ZK123	82157	5852521	King Billy	34/88	82.4	83.4	-0.5	1.95	8	136	3.57	-5	24.2	1.06	1.05	6350	39	54		Ogsd
ZK123	DD96ZK123	82157	5852522	King Billy	34/88	83.4	84.7	-0.5	6.95	57	394	0.21	13	1.74	3.79	1.52	3280	49	333		Oglc
ZK123	DD96ZK123	82157	5852523	King Billy	34/88	84.7	85.5	-0.5	5.24	81	297	0.18	18	1	2.8	0.68	35	64	398		Oglc
ZK123	DD96ZK123	82157	5852524	King Billy	34/88	85.5	87	-0.5	5.71	-5	304	0.23	9	1.56	3	0.51	1830	101	747		Oglc
ZK123	DD96ZK123	82157	5852525	King Billy	34/88	87	87.6	-0.5	4.66	8	267	0.21	18	4.01	2.62	0.52	400	243	323		Oglc
ZK123	DD96ZK123	82157	5852526	King Billy	34/88	87.6	88.6	-0.5	4.96	-5	272	0.17	20	2.97	2.62	0.5	1130	79	308		Oglc
ZK123	DD96ZK123	82157	5852527	King Billy	34/88	88.6	90	-0.5	3.06	-5	165	0.28	9	4.91	1.61	0.32	1730	98	384		Oglc
ZK123	DD96ZK123	82157	5852528	King Billy	34/88	90	91.9	-0.5	4.03	-5	226	0.24	10	6.74	2.12	0.4	3070	131	527		Oglc
ZK123	DD96ZK123	82157	5852529	King Billy	34/88	91.9	93	-0.5	6.29	17	348	0.2	18	6.65	3.12	0.54	1110	284	717		Oglc
ZK123	DD96ZK123	82157	5852530	King Billy	34/88	93	94.5	-0.5	6.11	18	341	0.07	31	5.28	3.14	0.56	373	375	850		Oglc
ZK123	DD96ZK123	82157	5852531	King Billy	34/88	94.5	96	-0.5	4.08	6	208	0.05	48	1.8	2.1	0.35	115	56	285		Ogsl
ZK123	DD96ZK123	82157	5852532	King Billy	34/88	96	99.5	-0.5	3.8	104	198	0.08	37	7.72	1.84	0.25	468	146	474		Ogsl
ZK123	DD96ZK123	82157	5852533	King Billy	34/88	99.5	101	-0.5	1.21	163	93	0.08	115	16.5	0.55	0.15	1200	136	546		Oglc
ZK123	DD96ZK123	82157	5852534	King Billy	34/88	101	101.6	-0.5	5.88	11	333	0.06	66	3.55	2.78	0.41	247	115	599		Ogsl
ZK123	DD96ZK123	82157	5852535	King Billy	34/88	101.6	103.8	-0.5	6.68	6	378	0.05	27	2.19	3.16	0.41	80	91	116		Ogsl
ZK123	DD96ZK123	82157	5852536	King Billy	34/88	103.8	104.6	-0.5	6.59	9	331	0.08	52	9.93	2.97	0.4	173	45	408		Ogsl
ZK123	DD96ZK123	82157	5852537	King Billy	34/88	104.6	107	-0.5	6.74	21	303	0.07	37	6.37	3.03	0.38	470	21	209		Ogsl
ZK123	DD96ZK123	82157	5852538	King Billy	34/88	107	109	-0.6	6.01	-5	294	0.05	15	3.89	2.82	0.37	114	12	93		Om
ZK123	DD96ZK123	82157	5852539	King Billy	34/88	109	111	-0.5	4.33	-5	236	0.05	9	3.03	1.89	0.29	391	-10	95		Om
ZK123	DD96ZK123	82157	5852540	King Billy	34/88	111	113.7	-0.5	2.96	-5	159	-0.05	-5	2.98	1.29	0.19	74	-10	69		Om

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Appendix V

King Billy Soil, Rock Chip and Stream sediment sampling Logs and Assay Results

Sampno	LocalE	LocalN	AMGE	AMGN	SampTyp	Depth	MRTLith	FieldID	Texture	Alt/Min	Colour	Comments
5470627	0	500	368400	5350700	Soil	0.4						Light brown to orange clay. Red and light green streaks. Small rock fragments - angular, and larger more rounded pebbles. Clay very soft and pliable.
5470628	25	500	368425	5350700	Soil	0.6						Dark brown and orange clay. Small rock fragments
5470629	50	500	368450	5350700	Soil	0.8						Orange and brown clay, very soft and pliable. Small rock fragments
5470630	75	500	368475	5350700	Soil	0.4						Light grey gravel - very soft and wet. Small rock fragments
5470631	100	500	368500	5350700	Soil	1						Predominantly light brown clay with orange/red, dark brown and green lenses. Very soft and gritty
5470632	125	500	368525	5350700	Soil	0.6						Orange clay - very compact and pliable, but quite stiff. Light grey lenses with small rock fragments
5470633	150	500	368550	5350700	Soil	0.4						Light grey gravel - angular rock fragments
5470634	175	500	368575	5350700	Soil	0.5						Light grey gravel - angular rock fragments
5470635	200	500	368600	5350700	Soil	0.4						Light grey gravel - angular rock fragments
5470636	225	500	368625	5350700	Soil	0.4						Light grey gravel - angular rock fragments
5470637	250	500	368650	5350700	Soil	0.6						Light grey gravel - angular rock fragments
5470638	275	500	368675	5350700	Soil	0.4						Light grey gravel - angular rock fragments
5470639	-25	500	368375	5350700	Soil	0.6						Light grey gravel - angular rock fragments
5470640	-50	500	368350	5350700	Soil	0.5						Light grey gravel - angular rock fragments
5470641	-75	500	368325	5350700	Soil	0.6						Light grey gravel - angular rock fragments
5470642	-100	500	368300	5350700	Soil	0.6						Light grey gravel - angular rock fragments
5470643	-125	500	368275	5350700	Soil	0.5						Light grey gravel - angular rock fragments
5470644	100	500	368390	5350690	Rock chip							
5470645	100	500	368390	5350690	Rock chip							Quartzite - hgighly silicified with hydrothermal vein, white to purple in colour with iron oxide or manganese
5470646	100	500	368355	5350672	Rock chip							
5470647	0	0	368230	5351180	Stream							
5470648	0	100	368260	5351050	Stream							
5470649	0	200	368270	5351000	Stream							
5470650	0	285	368300	5350940	Stream							
5470651	0	400	368270	5350800	Stream							
5470652	0	500	368390	5350710	Stream							
5470653	0	575	368325	5350660	Stream							
5470654	0	575	368300	5350660	Stream							

Assay Results for the King Billy Mag Anomaly T

77397	Ag	Al	As	Ca	Cd	Cu	Co	Fe	K	Li	Mg	Mn	Mo	Ni	Na	Pb	Sr	Zn	Cr	W	Sn	Ba	Ti	V	Au	Pt	Pd
5470627	-5	39250	-10	153	-2	1610	15	46560	7980	25	5850	170	-10	28	562	-50	13	38	126	-5	-3	104	4454	137	12	-0.5	1.7
5470628	-5	74700	-10	189	-2	137	15	123200	6850	51	11200	283	-10	69	433	-50	15	75	232	-5	5	84	10840	331	3	1.3	4.1
5470629	-5	37330	-10	134	-2	36	-5	53850	4430	21	3470	97	-10	22	193	-50	18	36	112	-5	5	57	8727	182	1	-0.5	1
5470630	-5	6190	-10	119	-2	7	-5	8480	2210	7	529	44	-10	-10	98	-50	7	-5	38	-5	-3	32	3408	47	-1	-0.5	1.9
5470631	-5	75520	-10	174	-2	49	11	39690	12080	46	7310	139	-10	73	427	-50	24	66	217	-5	4	68	12319	257	-1	0.6	1.8
5470632	-5	28030	-10	154	-2	9	-5	20100	3440	12	1610	43	-10	10	825	-50	13	11	119	-5	3	35	12034	146	1	-0.5	1.7
5470633	-5	6660	-10	225	-2	10	-5	7420	1650	6	488	48	-10	-10	147	-50	8	12	70	-5	-3	22	7164	42	-1	-0.5	-0.5
5470634	-5	9430	-10	104	-2	9	-5	9990	4230	7	780	48	-10	-10	257	-50	11	7	63	-5	-3	45	3704	45	-1	-0.5	-0.5
5470635	-5	12180	-10	107	-2	9	-5	4120	3520	12	577	25	-10	-10	155	-50	19	-5	68	-5	-3	22	4512	36	-1	-0.5	-0.5
5470636	-5	10440	-10	71	-2	19	-5	3860	3920	8	450	27	-10	-10	197	-50	20	11	43	-5	-3	37	2859	29	-1	-0.5	-0.5
5470637	-5	3920	-10	190	-2	9	-5	3150	1330	8	210	24	-10	-10	206	-50	27	6	32	-5	-3	27	1983	13	-1	-0.5	-0.5
5470638	-5	12420	-10	132	-2	6	-5	4090	4630	12	550	34	-10	-10	357	-50	33	7	93	5	-3	70	3989	19	-1	-0.5	-0.5
5470639	-5	12590	-10	93	-2	5	-5	4080	4520	10	709	29	-10	-10	311	-50	18	7	58	-5	-3	56	3290	28	3	-0.5	-0.5
5470640	-5	10860	-10	64	-2	8	-5	5030	4080	9	492	43	-10	-10	332	-50	18	7	38	-5	-3	56	1642	17	-1	-0.5	-0.5
5470641	-5	19340	-10	102	-2	-5	-5	4610	7650	10	822	32	-10	-10	472	-50	29	6	57	-5	3	83	2832	28	-1	-0.5	-0.5
5470642	-5	21810	-10	173	-2	10	-5	4460	5760	8	547	34	-10	-10	990	-50	51	9	56	-5	-3	61	4691	48	-1	-0.5	-0.5
5470643	-5	12960	-10	67	-2	7	-5	4550	4670	9	457	33	-10	-10	605	-50	31	-5	38	-5	-3	56	2086	21	-1	-0.5	-0.5
5470644	-5	65210	-10	1340	-2	35	33	79810	10300	46	24420	712	-10	92	10630	-50	52	130	248	-5	5	89	11115	300	1	2.4	5.6
5470645	-5	2270	-10	99	-2	12	6	32840	-500	4	137	273	-10	-10	107	-50	4	11	12	-5	-3	25	55	25	-1	-0.5	-0.5
5470646	-5	780	-10	76	-2	8	9	23130	-500	2	50	293	-10	-10	-50	-50	2	6	9	-5	-3	18	-50	19	-1	-0.5	-0.5
5470647	-5	8770	-10	172	-2	8	-5	9300	3180	12	1240	92	-10	-10	877	-50	8	29	1653	-5	-3	35	4012	34	-1	-0.5	-0.5
5470648	-5	11760	-10	190	-2	11	-5	12280	4180	13	1960	118	-10	-10	1020	-50	9	27	1529	-5	-3	31	4513	42	-1	-0.5	-0.5
5470649	-5	14830	-10	201	-2	21	-5	16060	5110	15	2980	152	-10	14	1130	-50	10	38	868	-5	-3	33	4444	53	-1	-0.5	-0.5
5470650	-5	15910	-10	241	-2	32	7	22980	4550	16	3110	222	-10	15	1580	-50	13	61	2305	-5	-3	21	6085	82	-1	-0.5	-0.5
5470651	-5	17960	-10	241	-2	36	8	26920	6090	15	3550	241	-10	19	1140	-50	11	67	0	0	0	0	0	0	-1	-0.5	-0.5
5470652	-5	24620	-10	285	-2	19	7	28220	8220	18	5180	229	-10	23	1550	-50	12	55	0	0	0	0	0	0	-1	6.8	-0.5
5470653	-5	27800	-10	386	-2	51	14	50150	4560	23	6570	385	-10	32	[illegible]	-50	32	107	0	0	0	0	0	0	16	1.3	1.3
5470654	-5	24760	-10	251	-2	30	7	31870	6710	23	5780	288	-10	28	1980	-50	13	65	0	0	0	0	0	0	-1	1.2	0.7

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Appendix VI

Rose Valley Wacker Sampling Geology and Assay Results

Sampno	DPO	Prospect	EL	LocalE	LocalN	AMGE	AMGN	SampType	Depth	Bedrock?	MRTLith	FieldID	Texture	All/Min	Colour	Comments
5852486	82156	ROSE VALLEY	28/88	400		361098	5347968	WACKER	1.3	Y	Ogui	Sis	Sand		LG	Micrite
5852487	82156	ROSE VALLEY	28/88	375		361073	5347970	WACKER	1	Y	Ogui	Sis	Sand		LG	Micrite
5852488	82156	ROSE VALLEY	28/88	350		361048	5347972	WACKER	1.3	Y	Ogui	Sis	Sandy clay		LG	Poss. micritic limestone + calcite veining
5852489	82156	ROSE VALLEY	28/88	325		361024	5347974	WACKER	7.4	N	Ogui	Sis	Sandy clay		GOB	Overburden/bedrock + ferruginous fragments
5852490	82156	ROSE VALLEY	28/88	300		360999	5347976	WACKER	8.6	Y	Ogui	Sis	Sandy clay		WLG	Buff colour but very reactive
5852491	82156	ROSE VALLEY	28/88	275		360974	5347978	WACKER	3.3	Y	Ogui	Sis	Sandy clay		LGDG	Clays mixed dk grey + lt grey
5852492	82156	ROSE VALLEY	28/88	250		360949	5347980	WACKER	6.3	Y	Oglc	Ssh	Clay		BLBO	Non calcareous slightly ferruginous clays
5852493	82156	ROSE VALLEY	28/88	225		360924	5347982	WACKER	1.2	Y	Om	Cg	Sandy clay		WB	Mixed fragments
5852494	82156	ROSE VALLEY	28/88	200		360899	5347984	WACKER	1	Y	Om	Sss	Sand		WB	White sandstone
5852495	82156	ROSE VALLEY	28/88	100		360800	5347992	WACKER	0.8	Y	Om	Sss	Sand		W	White sandstone
5852496	82156	ROSE VALLEY	28/88	75		360775	5347994	WACKER	1.5	Y	Om	Sss	Sand		W	White sugary sandstone
5852497	82156	ROSE VALLEY	28/88	50		360750	5347996	WACKER	1.6	Y	Om	Sss	Sand		W	White sugary sandstone
5852498	82156	ROSE VALLEY	28/88	25		360725	5347998	WACKER	1	Y	Om	Sss	Sand		W	White sugary sandstone
5852499	82156	ROSE VALLEY	28/88	0		360700	5348000	WACKER	2.2	Y	Om	Sss	Sand		WK	Moina sandstone

Sampno	82153	Ag	Al	As	Ba	Ca	Cu	Fe	K	Mg	Mn	Pb	Zn
5852486	5852486	-0.5	2.26	-5	78	29.3	5	0.43	1.01	0.41	131	28	128
5852487	5852487	-0.5	1.61	52	48	29.3	9	1.12	0.69	1.04	85	31	87
5852488	5852488	0.6	1.49	-5	53	21.1	-5	0.31	0.6	0.27	69	41	76
5852489	5852489	-0.5	4.51	25	128	7.62	-5	1.14	1.14	0.68	48	45	143
5852490	5852490	1.1	1	-5	38	33	-5	0.47	0.46	0.46	123	35	177
5852491	5852491	-0.5	3.96	-5	141	24.7	19	0.73	1.76	0.48	105	52	242
5852492	5852492	-0.5	12.7	76	357	0.25	76	2.12	3.72	0.74	19	533	167
5852493	5852493	-0.5	2.65	-5	239	0.42	-5	0.31	0.91	0.2	26	21	15
5852494	5852494	-0.5	0.36	-5	175	0.05	-5	0.12	0.07	0.02	-10	-10	5
5852495	5852495	-0.5	0.09	-5	27	-0.05	-5	0.15	-0.05	0.01	-10	-10	-5
5852496	5852496	-0.5	0.13	-5	11	-0.05	-5	0.15	-0.05	0.01	11	-10	-5
5852497	5852497	-0.5	0.1	-5	17	-0.05	-5	0.14	-0.05	0.01	-10	-10	-5
5852498	5852498	-0.5	0.05	-5	5	-0.05	-5	0.19	-0.05	0.01	11	-10	-5
5852499	5852499	-0.5	0.9	-5	96	0.06	-5	0.2	0.41	0.07	11	-10	6

Zeehan Carbonate : Grieves and Firewood Siding Rock Sample Results																											
Sample No	Prospect	EL	Dpo	Local E	Local N	AMG E	AMG N	Samp Type	MRTLith	Fieldid	Texture	Altn/mins	Colour	Comments	Ag	Al	As	Ba	Ca	Cu	Fe	K	Mg	Mn	Pb	Zn
5470286	GRIEVES	38/89	77399	60900	47400	363940	5349350	Rockchip	Ogul				LG	*Silicified Limestone*	*-0.5*	*0.84*	-5	*194*	*0.14*	-5	*0.18*	0.33	0.1	29	-10	-5
5470287	GRIEVES	38/89	77399	60920	47300	363820	5349300	Rockchip	Ogms				NDG	Secondary or primary pyrite in decomposed limestone	-0.5	0.04	299	-5	-0.05	-5	41.3	-0.06	-0.01	2	19	-5
5470288	FIREWOOD SIDING	34/88	77399	61000	45200	361710	5349000	Rockchip	Ogbr				LGDG	Silicified limestone breccia	-0.5	0.83	-5	176	-0.05	8	0.49	0.28	0.05	38	168	25
5470289	FIREWOOD SIDING	34/88	77399	61000	45200	361710	5349000	Rockchip	Ogbr				LG	Silicified limestone breccia	-0.5	0.33	-5	13	-0.05	5	0.22	-0.05	0.01	18	-10	-5
5470290	FIREWOOD SIDING	34/88	77399	61000	45200	361710	5349000	Rockchip	Ogbr				LGDG	Silicified limestone breccia	-0.5	1	-5	228	0.05	7	0.65	0.29	0.05	33	304	40
5470291	FIREWOOD SIDING	34/88	77399	60800	44550	361065	5348905	Rockchip	Ogbr				LG	?Limestone: chalky angular breccia	-0.5	0.75	-5	236	-0.05	-5	0.18	0.23	0.03	24	-10	-5

321044

Appendix VII

Detailed Helimag Data

3210?6

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ACN 000 057 125

Preliminary Notes and Observations of the Helicopter-borne Magnetic Survey Zeehan, Tasmania

Author:	SJ Tear J Tesselaar
Date:	July 1996
Submitted to:	Chief Geologist, Vic/Tas
Copies to:	Mineral Resources Tasmania CRAE - SE District CRAE - ETIG CRAE - Zeehan Allegiance Mining NL
Submitted by:	
Accepted by:	

CRAE Report No. 22222

List of Figures

List of Appendices

1. Introduction

Drillcore from the Gordon Limestone of the Zeehan area shows zinc mineralisation being related to weakly magnetic siderite alteration. This alteration predominantly occurs at the base of the Limestone just above its contact with the underlying Moina Sandstone. Siderite alteration can occur at the limestone's upper contact with the overlying Crotty Quartzite eg at Blackjacks and Myrtle whilst intense alteration is also associated with limestones in the middle of the Gordon Limestone eg the Oceana Mine and the Grieves South area. The magnetic response of the siderite is weak, in the range of 50-200 x 10-5 SI, but is deemed detectable by an airborne magnetic survey. Forward modelling indicated that the siderite would give weak aeromagnetic anomalies (1-5nT). Thus a helimag survey was commissioned to fly over all the Gordon limestone outcrops of the Zeehan under licence to CRAE.

The aim of the survey was to identify mineral-related siderite zones for follow-up diamond drilltesting. The target is a stratabound zinc/lead orebody hosted by the Ordovician Gordon Limestone with analogies to Irish-type Zn/Pb orebodies.

A separate survey was flown over the Gordon Limestone of McLean Creek. This area is known to have a large magnetic anomaly - attributed to a magnetite skarn - known as the Avebury target. In addition the nickel target areas at Melba Flats were also flown.

This report provides technical details of the survey and processing as well as some geological interpretations of the results. Locations of the prospects are shown in plan Tv1022.

The survey was flown in March 1995 by Universal Tracking Systems Pty. Ltd. with initial results received in December 1995. Data processing and some interpretation was undertaken by Tony Doe and John Tesselaar (CRAE - Orange).

Sub-divisions of the Gordon Limestone for drillhole logging purposes have been made on a lithostratigraphic and lithologic basis and is included elsewhere in this report.

2. Flight Survey and Data Processing Details

The flight line height was a nominal 30m with the line spacing approximately 60m with readings taken every 4-5m. A total of 2400 line km was completed covering the following prospects :- Sassafras, Blackjacks-Mariposa-Sunny Corner-Pyramid, Professor Range-Amber Creek-King Billy-Leatherwood, Myrtle-Grieves-Baura-Firewood Siding-Rose Valley. New areas between Leatherwood and Mariposa were also investigated and this included the Westerway and Tom Creek areas. Flight line maps are shown in Appendix I.

The data from the helimag survey was obtained as an XYZ file of easting, northing and total magnetic intensity. No terrain clearance data was provided with the original XYZ file.

Over each area of Gordon Limestone to be interpreted, a small (<3km2) data subset was selected. These areas were designed to include all of the Gordon Limestone but as little as possible of the surrounding rocks, particularly the Dundas Group which tended to 'swamp' the more subtle magnetic data variations of the limestone. This data was then imaged.

The vertical derivative of the magnetic data was produced along the flight line using TRAKPAK. This data was then imaged with the previously existing geology data superimposed. Some of the small linear anomalies coincided with mapped siderite. Other lithological units were also mapped eg the Moina Sandstone and the Crotty Quartzite.

Where applicable, magnetic inversion using MAGMOD was undertaken over the siderite-like anomalies. In most cases, anomalies over 1nT were able to be successfully inverted. These models should only be used as a guide as to the geometry of the source of the anomalies. This is due to :-

- There is no account of terrain clearance;
- The anomalies have small amplitudes;
- Not all lines were perpendicular to strike;
- The problem of "non-uniqueness" in magnetic inversion.

3. Magnetic Interpretations

Initial raster images failed to highlight major zones of inferred siderite alteration (plan Tv1026). Removal of regional gradients and the selective use of sub-area vertical derivative data greatly improved the resolution (plan Tv 1027). From the modelling it was impossible to distinguish between siderite zones and other stratabound weakly magnetic units.

As a result of this work a much better understanding was gained of the geology of the Ordovician-Silurian sequence in the Zeehan area.

The Gordon Limestone is relatively more magnetic than the surrounding clastic sequences whilst the Siltstone Unit of the limestone is less magnetic than the limestone. The high magnetic susceptibility of the surrounding Cambrian Dundas Group of sediments, volcaniclastics and basic intrusions caused imaging problems. Major units which appeared as magnetic highs included the Upper Dolomite Unit of the Gordon Limestone (possibly other dolomitic zones are relatively magnetic but lack of geochemical surface control could not confirm them) and the Amber Slate of the Silurian clastic sequence. Major structures are difficult to identify and follow. Interpreted linears deemed to represent faults show a lack of continuity eg the Firewood Siding Fault and the Little Henty Fault.

Comments on the interpretation of these sub-areas are :-

3.1 King Billy (plan Tv 1140)

- The southern margin of the Gordon Limestone is marked out as a major anomalous zone. In part, the anomalous horizon is coincident with the Dark Clay and Siderite Units at the base of the Gordon Limestone which have elevated zinc values. However, it is possible that the limestone is flat dipping with underlying unconformable Cambrian sediments (?volcaniclastics locally) close to the surface and thus causing an anomaly 'over-shoot' into the Gordon Limestone outcrop (370000mE, 5351500mN).

- The southern margin anomaly is one order of magnitude greater than those anomalies which have been used for other potential siderite modelling.

- There is a large magnetically elevated zone at the west end of the prospect which is associated with an inferred cross fault, siderite and particularly dolomite alteration. There is a facies thickness variation implying that this cross fault may be a re-activated syn-sedimentary fault (369450mE, 5352000mN).

- A very high amplitude N-S striking linear magnetic anomaly lies Southwest of the Gordon Limestone (2 orders of magnitude greater than any limestone anomaly). This N-S anomaly is hosted by Cambrian sediments. An initial field inspection suggests that the cause is a mafic breccia unit similar to the breccias seen at Tennant Creek in the Northern Territory (368350mE, 5350800mN).

3.2 Firewood Siding (plan Tv 1143)

- Processing of the vertical derivative data has produced a plethora of potential siderite alteration-related anomalies.

- Significant magnetic highs occur at the south end of the prospect @361000mE, 5347900mN and 361100mE, 5348100mN. These highs are within a major elevated magnetic zone in contact with the Moina Sandstone anticline.
- There is an inferred siderite zone beneath the Siltstone Unit at West Baura (361700mE, 5349250mN)

- There is a possible siderite zone 500m south of the above locality proximal to the major Firewood Siding Fault;

- Other potential siderite zones include along strike from the above site, at 361900mE, 5348100mN, south of the main outcropping silica breccia body (southern end of the Firewood Siding prospect).

- The Firewood Siding Fault is difficult to trace across the limestone.

- Bridges over the creeks are identifiable as cultural anomalies eg. 362100mE, 5349200mN.

- The Siltstone Unit is mappable for approximately 3kms.

3.3 Professor Range (plan Tv 1144)

- A line of relatively strong magnetic highs occurs along the contact between the Gordon Limestone and the over-thrusted Owen Conglomerate.

- Some of these magnetic highs appear to be underlain by Gordon Limestone and warrant drill testing eg 365800mE, 5351400mN.

3.4 Amber Creek (plan Tv 1140)

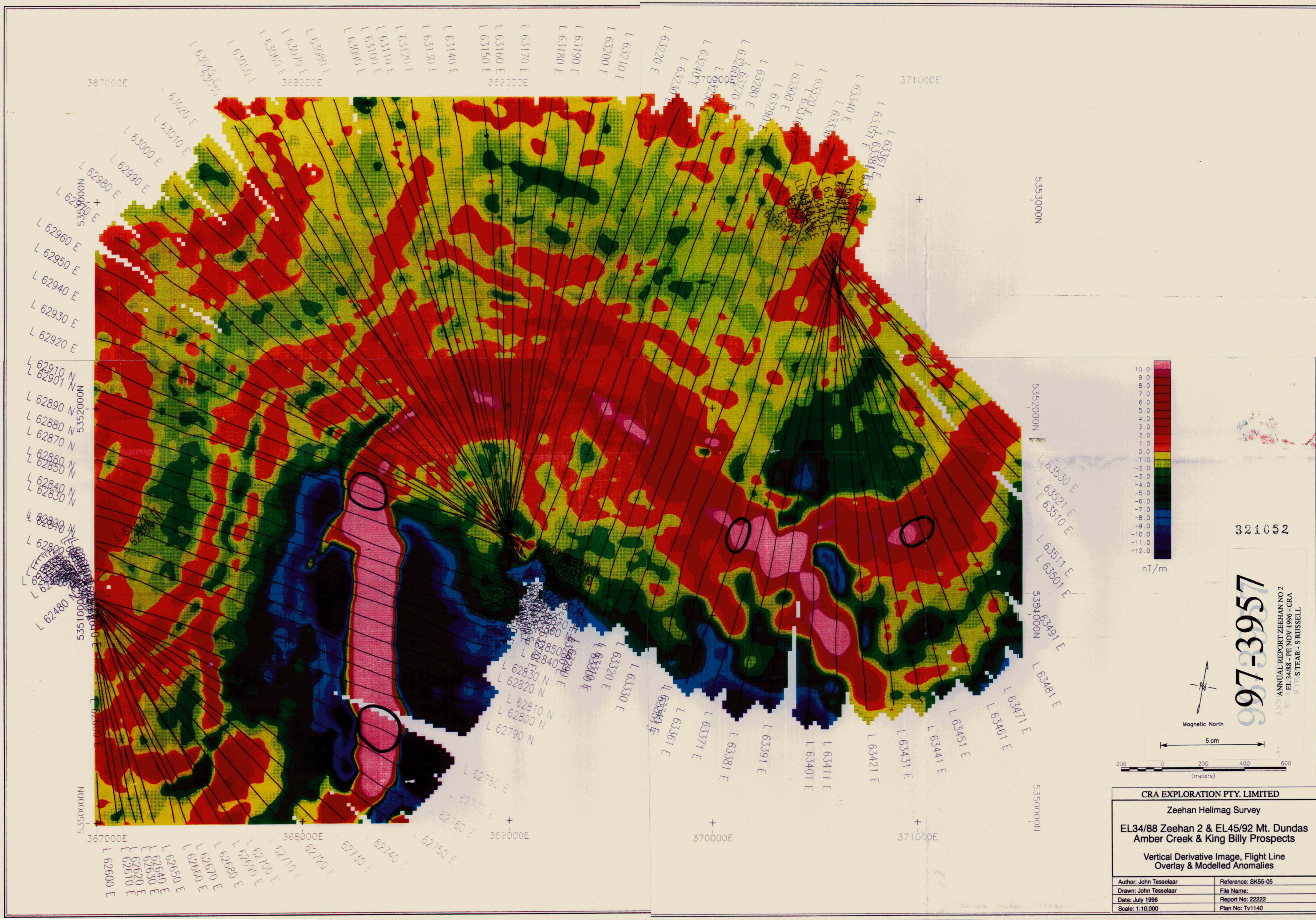
- The Siltstone Unit is discernible for most of the prospect as is the Crotty Quartzite/Gordon Limestone contact.

- A distinct, arcuate linear feature occurs at the prospect's southern end at the junction with Professor Range (367300mE, 5350250mN). No explanation is offered.

4 5. General Geological Interpretation Summary

- The Amber Slate is a non-calcareous slate of Silurian age which is recognised in the dataset as a magnetic high.
- The Crotty Quartzite appears on the vertical derivative map as a magnetic low.
- The Gordon Limestone appears as a magnetic high except for the non-calcareous, argillaceous Siltstone Unit eg King Billy, Amber Creek, Grieves, Myrtle, Baura and Firewood Siding. The Siltstone Unit is not apparent in the magnetic data at Blackjacks, Mariposa, Sunny Corner Tom Creek and Pyramid.
- The Moina Sandstone is a magnetic low near the overlying Gordon Limestone. At Grieves this low unit is 200-300m thick before passing down sequence into a magnetic high. This high unit may be part of the Owen Conglomerate.
- The Owen Conglomerate is generally a magnetic high eg Professor Range and Pyramid.
- Major, brittle faults are not readily identifiable, often disappearing along strike eg the Balstrup Fault in the Pyramid and Tom Creek areas.
- Parts of the Gordon Limestone display more continuously intense magnetic zones eg at Grieves and Firewood Siding South. This may be a reflection on mineral fluids having altered the limestone particularly via dolomitisation. Alternatively these highs may be a reflection of powerful surface weathering producing surficial de-calcified clays. It is possible to say that the rotting of variably composed limestone may give rise to differential surface effects that have different magnetic susceptibilities.
- The diamond drilling identified siderite zones at Blackjacks, Mariposa and Grieves can be seen in the magnetic data. However numerous anomalies of a similar intensity occur elsewhere, generally in areas of the Gordon Limestone considered as non-prospective.
- There are several targets in the magnetic data that lie at the base of the Gordon Limestone which require drill testing.

Simon Tear
John Tesselaar



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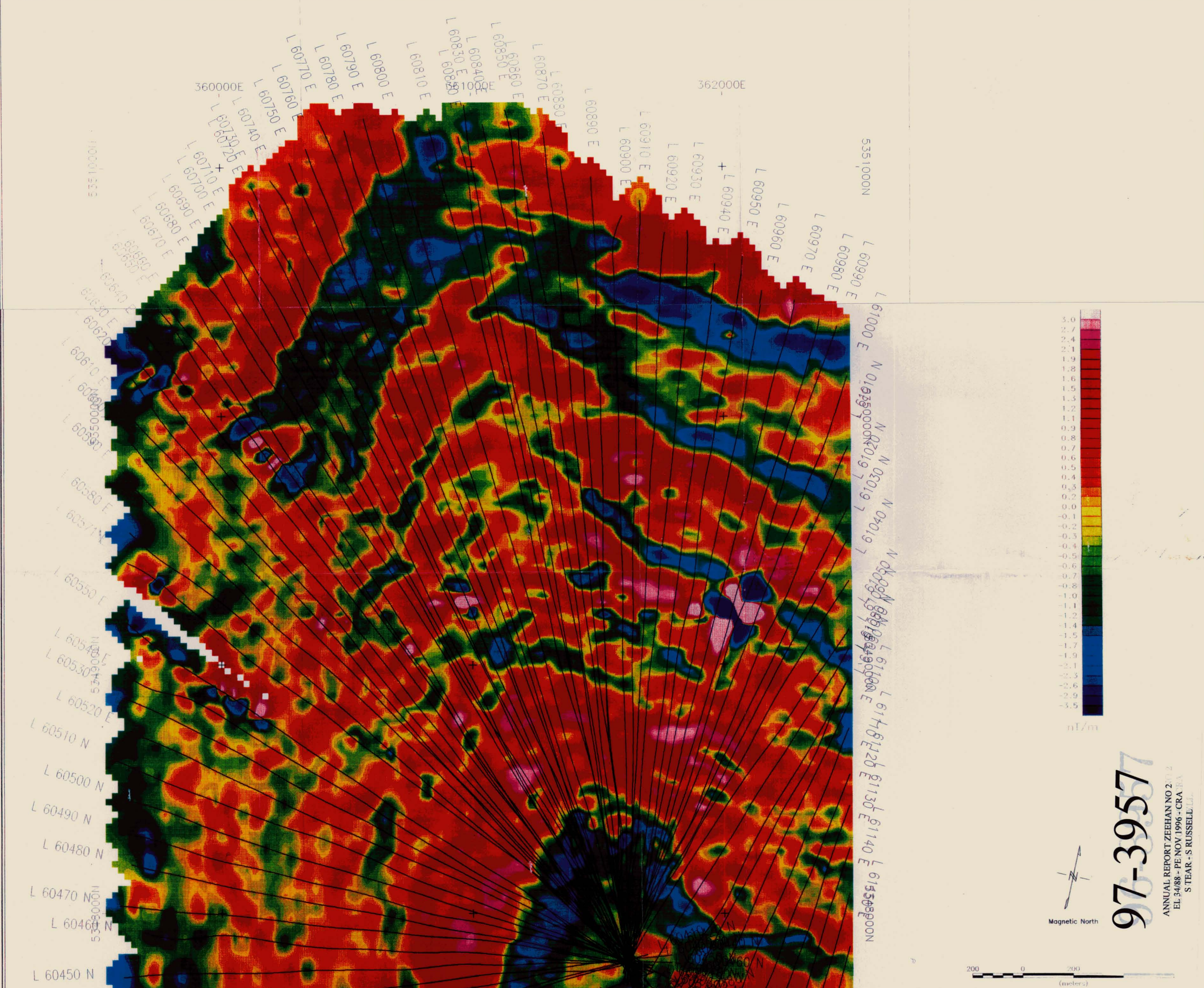
Zeehan Helimag Survey

EL34/88 Zeehan 2 & EL45/92 Mt. Dundas
Amber Creek & King Billy Prospects

Vertical Derivative Image, Flight Line Overlay & Modelled Anomalies

Author: John Tesselaar	Reference: SK55-05
Drawn: John Tesselaar	File Name:
Date: July 1996	Report No: 22222
Scale: 1:10,000	Plan No: Tv1140



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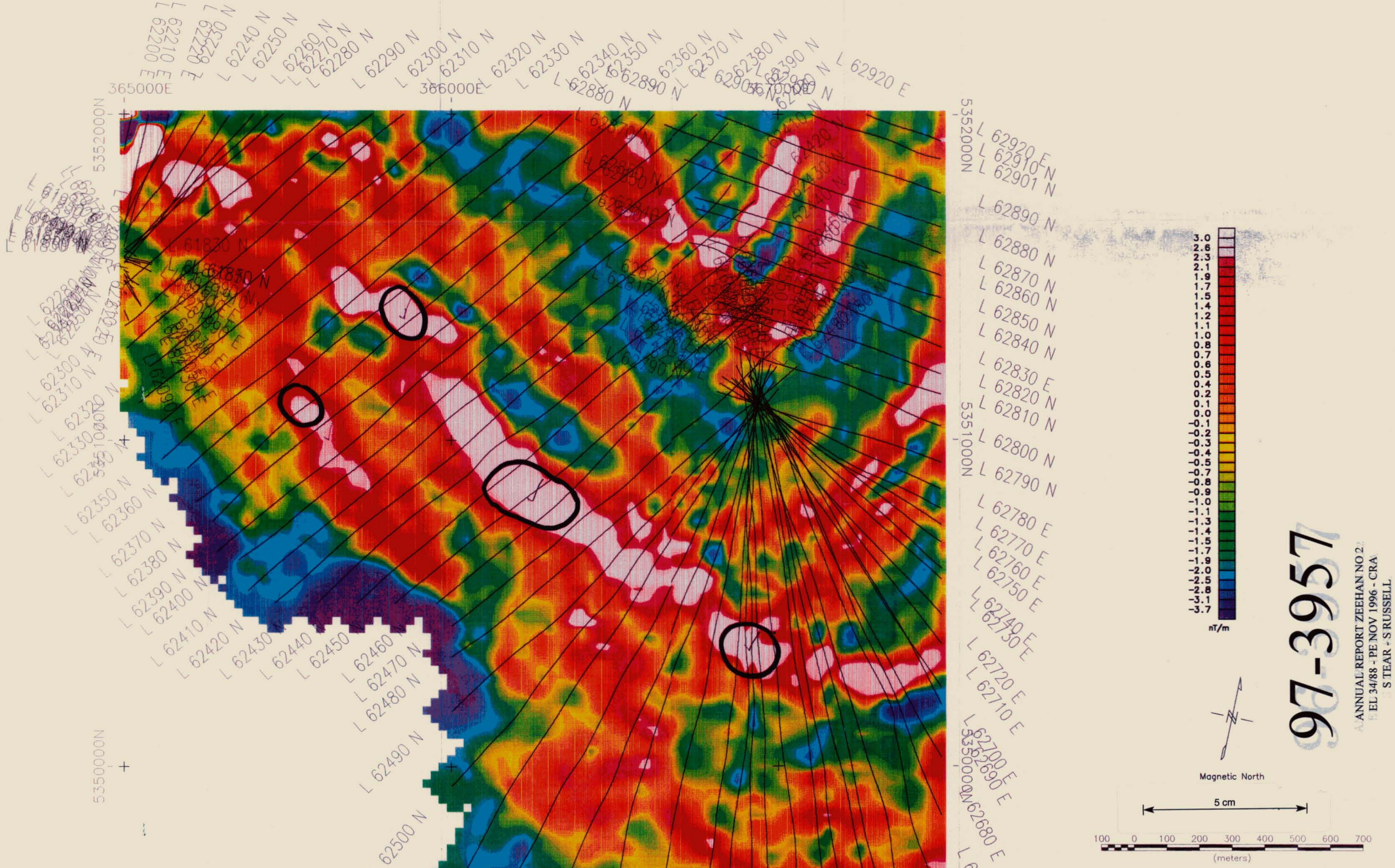
Zeehan Helimag Survey

EL28/88 Zeehan 1 & EL34/88 Zeehan 2
Firewood Siding Prospect

Vertical Derivative Image, Flight Line Overlay & Modelled Anomalies

Author: John Tesselaar	Reference: SK55-05
Drawn: John Tesselaar	File Name:
Date: July 1996	Report No: 22222
Scale: 1:10,000	Plan No: Tv1143



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CRA EXPLORATION PTY. LIMITED

Zeehan Helimag Survey

EL34/88 Zeehan 2 - Professor Range Prospect

Vertical Derivative Image, Flight Line Overlay & Modelled Anomalies

Author: John Tesselaar	Reference: SK55-05
Drawn: John Tesselaar	File Name:
Date: July 1996	Report No: 22222
Scale: 1:10,000	Plan No: Tv1144

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Appendix I

Flight Line Maps

CRAE AIRBORNE MAGNETIC SURVEY, ZEEHAN AREA
VERTICAL DERIVATIVE (GEOSOFT GRID)
CRAE SURVEY NUMBER T27M AMG PROJECTION ZONE 55 DATUM AGD 66
CELL SIZE 20M RESAMPLED TO 10M PLOT NO QIP0497 1:50,000

CRA

CRA EXPLORATION PTY. LIMITED

Zeehan Helimag Survey

Vertical Derivative Map

Author: John Tesselaar	Reference: SK55-05
Drawn: John Tesselaar	File Name:
Date: July 1996	Report No: 22222
Scale: 1:50,000	Plan No: Tv1027

321056

CRAE AIRBORNE MAGNETIC SURVEY, ZEEHAN AREA
TOTAL FIELD (GEOSOFT GRIDDING)
CRAE SURVEY NUMBER T27M AMG PROJECTION ZONE 55 DATUM AGD 66
CELL SIZE 20M RESAMPLED TO 10M PLOT NO QIP0496 1:50,000

CRA EXPLORATION PTY. LIMITED	
Zeehan Helimag Survey Total Magnetic Intensity Map	
Author: John Tesselaar	Reference: SK55-05
Drawn: John Tesselaar	File Name:
Date: July 1996	Report No: 22222
Scale: 1:50,000	Plan No: Tv1026

321057

Appendix 8 of TCR 96-3957
96-3957A

Appendix VIII

Basin Analysis Report

ORDOVICIAN GORDON GROUP CARBONATES,

ZEEHAN REGION, TASMANIA, AUSTRALIA -

STRATIGRAPHY AND PALAEOENVIRONMENTS

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Final Report 15-11-1995

CONTENTS

321060

ABSTRACT

The Gordon Group in the Zeehan area comprises 3 conformable formations; the Ugbrook, Myrtle (new) and Black Jacks (new). The Ugbrook Fm, first defined in the Mole Creek area, was deposited in protected shallow subtidal to low intertidal waters in an offshore bar to lagoonal to lagoonal-island environment during the Early Caradoc.

The basal Ugbrook interdigitates with the siliciclastic Moina Fm and suggests that the Early Caradoc shoreline was at or very close to Black Jacks. A transgression shifted these environments northwards and eastwards during the Caradoc and Ashgill.

The tidal flat complex of the Myrtle Fm developed throughout the area in the mid-Caradoc and consists of fifteen 1m to 4m thick Punctuated Aggradational Cycles (PACs) which can be correlated throughout the area. The Myrtle Fm is similar lithologically, environmentally and chronostratigraphically to the Lower Limestone Member of the Florentine Valley.

The Myrtle Fm is succeeded by mainly shallow to moderately deep subtidal alternating micrites and shales with minor PACs, belonging to the Black Jacks Fm which is similar to the Upper Limestone Member of the Florentine Valley. The lack of PACs in the Upper Black Jacks and the very common occurrence of coarse carbonates in the Myrtle stratigraphic drillcore suggests that the Myrtle area might have been in a slightly deeper and more rapidly subsiding region. The Lords Member of the Black Jacks Fm is present in several of the drillcores and, as is normal elsewhere in the state, varies in thickness and lithology from mudstones to coarse sandstones. Minor PACs and some faunal horizons help in the correlation of the Black Jacks.

INTRODUCTION

At the request of CRA, 8 full days in October 1995 were spent logging core through Ordovician sedimentary sequences from drillholes in the Zeehan area. An extra four days were allocated to plotting, drafting, report preparation and the examination of thin sections and fossils. Logging concentrated on the Gordon Group carbonates but short sections of the underlying Denison Group (Moina Fm) and overlying Eldon Group (Crotty Fm) siliciclastics were also examined.

The Gordon Group carbonates are deformed and the extent of stratigraphic loss or repetition is difficult to establish from the numerous veined and crushed intervals. In any sedimentary basin analysis it would be desirable to plot isopachs in order to define the basin shape and its evolution through time. Unfortunately, depending on the relation of bedding to the principal axis of the strain ellipsoid, bedding thickness may be increased or decreased substantially. Tectostylolites, which are pervasive in the Zeehan cores, will decrease stratigraphic thickness. They preferentially affect more argillaceous sections and the amount of section loss will (as with cleavage) depend on their angle of incidence with bedding. This problem is soluble but not within the confines of this study. A full palinspastic study would also need to remove, in map view, the Devonian folding and the thrust faulting.

LITHOSTRATIGRAPHY

Several major lithostratigraphic units are recognisable in the Zeehan cores. The Gordon Group comprises the Ugbrook Fm, the Myrtle Fm (new name) and the Black Jacks Fm (new name). The Black Jacks Fm includes the Lords Siltstone Member (Fig.1). The positions and suggested correlations of these units are shown in Fig. 5 (large diagram in pocket). All thicknesses are uncorrected downhole distances rather than dip-corrected stratigraphic thicknesses.

Denison Group, Moina Formation

The Moina Fm of the Denison Group underlies the Gordon Group in northern and western Tasmania (Fig. 2). The boundary between the Moina Fm and the Gordon Gp is everywhere marked by a siltstone-mudstone transitional zone that may be a metre thick or 30m thick. This transition is 200m thick in the Florentine Valley and is known as the Florentine Valley Fm. The separation between the Denison Gp and the Gordon Group is based on the dominance of siliciclastics (Denison Gp) and limestone (Gordon Gp). The siltstone-mudstone transition is therefore historically and pragmatically regarded as the topmost part of the Moina Fm and the base of the Gordon Gp is defined on the incoming of carbonates. However, where there is an interdigitation of siliciclastics and carbonates, as in DB111, or where the lowest limestones are replaced by siderIte or are mineralised then the placement of the boundary may be arbitrary. In all sections, delineation of the boundary has to regarded as a matter of taste. In most sections I have taken the boundary to be the first obvious and definite limestone.

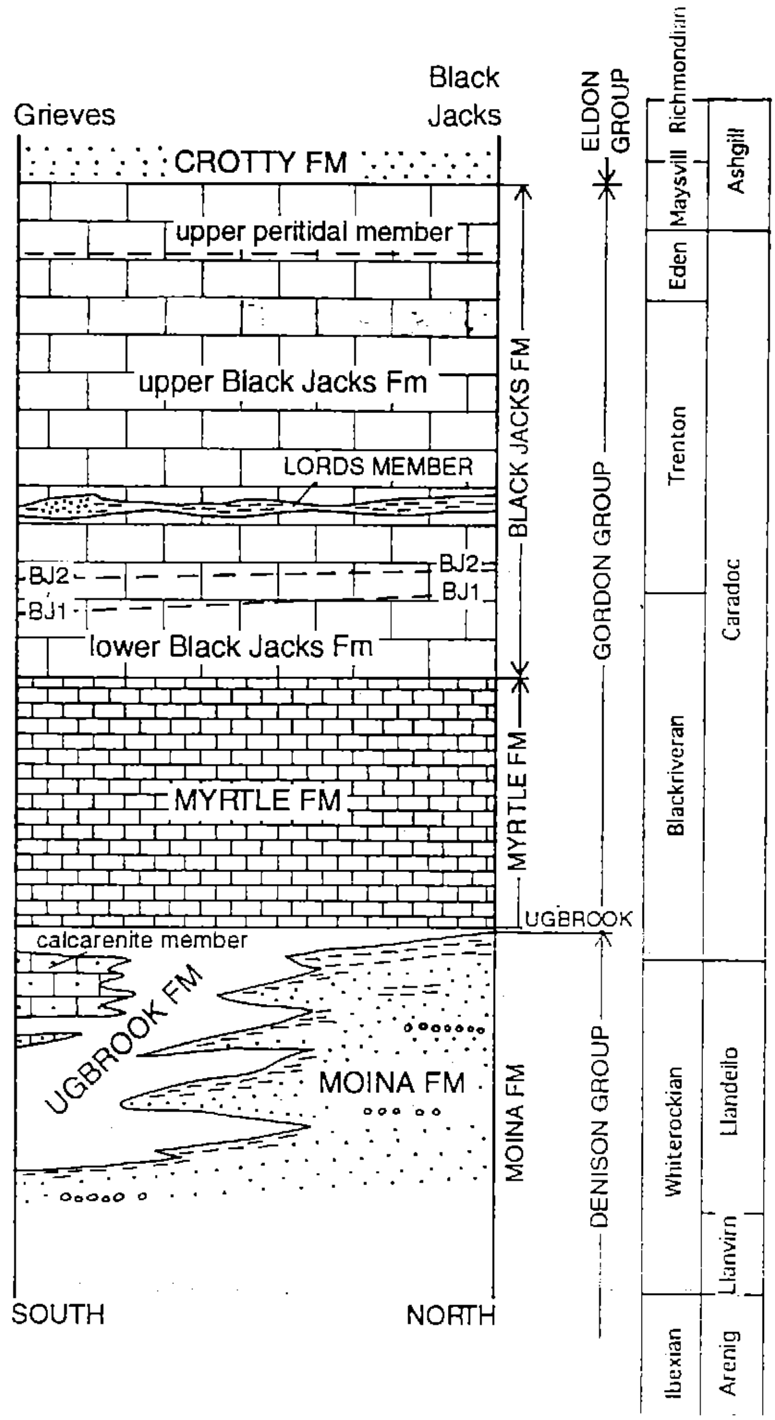

Fig.1 Summary of Ordovician lithostratigraphy in the Zeehan region.
Chronostratigraphic units are based on the standard North American scheme and the standard British scheme. Correlations are most easily made to the American scheme but the British scheme is used in the text because of its greater familiarity.

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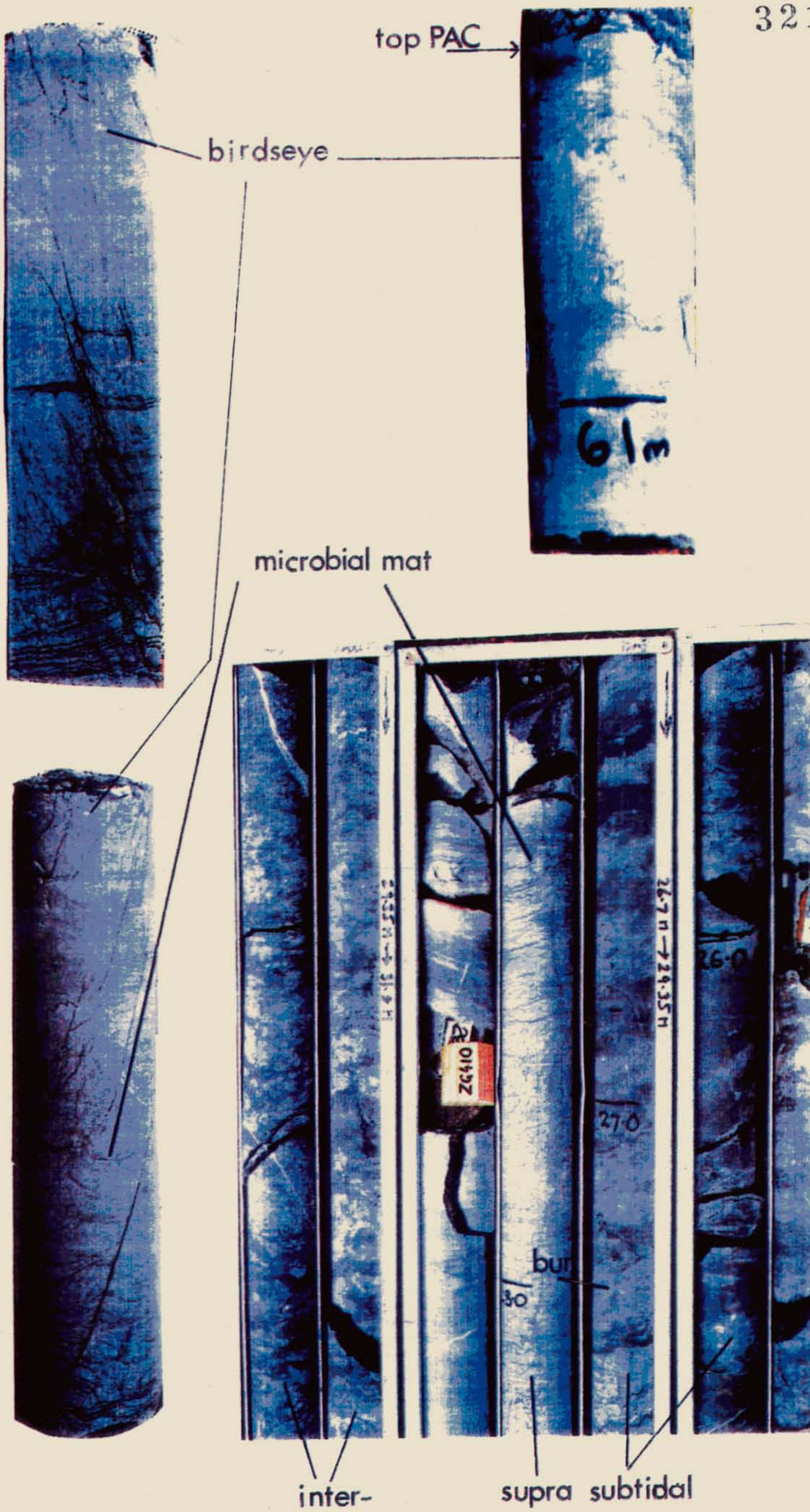

Plate 1 Typical PAC lithologies from ZG 410. Note darkening of limestone from shallow to deep. Core between 26.7m and 27m is typical subtidal alternation of argillaceous and micritic limestone and this lithology is typical of much of the Black Jacks Fm. but forms a small percentage of the Myrtle Fm. Boundary between Myrtle Fm and Black Jacks Fm is at 27.5m.

Ugbrook Formation (Burrett & Goede 1987, Burrett *et al.* 1989)

The siltstones of the upper part of the Moina Fm are succeeded by alternating thin micrites and shales with, in some cores, siltstones and sands (notably DB111). These centimetre-decimetre scale alternations are frequently bioturbated and often nodular (due to sedimentary boudinage). Pelloids and comminuted shells are very common. Asaphid trilobites are present but other identifiable fossils are rare. Several sections have developments of biocalcarenites and/or biosparites composed mainly of crinoidal debris. These sequences are very similar to the Ugbrook Fm in Mole Creek (Burrett *et al.* 1989; Appendix C) and, rather than erect a new name, I will use that term. This lithology is only a few metres thick in DB 110 (possibly 40m thick if a sideritised zone is included) and thickens towards Myrtle which also has a thick development of the crinoidal biospararenite member.

Myrtle Formation (new name)

The Myrtle Fm consists of between 40-170m of micrites, biomicrites, dolomitised micrites and minor calcarenites and shales deposited as upwardly shallowing tidal flat cycles known as Punctuated Aggradational Cycles (PACs). These were first recognised and used as a correlation tool by Calver (1977). Unfortunately, he did not publish and PACs have since been recognised worldwide as a useful correlation and palaeoenvironmental tool. The PAC concept is summarised in Appendix B and photographs of representative lithologies are shown on the attached photographs (Plate 1). Calver (1977) used PACs to correlate throughout the Florentine River Valley recognising 18 PACs in the Lower Limestone Member of the Benjamin Limestone. In the Florentine Valley, and in Zeehan, this correlateability is due to a basinwide or at least sub-basinwide response to changing sea level. PAC boundaries may therefore be regarded as essentially isochronous horizons. Fifteen PACs are recognised in the Myrtle Fm. and each section has most of them. The extent of faulting in ZG 403 is clear as only the first PAC is present.

Black Jacks Formation (new name)

The Myrtle Fm is succeeded by the Black Jacks Fm which consists of alternating micrites and shales with some biomicrites, calcarenites and calcisiltites. Two PACs occur in the Lower Black Jacks but are not present in every section. These are labelled BJ1 and BJ2 on Fig. 5. The Lords Member is a thin (1m-15m) siltstone-shale-sometime sandstone unit that is surprisingly variable on a kilometre scale for a unit that appears over most of western Tasmania from Precipitous Bluff on the south coast to the Florentine Valley to Zeehan to Mole Creek (Fig.2). The Lords Member equivalent at Mole Creek (the Mole Creek Fm) is discontinuous (see p.7 of Appendix C). A coarse, quartz sandstone occurs at the appropriate stratigraphic level in ZF 37 (Firewood Siding). The Lords Member is characterised, statewide, by a distinctive fauna consisting of abundant *Pliomerina* trilobites, strophomenid brachiopods (*Sowerbyites*) and the Tasmanian endemic ostracod *Dominina*.. The Lords Member lithology/fauna does not appear suddenly but is preceded by a gradual deepening of both biofacies and lithofacies.

The Upper Black Jacks Fm is completely dolomitised in some holes (ZR 104) and partially in others (DTM 84-6, DTB 84-1). Complete dolomitisation is unusual in the Gordon Group and increased porosity, including vuggy porosity, is evident in ZR 104 due to the 12% volume loss when calcite is replaced by dolomite. As dolomitised limestones are important petroleum reservoirs (and therefore porous for ore forming fluids) it might be useful to plot the distribution of dolomitisation within the Gordon Group at Zeehan (see Appendix A).

Where undolomitised, there is an abundant coral-stromatoporoid fauna, some of which is correlated to the widespread 'Den fauna'. A diverse trilobite-brachiopod-bryozoan fauna, which in previous studies has been called the 'Smelters fauna' (Zeehan Smelters fauna described by Pitt (1961) and mentioned by Banks and Burrett (1980), occurs below an 'upper peritidal member '. This 'upper peritidal member' occurs in ZF 37, DS 98, DTM 84-6 and DB 110 but is not obvious in ZM190.

PALAEOENVIRONMENTS

Most sections of the Gordon Group were deposited in predominantly very shallow subtidal to peritidal conditions on a mini-platform. due to a marine transgression from the south, west and east towards the Precambrian/Cambrian islands of the Tyennan and Rocky Cape regions (Fig. 3). Thick siliciclastic sandstone sequences, followed

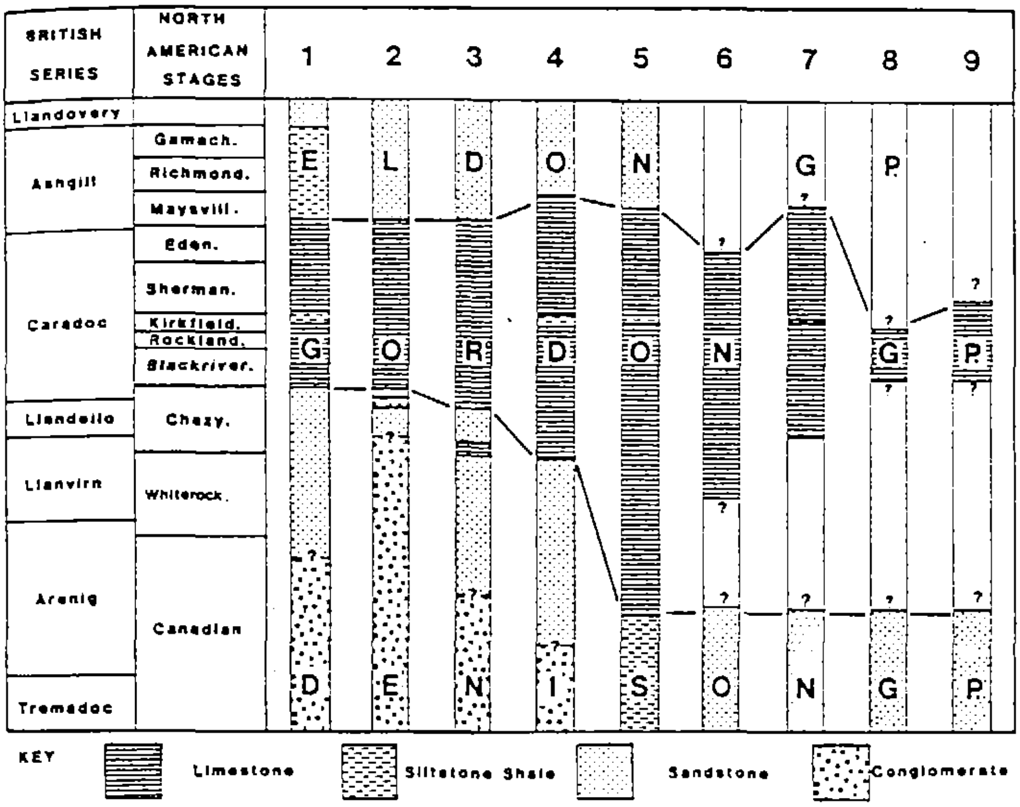

Fig.2. Simplified stratigraphic columns showing diachronous base of the Gordon Gp and of the Moina Fm. 1=Queenstown, 2=Vale of Belvoir, 3=Lower Gordon River.4=Mole Creek, 5=Florentine Valley, 6=Ida Bay, 7=Precipitous Bluff, 8=Point Cecil, 9=Surprise Bay. (Burrett *et al.* 1984).

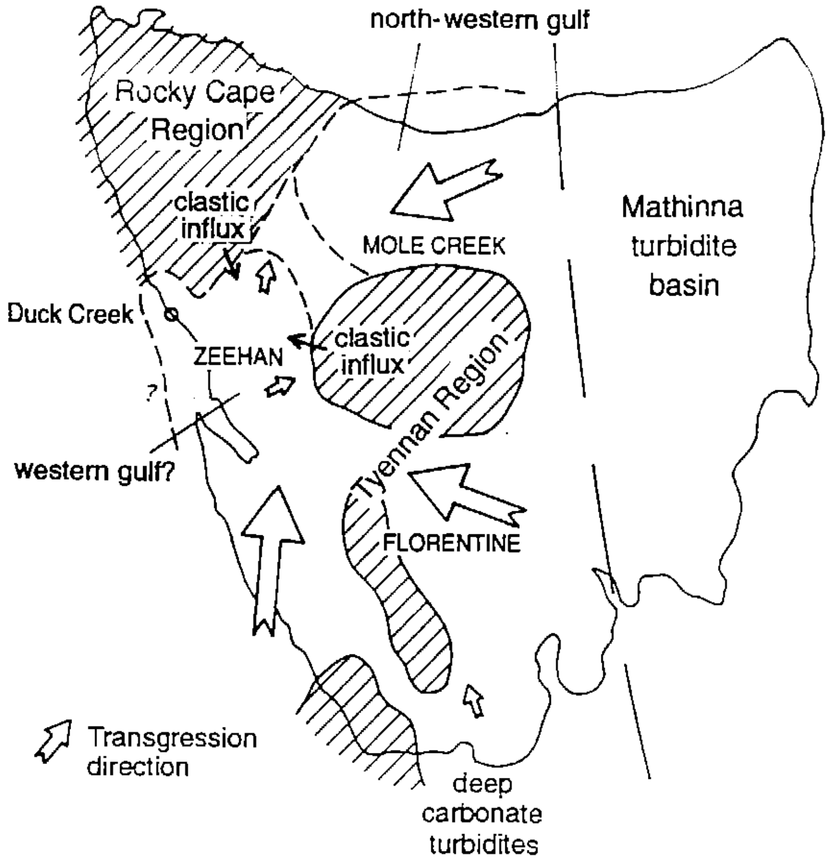

Fig.3. Generalised palaeogeography of the Tasmanian miniplatform in the Caradoc showing inferred directions of transgression. Dotted link between Tyennan and Rocky Cape regions may be an isthmus transgressed during Late Caradoc times.

by thick carbonate successions were gradually built up. This transgression started in the Tremadoc (in the Florentine Valley) and continued up to the Late Caradoc or even Early Ashgill (Figs.2-3). Probably much of the Tyennan and Rocky Cape regions were still emergent in the Late Ordovician (Ashgill). The timing of the transgression is mainly determined from conodont dates on the lowest Gordon Group carbonates with supplementary information from macrofossils in the underlying Denison Group siliciclastics (Fig.2). In the north of the state, the transgression moved towards the Tyennan and Rocky Cape regions from the north and east possibly forming an east-west aligned gulf (Burrett 1978). In the west, the transgression was from the south towards the west and north. Very thin sequences of the Gordon Group are found at Duck Creek (just to the north of the Heemskirk Granite) and at Heazlewood River. It is possible that a similar gulf to the one in the northwest existed in the west of the state. The siliciclastic sands at the Lords level in the Firewood Siding hole (ZF 37) also suggest proximity to land. A solution to this palaeogeographic problem depends on studies on the Ordovician around Queenstown, outcrops south of Grieves and the poor limestone outcrops between Zeehan and the Vale of Belvoir and south of Firewood Siding.

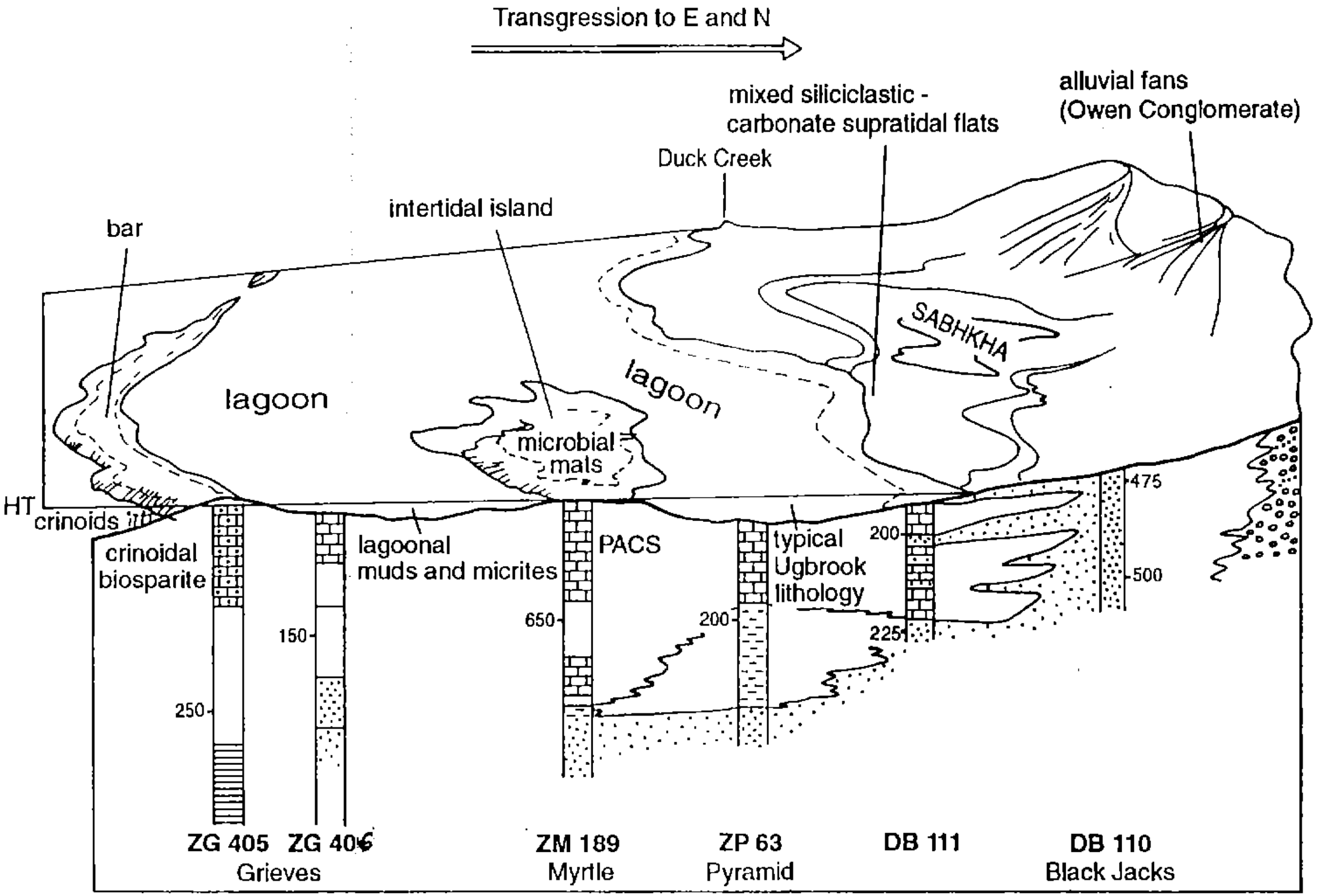

Fig. 4 Environmental reconstruction of the Zeehan area for early Ugbrook Fm times (about Early Caradoc) from the south of the area at Grieves to Black Jacks in the north. Shoreline is to the north (right) and east (behind the viewer). Not to scale. HT = normal high tide level. Numbers refer to down hole depth in m not stratigraphic thickness.

The Ugbrook Fm thins dramatically from DB111 to DB 110 and there is no suggestion that this is due to Devonian faulting. Unlike the other cores examined, the Ugbrook in DB 111 has several coarse siliciclastic interbeds as well as reddened tops to PACs in its basal part. The simplest explanation for this is that the (irregular) shoreline was between DB111 and DB 110 in early Ugbrook time (approximately mid-Caradoc or Blackriveran time) as shown in Fig.4, with clastic debris being derived from the Tyennan region to the east. This date, or a slightly younger one, also applies to the basal carbonates at Duck Creek and Heazlewood River. The typical Ugbrook micrites and pelloidal bioturbated shales were deposited in a lagoon formed behind (north of) a northerly or northeasterly migrating offshore carbonate bar with the minor PAC carbonates formed on intertidal islands within the lagoon (Fig.4). As the transgression continued, the carbonate bar moved from Grieves towards Myrtle during late Ugbrook time. Stabilisation occurred during Myrtle times (Upper Blackiveran) with the whole Zeehan area covered with waxing and waning PACs. Probably by that time, the shoreline (i.e. high supratidal limit) had moved north to Duck Creek and east onto the Tyennan region.

Deepening occurred after Myrtle Fm times, probably due either to the incapacity of the carbonate factory to keep-up with rising sea level or to an increased rate of basinal subsidence. Open subtidal sediments were deposited over the whole area with brief peritidal flat deposition (BJ 1 and BJ2) at Grieves, Myrtle (ZM189) and at Black Jacks (DB110).

The Myrtle core, ZM189, is unusual in that coarse grained carbonates including sparites, spararenites, calcarenites, biosparites are common through the section. This is presumably the consequence of the production of large bioclasts due to deposition further from the micrite producing tidal flats and due to the preponderance of a good subtidal fauna such as crinoids.

The Lords event appears to be isochronous across the whole Tasmanian miniplatform. It was a time of uplift in the Tyennan region leading to coarse quartzite conglomerates being deposited within the middle of the Benjamin Limestone Fm to the west of the Florentine Valley (in the Vale of Rasselas), a deepening in most sections but a shallowing in the deepwater Surprise Bay sequence (Burrett *et al.* 1984). The Lords event was clearly a significant but short lived epeirogenic episode during the mid-Trentonian (Late Caradoc). Normal shallow subtidal conditions resumed during the remainder of Black Jacks time except for a widespread peritidal interlude in late Black Jacks time (Late Trentonian/Early Ashgill). This upper peritidal interval is not found in the Upper Black Jacks Fm at Myrtle (ZM190) which again may suggest that Myrtle may have been in slightly deeper water. The upper peritidal member may correlate to a similar shallowing interlude recognised in the Overflow Creek Fm at Mole Creek.

CONCLUSIONS

The Gordon Group sequence at Zeehan, although starting later during the earliest Blackriveran rather than in the Chazyan, is similar to that at Mole Creek and dissimilar to that in the Florentine Valley. It lacks the oncolitic Standard Hill Fm but the fauna, lithofacies and interdigitation of the Ugbrook with the Moina is very similar. The Myrtle Fm has similarities with both the thicker Lower Limestone Member in the Florentine Valley and the Sassafras Creek Fm at Mole Creek. The generally subtidal Black Jacks Fm is, though, closer to that of the Upper Limestone Member of the Florentine Valley than to the dominantly peritidal Dogs Head and Overflow Creek Fms at Mole Creek.

Interdigitation of the Moina with the Ugbrook and a greatly thinned Ugbrook sequence at Black Jacks suggests that the Blackriveran (Early Caradoc) shoreline was at about the position of DB 110, moving eastwards onto the Tyennan region and northwards towards Duck Creek by the Late Blackriveran.

Identification of PACs or shallowing-upward sequences in the Myrtle Fm and in the Upper Black Jacks Fm allows correlation across the region.

There are several argillaceous horizons present in some sections and the identification of the Lords Member is helped by the identification of its characteristic fauna and by the lithofacies deepening prior to its deposition.

RECOMMENDATIONS

Chronostratigraphic correlations in the Zeehan area could be improved substantially by employing conodonts. Conodonts are rare in peritidal sections but this study has shown that there are sufficient subtidal intervals that would yield sufficient useable conodont elements per kilogram of core. If this was coupled with an intensive study of the macrofossils then very reliable chronostratigraphic correlations are possible. Conodonts also record the maximum temperature that they have experienced and, more importantly, are pitted in a characteristic manner by hydrothermal fluids. Such a study could define flowpaths of hydrothermal fluids.

There are sufficient drillholes to define the extent of any basin or basins by the use of isopachs. However, a complete palinspastic study is recommended that takes into account extension due to cleavage and stratigraphic loss due to tectostylolites as well as removing the effects of Devonian folding and thrusting.

The extent of pervasive dolomitisation in the Black Jacks Fm should be plotted. This might reveal a zone of enhanced porosity/ permeability within the Gordon Group into which hydrothermal fluids might have flowed (see Appendix A).

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Appendix A

Dolomitization and its control on porosity and reservoirs in the Trenton Limestone
(from North, 1985 p.198-199).

Appendix B

Peritidal Carbonates from Walker and James Eds 1992. Facies Models. Geological Association of Canada.

Appendix C

Lithostratigraphy at Mole Creek , Burrett et al. 1989.

Appendix A

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recrystallization, and most commonly of *dolomitization*. About 80 percent of all hydrocarbon reserves contained in carbonate reservoirs in North America are in essentially pure dolomites. This percentage is by no means representative of other regions of the world, and unquestionably reflects the number of North American carbonate reservoirs that are Paleozoic in age. In the Persian Gulf Basin, with the most prolific carbonate reservoirs in the world, the proportion of dolomite reservoirs is no more than 20 percent.

The replacement of $CaCO_3$ by dolomite involves a loss of volume of about 12.3 percent, and a consequent increase in porosity by that amount, if the replacement is molecule for molecule. It may not always be so, because volume for volume replacement is also possible. Yet it remains the case that in many fields having partially dolomitized carbonate reservoirs the oil is restricted entirely to the dolomitized portion. This portion is favorable because of *partial* dolomitization, preferentially of the finer-grained components of the limestone, and later leaching of the remaining calcitic parts which are more soluble. The most-quoted example of this phenomenon is the sprawling Lima–Indiana field south of the Great Lakes (Fig. 13.52). The oil is confined to porous dolomitic zones in the Ordovician Trenton Group where it passes over the axis of the broad, bifurcating Cincinnati Arch. Updip, porosity disappears in the unaltered limestone and only gas is recovered. Among the fields providing case histories for this book is the Jay field in Florida (Ch. 26), another example of restriction of oil to the dolomitized part of a carbonate formation. Up the dip, the undolomitized micritic limestone lacks porosity and is barren of oil. Most carbonate producing basins afford comparable examples.

An intriguing small example is provided by the Dover field, at the southwestern extremity of Ontario in Canada, like Lima–Indiana in the Ordovician Trenton Group. During the 1920s, articles on oil-bearing structures quoted Dover as an example of the rare synclinal trap. The syncline is controlled by an elongate fracture zone (Fig. 13.53) along which migrating waters have been able to dolomitize a considerable thickness of strata; the oil is restricted to the porous dolomite and therefore to the "syncline." The Albion–Scipio "trend", in Michigan's part of the same basin, is very similar and produces from the same formation (Fig. 13.52). From outside the normal concern of petroleum geologists comes the parallel case of Mississippi Valley-type lead–zinc deposits, in some of which it is established that the brines, derived from evaporite deposits, that deliver the metals also bring about dolomitization.

The selective nature of dolomitization extends to its

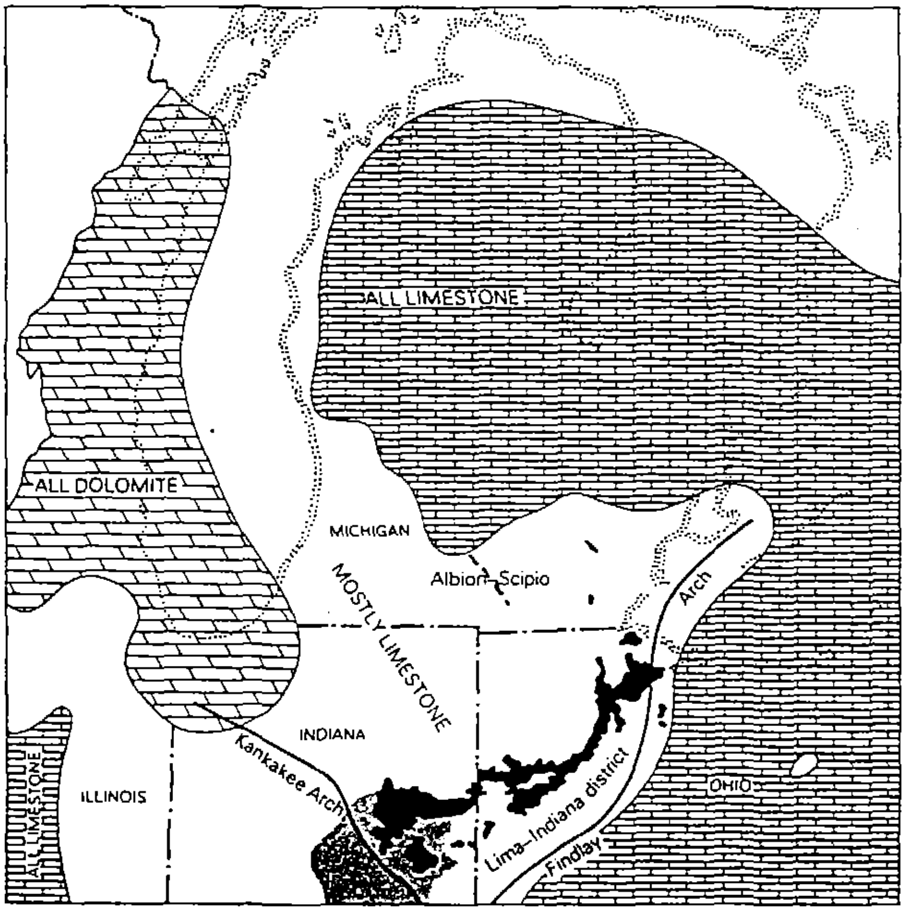


Figure 13.52 Michigan Basin in Middle Ordovician time, showing the Cincinnati Arch bifurcating into two arches as it crosses the basin from the south. The Trenton Group carbonates are dolomitized over the arches and along linear fracture zones; oil accumulations are restricted to the dolomitized portions. Dotted outlines on map delineate present Lakes Michigan and Huron. (After K. K. Landes, *Petroleum geology of the United States*, New York: Wiley–Interscience, 1970; and G. V. Cohee, US Geol. Survey Preliminary Chart no. 9, 1945.)

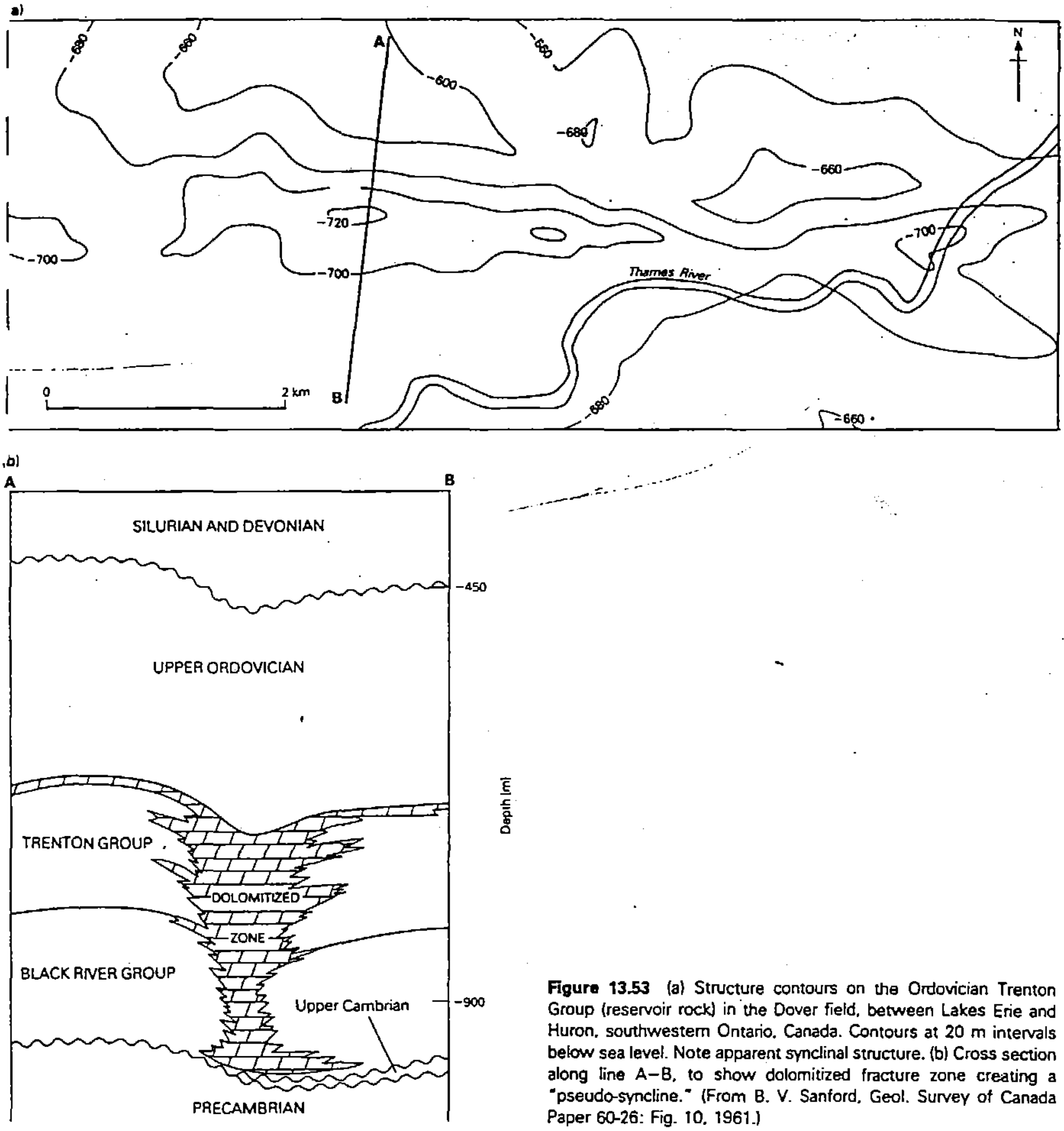
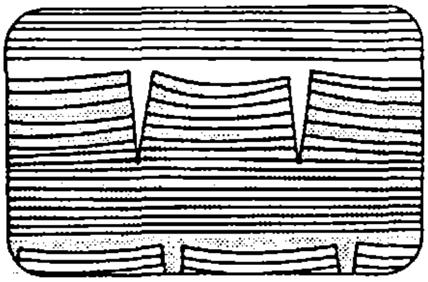


Figure 13.53 (a) Structure contours on the Ordovician Trenton Group (reservoir rock) in the Dover field, between Lakes Erie and Huron, southwestern Ontario, Canada. Contours at 20 m intervals below sea level. Note apparent synclinal structure. (b) Cross section along line A–B, to show dolomitized fracture zone creating a "pseudo-syncline." (From B. V. Sanford, Geol. Survey of Canada Paper 60-26: Fig. 10, 1961.)

effects on skeletal remains. Aragonite is much more easily dolomitized than is calcite, so shells of gastropods, cephalopods, and corals are dolomitized earlier than those of brachiopods, ostracodes, or echinoids. Well sorted crinoidal or shelly limestones are less dolomitized than surrounding rocks which contain less coarse material and more cement. Calcareous algae are easily dolomitized because high-magnesium calcite is deposited on them during their lives, and the algae themselves reduce sulfate which would otherwise inhibit dolomitization (especially of calcite). The vast mats of algae in the shallow epicontinental seas of the great Paleozoic transgressions are undoubtedly a factor in the prevalence of Paleozoic dolomites. There is very little dolomite in the stratigraphic record since the early Cretaceous, especially in the Northern Hemisphere. This may be because the present oceans, originating at that time, have a distribution and orientation different from those of earlier oceans, and epicontinental seas in low latitudes are highly restricted.

Appendix B



16. Peritidal Carbonates

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INTRODUCTION

Limestones and dolostones composed of calcareous sediment deposited in very shallow seawater and on muddy tidal flats are probably the most conspicuous carbonate facies in the rock record (Fig. 1). The term *peritidal* (from the Greek *peri*, meaning around or near, and tidal, relating to tides) was coined in passing by Folk (1973) and has proven a useful general name for the spectrum of nearshore and shoreline depositional environments and facies.

What distinguishes these rocks is their wide variety of features that can be compared directly with modern analogues, making them both easy to recognize in the field and important paleobathymetric indicators. The facies are generally arranged vertically in a *shallowing-upward sequence* (James, 1984), now referred to as a *shallowing-upward succession*, in which marine sediments are overlain successively by muddy carbonates deposited in paleoenvironments subject to varying periods of exposure. This vertical stacking of peritidal and related facies is a valuable record of the dynamics of carbonate platform development, on both large and small scales. It hints at extrinsic factors such as relative sea level change and climate, and records the effect on periodically exposed sediment of biotic evolution through geologic time. Peritidal carbonates are also economically important because they host Pb and Zn deposits and frequently form hydrocarbon reservoirs.

In this chapter, we first summarize the tidal flat environment from a Recent standpoint. We then discuss how the record of carbonate tidal flats may have changed through time in response to biological evolution and provide ancient examples of commonly encountered peritidal facies, with evidence for their interpretation. Finally, we outline how peritidal facies are preserved in the stratigraphic record, describe current hypotheses used to explain stratigraphic repetition and suggest how these facies can best be used in sequence stratigraphic analysis.

Figure 1 Panorama of Cambrian shallow water limestones and dolostones, Dezaiko Range, east-central British Columbia. Distinctive "stripy" bedding of lower unit, to the right of the small ice field, is from peritidal facies of the Snake Indian Formation. The unit in the middle of the photograph is the Eldon Formation, consisting of locally dolomitized subtidal limestones, and the left side comprises peritidal limestones of the Lynx Group.

THE PERITIDAL ENVIRONMENT

The understanding of tidal flat carbonate rocks underwent a dramatic boost with the largely petroleum company-funded research on Holocene tidal flats during the 1950s and 1960s. This produced comprehensive studies on shallow water sedimentation of south Florida (Ginsburg, 1956; Gebelein, 1977; Enos and Perkins, 1979), Andros Island of the northern Bahamas (Hardie, 1977), Belize (Wantland and Pusey, 1975), the Arabian (Persian) Gulf (Purser, 1973), and Shark Bay, Western Australia (Logan *et al.*, 1970, 1974). Observations from these areas were quickly applied to ancient examples (e.g., Beales, 1958; Roehl, 1967; Matter, 1967; Laporte, 1967; Ginsburg, 1975; Schwarz, 1975), which ushered in the modern era of carbonate sedimentological thinking. These Holocene examples, together with more recently studied flats in the Caicos Islands (Wanless *et al.*, 1988) and southern Australia (Burne and Colwell, 1982; Belperio *et al.*, 1988) are fundamental reference points for the interpretation of carbonate rocks and illustrate the wide variety of potentially preservable peritidal environments. The carbonate tidal flat is an easily accessible area and students are encouraged to explore for themselves a modern example.

Three bathymetric zones are recognized in the nearshore setting: subtidal, intertidal and supratidal (Fig. 2).

The subtidal zone is permanently submerged and ranges from low-energy, lagoonal environments to higher energy shoals. Semimonthly neap tides may briefly expose the shallowest portions. The intertidal, or littoral, zone lies between normal low- and high-tide levels and is therefore submerged on a diurnal or semidiurnal basis. It is generally dissected by subtidal creeks and dotted with brackish or saline ponds. The supratidal zone is above normal high tide, and is flooded only during storms and semimonthly spring tides. It may become evaporitic in semiarid and arid climates, and for these supratidal flats the Arabic word *sabkha* has been adopted by sedimentologists (Chapter 19).

The three-fold environmental subdivision is only an approximation, however, since tidal flats are often geographically complex, and tidal range can be modified by winds. While the environments are due to the variable submergence and emergence brought about by lunar tides, little sediment is transported onto the flats by the daily rise and fall in sea level. It is storms, which stir up the adjacent offshore sediments and drive sediment-laden waters up the tidal creeks and onto the flats, that result in sediment deposition. Even so, it is still the depositional environments, which are generated by daily lunar tides, that contain the distinctive sedimentary features that allow us to pinpoint facies so precisely. One approach to the analysis of environmental subdivision is to assign a specific, quantitative "exposure index" to lithologic features based on Holocene examples (see Hardie, 1977), but few ancient deposits have been described in this way (Smosna and Warshauer, 1981).

Marine coastlines can be separated into microtidal (<2 m), mesotidal (2-4 m) and macrotidal (>4 m) settings. Tidal range depends on basin shape and water depth. Strong tidal currents are generated when water is forced through relatively narrow straits or mouths of bays or over shallow shoals. Modern peritidal carbonate environments are exclusively microtidal. There is as yet no satisfactory way of judging ancient tidal range, but the scarcity of sedimentary structures formed by strong tidal currents suggests that most ancient carbonate peritidal settings were also microtidal.

Where do they form?

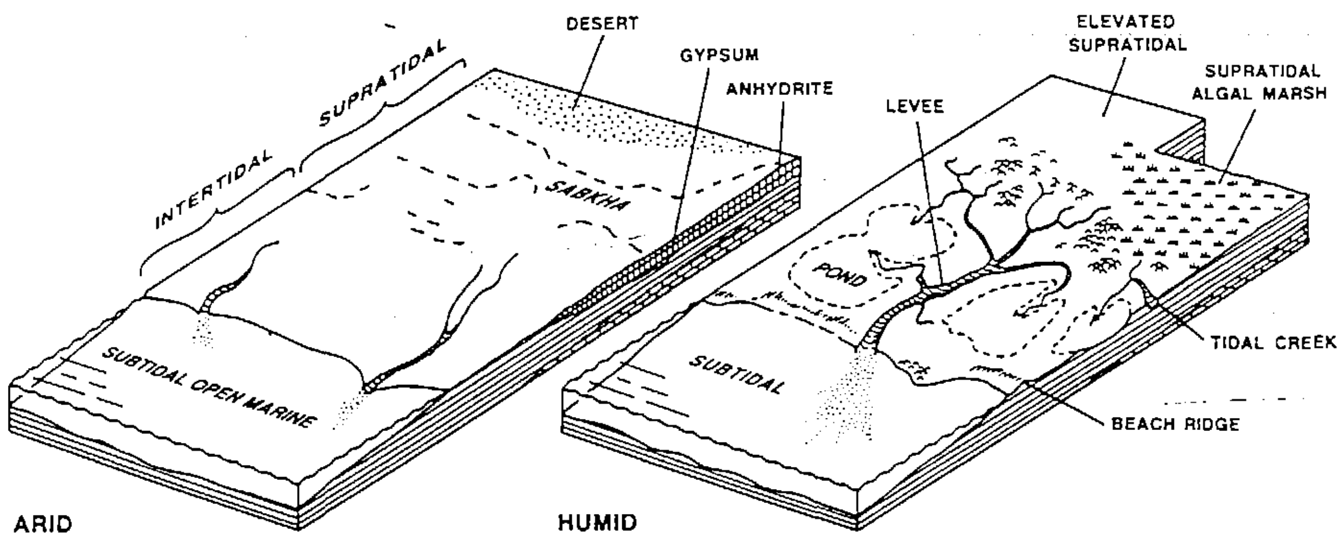
Carbonate sediment, generated mostly in the subtidal zone (the *carbonate factory*), can be subsequently transported and molded into tidal flats by physical processes. In this sense, tidal flats are repositories of allochthonous sediment, and accrete as wedges along shorelines (e.g., Qatar, Shark Bay, Spencer Gulf), in the lee of rocky islands (e.g., northern Bahamas, Caicos, Belize), spits (e.g., Florida) and reefs and shoals (e.g., Trucial Coast), and as discrete islands and banks in shallow seas (Fig. 3). This last setting is inferred from ancient examples because modern shelves are comparatively narrow and not directly analogous to the broad epeiric seas that were common in the past.

For muddy tidal flats to form they must be protected from open ocean swells and such protection can be provided by a platform rim or in the case of a ramp or unrimmed platform, by nearshore carbonate sand shoals (Fig. 4). Muddy tidal flats do not, therefore, generally occur in the facies spectrum of high-energy, unrimmed platforms, except behind nearshore shoals or islands.

Holocene carbonate tidal flat environments

Shallow subtidal and lower intertidal

The shallow seafloor oceanward of modern tidal flats is generally a bio-



CARBONATE TIDAL FLATS

Figure 2 Block diagram showing the main morphological elements of a carbonate tidal flat. Left: a hypersaline tidal flat with few channels bordering a desert and developing evaporite deposits (based on modern Persian [Arabian] Gulf). Right: normal-marine tidal flat with many creeks, or channels, and ponds in a humid to sub-humid setting (based on modern Bahamas).

turbated and pelleted lime mud variably rich in shelly material from benthic oganisms, and commonly supports a cover of sediment-stabilizing sea grasses (Chapter 15). Protective low-relief banks of cross-stratified oolitic or bioclastic sand are present in some higher-energy nearshore areas where wave agitation is frequent.

In tranquil settings of normal salinity, the lowermost intertidal zone tends also to be a thoroughly bioturbated mixture of lime mud, pellets and bioclasts. This sediment is usually covered during low tide with an ephemeral microbial ("algal") slick that is the source of food for grazing organisms such as gastropods and worms. Crabs, shrimps, worms and fish are responsible for the bioturbation in the underlying sediment. Many low-energy flats are fronted by beaches of bioclastic sand winnowed from creeks and ponds or the adjacent seafloor during storms. Beach sands can be partially lithified by synsedimentary cement composed of aragonite fibres or bladed and micritic high-Mg calcite, forming gently seaward-dipping layers of beachrock. Beachrock tends to be crumbly and easily eroded, and supports a hard-substrate biota of encrusting and boring invertebrates, plants and microbes.

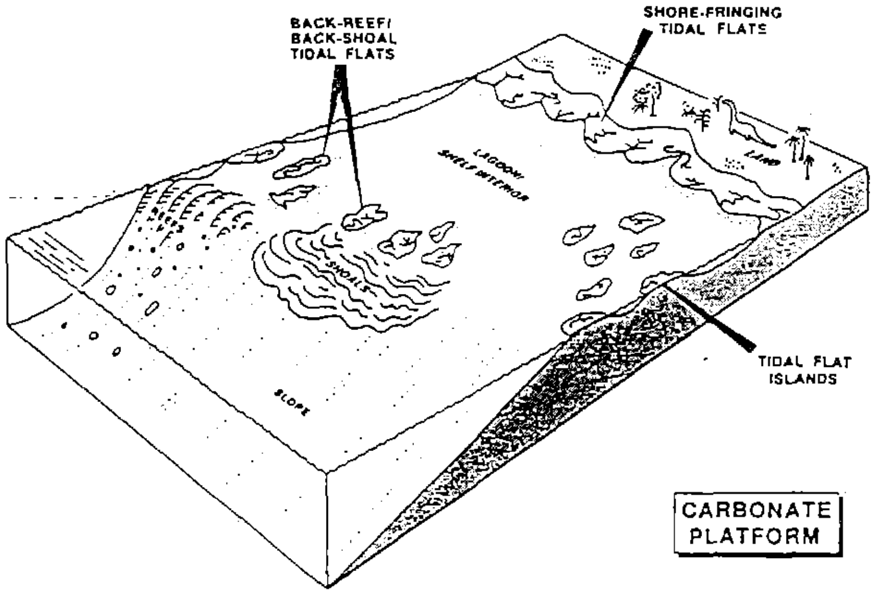


Figure 3 Block diagram of a carbonate platform, with basinward to left and landward to right, showing possible locations of tidal flats: in the lee of reefs and carbonate sand shoals, as islands, and as shoreline deposits.

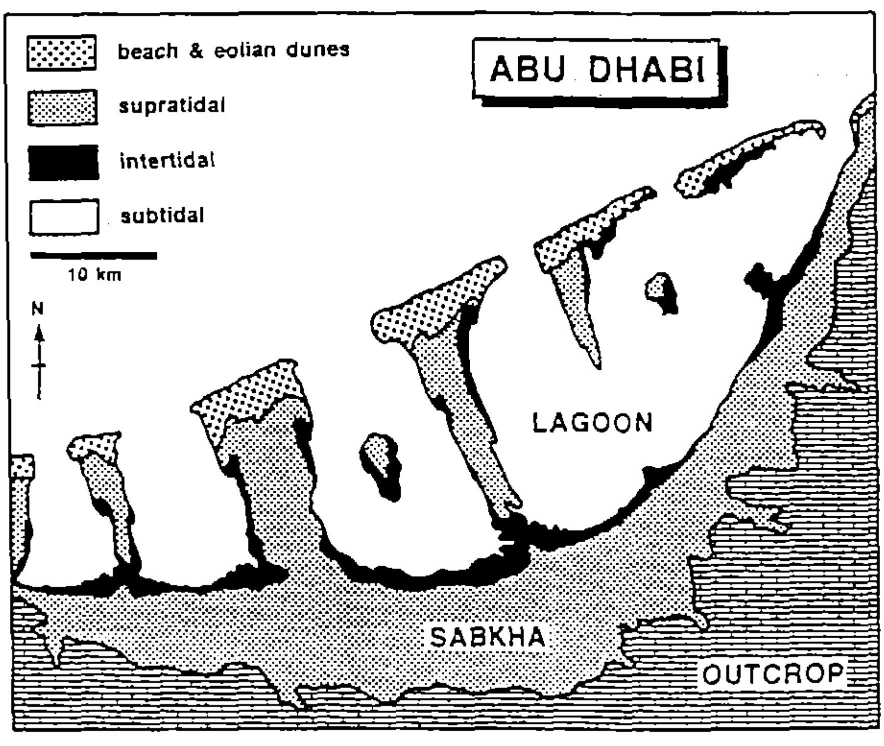


Figure 4 Simplified map of modern tidal flat areas near Abu Dhabi, Persian (Arabian) Gulf; based on Purser (1973).

Intertidal flats

Higher in the intertidal zone, microbial mat cover is more permanent, and forms thick, leathery carpets that can be locally shrunken, torn and folded over (Fig. 5). These exhibit various surface features such as pustules, blisters, wrinkles, crenulations or small, domical stromatolites. These mats are composed of a variety of filamentous and coccoid cyanobacteria ("blue-green algae") and bacteria, and are responsible for the millimetre-scale lamination exhibited by most of the sediment beneath them. The taxonomic makeup and surface appearance of such mats varies with degree of subaerial exposure and can be reflected in the microscopic nature of the underlying lamination. This type of lamination was called "algal" or "cryptalgal" before geologists became familiar with the detailed biological nature of the mats; "microbial" seems now to be the preferred adjective.

Ponds and creeks

Ponds containing brackish or hypersaline water are a common feature of the intertidal zone (Fig. 6), especially in more humid climates. These contain a restricted biota of microbial mats, foraminifera, gastropods, small bivalves, shrimps, ostracodes, and nematode and polychaete worms that is adapted to fluctuating salinity. This assemblage, living in a stressed environment, is typically one of high numbers of individuals but low species diversity, different from the immediate offshore biota. Copses of mangroves are usually present, except in the most arid areas. Also characteristic of the intertidal zone are permanently submerged tidal creeks or channels that are the conduits for tidal flooding and draining (Fig. 6). Such tidal creeks (least common in arid settings) are up to several metres deep and tens of metres wide, and contain a basal lag of semilithified intraclasts eroded from the surrounding flats and flanking levees, and bars of bioclastic sand winnowed from the ponds. Supratidal levees protrude above high-tide level and are microbially laminated. Creeks migrate laterally, as they do in siliciclastic tidal flats, and leave behind a vertical succession of cross-stratified, intraclastic and bioclastic sand overlain in turn by bioturbated bioclastic and peloidal lime mud and microbially laminated sediment. The amount of lateral migration of creeks and the proportion of the internal facies mosaic of intertidal flats that is generated by such migration are not well understood, but studies of modern flats suggest that it may be considerable (Hardie, 1977).

Supratidal flats

Most of the sediment surface in the upper intertidal and supratidal zones is covered by microbial mats that are typically shrunken into desiccation polygons and commonly dislodged into chips or intraclasts. The laminated sediment beneath these mats is generally fine grained with occasional coarser intercalations that reflect deposition by exceptional storms and, in some regions, by winds blowing off the neighbouring land surface. Beds and nodules of anhydrite precipitate in these sediments in arid settings (Chapter 19). In many areas, the supratidal zone is the locus of widespread synsedimentary cementation by microcrystalline aragonite, high-Mg calcite, or dolomite. This forms lithified pavements a few centimetres thick that are usually broken into intraclasts by forces exerted during crystal growth, groundwater pore pressure, or the roots of halophytic (salt-tolerant) plants such as grasses and mangroves. Evaporating sea spray can be responsible in some arid areas for fans and isopachous layers of fibrous aragonite that encrust stable substrates such as beachrock and shells, forming objects termed coniatolites.

Landward parts of the supratidal zone grade into eolian deposits, soils or freshwater marshes and lakes, or onlap bedrock surfaces, depending on the region's geography and climate. Marshes and lakes, which exist in the more humid areas and have fluctuating water chemistry, are characterized by microbial mats and stromatolites: these are partially lithified by high-Mg calcite cement and calcification of organic substrates, and are interbedded with thin-bedded, locally bioturbated lime mud and bioclastic and peloidal carbonate sand deposited during storms. Much of the microbially laminated sediment shows fenestral fabric, i.e., the presence of millimetre-

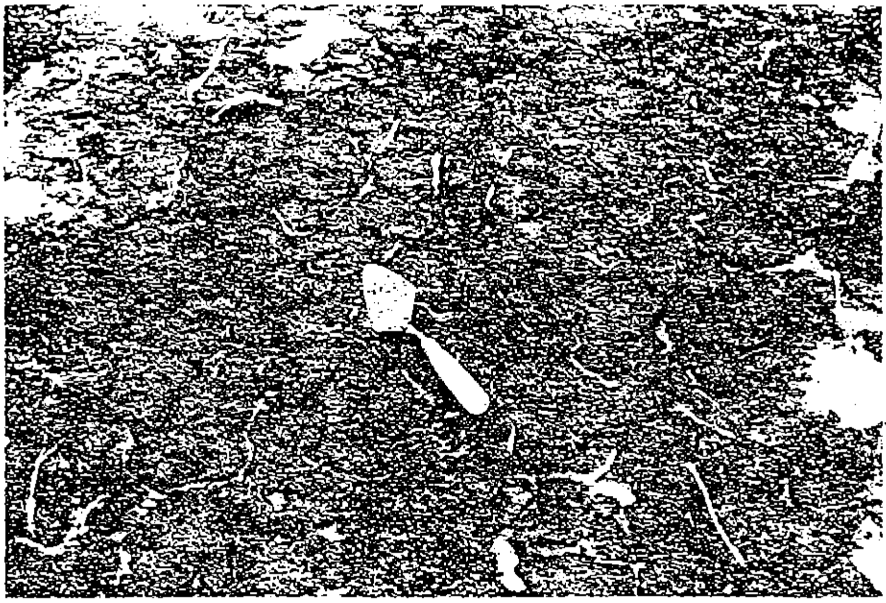


Figure 5 Upper intertidal microbial mat mainly composed of filamentous cyanobacteria (*Microcoleus*) that has shrunken into desiccation polygons. Boca Jewfish, Bonaire; trowel is about 25 cm long.

Figure 6 Oblique aerial photograph of the tidal flats on the northeast coast of Andros Island, Bahamas, looking north. Offshore subtidal is to the left. The white areas along the channel edges are supratidal levees. The dark patches are intertidal microbial flats between the levees and around the periphery of the mainly subtidal ponds. The field of view is about 3 km across

to centimetre-sized subhorizontal, sheet-like pores formed as voids bridged by microbial mats or as molds of degraded mats. Decimetre-scale tepee structures (Fig. 7), consisting of disrupted and overthrust crusts of lithified, tufa-like fenestral sediment giving an inverted V-shaped cross section, form in areas of groundwater discharge (Kendall and Warren, 1987). These also contain complex generations of internal sediment and aragonite and high-Mg calcite cements.

Geological evolution of peritidal facies

Biological and environmental developments through geologic time have exerted an important influence on the nature of carbonate tidal flats. This is manifest in several ways, via 1) the increase in diversity of carbonate-secreting organisms and consequent change in sediment type, 2) the evolution of bioturbating and herbivorous invertebrates, and 3) the evolution of angiosperms.

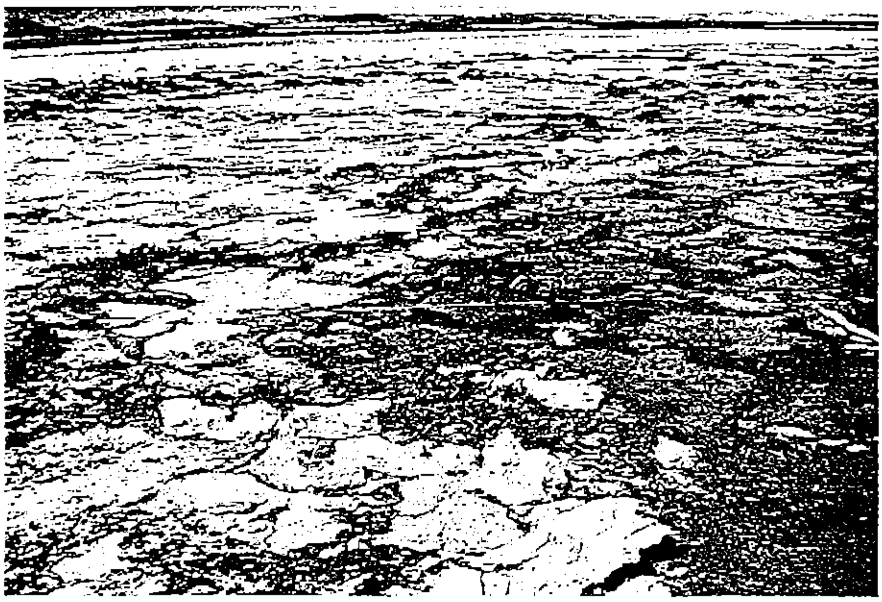


Figure 7 The supratidal flat at Fisherman Bay, Spencer Gulf, southern Australia. The polygonal crusts are lithified and have been thrust into teepees by episodic groundwater resurgence. Crusts in the foreground are roughly 30 cm across.

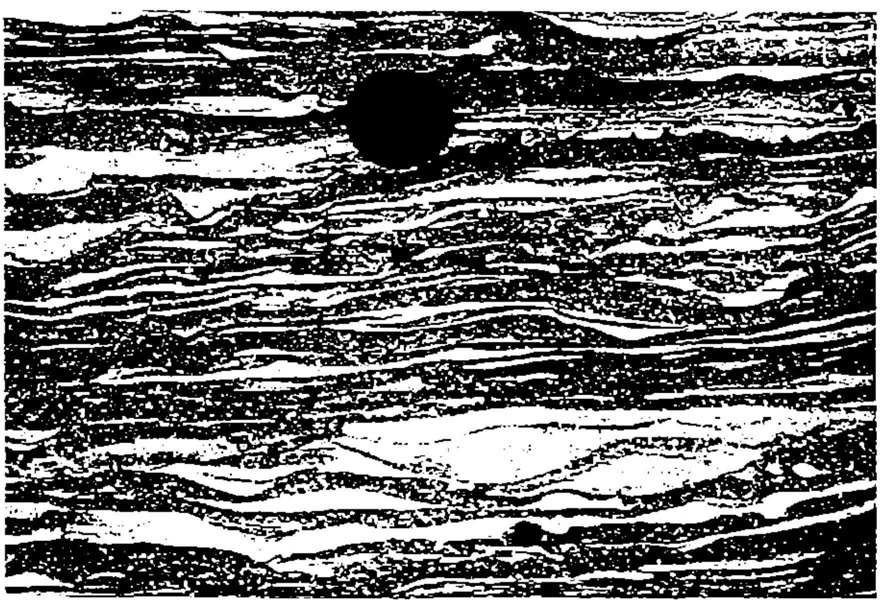


Figure 8 Outcrop of lenticular and wavy beds of wave-rippled peloidal grainstone (light coloured) in argillaceous dolostone (dark coloured), probably deposited in the lower intertidal zone. Petit Jardin Formation (Upper Cambrian), Port-au-Port Peninsula, western Newfoundland; lens cap is 6 cm across.

The subtidal carbonate factory was in its infancy during Precambrian time, when $CaCO_3$ was extracted from seawater by inorganic and microbial processes only. Peritidal strata during this phase in Earth's history are composed of ooids, intraclasts, stromatolites, supratidal tufas, and variable amounts of lime mud. Some subtidal units are entirely siliciclastic, and large-scale cyclicity of alternating calcareous and noncalcareous facies (e.g., Grotzinger, 1986; Bertrand-Sarfati and Moussine-Pouchkine, 1988) may have involved basin-wide, or greater, changes in carbonate saturation of seawater. The dramatic increase in skeleton-secreting and sediment-ingesting invertebrates beginning in Cambrian time meant that the carbonate factory changed in character and increased its output manyfold. New types of sedimentary particles appeared, in the form of abundant shells, fecal pellets, and carbonate mud from the breakdown of fragile skeletons and other biologically influenced precipitates. This no doubt changed the nature of tidal flats by causing increased mobility of the substrate, making it less and less likely to be cemented quickly or encrusted by stromatolite-forming microbial mats except in hypersaline areas (Pratt, 1982). It has been commonly held (Garrett, 1970) that grazing invertebrates such as gastropods caused intertidal stromatolites to become scarce after the Proterozoic, but the above sedimentary reasons rather than ecologic pressure seem likely to have been responsible for this decline.

Proterozoic tidal flat carbonates are distinctive too because, in comparison with other Precambrian carbonate facies and younger sediments, they were the preferred sites of diagenetic silica precipitation and formation of chert nodules (Maliva *et al.*, 1989). These cherts are important because they host the bulk of the Precambrian fossil record (Knoll *et al.*, 1991).

Bioturbation became a sediment-

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modifying process in Late Proterozoic time. Diversification of microbes, especially those involved in the breakdown of organic material, must have occurred in tandem with invertebrate diversification and the resulting appearance of new organic substances. The organic content and therefore the geotechnical properties of tidal flat sediments surely changed in the early Paleozoic. The effect of bioturbation seems to have increased dramatically after the late Paleozoic or earliest Mesozoic (Thayer, 1983; Bottjer and Ausich, 1986; Pratt, 1991). This was heralded by the evolution of a more diverse fauna including animals, such as certain shrimps and crabs, capable of burrowing as deeply as 1 m. Consequently, tidal bedding that would have been preserved in the Precambrian and early Paleozoic was commonly destroyed by infaunal activity, except in the upper intertidal and supratidal zones. Furthermore, intertidal to supratidal sedimentary and organosedimentary structures that escaped destruction were often subsequently bioturbated when buried by subtidal or lower intertidal sediments with an active deeply burrowing infauna.

Evolution of angiosperms since Cretaceous time has meant that the disruption of tidal flat sediments by halophytic plants has become a characteristic of Cenozoic deposits. In addition, shallow subtidal sea bottoms are especially well stabilized by the rhizomes (roots) of angiosperm sea grasses *(Thalassia, Posidonia, Cymodocea)*. Such grasses also support a prolific encrusting biota that supplies fine-grained carbonate sediment to the factory. These carpets of sea grasses, however, are disrupted only by intense storms, causing "blowouts" (Wanless, 1981), and we suggest that pre-Cenozoic subtidal sediments, especially silt- and sand-sized particles, might have been more readily moved onto tidal flats than they are now, because they were not bound by these grasses. This is analogous to the suggestion that the post-Devonian presence of widespread terrestrial plant cover, with its stabilizing, soil-forming and weathering attributes, affected the subaerial sedimentary system of the Earth. It may partly explain why some early Paleozoic intertidal carbonates look so much like siliciclastic counterparts from settings that lack significant seagrass communities.

Ancient peritidal carbonate facies

Environmental interpretation of peritidal limestones and dolostones is easily achieved in the broad sense, especially when they contain features unequivocally of subaerial origin. However, some facies cannot be assigned confidently to a bathymetric position, and for these Walther's Law must be invoked. Furthermore, tidal processes involve such a variety of energy regimes, sediment sizes and climates that there may be a limit as to

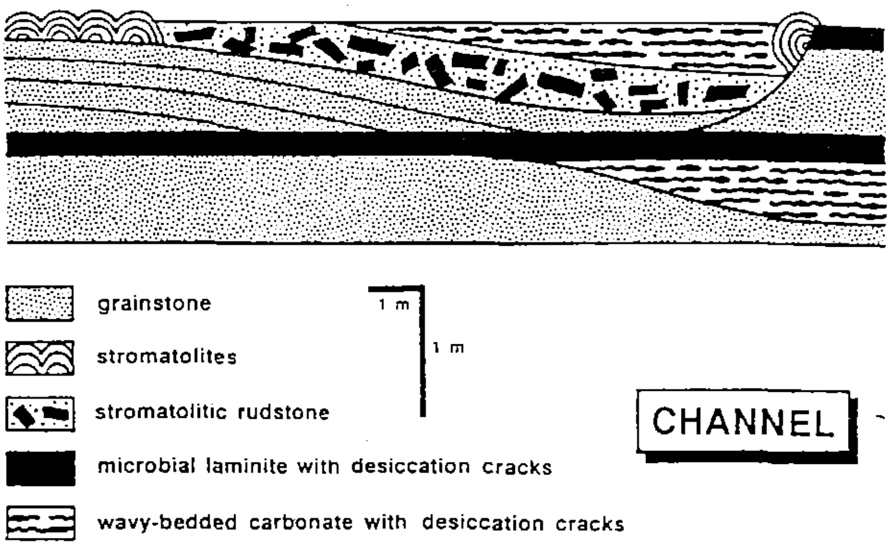

Figure 9 Simplified outcrop sketch of hypothetical channel or creek deposits cut into tidal flat facies, based on examples from the Waterfowl Formation (Upper Cambrian, Rocky Mountains, Alberta; Waters *et al.*, 1989) and Elbrook-Conococheague Formations (Middle and Upper Cambrian, Virginia; Koerschner and Read, 1989).

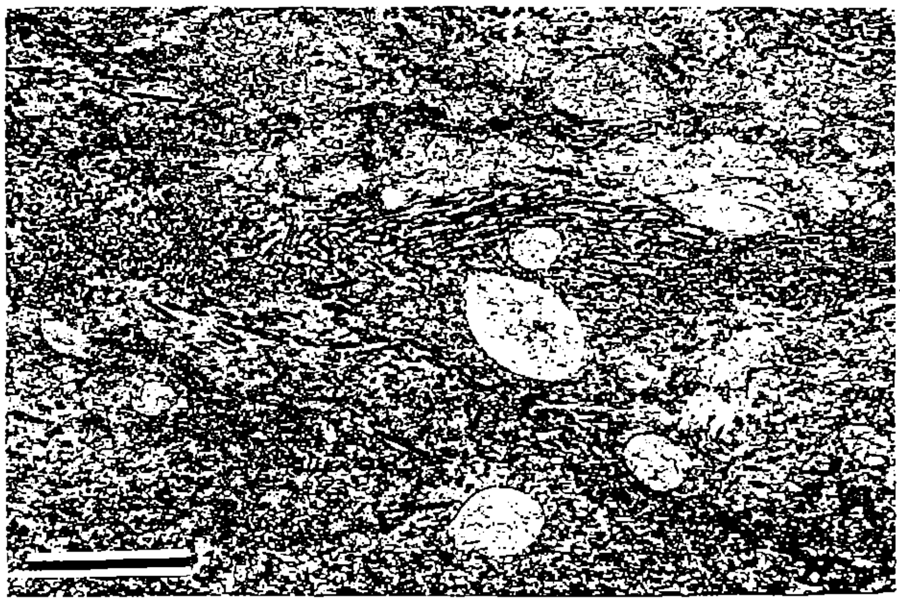

Figure 10 *Thin section photomicrograph of limestone composed of loosely packed micrite,* micrite peloids, articulated ostracode valves, and calcimicrobe *(Girvanella)* filaments with organic-rich walls. This sediment is interpreted to have been deposited in a tidal flat pond because of the low-diversity biota and the calcification of filamentous cyanobacterial thalli. Table Point Formation (Middle Ordovician), Port-au-Port Peninsula, western Newfoundland; scale bar is 1 mm.

how precise an interpretation one can make. The present level of detail is generally at the scale of units decametres to metres in thickness; few studies have gone down to the scale of individual beds and laminae.

Shallow subtidal and lowermost intertidal facies
Precambrian subtidal rocks are the most difficult to recognize, because the carbonate was produced by inorganic or microbially mediated precipitation, and there were no distinctive skeleton-secreting organisms. Such subtidal facies tend to be variably siliciclastic, or frequently dolomitized lime mudstone with local oolitic, peloidal or intraclastic beds. Nearshore limestones of Phanerozoic age are fossiliferous, commonly bioturbated to some degree, and may exhibit patch reefs and oolites. Units of thinly interbedded bioturbated lime mudstone and wackestone and ripple or dune cross-laminated grainstone that are overlain by rocks exhibiting clearly supratidal facies are typical. Subtidal and lower intertidal carbonates of Mesozoic and Cenozoic age are commonly thick bedded and totally bioturbated, reflecting the post-Paleozoic increase in the diversity and effect of the bioturbating fauna.

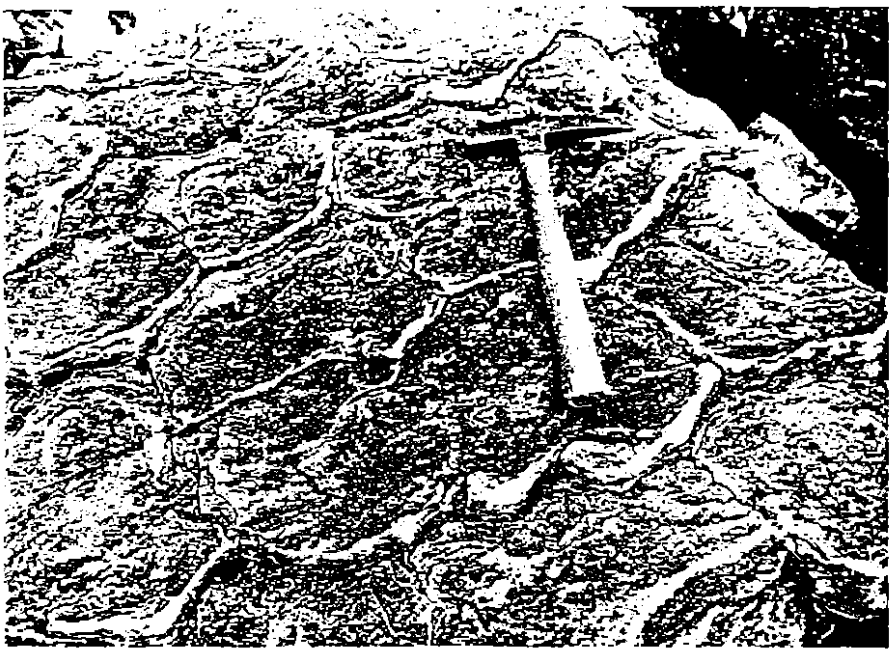

Figure 11 A bedding plane of desiccation-cracked polygons in which the edges of each polygon are curled up, probably because the original microbial mats shriveiled upon exposure. East Arm Formation, Upper Cambrian, Bonne Bay, western Newfoundland; hammer is 30 cm long.

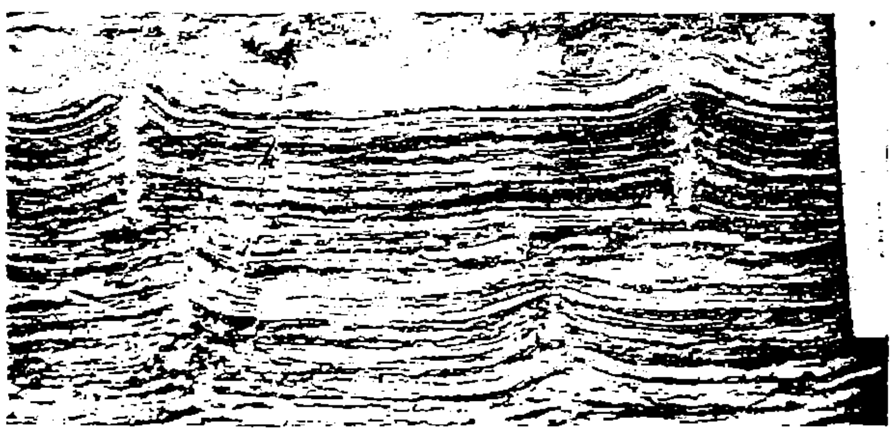

Figure 12 A cross section of desiccation cracks in microbially laminated peritidal dolostones; Providence Island Dolomite, Middle Ordovician, Lake Champlain, New York State.

Intertidal flat facies
Wavy-, lenticular- and flaser-bedded peloidal lime mudstone or grainstone (calcisiltite) and dolomitized argillaceous lime mudstone (sometimes interbedded with small hemispheroidal stromatolites), arising from the alternation between slack water and sediment transport by both unidirectional currents and waves under lower flow regime, are particularly distinctive of Precambrian and lower Paleozoic sequences (Fig. 8). This facies is directly comparable to the tidal bedding in siliciclastic peritidal deposits, including those forming in many modern settings (see Reineck and Singh, 1980). The carbonate strata, however, commonly contain intraclastic horizons which are absent in siliciclastic counterparts. Phanerozoic intertidal facies frequently have bioclastic layers. Well-sorted coquinas were likely washed in from the subtidal zone by storms, whereas poorly sorted shelly deposits containing a low-diversity assemblage of gastropods or bivalves probably represent the in situ intertidal fauna. Laminae that appear laterally continuous, undulating and uniform in thickness, are typically intercalated in this facies, and record periods of stabilization or binding of the substrate by a microbial mat. This tidal bedding can be burrowed in Phanerozoic sequences, and in the lower Paleozoic the trace fossil fauna is dominated by a low-diversity assemblage of horizontal burrows and U-shaped forms like *Arenicolites* and *Diplocraterion*. As with subtidal deposits, post-Paleozoic intertidal sediments are likely to be thoroughly churned: bioturbated, poorly fossiliferous lime mudstone units may be interpreted as intertidal if other criteria, such as vertically juxtaposed beds with desiccation cracks, are evident.

Tidal creek facies
Rocks specifically interpreted as having accumulated in tidal creeks or channels piercing intertidal flats are relatively uncommon. The reasons for this are mainly 1) the rarity of laterally

extensive exposures that intersect the possible margins of channels once they stop migrating laterally, 2) the difficulty in distinguishing creek fills from regressive packages with a basal, higher-energy component that resulted from tidal flat progradation, 3) the similarity between bedforms and lateral-accretion bedding from bar migration in channels and inclined and tabular cross stratification from migrating offshore carbonate sand shoals, and 4) the difficulty in separating creeks in tidal flats from channels between adjacent offshore islands or shoals. The presence of flat-pebble and blocky intraclasts derived from the surrounding flats and levees, respectively, along with bipolar (herringbone) cross stratification typically exhibiting reactivation surfaces and *tidal bundles* (couplets of sandy and muddy laminae), seem to be diagnostic of creek or channel deposits (e.g., Pratt and James, 1986). Grainstone beds with erosional bases and containing stromatolite or thrombolite mounds in some Proterozoic and Cambrian sequences are reasonably interpreted as channel deposits, (Koerschner and Read, 1989; Wright *et al.*, 1990). Waters *et al.* (1989) and Cloyd *et al.* (1990) have mapped Cambrian channels at least 10 m wide and 1 m deep with erosional bases, filled with lateral-accretion beds of individually graded, locally bipolar cross-laminated grainstone containing desiccation-cracked lime mud drapes and reactivation surfaces (Fig. 9). Care must be taken in late Proterozoic and early Paleozoic carbonates, however, to differentiate subaerial (desiccation) cracks and other cracks of submarine origin (Knoll and Swett, 1990; Cowan and James, 1992).

Figure 13 Polished slab of clotted and peloidal lime mudstone showing microbial lamination and fenestral fabric of laminoid, millimetre- to centimetre-sized, cement-filled pores. This distinctive fabric probably formed in the upper intertidal or lower supratidal zone. Eldon Formation (Middle Cambrian), Exshaw, Alberta; scale bar is 1 cm.

Beach facies

Beaches, which also have not been reported frequently from ancient tidal flat sequences, are characterized by seaward-dipping, low-angle laminae and thin beds of grainstone, often with hardgrounds exhibiting bored surfaces. This facies passes laterally to subtidal deposits in the seaward direction and tidal-bedded strata in the landward direction (e.g., Inden and Moore, 1983; Waters *et al.*, 1989). Steeper shorelines, such as Tertiary and Quaternary examples from the Mediterranean and Red seas, are often onlapped by gravelly beds of well-rounded pebbles and large shells.

Pond facies

Recognition of schizohaline pond deposits on humid intertidal flats may be impossible in most rock sequences unless the ponds were particularly long-lived. In one example (Pratt, 1979), burrowed wackestone containing ostracodes and horizontal meshes of *Girvanella* filaments with organic-rich walls (Fig. 10) are intercalated within burrowed and microbially laminated lime mudstone and tidal-bedded dolostone and lime mudstone. The restricted biota of this deposit, the well-preserved microbial remains, and its lenticular geometry within a peritidal sequence argue against a normal-marine subtidal environment.

Supratidal facies

Microbially laminated limestone or dolostone, usually with desiccation cracks and coarser rippled layers, is a common peritidal rock type (Figs. 11, 12); such rocks, however, may be

Figure 14 Thin section photomicrograph of peloidal and clotted micrite containing bioclasts (mainly ostracodes and gastropods) and exhibiting fenestral fabric. Upper parts of the laminoid fenestral pores have pendant fringes of fibrous calcite cement (grey coloured) suggesting that this sediment was deposited in the upper intertidal zone and that the fibrous calcite precipitated as marine or mixed waters percolated through the pores during low tides. Table Point Formation (Middle Ordovician), western Newfoundland; scale bar is 1 mm.

upper intertidal or supratidal in origin. In older Phanerozoic sequences, a supratidal setting might be inferred if bioturbation is rare or absent, or there is evidence for prolonged subaerial exposure such as evaporites, karst horizons or paleosols. Intercalated within many microbially laminated rocks are intraclastic horizons, which are analogous to pavements of microbial mat chips or fragments of cemented crusts in modern supratidal environments. Fenestral lime mudstone and peloidal grainstone (Fig. 13) are common (Shinn, 1983b) and, by analogy with tidal flats of Florida and the Bahamas, were probably deposited in moist supratidal "algal marshes" or around ponds. This facies sometimes exhibits features, such as pendant fibrous cement (Fig. 14), brecciated crusts and tepees, pisolites and pores with geopetal sediment floors, suggestive of flushing by downward-percolating seawater and rainwater and upward-flushing by groundwaters in a subaerial environment. Precambrian supratidal deposits often contain digitate stromatolites, millimetres to centimetres in diameter, which have been interpreted as supratidal, tufa-like aragonite precipitates (e.g., Grotzinger, 1986). Post-depositional leaching of evaporites causes collapse brecciation in supratidal facies.

THE PERITIDAL SHALLOWING-UPWARD SUCCESSION

Ancient peritidal carbonate lithofacies are characteristically organized stratigraphically into metre- to decametre-thick, shallowing-upward successions (Fig. 15) each with a basal subtidal unit, intermediate intertidal facies, and an upper supratidal unit with or without a terrestrial horizon on the top (James, 1984; Wright, 1984; Tucker and Wright, 1990). Contacts between the members are gradational or sharp and may show evidence of local synsedimentary scour. Walther's Law tells us that, if there are no major depositional breaks, we can reconstruct the ancient environmental mosaic by dealing out each facies like a deck of cards. There are departures from this ideal pattern, however, and it is not unusual to find the supratidal member overlain by intertidal facies, or components missing because of nondeposition or erosion.

Characteristics

The lithologic nature of the subtidal → intertidal → supratidal succession is variable, reflecting the broad spectrum of intertidal and supratidal depositional environments, the dictates of biotic evolution and past changes in ocean chemistry. Such peritidal shallowing-upward successions can be subdivided into two types, low energy (Figs. 16, 17) and high energy (beach; Fig. 18), and both may show the effects of climate, such as thin beds of evaporites, especially anhydrite (Chapter 19).

In the simplest case, and referring only to the Phanerozoic, low-energy shallowing-upward successions have a burrow-mottled, variably argillaceous lime mudstone to wackestone or packstone lowest member, often with a basal bioclastic and intraclastic grainstone or rudstone as a transgressive lag on top of the pre-existing succession (Fig. 16). Patch reefs may be present in the subtidal member. The intertidal member exhibits thin-, lenticular- and wavy-bedded, variably bioturbated lime mudstone and bioclastic, peloidal and sometimes oolitic grainstone, locally with small domical stromatolites. This grades upward to an upper intertidal and supratidal member that is usually a microbially laminated, locally desiccation-cracked, slightly argillaceous lime mudstone frequently exhibiting fenestral fabric, with thin interbeds of intraclastic horizons and laminae of peloidal or bioclastic grainstone. If the sediments were laid down in an arid climate, nodular to wavy beds of anhydrite may displace and replace sediment of the intertidal and supratidal members (Fig.16). Higher-energy cycles (Fig. 18) also have a bioturbated subtidal bioclastic basal member, but the intertidal component is made up of bioclastic and/or locally oolitic grainstones representing beach deposits. These may exhibit inclined- and cross-stratification and hardgrounds. The upper intertidal and supratidal units are generally desiccation-cracked microbial laminites.

Both kinds of shallowing-upward successions can have a capping horizon of marsh sediments, paleosol or calcrete. Successions may be separated from overlying units by a karst surface caused by subaerial weathering, or an erosion surface formed during the environmental shift responsible for the next succession. Supratidal sediments may show the diagenetic effects of groundwater dis-

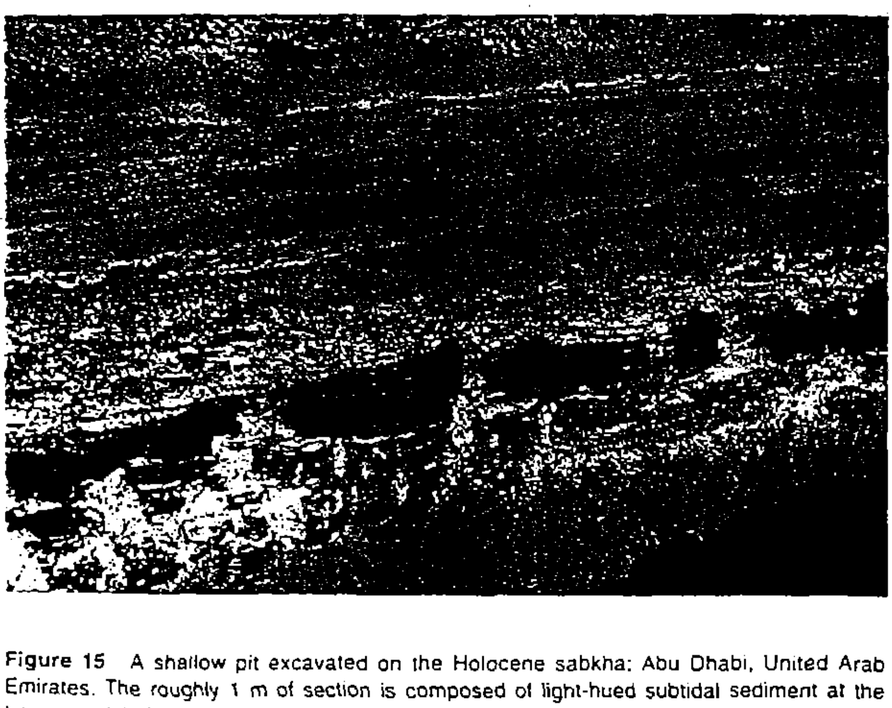

Figure 15 A shallow pit excavated on the Holocene sabkha: Abu Dhabi, United Arab Emirates. The roughly 1 m of section is composed of light-hued subtidal sediment at the base, overlain in turn by conspicuous black intertidal microbial mats with desiccation cracks and light-coloured supratidal sediment and capped by eolian quartz-rich sands. Photo courtesy P. Scholle.

charge, such as tepees, cements and leaching of evaporites.

A warning! Tidal creek or channel fills can look suspiciously like shallowing-upward successions produced by tidal flat progradation (Fig. 18). Predictably, they should be composed of a basal intraclastic, peloidal and bioclastic grainstone lag or bar facies, overlain by thin-bedded and bioturbated lime mudstone and wackestone, and capped by microbially laminated lime mudstone, recording waning energy conditions as the creek is abandoned (e.g., Waters *et al.*, 1989; Cloyd *et al.*, 1990). Unless a channel margin or lateral-accretion bedding is exposed, or blocky intraclasts from margin collapse are present, these deposits could easily be misunderstood.

Geometry

To interpret how any particular peritidal shallowing-upward succession may have developed there must be firm local and regional lateral control on the distribution of units; bed or event correlation must be demonstrable. Besides walking or tracing out individual beds, the lithologic features that may be widely correlatable in peritidal successions are subaerial exposure horizons (karst surfaces, collapse breccias and paleosols), evaporite beds and siliciclastic horizons resulting from sea level fall. We recognize two geometries. *Laterally continuous* metre-scale successions are widespread, possibly platform-wide, and correlatable. *Laterally discontinuous* metre-scale successions are local in extent and noncorrelatable and supratidal facies can be traced laterally into intertidal and/or subtidal facies over kilometre-scale distances.

Origin

An aspect of carbonate sedimentology that has become a maxim over the last decade, for Phanerozoic rocks at least, is that healthy carbonate platforms, i.e., those not stressed by environmental conditions like cold water, hypersalinity, turbidity or nutrient poisoning that hinder organism growth, can produce enough carbonate sediment to aggrade, and commonly a surplus, causing progradation, while relative sea level rises (Schlager, 1981). Shallow water sediments thus overlie deeper water facies. Each shallowing-upward peritidal succession records the vertical and lateral accretion of a single tidal flat to a level just exceeding high-tide mark; if there was no subsidence or sea level change, the thickness of the intertidal-supratidal component might approximate the tidal range, but if there was any relative sea level change, the thickness is no indication of this at all.

There are currently three models used to explain how a shallowing-upward succession forms 1) as a prograding wedge, 2) as a simultaneously

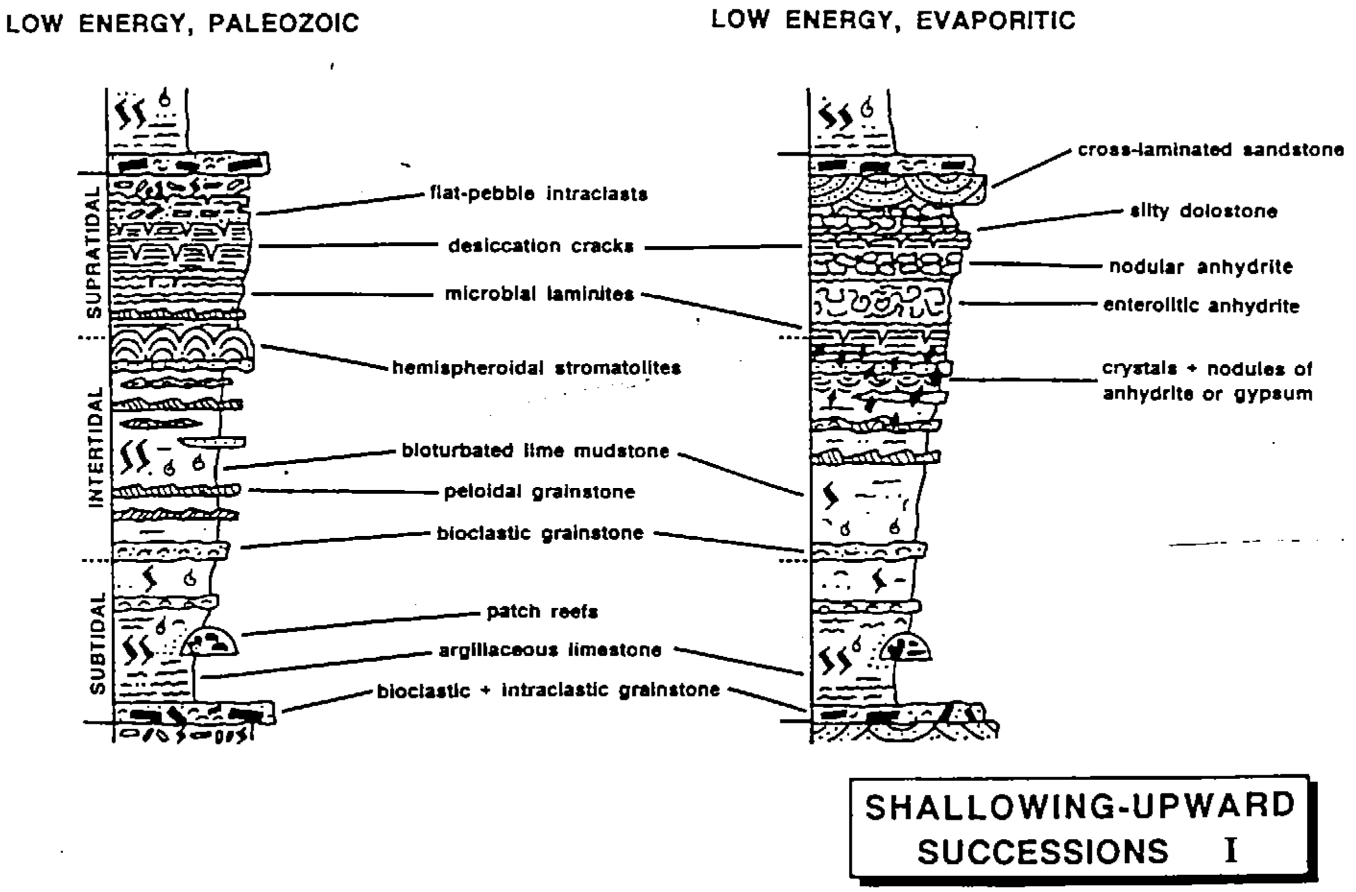

Figure 16 Hypothetical vertical profiles of individual low-energy, metre-scale, peritidal shallowing-upward successions. Left: from the lower Paleozoic; upper Paleozoic examples might exhibit calcretes at the top. Right: an evaporitic example (Chapter 19). No scale is implied, but each succession is typically 1-10 m thick.

aggrading sheet or, 3) as a mosaic of tidal flat islands (Fig. 19).

The prograding wedge

Holocene shallow-marine and peritidal environments are dynamic in that they shift geographically over geologically short periods of time in response to both local and regional changes in climate, prevailing wind direction, current pattern, and sediment supply. A single coastline, for example, may possess tidal flats that are accumulating and prograding, and tidal flats that are dormant or are eroding (e.g., Shinn *et al.*, 1969; Strasser and Davaud, 1986). Regardless, to generate a single, laterally extensive wedge that has peritidal, shallowing-upward attributes throughout, the tidal flat must prograde laterally from a nucleus. Such accretion can develop seaward from land, outward from islands, or shelfward from platform margin buildups and/or shoals. It must be stressed that deposition on the tidal flat is a physical process. Sediment generated on the platform is swept onto the flats by storms producing the gradually prograding tidal flat wedge. As such, the size and dynamics of the peritidal wedge are primarily a function of the health and nature of the source area (the subtidal carbonate factory) and the way in which sediment is redistributed on the platform (i.e., how much is transported to the flats, how much stays in place, how much is transported offshore into deep water).

The Holocene record of sea level change is one of rapid rise between 11 ka and 6 ka, followed by decelerated rise from 6 ka to the present. There are, unfortunately, few tidal flats that have been cored in enough detail to provide a good three-dimensional stratigraphic picture of deposition during this period. As a result of this small data base it is difficult to make generalizations. Nevertheless, at present there appear to be two styles of progradation (Fig. 20), *simple offlap* and *staggered offlap* (Hardie and Shinn, 1986). Simple offlap is typified by the gradually prograding wedge along the southern coast of the Persian (Arabian) Gulf. Staggered offlap is characterized by the northern Bahamas tidal flats. In the latter case the tidal flat does not seem to have prograded but instead aggraded behind a protecting beach ridge. The vertical succession is mainly burrowed sediment, reflecting deposition in a variety of pond, channel and intertidal flat environments, capped by laminated upper intertidal to supratidal sediments. It is thought that tidal flat sedimentation began only when the offshore carbonate sand bar emerged to become a barrier. Once the flat aggraded to sea level, progradation took place by a series of jumps followed by back filling (Hardie, 1986). Such successions in the rock record should

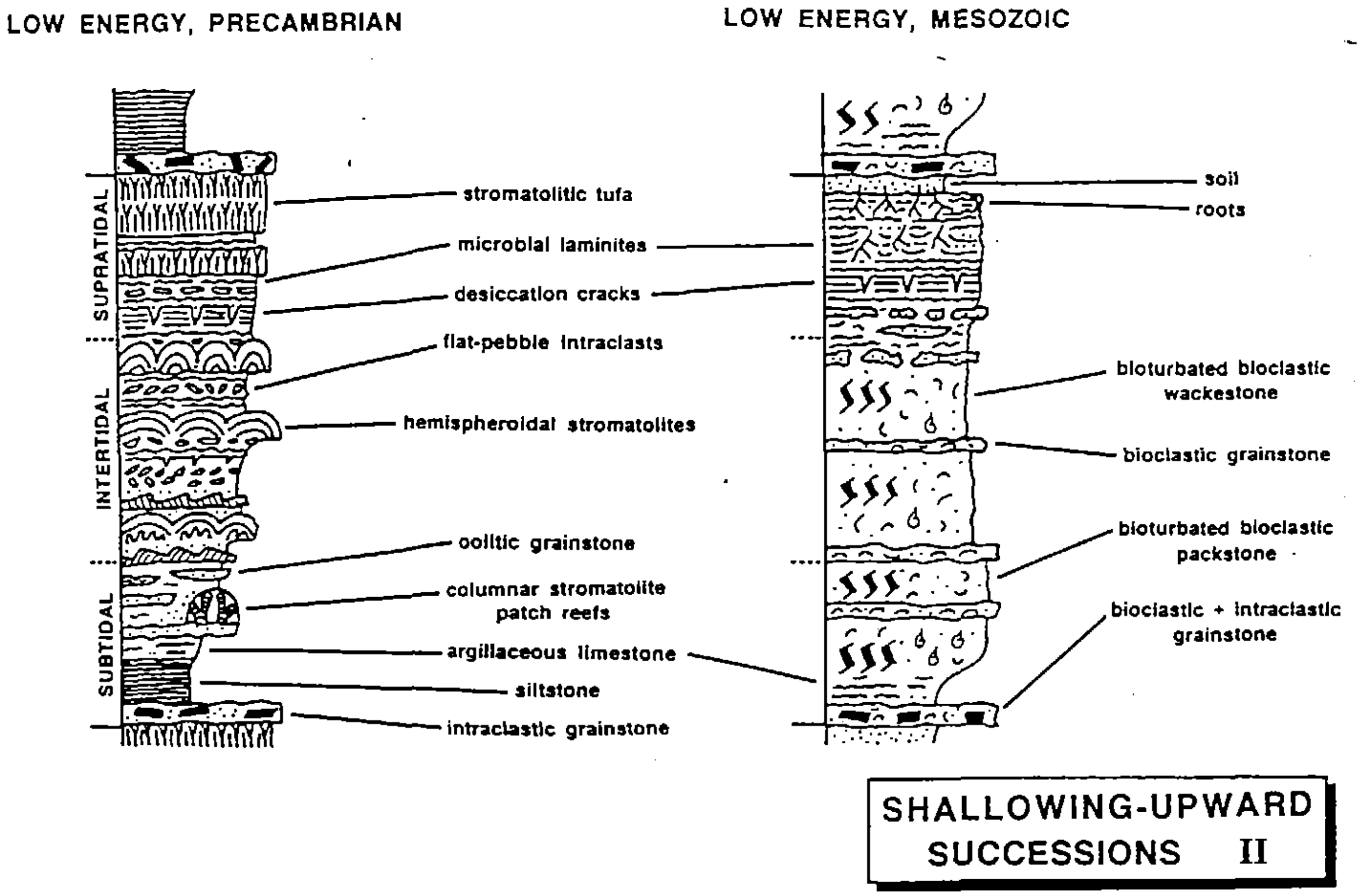

Figure 17 Hypothetical vertical profiles of individual low-energy, metre-scale, peritidal shallowing-upward successions from the Precambrian (left) and Mesozoic (right). A comparison of these with the Paleozoic example in Figure 16 shows some of the lithologic changes exerted by biotic evolution through geologic time.

contain remnants of these barriers. The Abu Dhabi sabkha is reported to have buried barriers (Warren and Kendall, 1985) and may have also developed, in part, through staggered offlap.

For a wedge of tidal flat sediment to prograde from the strandline across an entire platform, accumulation of sediment must occur under relatively stable hydrographic conditions (i.e., sea level and climate) for the length of time represented by progradation. A rapid rise in sea level would flood the broad supratidal flat and halt progradation, whereas any fall in sea level would strand the tidal flat before transplatform progradation was complete.

This style of accumulation has been proposed to explain the extensive Cambro-Ordovician peritidal strata of the southern Appalachians (Hardie, 1986). Metre-scale peritidal shallowing-upward successions of this epeiric platform have been correlated (but not traced) for distances greater than 100 km parallel and perpendicular to depositional strike. Progradation at this scale, however, would produce vast areas of abandoned supratidal flats behind the prograding shoreline, far distant from the subtidal source of sediment and exposed to protracted subaerial diagenetic effects. Since constant and uniform subsidence would inundate this supratidal surface, progradation must have taken place while relative sea level was stationary or gradually falling. If progradation was simple offlap, then successions will be laterally continuous. If progradation was staggered offlap, successions will be discontinuous and separated by lenticular beach deposits.

Simultaneously aggrading sheet

In this situation, continuous in situ carbonate sediment production results in aggradation of the seafloor steadily to sea level. The entire platform becomes intertidal and then supratidal, and can be completely exposed before flooding and deposition of the next overlying succession (Fig. 19). There are no Holocene analogues for this process; it is derived entirely from interpretation of the rock record, and therefore is poorly constrained. Platform-wide peritidal exposure under these circumstances cannot be *intertidal* per se, because it is unlikely that tides could operate across such a vast horizontal distance all at once. Instead, alternating flooding and exposure would have to be induced through the movement of the sea surface by periodic storm surges or persistent winds. Such a style of *occasional* exposure and submergence may be difficult to distinguish in the rock record from true *intertidal* conditions. This hypothesis demands that at least some sediment be produced on the flats when the whole platform is in the intertidal-supratidal environment. Such accretion could predictably produce platform-wide, laterally continuous, metre-thick shallowing-upward successions, such

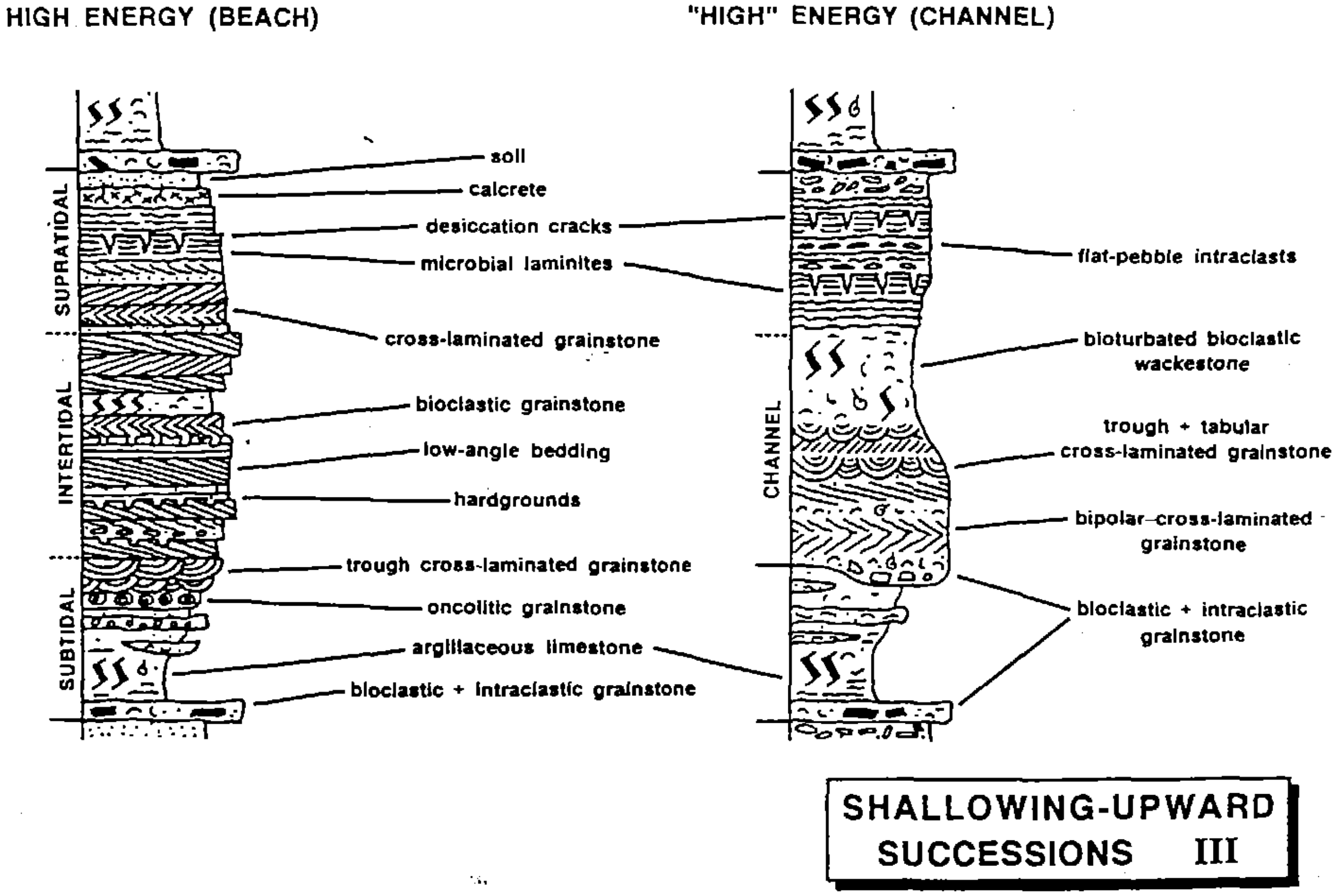

Figure 18 Hypothetical vertical profiles of individual high-energy, metre-scale, peritidal shallowing-upward successions, from a setting characterized by beach development (left) and a tidal flat penetrated by channels or creeks (right).

as those inferred from Cambrian strata by Koerschner and Read (1989).

Tidal flat islands

An alternative model has been postulated to explain shallowing-upward peritidal successions that are demonstrably laterally discontinuous (Pratt and James, 1986). In this *tidal flat island* model deposition is envisioned as taking place on a platform dotted by a mosaic of exposed low-relief islands and intertidal banks separated by subtidal source areas (Fig. 19), with the whole complex shifting laterally and vertically through time in response to a range of local and regional hydrographic conditions. Such islands are developed today in Florida Bay and illustrate two modes of Holocene accumulation, 1) physically deposited mud banks capped by prograding intertidal and supratidal sediments, and 2) entirely supratidal deposition of a coastal mud flat, later dissected by erosion (Enos and Perkins, 1979; Wanless and Tagett, 1989). These islands, however, have not migrated much during the relatively short period of Holocene flooding. If viable, this tidal flat island model severely limits the architectural predictability of ancient platforms, as the constituent facies, particularly the supratidal caps, are of inherently limited regional extent.

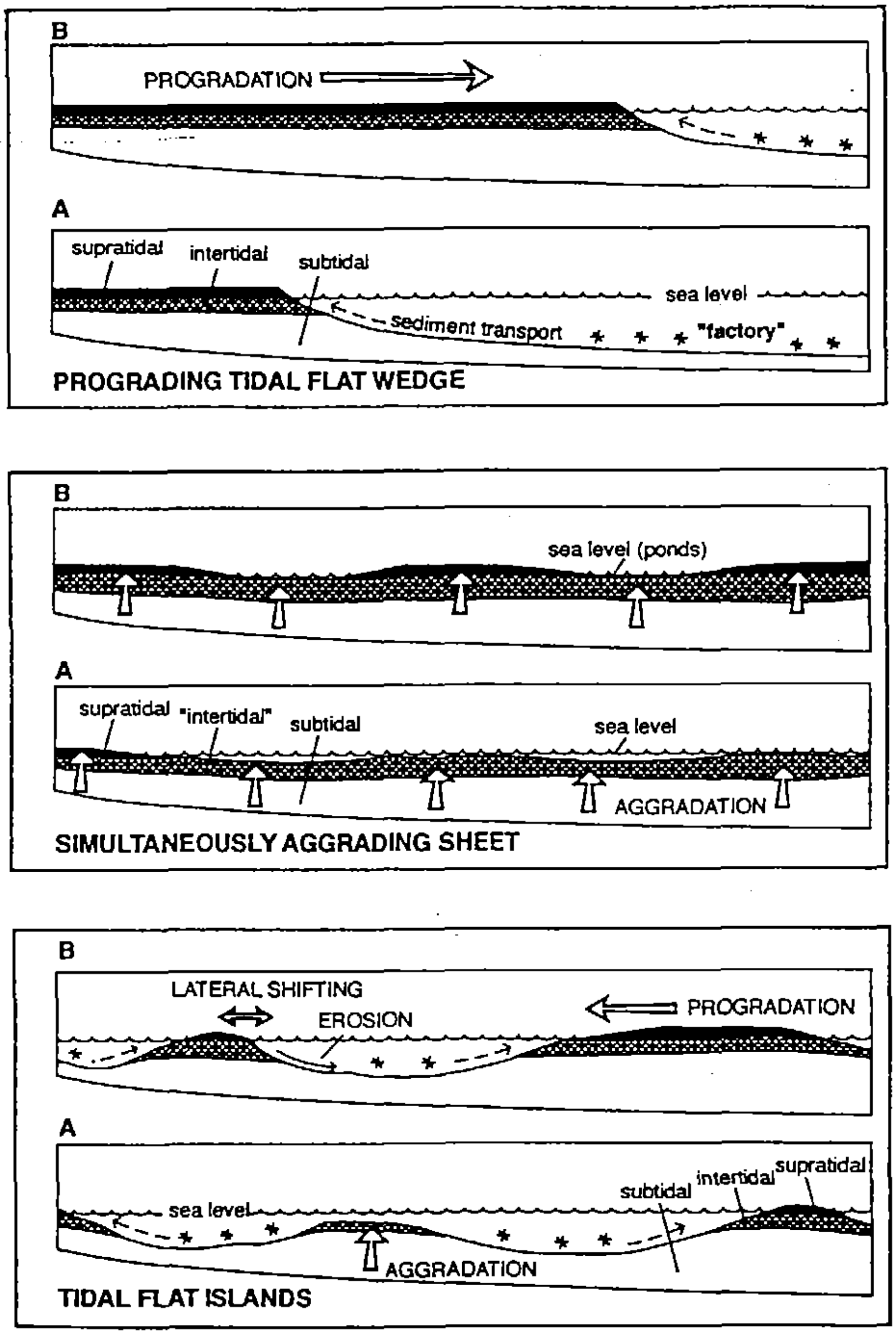

Figure 19 Diagrams illustrating various ways in which a metre-scale, peritidal, shallowing-upward succession can form. A prograding wedge is generated by sediment transported onto the tidal flat from the offshore carbonate factory. A simultaneously aggrading sheet accretes vertically to sea level and the whole platform becomes sequentially intertidal and then supratidal. Tidal flat islands nucleate and accrete by aggradation and progradation and shift in response to hydrographic forces.

Asymmetry

Why is a metre-scale, peritidal shallowing-upward succession asymmetric? The characteristic asymmetry of a typical shallowing-upward succession, i.e., subtidal (A), intertidal (B) and supratidal (C) stacked in ABC → ABC *hemicycles* (Figs. 16, 17, 18), as opposed to full CBABC cycles, is generally attributed to problems with the source area during platform inundation. If the flooding which begins a succession were gradual, then the seafloor during initial submergence is thought to have been too wave swept and/or too shallow or restricted to produce much carbonate sediment. Thus there is a "lag time" or "lag depth" (Hardie, 1986) before the seafloor becomes deep enough to actively produce sediment that is subsequently moved onto the tidal flats. In some successions this time interval is represented by a coarse-grained "transgressive" facies at the base, whereas in others there is no obvious record of this hiatus in deposition. Alternatively, if flooding was rapid, then supratidal facies (C) would be rapidly drowned and intertidal facies (B) would not have time to accumulate.

PERITIDAL CYCLOSTRATIGRAPHY

The stratigraphic record of ancient peritidal carbonates tends to be one of persistent repetition of the basic metre-scale, shallowing-upward succession, imparting a characteristic *cyclic* or, more appropriately, *rhythmic* appearance to the strata. While Holocene tidal flats sometimes provide an analogue for the generation of one shallowing-upward succession, the cause of stratigraphic repetition must be derived from the rock record. The Pleistocene history of climate and sea level change, although the most detailed and best understood of past epochs, has left a stratigraphic record of limited usefulness because sea level fluctuations were so large that they did not result in stacked metre-scale shallowing-upward successions. Consequently, there is currently much discussion as to what causes the rhythmic stacking into thick stratigraphic packages of ancient shallowing-upward successions. Debate has centred around the question of whether the new space made available for each successive shallowing-upward succession is the result of 1) recurring sea level changes (perhaps eustatic) at the same scale and temporal rhythm as the lithologic packaging; or 2) a high-frequency packaging mechanism *intrinsic* to processes of carbonate sedimentation which are superimposed on a low-frequency or irregular sea level rise. These are the *allocyclic* and *autocyclic* mechanisms, respectively, (see also Wilkinson, 1982). The two stacking mechanisms are not necessarily mutually exclusive, and it is uncertain at the moment whether or not evidence for either mechanism can be isolated in the rock record (Hardie *et al.*, 1991; Read *et al.*, 1991).

There is good evidence that a typical shallowing-upward succession was deposited within a time span of 10-100 k.y. (Algeo and Wilkinson, 1988). This is a scale of resolution beyond that provided by biostratigraphic methods. Much of the time represented by stacked shallowing-upward successions, however, is accounted for by hiatuses. Thus the time of deposition for a given tidal flat succession may be only a small fraction of the total apparent stratigraphic time; Wilkinson *et al.* (1991) have suggested as little as 3-30 per cent for some successions.

Autocyclicity

The driving force behind autocyclicity is the dynamics of sedimentation on the platform. Assuming optimum conditions, production rates for shallow-marine carbonate detritus could potentially provide enough sediment over a period of 10-100 k.y. to account for tidal flat aggradation to sea level or progradation of many tens to perhaps hundreds of kilometres under essentially static sea level conditions on a gradient which experienced typical passive-margin rates of subsidence (see also Hardie and Shinn, 1986).

Progradation is inherently limited by the sediment budget of the carbonate platform. For example, in a model first proposed by Ginsburg (1971; see Bosellini and Hardie, 1973; Mossop, 1979), a tidal flat wedge is envisioned as prograding across a gently inclined, gradually subsiding platform under static or slowly changing sea level (Fig. 19). As progradation covers the platform, the subtidal source area for tidal flat sediments becomes increasingly smaller (and deeper). Eventually the source area is too small or too deep to provide sediment for the tidal flat, so sedimentation stops. If relative sea level continues to rise, however, soon the whole platform will once again be subtidal and, after a lag period, the carbonate factory will be robust enough for sediment production, and the cycle will begin again.

The meagre areal coverage of present-day tidal flats makes it difficult to envision a platform literally choking itself off through hundreds of kilometres worth of tidal flat progradation under steady-state sea level and subsidence conditions. Furthermore, it should be emphasized that interpretations of platform-wide progradation in ancient examples are usually based on correlation of strata assumed to be diachronous, not on continuous stratigraphic exposure.

Under conditions of platform-wide *aggradation* it is thought that, once flooded, a shallow platform could generate enough sediment in situ that the whole seafloor would inexorably build to sea level (Fig. 19). Fundamental to this hypothesis is the ability of the "intertidal" and "supratidal" environments to produce sediment. The next cycle would accrete once relative sea level rise had submerged the platform in water deep enough for subtidal sedimentation to begin again. Critics of this hypothesis argue that, in order for the sediment surface to intersect the air/water interface on a platform-wide scale, there must be a sea level fall (albeit minor — a metre or less?), because it is unlikely that the seafloor would everywhere build right up to sea level of its own accord. This model is based on examples where shallowing-upward successions are correlated on a regional scale and assumed to be synchronous deposits.

Tidal flat islands are in part aggradational and in part progradational and their location is thought to shift through time in response to changing hydrographic conditions (Fig. 19). During intervals of prolonged static sea level, or slow sea level rise, they would, like the

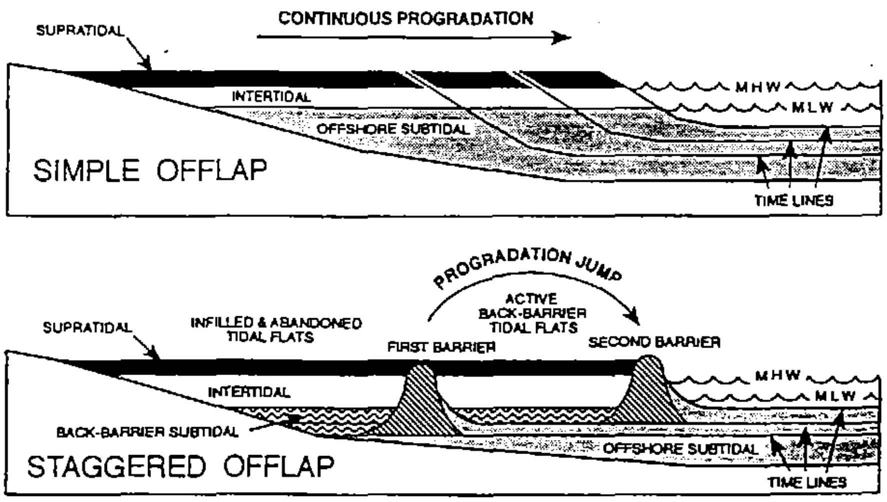

Figure 20 A diagram depicting two styles of tidal flat progradation envisioned from Holocene tidal flats. Simple offlap takes place by continuous progradation. Staggered offlap takes place by formation of an offshore bar which creates a leeward, protected setting in which tidal flat aggradation occurs. Once the flat builds to sea level it becomes dormant until another bar forms seaward and the process of backfilling begins again. Adapted from Hardie (1986).

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prograding wedge, gradually choke off local source areas, eventually becoming dormant. For sedimentation to begin again after a period of local stasis and probably protracted exposure of supratidal flats, there must be creation of new accumulation space. Under conditions of more rapid long-term sea level rise, and continually renewed accumulation space, the islands would form a series of laterally discontinuous peritidal units.

These autocyclic models express a basic premise that pervades current thinking about peritidal carbonates. Persistent and ubiquitous stratigraphic repetition of the basic shallowing-upward succession seems to indicate that these systems are, *at least in part*, intrinsically self-governing.

Allocyclicity

The extrinsic factors of subsidence and eustacy, which cause relative sea level change, have long been assumed to exert strong control on *large-scale* peritidal stratal patterns. High-frequency, low-amplitude sea level changes, the fourth- and fifth-order fluctuations of sequence stratigraphy (Chapter 2), are commonly invoked to drive the packaging of metre-scale, shallowing-upward peritidal successions (Grotzinger, 1986; Koerschner and Read, 1989; Read *et al.*, 1991). In this situation, a metre-scale rise in relative sea level provides a *window of opportunity*, in the sense of both time and accumulation space, for the generation of a single shallowing-upward succession (Fig. 21). Deposition occurs while sea level is rising and at its apex, and is arrested by sea level fall.

Formation of the shallowing-upward succession in this window is envisioned in different ways by different workers. All three styles of accretion presented above are viable within this scheme (prograding wedge, Grotzinger, 1986; aggradation, Koerschner and Read, 1989; and tidal flat islands, Strasser, 1988). Extrinsically controlled metre-scale successions of many kinds, including peritidal, have also been called *punctuated aggradational cycles* (PACs; Goodwin *et al.*, 1986) or more recently *metre-scale allocycles* (Anderson and Goodwin, 1990). Such cycles are metre-scale units, bounded by surfaces of abrupt change to deeper or disjunct facies and comprising a suite of contemporaneous facies, all of which shallow upward. The peritidal portions of such cycles are thought to be aggradational, but there is no reason why they could not be progradational (either wedges or islands).

The most commonly postulated external controls to drive, or at least reset, the system at the end of each shallowing-upward succession are rhythmic eustatic change or jerky subsidence. While spasmodic subsidence with the required short frequency has been documented from seismically active areas and for passive margins where listric faulting is common (e.g., Cisne, 1986; Hardie *et al.*, 1991), the importance of subsidence rate changes as a control on stratigraphic rhythmicity in peritidal shallowing-upward successions is unclear. Sudden base level drops have not been observed in modern passive margin platforms, and ancient epeiric settings, where much of the peritidal record is found, seem unlikely to have experienced metre-scale, high-frequency spasms of subsidence. Because there is currently no known frequency to such tectonism, it is difficult to use, and as yet impossible to model this mechanism as a universal control of stratigraphic rhythmicity. Nevertheless, the mechanism should not be dismissed as a potential control, especially in tectonically active regimes (e.g., Fischer, 1964; Knight *et al.*, 1991).

In the early to mid-1970s studies of DSDP sediment cores and relict coral reef terraces demonstrated that the Pleistocene record of eustatic change is one of superimposed orders of sea level variation (orders, in the sense of both magnitude and frequency; Chapter 2). Deep sea sediments were analyzed for oxygen isotopes (as proxy to glacial ice volume) and revealed a long-term (100 k.y.), 100 m-scale, asymmetric sea level oscillation. Pleistocene fossil reef data suggested that a shorter term (20 k.y.) sea level oscillation was superimposed on the longer term fluctuation. These various orders of eustatic change have been correlated to those predicted for ice-house glaciation driven by celestial mechanics, i.e., the Milankovitch rhythm (e.g., Fischer, 1986). It has been postulated that the stratigraphic rhythmicity apparent in ancient peritidal carbonates reflects a similar *composite eustasy* (Goldhammer *et al.*, 1987), both icehouse and greenhouse, of celestial origin. If astronomically forced composite eustasy is indeed the primary driver in the packaging of shallowing-upward successions, then presumably modulation of various orders of superimposed eustatic cycles could have provided potentially limitless rhythms to the stratigraphic record (Bova and Read, 1987; Koerschner and Read, 1989; Read *et al.*, 1991).

The common challenge to allocyclicity is that extrinsic controls on peritidal sedimentation are neither demonstrable in, nor theoretically re-

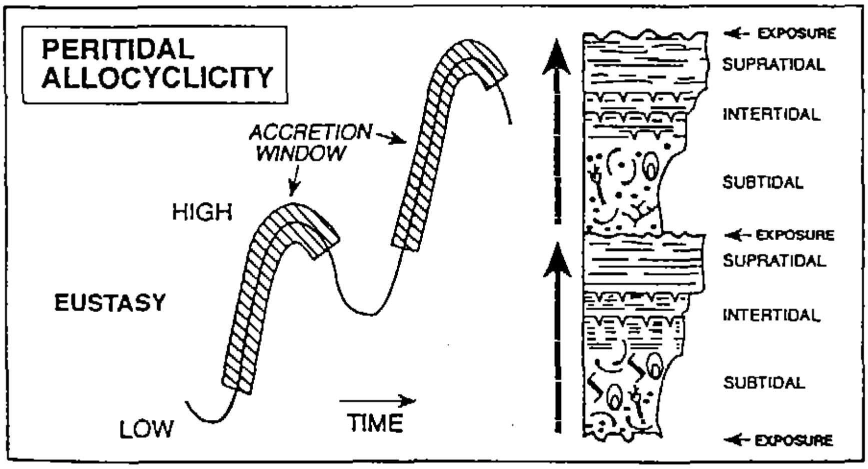

Figure 21 A diagram illustrating the relationship between fluctuating sea level and stacked metre-scale, peritidal, shallowing-upward successions. Sea level rise provides a window of opportunity for the succession to accrete as a prograding wedge, as a simultaneously aggrading sheet or as tidal flat islands. Sea level fall terminates accretion and results in subaerial exposure.

quired to generate metre-scale shallowing-upward successions. It is hard, however, to imagine sea level remaining static for a long period of time, and therefore difficult, if not impossible, to dismiss some extrinsic control on succession development. Allocyclic, platform-wide event stratigraphy should not be underestimated, but its deterministic role in peritidal cyclostratigraphy is still uncertain.

The search for controls and rhythms

Significant effort has recently been devoted to unravelling the meaning of possible stratigraphic rhythms in stacked shallowing-upward successions by numerical analysis. Because peritidal carbonates are so sensitive to changes in climate and sea level, it was widely suspected (hoped?) that this rhythmicity might retain a causative signal of ancient climate and sea level fluctuations. If allocyclic eustatic control on stratal packaging is assumed, then reconstruction of the strata-generating sea level curve can be used as a tool to correlate and explain temporally correlative strata (Read and Goldhammer, 1988).

At the current level of understanding and data base, it is not possible to isolate unequivocal evidence in the rock record for either allocyclic or autocyclic control on most peritidal stratal patterns. Reasonable-looking, synthetic, one-dimensional stratigraphic sections can, however, be generated by varying the critical input parameters of cycle amplitude, duration and asymmetry, bathymetry for each facies, lag time (depth), type of sediment, sedimentation rate, regional and local subsidence, isostatic compensation, wave damping, tidal range, and platform slope and dimension (Grotzinger, 1986; Read *et al.*, 1986; Goldhammer *et al.*, 1987; Spencer and Demicco, 1989). These sections can then be compared to actual examples and eventually a match may be achieved. When similar modelling techniques are used to simulate two-dimensional (multisection) architecture it is often found that the time needed for a peritidal wedge to prograde across the platform is longer than that predicted by Milankovitch rhythms, and the wedges become *stranded*.

Techniques, such as relative time series analysis and *Fischer plotting*, which made a good case for allocyclic forcing of some examples of platform carbonate rhythmicity, i.e., stratigraphic patterns attributable to rhythmic Milankovitch composite eustasy (Goldhammer *et al.*, 1987, 1990), cannot be used for the analysis of metre-scale *peritidal* shallowing-upward successions. Relative time series analysis to reveal the rhythms of sedimentation are invalid for progradational wedges, either local or platform-wide in extent, because such deposits are by nature diachronous, and thicknesses of resultant shallowing-upward successions vary with position on the regional gradient and/or platform topography. Fischer (1964) presented a graphic means of plotting time versus cumulative thickness for laterally continuous, stacked, peritidal shallowing-upward successions. Fischer plots have often been used in recent studies of cyclic strata because they are designed to reveal changes in accumulation space which deviate from that space generated solely by subsidence; these deviations are postulated to result from changes in sea level. However, interpretations of Fischer plots are essentially model driven. For them to be viable two assumptions must be satisfied: 1) each peritidal succession must have been deposited in the same amount of time as every other succession in the chain, and 2) there must be few, if any, missing tidal flat successions. The use of Fischer plots is therefore dubious for any peritidal successions which formed as prograding wedge-shaped tidal flats. It is likely that variations in both the tempo and magnitude of changes in accumulation space, however they are caused, account for stacks of shallowing-upward successions which vary in thickness. Whereas demonstration of allo- or autocyclic control of stratal patterns in stacked shallowing-upward successions appears out of reach at this time, more sophisticated models, particularly those which integrate peritidal rhythms with coeval subtidal and perhaps offplatform stratal patterns, hold promise.

PERITIDAL SEQUENCE STRATIGRAPHY

The concepts of sequence stratigraphy were developed in terrigenous clastic successions and carbonates have only recently been analyzed in this fashion (Chapter 14). *Systematic* packaging of the basic metre-scale shallowing-upward succession is less common and seems less straightforward, or less well developed in carbonates compared to siliciclastics. This difference likely reflects the fundamental differences between carbonate and siliciclastic sediments generally. We have, therefore, avoided the term *parasequence* in this treatment of carbonate tidal flat deposits.

Peritidal deposits are not indicative of any particular systems tract because the controls on tidal flat development, such as climate, platform circulation, wind patterns and tidal range, vary with each platform's unique history and configuration. Nevertheless, tidal flat deposits are potentially useful in delineating sequences and their component systems tracts in two ways, 1) geographic position of the tidal flat on the platform may track long-term changes in sea level, and 2) changes in large-scale accumulation space, and thus sequences, can be recognized through analysis of stacking patterns (packaging) of shallowing-upward successions.

Tracking sea level

Tidal flats can be the first facies overlying a sequence boundary, deposited as the rate of relative sea level fall decreases and the sea slowly floods back across the platform. As third-order sea level fluctuates in response to long-term, large-amplitude driving forces, the location of the strandline on the platform will change. If conditions are favourable for their development, land-fringing tidal flat deposits will mark the position of coastal onlap through the third-order eustatic cycle (i.e., the "onlap-offlap" geometry of Hardie, 1986; Fig. 22). Sarg (1988) documented the utility of tidal flats at the outcrop scale in a sequence stratigraphic context for the Permian of New Mexico, where a sequence boundary and shelf-margin wedge systems tract were recognized in part by the downdip, basinward position of onlapping tidal flat deposits.

Stacking

The stratigraphic patterns of *laterally continuous*, metre-scale, shallowing-upward successions generated by prograding tidal flat wedges, can be envisaged in the framework of long-term changes in relative sea level. Third-order sea level changes are thought to "modulate" the higher-frequency, fourth- and fifth-order sea level cycles represented by the tidal flat successions. This has two consequences.

Long-term, third-order fluctuations in sea level should carry the window of opportunity in which each individual metre-scale succession is formed back and forth across the platform. Depending upon the balance between different rates of subsidence, eustasy and sedimentation, the window will be geographically repositioned during each consecutive fourth or fifth-order change in relative sea level to result in backstepping, offlapping or stacking of peritidal shallowing-upward successions. Figure 22 illustrates, in a conceptual way, how this might work on an inclined shelf. If the rate of change of long-term relative sea level is *low*, the geographic position of successive windows should remain roughly the same. Thus, peritidal successions in lowstand (position 1) and early highstand (position 3) systems tracts will probably be stacked in one place and will be relatively thin because the rate of addition of new accumulation space is low. If the rate of change is *high*, the window should be forced backward and forward across the shelf. This will likely result in either relatively thick, backstepped tidal flat successions (position 2 – transgressive systems tract) or relatively thin successions which offlap in a shingled fashion (position 4 – late highstand or early lowstand systems tracts). It must be stressed that the distance of progradation in each case will be specific to each peritidal package on each shelf.

Long-term sea level rise should accentuate short-term rises and suppress short-term falls; long-term falls in sea level will have the opposite effect. The relative proportions of subtidal, intertidal and supratidal facies in successive shallowing-upward successions may change systematically in response to this long-term modulation of short-term changes in accumulation space. This relationship is as yet hypothetical, and interpretations of such controls in ancient strata are necessarily model driven.

SUMMARY

Peritidal limestones and dolostones exhibit a large number of easily recognized sedimentary and biosedimentary structures. While some of these are individually equivocal bathymetric indicators (stromatolites or wave-rippled beds, for example, can form in subtidal areas), in most cases the features can be used collectively to make a firm environmental conclusion. A boon to interpreting ancient peritidal facies is the wealth of knowledge gained from modern settings. Very often a one-to-one lithologic comparison can be made, leading to a refined understanding of paleoenvironments and paleoclimates in individual cases. A *hierarchy of models* has been formulated that deals with successive levels of interpretation of peritidal carbonate strata.

These kinds of rocks fall into two main depositional systems, low-energy tidal flats and higher-energy beaches. The facies associations are fairly distinctive for each setting: this is the first tier of models to guide basic interpretations.

The vertical record of peritidal facies commonly shows a trend from subtidal limestone through intertidal sediments to supratidal deposits, at a metre scale, as tidal flats aggrade to sea level and prograde laterally. Peritidal models are therefore shown as shallowing-upward successions as a reminder of these dynamic processes.

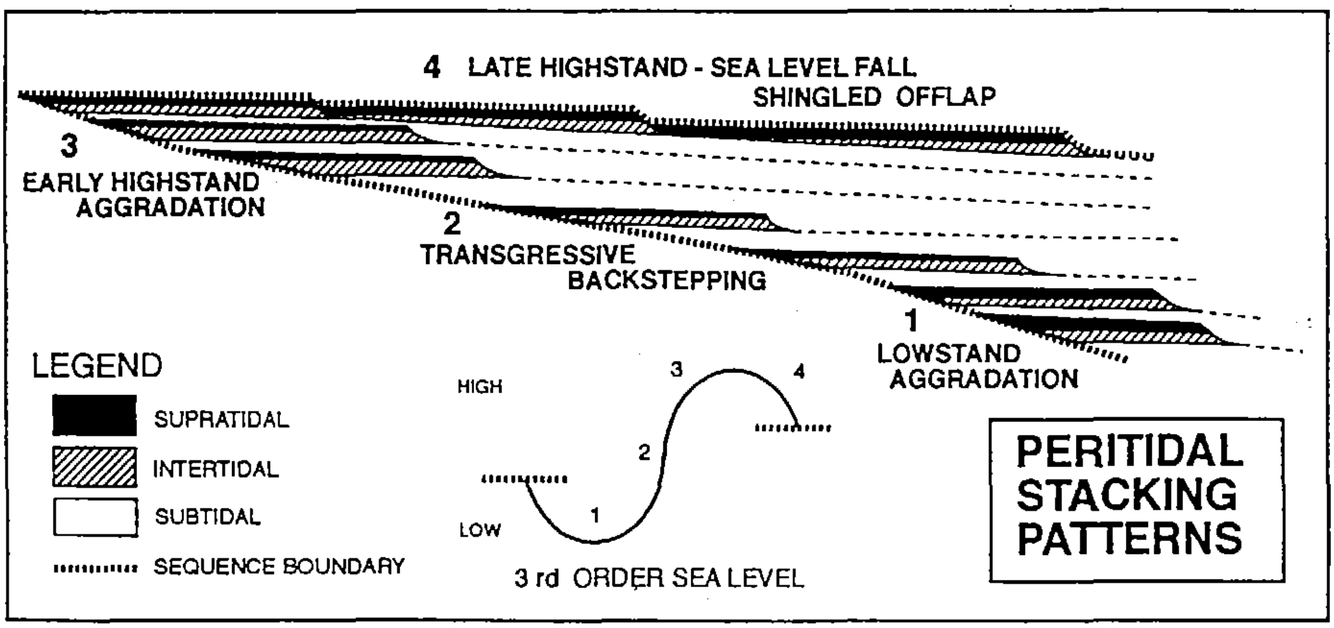

Figure 22 A diagram illustrating the hypothetical stratigraphy of metre-scale, peritidal, successions between two sequence boundaries. Each succession formed by progradation which took place in the window of opportunity produced by short-term fourth- and fifth-order fluctuations in relative sea level during a long-term, third-order rise and fall of sea level. Slow, third-order, sea level-controlled movement of the strandline will dictate where tidal flats develop on the shelf. The balance between sea level changes, sedimentation, and subsidence will dictate how successive tidal flats will stack, backstep or offlap.

These models, as predictors, point to departures from the norm and other irregularities that might have important implications regarding intrinsic or extrinsic controls on deposition. They also provide a framework within which the diagenesis of the sediment can be tracked.

Peritidal carbonates occur repetitively in stratigraphic sequences, often in a seemingly regular, or cyclic, fashion. There is much debate about whether these metre-scale, shallowing-upward successions are platform-wide responses to allogenic forces such as spasmodic subsidence or episodic eustasy, or whether they represent localized tidal flat shorelines and islands shaped by autogenic, i.e., hydrographic, controls. Sedimentologists have their work cut out for them by these models; we are now charged with the job of deciding, if possible, which one best explains our own successions, or if a new approach is necessary. It is an exciting field of research, one that weds careful and precise field observations with increasingly sophisticated numerical modelling.

ACKNOWLEDGEMENTS

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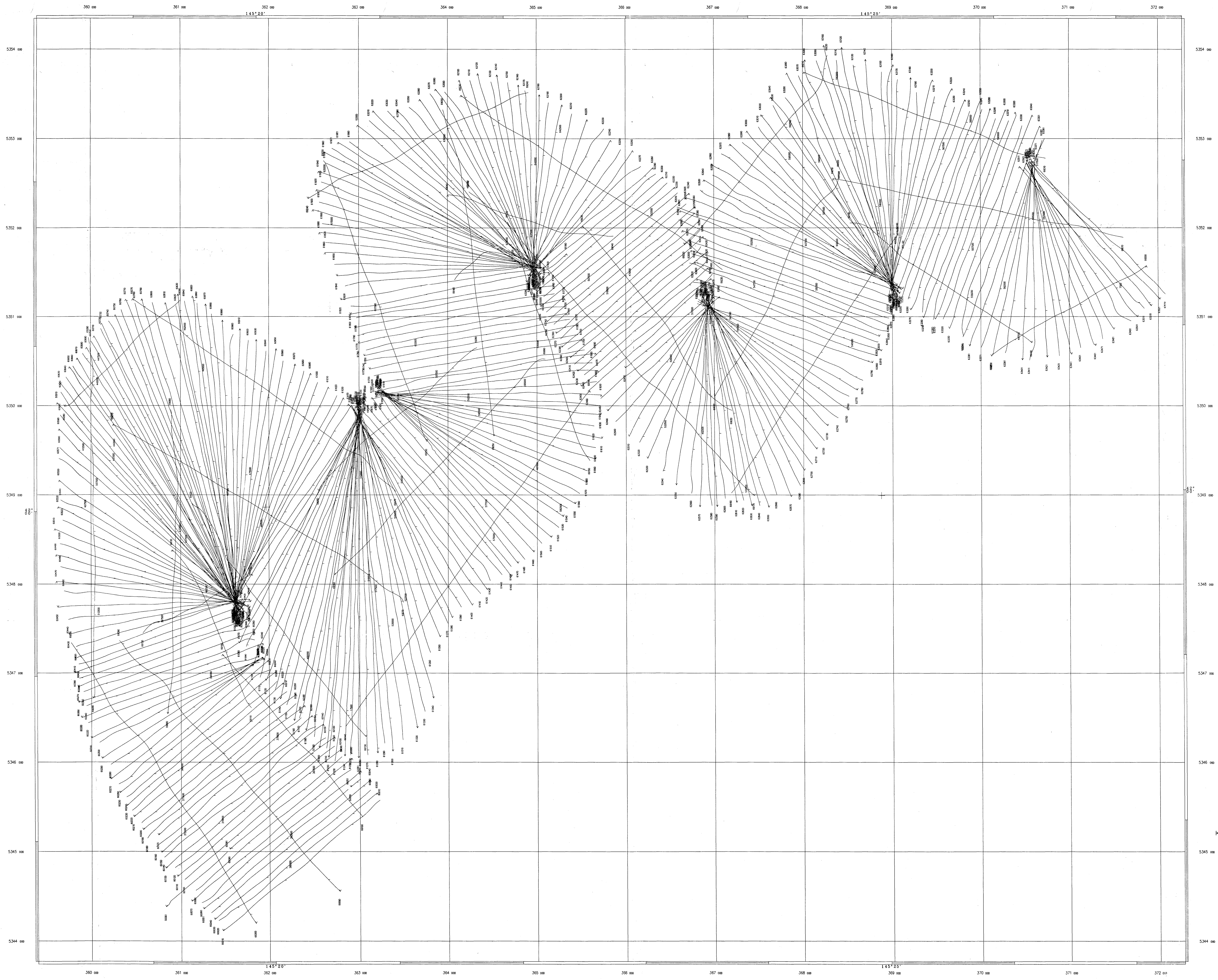

AIRBORNE SURVEY SPECIFICATIONS

Flight Line Direction:	CRA Digitised
Flight Line Separation:	CRA Digitised
Tie Line Direction:	CRA Digitised
Tie Line Separation:	CRA Digitised
Mean Terrain Clearance:	30 metres
Sample Interval:	3-4 metres
Navigation:	Differential GPS
Survey Flown:	March 1995

AIRBORNE SURVEY EQUIPMENT

Acquisition:	UTS Geophysics
Aircraft:	AS350B Helicopter
Magnetometer:	Geometrics G-833 Helium
Resolution:	0.001 nT
Sensitivity:	0.001 nT
Recording Interval:	10 Hz
Compensation:	RMS AADC II Compensator

PROCESSING DETAILS

Diurnal Corrections Applied
Tie Line Levelling Applied

PRELIMINARY
UTS GEOPHYSICS

Grid North

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0 200 400 600 800 1000
Scale 1: 15000

5 cm

UTS Geophysics

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CRA EXPLORATION PTY LIMITED

AREA 6 - TASMANIA
DETAILED HELI-MAG SURVEY
FLIGHT PATH MAP
SHEET 1 OF 1

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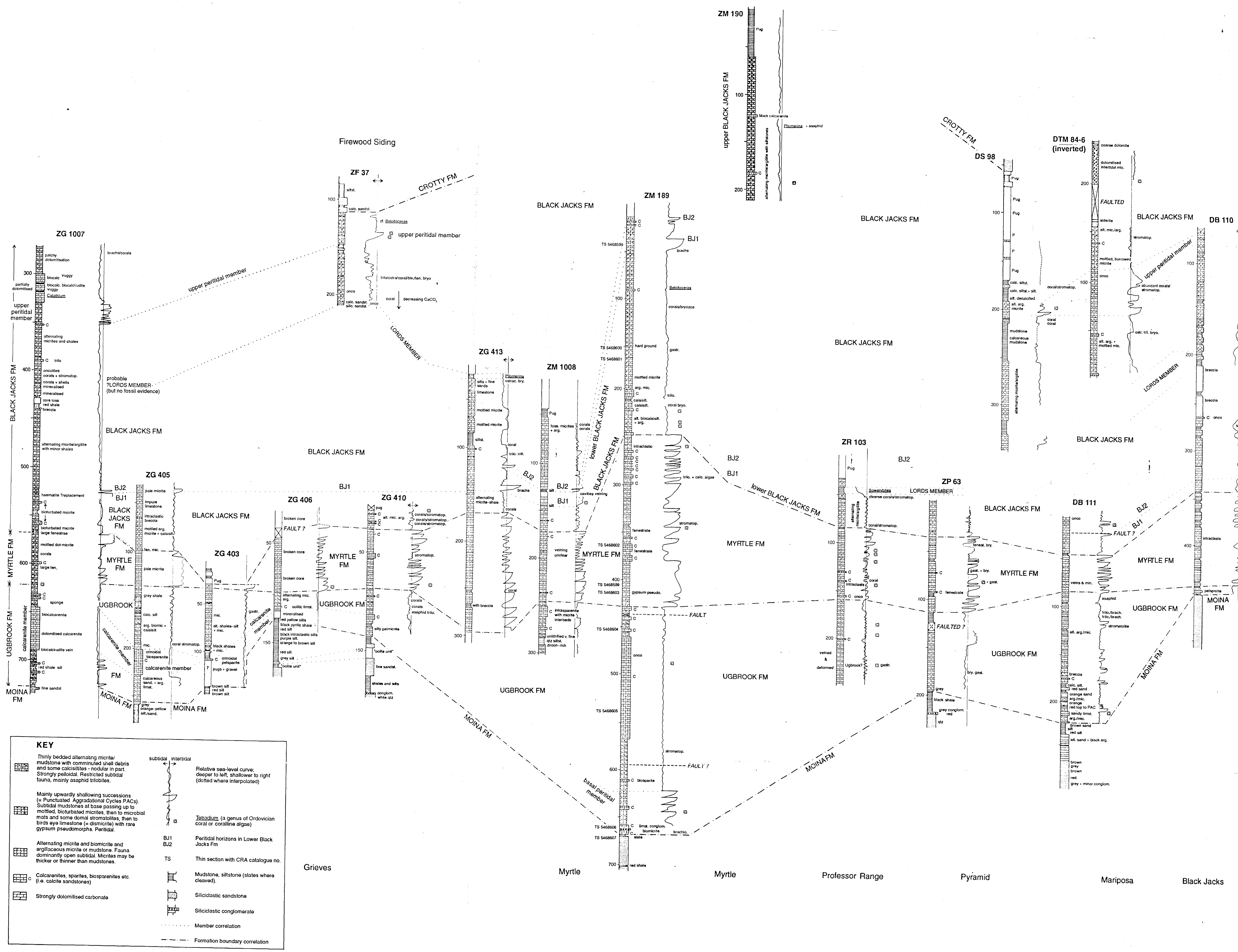

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Appendix VIII / Fig. 5

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Appendix IX

Zinc mineralisation in the Gordon Limestone

Zinc Mineralisation in the Gordon Limestone

CRAE's exploration and research activities directed at locating carbonate-hosted Zn-Pb mineralisation within Gordon Limestone at Zeehan have led to a number of mineralisation styles being recognised. The following discussion is a synthesis of CRAE's current level of knowledge, grained from work throughout the Zeehan area.

CRAE's exploration activities in the Zeehan area have indicated that Zn-Pb mineralisation within the Gordon Limestone may be pre-Devonian in age, and therefore unrelated to the Tabberabberan Orogeny. On this basis, it is possible that carbonate-hosted Zn-Pb mineralisation may be more widespread than that presently under evaluation at Zeehan.

The Gordon Limestone originally occupied a large area, deposited at the close of a major period of tectonic activity that produced the metal-rich Mount Read Volcanics. During and immediately before carbonate deposition the tectonic regime was still unstable, evidenced by rapid changes in stratigraphic thickness of Ordovician strata. Hydrothermal systems may have continued to emit metals into this system, focused by basement irregularities and syn-sedimentary faults.

The present Gordon Limestone exposure is a vestige of Devonian deformation. Ordovician mineralisation may have a distribution totally independent of the well-documented Devonian systems.

Five targets are recognised for the carbonate-hosted Zn mineralisation in Gordon Limestone at Zeehan, subdivided by the stratigraphic interval in which they are hosted (Figure):-

- stratabound at the lower limestone-sandstone contact
- stratabound at the upper limestone-quartzite contact
- stratabound within a sub-unit in the middle of the limestone sequence
- structurally controlled discordant mineralisation
- surficial "clay-hosted" accumulations developed above primary mineralisation.

Stratabround at the lower limestone-sandstone contact

Mineralisation at Grieves and Mariposa falls into this category. Alteration located at Blackjacks, Pyramid and Professor Range may also belong to this deposit type.

This position is characterised by carbonaceous and/or ferruginous clays resting on the Moina Sandstone, in turn overlain by a massive siderite zone. The siderite zones passes stratigraphically upward either gradationally or abruptly into unaltered and unmineralised limestone. The clay layer may be up to 50m thick and the siderite zone up to 25m thick. Both may contain Zn mineralisation up to several percent. The clay and siderite zone are laterally quite uniform and it may be that the mineralisation is actually stratiform.

Mineralisation of this style has an alteration halo that is both visually and geochemically distinct. This halo, characterised by vughy, broken or massive recrystallised Fe-carbonate and Fe-rich clays, may extend laterally hundreds of metres beyond the main Zn mineralisation, and thus present a considerably larger target than the mineralised core. Lateral alteration geochemistry is reflected by Fe-Mn-As-Zn. Stratigraphy above the mineralised core is a weaker halo of elevated Zn (± As).

Ore mineralogy, based on work at Grieves, is complex with a mixture of zincian siderite and minor sphalerite in the siderite zone, and a Zn-clay with minor to moderate amounts of sphalerite in the siderite zone, and a Zn-clay with minor to moderate amounts of sphalerite in the clay zone. It is not known whether this is a regional characteristic of this position.

The stratiform character, replacive style of alteration/mineralisation, intense Fe-Mn alteration, and reasonably predictable geometry suggest similarities to Navan or Reocin.

Stratabound at the upper limestone-quartzite contact

Low-grade but widely anomalous zones from Firewood Siding, Grieves, Professor Range, Sunny Corner, and Mariposa are examples of this type.

Upper zone mineralisation occurs near the contact between the limestone and overlying Crotty Quartzite. Mineralisation is not closely bound to the upper quartzite contact, but may "wander" up to 100m stratigraphically below the contact.

Mineralisation appears characterised by widespread but low-level Zn in the 0.1% to 2% Zn range. None of the prospects tested has revealed a higher-grade core, although given the limited drilling it is entirely possible high-grade cores may exist. Limited mineralogy suggests all Zn to be as sphalerite.

Air-core drilling shows the mineralised zones to be comprised of clays and decomposed carbonate. Rare fresher material is usually a granular recrystallised dolomite, and can be ferroan. Intense siderite alteration is absent. A detailed geochemical study of the alteration has not been completed.

The upper zone style may be occurring within karstic structures formed by Ordovician weathering before deposition of the Crotty Quartzite. This setting is analogous to Bleiberg or Cracow-Silesia.

Stratabround in a middle sub-unit of the limestone sequence

Currently two occurrences fall into this grouping, Grieves middle zone, and Oceana. Apart from their stratigraphic concurrence, these two deposits may not share many other similarities.

The mineralised middle sub-unit is equidistant from the upper and lower contacts, although facies variations may affect the location at other prospects. Mineralisation is breccia hosted, and in the case of Grieves has a linear aspect. For Grieves there is very little indication of proximity to mineralisation as there is virtually no alteration outside the breccia zone itself.

Mineralogy at Grieves is a mixture of zincian siderite and sphalerite. Oceana is dominated by galena with subordinate (?) sphalerite. There is also intense siderite alteration at Oceana, presumably containing Zn?

Zinc grades at both prospects are high, locally forming massive sulphide.

There has been insufficient work completed at Grieves middle zone to suggest any controlling mechanisms.

Structurally controlled discordant mineralisation

Most mineralisation in the Zeehan area is structurally controlled. Mineralisation at the historic Mariposa mine, and at Myrtle belong to this type. Possibly some of the mineralisation at Oceana is also structurally controlled.

Structurally controlled mineralisation may occur at any stratigraphic level. It appears to be late-stage filling of brittle fractures. Alteration of wall-rocks is absent, and the gangue to mineralisation may be pure calcite. Mineralisation within the structures is patchily distributed. Ore minerals are coarse-grained sulphides.

Devonian deformation is the likely cause of the fracturing and mineralisation. Potential deposit size is small, although the presence of discordant mineralisation may indicate a nearby stratabound source. Late-stage structurally controlled deposits *per se* are not currently considered a valid CRAE target.

Surficial "clay-hosted" accumulations developed above primary mineralisation
Surficial Zn accumulations within decomposed carbonate was CRAE's original target for carbonate exploration in Zeehan. All currently tested prospects were selected due to the presence of known surficial mineralisation.

It has now been conclusively demonstrated that the surficial mineralisation occupies the surface trace of underlying stratabound mineralisation. Geometry of the surficial deposits are therefore dependent on the shape and extent of this underlying mineralisation. Depth extent of the Zn-rich clays and decomposed carbonates averages 10m to 20m, but have been reported to be over 100m at Oceana.

A thin layer of decomposed carbonate exists over large areas of limestone, but this layer only thickens and becomes substantially Zn-rich as "basement" mineralisation is approached. Areas of +0.1% Zn in the clay layer are regionally extensive, indicating substantial dispersions from the primary zone. Clay thickness and Zn grade may be useful vectors toward primary zones. Geochemically inert peat and gravels up to 5m thick obscure the clays and limestone over virtually the entire trace of the Gordon Limestone.

Zinc ore mineralogy is dominantly to exclusively sphalerite.

Because of their restriction to the surface zone, the potential size of the surficial deposit is somewhat limited. They are probably unlikely to be a CRA target in themselves. Their main attraction is their usefulness as an indicator of the underlying primary mineralisation. If a large primary deposit suitable to CRAE's requirements can be identified, then the surficial deposits would possible be an easy way to generate short-term cash-flow whilst the major deposit was being developed.

Zinc-rich clay deposits overlying primary carbonate mineralisation have been described at Tynagh and Silvermines.

R.G. Parkinson (1994)