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BILLITON AUSTRALIA
 THE METALS DIVISION OF
 THE SHELL COMPANY OF AUSTRALIA LTD

E.L. 39/83 - CATTLEY RANGE

Progress Report on Exploration for the Period
 23/8/88 to 22/8/89

OPEN FILE

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CONTENTS

SUMMARY

- 1.0 INTRODUCTION
- 2.0 PREVIOUS EXPLORATION
- 3.0 EXPLORATION COMPLETED 1988-1989
- 4.0 GEOLOGICAL SETTING
- 5.0 EXPLORATION RESULTS
 - 5.1 Percussion Drilling
 - 5.2 Alteration Geochemistry
 - 5.3 Lead Isotopes
 - 5.4 Oxygen Isotopes
 - 5.5 Down Hole EM
- 6.0 CONCLUSIONS & RECOMMENDATIONS

LIST OF FIGURES

Fig 1 : Exploration Licence 39/83 Renewal Area	1:100,000
Fig 2 : Stratigraphic Diagram for Dundas Group in Que-Hellyer Area	
Fig 3 : Geological Relationship to the Que Hellyer Volcanic Complex	1:100,000
Fig 4 : Black Marsh Road Proposed Percussion Drilling Section	1: 5,000
Fig 5 : Percussion Drill Section Black Marsh Road	1: 500
Fig 6 : Max Min EM Anomaly Positions & Proposed Drill Tests	1: 5,000
Fig 7 : Line 10600N Percussion Drill Section CRP 88-3	1: 500
Fig 8 : CRD 88-1 Down Hole Plot Na_2O , CaO , K_2O , TiO_2	1: 1,670
Fig 9 : CRD 88-1 Down Hole Plot Sr, Ba, Zr, Rb	1: 1,670

LIST OF APPENDICES

- Appendix 1 : Whole Rock and Trace Element Analyses
- Appendix 2 : Lead Isotope Compositions. Report by CSIRO.
- Appendix 3 : Oxygen Isotope and Petrological investigation of altered rocks in the Cattley Range Area.
- Appendix 4 : Percussion Drill Logs CRP 88-1,2,3.
- Appendix 5 : Down Hole EM Profiles CRD 88-1, CRP 88-3.
- Appendix 6 : Max Min EM Profiles and brief interpretation report

SUMMARY

Exploration Licence 39/83, of 22km², is located 13kms NNE of Hellyer and covers a sequence of altered volcanoclastics, sediments and minor volcanics that are most probably younger than the Central Volcanic Sequence and Lower Dundas Group.

Previous exploration has involved geological mapping, rock chip sampling, stream sediment surveying, EM 37 surveying, costeaning, diamond/percussion drilling and alteration/isotope studies.

Only minor base metal mineralization has been intersected in core but the strength of alteration warranted further study. Lead isotope determinations indicate a Cambrian age for the mineralization but oxygen isotopic evidence suggests that the alteration is local and associated with the intrusion of dacitic porphyries.

Field evidence for the presence of intermediate lavas has been disputed by the Mines Department who consider these rock types to be of intrusive origin. The presence of fine laminated chalcedonic ash beds between these intermediate rock units and the observation of amygdaloidal textures supports the former interpretation while petrographic work indicates doleritic textures, favouring the latter.

Recent down hole EM surveying of one drill hole, CRD 88-1, indicates the presence of an off hole conductor that has not been satisfactorily explained. The lack of response observed from a ground survey is disconcerting and may indicate a problem of EM coupling.

1. INTRODUCTION

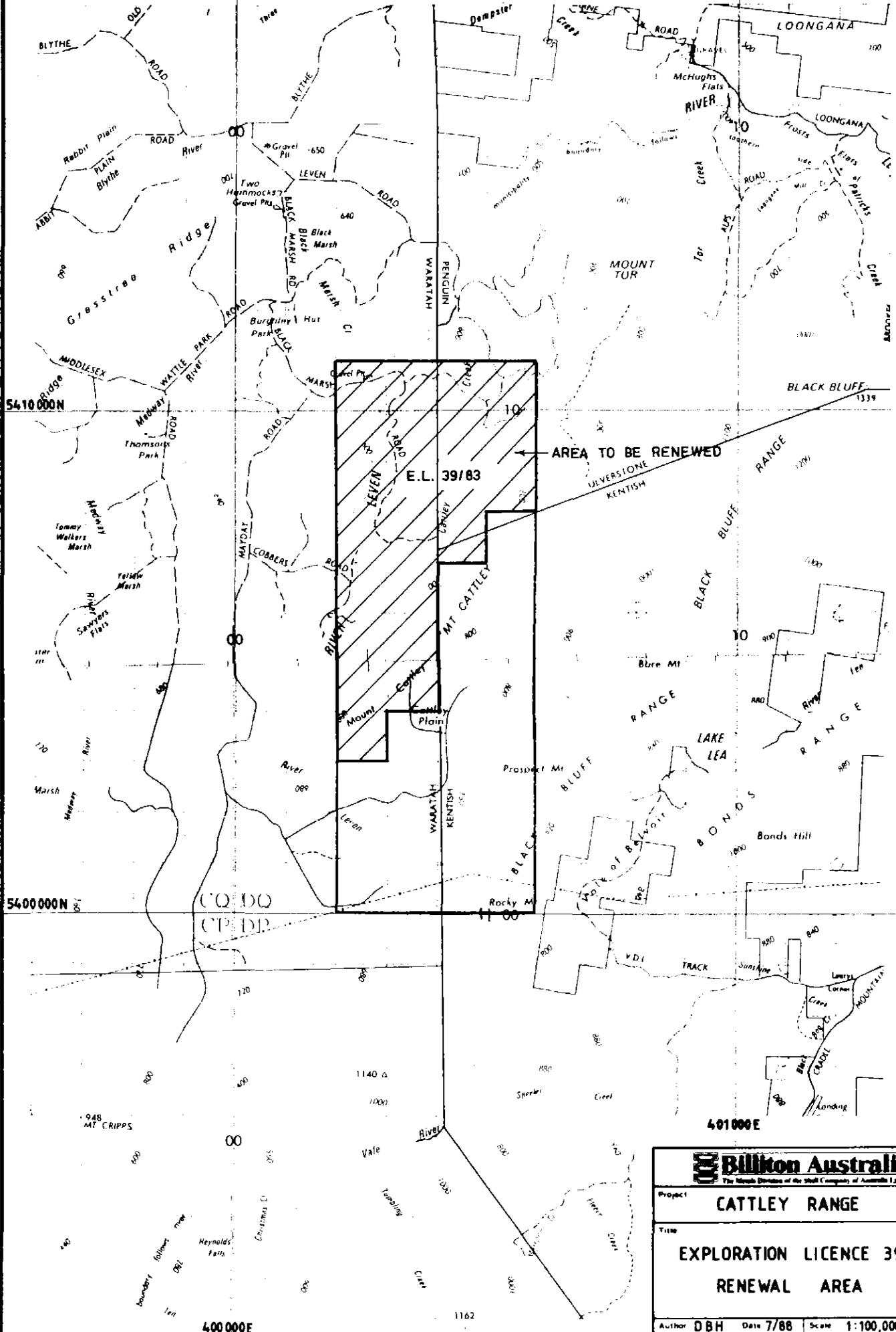
Exploration Licence 39/83, covering 44km², was granted to the Shell Company of Australia Ltd. on 22nd August, 1983. The tenement was reduced by 50% in area on the 22nd August 1988 and a separate report has documented exploration completed on the relinquished portion. The area is located 50 kms south of Burnie partially within an APPM Concession and encloses the Cattley Range. (Fig. 1).

The principal exploration target within the licence is massive volcanogenic base metal sulphides with type characteristics of Hellyer-Que River and Rosebery. These classic VMS deposits show gross similarities in regional setting, character and genesis; features that can be used in exploration for other deposits of similar style.

The gross exploration philosophy applicable to this licence relates to the strike/stratigraphic proximity of Hellyer (13kms) the continuity of a major rift margin fault (Henty Fault) north from Hellyer and the presence within the licence and adjacent licences of strongly altered and geochemically anomalous lithologies (Two Hummocks, Cattley North, Basin Road).

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Billton Australia The Mining Division of the Shell Company of Australia Limited			
Project CATTLEY RANGE			
Title EXPLORATION LICENCE 39/83 RENEWAL AREA			
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Drawing No.	Fig. No.		

2. PREVIOUS EXPLORATION

Details of exploration carried out prior to the current term are listed in the following Billiton reports:

08.2489, 08.2887, 08.3410, 08.3545, 08.4106.

In particular, report 08.4106 "Progress Report on Exploration for the Period 23/8/87 to 22/8/88" summarizes previous exploration by Billiton.

3. EXPLORATION COMPLETED 1988-1989

An evaluation of the alteration assemblage continued during the licence term. In addition, percussion drilling was attempted to evaluate shallow geophysical-geological targets.

- Geochemistry : a total of 31 drill core samples from CRD (Appendix 1) 88-1 were analysed for silicates + Sr, Ba, Zr, Rb. In addition, 38 rock chip samples were collected and analysed for silicates + Ba Sr Rb La Zr Nb Y Ce.
- Lead Isotopes : a total of six samples were submitted to the (Appendix 2) CSIRO for lead isotope analysis. The samples originated from both surface outcrop and drill core.

- Oxygen Isotopes : a brief study was completed by Dr. G. Green (Appendix 3) of the Tasmanian Department of Mines. A total of seven oxygen isotope determinations and petrological examinations were made.

- Percussion : a total of 214 metres of drilling was completed in three holes (CRP 88-1,2,3). All holes (Appendix 4) were prematurely terminated in post-Cambrian cover due to hole collapse. Consequently, no samples were submitted for analysis.

- Down Hole EM : Drill holes CRD 88-1, CRP 88-3 were surveyed (Appendix 5) to determine the presence or proximity of a conductive source.

- Max Min EM : Two short lines were completed over previously identified geophysical anomalies. (Appendix 6)

4. GEOLOGICAL SETTING

Local and regional aspects of the geological setting have been previously discussed (1988 Annual Report 08.4106) but additional information is now available from the Mines Department mapping project.

Several important comments are made here as they bear directly upon previous interpretations put forth by Billiton.

- 1) The Mines Department consider the Cambrian sequence within the licence area to be at a higher stratigraphic level than the sequence at Que-Hellyer (Fig. 2). Whilst this cannot be proved, correlation of the sequence north of the Que-Hellyer complex on the Cradle Link Road with that within the Cattley Range - Two Hummocks area suggests this inference. From an economic viewpoint, this interpretation neither increases or decreases the prospectivity of the licence area. Within the time frame expected for evolution of the Mt. Read Volcanics, mineralizing episodes may be expected at various time - stratigraphic intervals and hence it is more a function of local volcanism than strict time equivalence with other volcanic regimes.

- 2) The Mines Department see no evidence for the presence of a major fault between the shallow west dipping greywacke sequence within the Leven River and the steeply east dipping volcanoclastic sequence east of the Leven River. This dramatic contrast in rock type and bedding attitude may well be explained by folding but evidence does exist in the northern costeans and drill hole CRD 88-1 to suggest a faulted contact. (Fig. 3).

- 3) The dacitic-andesitic "lavas" interpreted in drill hole CRD 88-1 are considered by the Mines Department to be of intrusive origin. In fact, they are termed "feldspar hornblende porphyries". However, two facts cast some doubt on this interpretation: viz 1) amygdaloidal textures have been recognized; 2) finely banded chalcedonic sediments occur between dacitic "flow" units. Contacts are sharp and the units have been interpreted by Billiton as inter-flow horizons.

Further work is required by Billiton to satisfy our interpretation as there are major economic implications. Further petrological work and whole rock analyses may aid in this conclusion.

5. EXPLORATION RESULTS

5.1 Percussion Drilling

Percussion drilling was attempted in the southern portion of the licence along strike from a previous diamond drill section (5600N). Two holes were drilled along Black Marsh Road between lines 7100N and 7400N to test for the presence of the Cattley Fault and for the continuation of andesitic ?lavas intersected to the south. Both holes failed to pene-

trate a layer of Ordovician pebble to boulder river wash beneath the Tertiary basalt cap and hence no satisfactory results were achieved.

Details of these holes are summarized below and in Figures 4, 5.

Hole No : CRP 88-1
 Collar Co-ords : 7260N 11340E
 Inclination : Vertical
 Summary Log : 0-20 Tertiary basalt.
 20-22 Tertiary chalcedonic sediment.
 22-44 Tertiary basalt.
 44-49 Tertiary chalcedonic sediment.
 49-64 Tertiary basalt.
 64-66 Tertiary grey clays.
 66-70 Ordovician pebbles, gravels of
 probable river wash.
 EOH 70m

Hole No : CRP 88-2
 Collar Co-ords : 7320N 11450E
 Inclination : Vertical
 Summary Log : 0-12 Tertiary basalt.
 12-16 Tertiary siliceous sediment.
 16-22 Tertiary basalt.
 22-26 Tertiary pink siliceous sediment.
 26-72 Tertiary basalt.
 72-76 Tertiary grey clays
 76-82 Ordovician quartzite, pebble conglom-
 erate, probable river wash.
 EOH 82m

Two metre samples have been collected from each of the three holes but not submitted for analysis.

Percussion drilling was also attempted on line 10600N where an earlier EM 37 survey had defined a weak near surface conductor beneath a Tertiary Basalt cap. (Fig. 6). Although the EM response was considered to be probably due to conductive clay layers within the basalt there was sufficient doubt to warrant a subsurface test. Accordingly,

a line of Max Min EM was run (see Appendix 6) across the anomaly position to locate the anomaly precisely (the grid has been recently destroyed by logging operations). A vertical percussion hole was then drilled to intersect the anomaly at between 50 and 100 metres. Poor ground conditions (loose gravels, caving) prevented penetration to the lower anomaly position but a partial test was achieved. Details of this drill hole are summarized below and in Figure 7.

Hole No : CRP 88-3
Collar Co-ords : 10600N 10537E
Inclination : Vertical
Summary Log : 0- 4 Tertiary gravels, cobbles
 4-14 Tertiary clays.
 14-36 Tertiary basalt
 36-44 Tertiary clays
 44-64 Tertiary basalt
 64-72 Ordovician quartzite, pebble conglom-
 merate well rounded, probable river
 wash.
EOH 72m Hole cased with PVC to 72m.

Down hole EM surveying of this hole has been carried out and it is likely that the river wash layer is responsible for the anomaly. (see Section 5.5).

5.2 Alteration Geochemistry

Sampling of drill hole CRD 88-1 has been carried out on a regular basis to determine down hole geochemical trends. In addition, rock chip sampling from surface outcrop was completed to determine levels of alteration on an areal basis. (see Appendix 1).

Down hole plots of CRD 88-1 are shown in Figures 8, 9. Depletion in Na₂O, Sr is sporadic and associated at least in one case with an intrusive quartz porphyry. A marginal enrichment in Rb is also noted. A visual comparison has been made between samples of drill holes CRD 86-1, CRD 88-1 and surface rock chips with samples from unaltered Mount Read Volcanics and altered Rosebery samples. This is summarized below in Table 1.

TABLE 1 : Comparison of Cattley Range, Rosebery & MRV

<u>Element/ Oxide</u>	<u>Samples</u>				
	<u>Unaltered MRV</u>	<u>Altered Rosebery</u>	<u>CRD88-1</u>	<u>CRD86-1</u>	<u>Rock Chips</u>
Na ₂ O	3.1 %	0.3 %	2.51%	* 0.2%	*0.27%
Sr	185ppm	21ppm	*79ppm	*32ppm	*14ppm
CaO	0.3 %	0.2 %	2.7 %	3.27%	*0.02%
TiO ₂	0.38%	0.27%	0.34%	0.46%	0.44%
Rb	144ppm	215ppm	130ppm	N/A	151ppm
K ₂ O	3.1 %	4.5 %	*3.79%	*4.14%	3.63%
SiO ₂	73.8%	74.7%	66.1%	64.06%	72.73%

It is apparent from this table that alteration in CRD 86-1 (as observed from depletion trends) is far more intense than in CRD 88-1. In detail it is noted that there is also an intense alteration halo surrounding the quartz porphyry intrusives, especially in CRD 86-1. It therefore seems likely that the alteration observed is local only and due to restricted hydrothermal activity in the vicinity of the intrusives.

5.3 Lead Isotopes

Six samples from known base metal occurrences within the licence area were submitted to the CSIRO for lead isotope determinations. The results of this work are fully documented in Appendix 2 but in essence they indicate that the mineralization has a similar signature to a typical Cambrian volcanogenic system. In fact, 5 of the 6 samples cluster tightly within the Rosebery and lower Que River/Hellyer fields. This analysis verifies that observed mineralization is not related to a Devonian mineralizing event and also that the mineralization was introduced at a similar time and from a similar source as the typical Cambrian VMS systems. The paucity of observed mineralization within the licence however remains enigmatic.

5.4 Oxygen Isotopes

Dr. Geoff Green of the Tasmanian Department of Mines was engaged to carry out a short study of the CRD 86-1, CRD 88-1 drill core. Specifically it was requested that oxygen isotopic determinations be made in an attempt to quantify likely alteration conditions and source. Results of this work are contained in a report by Dr. Green in Appendix 3.

The conclusions drawn from this study are:

1. the alteration and mineralization intersected in CRD 86-1 is a local feature related to a dacitic intrusive.
2. the oxygen isotopic contents are not consistent with those from either Kuroko or Tasmanian VMS deposits.
3. the intermediate rocks from the bottom of CRD 88-1 are doleritic in texture and are part of an intrusive body.

These conclusions do not provide favourable comment for future work in the vicinity of the drill holes. Certainly the lack of pyrite and base metals in the system is a major negative feature and would tend to support the concept of a localized low temperature alteration system.

5.5 Down Hole EM

Down hole surveying of drill holes CRP 88-3, CRD 88-1 was carried out under the following specifications:

CRD 88-1 (5900N, 12005E) 306m total depth
Tx Loop co-ords: 6000N, 5800N
(200 x 200m) 11950E, 12150E
Reading interval 10 metres

CRP 88-3 (10600N, 10537E) 72m total depth
Tx Loop co-ords: 10650N, 10550N
(100 x 100m) 10590E, 10490E

Down hole profiles are attached in Appendix 5. Although no detailed modelling has been carried out, the following comments by N. Hungerford are made:

The profile down CRP 88-3 indicates a conductive zone in the basalt at about 45 metres. This is coincident with a clay layer which probably explains the down-hole anomaly. The Max-Min anomaly could well have the same cause.

The shallow conductive zones in CRD 88-1 may be due to weathering (clays) in the contact (fault?) logged at about 35 metres depth. An off-hole conductor is indicated at the end of the hole, but since the anomaly is not completely covered, further down-hole work is required to determine where the conductive source might be.

6. CONCLUSIONS & RECOMMENDATIONS

Percussion drilling to determine the presence of the postulated Cattley Fault was unsuccessful in that thick post Cambrian poorly consolidated gravels prevented penetration. Similarly, percussion drilling of an EM anomaly was not definitive although the source of the response is most probably due to thick river wash deposits.

Whole rock and trace element analyses from drill core and rock chips have quantified the extent of alteration observed in core. The pronounced carbonate-sericite alteration and Na_2O depletion in CRD 86-1 is most probably a local feature related to the presence of acid intrusive bodies. This conclusion is supported by oxygen isotopic determinations that suggest the alteration system is a low temperature localized one related to intrusion of these same intrusives.

The identification of dacitic lavas in drill hole CRD 88-1 is disputed by both the regional mapping team (Pemberton 1988) and Dr. G. Green. The latter workers consider the intermediate rocks to be intrusive in form and doleritic in texture.

Lead isotopic analyses of mineralized samples from the licence area suggest a Cambrian signature identical with that of known VMS deposits. This is positive evidence of a Cambrian mineralizing event but may be a function of local diagenesis or localized hydrothermal activity only.

Results of a recently completed down hole EM survey of CRD 88-1 indicate the presence of an off hole conductor at the end of the drill hole. The orientation and characteristics of this conductor are unknown and further EM work is required to fully evaluate this anomaly. It is an unusual feature, however, as no EM response from the ground survey was recorded.

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APPENDIX 1

Whole Rock & Trace Element Analyses



technology and enterprise

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NATA CERTIFICATE

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4 October 1988

Mr Trevor Francis
Classic Comlabs Limited
305 South Road
MILE END SOUTH SA 5031

REPORT AC 832/89

YOUR REFERENCE:	8AD3153
REPORT COMPRISING:	Cover sheet Pages I1 - I8
DATE RECEIVED:	29 September 1988
Approved Signatory:	Don Patterson

*Rock chips
Whole Rock
(to accompany
Comlabs 8AD3153)*

Manager, Chemistry Services
for Dr William G. Spencer
General Manager
Applied Sciences Group

The report relates specifically to the sample tested and also the entire batch in so far as the sample is truly representative of the sample source.

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Analysis code ORE 2/1

Report AC 832/89

Page 11

NATA Certificate

Results in percentages

	14380	14381	14382	14383	14384
SiO ₂	66.8	72.7	73.0	73.5	73.2
TiO ₂	0.48	1.06	0.23	0.20	0.24
Al ₂ O ₃	15.0	14.2	12.3	11.9	14.9
Fe ₂ O ₃	5.20	2.56	5.50	5.50	4.00
MnO	0.03	<0.01	0.82	1.09	0.07
MgO	1.76	0.75	0.47	0.36	0.43
CaO	0.09	0.09	0.09	0.03	<0.01
Na ₂ O	2.88	0.13	0.14	0.08	0.07
20	4.32	4.04	3.82	3.60	4.52
P ₂ O ₅	0.09	0.18	0.04	0.04	0.03
LOI	3.00	3.82	3.90	3.26	3.32
Totals	99.6	99.5	100.3	99.6	100.8

Total FE as Fe₂O₃

022

Analysis code ORE 2/1 Report AC 832/89

Page 12

NATA Certificate

Results in percentages

	14385	14386	14387	14388	14389
SiO ₂	76.0	75.3	64.8	68.6	79.8
TiO ₂	0.11	0.28	0.94	1.01	0.23
Al ₂ O ₃	10.8	14.7	15.9	15.0	12.2
Fe ₂ O ₃	4.44	1.83	7.30	4.90	1.46
MnO	0.75	0.01	0.04	0.02	<0.01
MgO	0.30	0.44	0.96	0.89	0.38
CaO	<0.01	<0.01	0.02	<0.01	<0.01
Na ₂ O	0.09	0.08	0.10	0.13	0.07
K ₂ O	3.40	4.64	3.40	4.32	2.12
P ₂ O ₅	0.02	0.03	0.09	0.12	0.03
LOI	2.94	2.86	6.05	4.48	4.52
Totals	98.8	100.2	99.6	99.5	100.8

 Total FE as Fe₂O₃

Analysis code ORE 2/1

Report AC 832/89

Page 13

NATA Certificate

Results in percentages

	14390	14391	14392	14393	14394
SiO ₂	73.2	70.6	66.3	65.1	67.0
TiO ₂	0.35	0.34	0.54	0.39	0.40
Al ₂ O ₃	14.9	15.1	18.3	18.5	17.7
Fe ₂ O ₃	2.62	3.14	3.52	3.96	3.68
MnO	<0.01	0.01	0.09	0.03	0.12
MgO	0.40	0.69	0.84	1.08	0.91
CaO	<0.01	<0.01	<0.01	<0.01	<0.01
Na ₂ O	0.47	0.88	0.14	0.57	0.25
K ₂ O	3.82	4.22	4.12	4.92	3.28
P ₂ O ₅	0.03	0.03	0.06	0.06	0.04
LOI	5.10	4.86	6.90	6.40	7.20
Totals	100.9	99.9	100.8	101.0	100.6

Total FE as Fe₂O₃

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Analysis code ORE 2/1

Report AC 832/89

Page 14

NATA Certificate

Results in percentages

	14395	14396	14397	14398	14399
SiO ₂	71.5	73.3	78.0	73.4	67.4
TiO ₂	0.37	0.30	0.54	0.28	0.35
Al ₂ O ₃	15.9	14.6	11.0	15.2	19.6
Fe ₂ O ₃	2.42	2.90	2.68	2.22	1.51
MnO	0.06	0.04	<0.01	<0.01	<0.01
MgO	0.76	0.63	0.71	0.35	0.69
CaO	<0.01	<0.01	<0.01	<0.01	<0.01
Na ₂ O	0.09	0.08	0.11	0.06	0.04
K ₂ O	3.60	2.94	2.24	1.59	3.50
P ₂ O ₅	0.04	0.04	0.04	0.03	0.02
LOI	5.20	5.35	4.00	6.45	6.80
Totals	99.9	100.2	99.3	99.6	99.9

Total FE as Fe₂O₃

025

Analysis code ORE 2/1

Report AC 832/89

Page 15

NATA Certificate

Results in percentages

	14400	16001	16002	16003	16004
SiO ₂	76.4	62.9	71.9	78.2	76.0
TiO ₂	0.16	1.27	0.33	0.24	0.43
Al ₂ O ₃	14.1	16.9	14.1	12.0	13.4
Fe ₂ O ₃	0.97	8.50	5.25	2.74	2.66
MnO	<0.01	0.01	0.11	0.01	<0.01
MgO	0.36	0.87	0.47	0.57	0.51
CaO	<0.01	<0.01	<0.01	<0.01	<0.01
Na ₂ O	0.14	0.29	0.34	0.19	0.15
K ₂ O	3.82	2.98	3.20	2.62	3.84
P ₂ O ₅	<0.01	0.28	0.03	0.04	0.03
LOI	3.24	6.20	3.82	3.42	3.24
Totals	99.2	100.2	99.5	100.0	100.2

Total FE as Fe₂O₃

026

Analysis code ORE 2/1 Report AC 832/89

Page 16

NATA Certificate

Results in percentages

	16005	16006	16007	16008	16009
SiO ₂	69.1	66.5	73.1	72.8	80.0
TiO ₂	1.16	0.97	0.19	0.47	0.18
Al ₂ O ₃	17.3	15.0	16.2	12.4	8.45
Fe ₂ O ₃	2.28	7.45	2.54	5.45	4.42
MnO	<0.01	<0.01	<0.01	0.04	<0.01
MgO	0.79	0.91	0.50	0.86	0.36
CaO	<0.01	<0.01	<0.01	0.08	<0.01
Na ₂ O	0.20	0.11	0.40	0.14	0.12
K ₂ O	5.20	3.62	4.06	3.90	2.60
P ₂ O ₅	0.05	0.05	0.05	0.09	0.02
LOI	3.48	5.25	3.66	3.86	2.74
Totals	99.5	99.8	100.7	100.1	98.9

 Total FE as Fe₂O₃

027

Analysis code ORE 2/1

Report AC 832/89

Page 17

NATA Certificate

Results in percentages

	16011	16013	16014	16015	16016
SiO ₂	84.7	74.6	78.1	69.1	79.3
TiO ₂	0.16	0.30	0.37	0.55	0.22
Al ₂ O ₃	7.85	12.2	11.0	13.8	11.1
Fe ₂ O ₃	1.59	3.28	3.86	5.55	1.32
MnO	<0.01	<0.01	<0.01	0.14	<0.01
MgO	0.40	0.43	0.75	0.94	0.65
CaO	<0.01	<0.01	<0.01	0.01	<0.01
a ₂ O	0.15	0.44	1.09	0.03	<0.01
K ₂ O	2.12	3.50	2.56	4.24	3.58
P ₂ O ₅	0.02	0.03	0.06	0.11	0.03
LOI	2.28	3.28	3.04	4.32	2.86
Totals	99.2	98.0	100.8	98.8	99.0

 Total FE as Fe₂O₃

028

Analysis code ORE 2/1

Report AC 832/89

Page 18

NATA Certificate

Results in percentages

	16017	16018	16019
SiO ₂	76.7	70.6	74.3
TiO ₂	0.23	0.44	0.26
Al ₂ O ₃	12.7	15.6	14.0
Fe ₂ O ₃	1.47	2.02	1.48
MnO	0.01	<0.01	<0.01
MgO	0.60	0.84	0.52
CaO	<0.01	<0.01	<0.01
La ₂ O	<0.01	<0.01	<0.01
K ₂ O	4.42	4.94	4.36
P ₂ O ₅	0.04	0.09	<0.01
LOI	2.92	3.94	3.14
Totals	99.1	98.4	98.0

Total FE as Fe₂O₃



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Mr. David Hall
Billiton Australia Ltd
30 Mersey Main Rd
Spreyton
DEVONPORT
TAS 7310 Australia

JOB NUMBER: 8AD3153

Your Reference: 11638/LD51/JPR

Date Received: 26-SEP-1988 Turnaround 16 days
Date Relayed: 12-OCT-1988
Date Reported: 12-OCT-1988

Number of Samples: 38 Report Analyte Codes
N.A. - Not Analysed.
L.N.R. - Listed But Not Received.
I.S. - Insufficient Sample for Analysis.

Report Comprising: Cover Sheet
Pages 1 to 4

Comments:

Please find enclosed an Amdel Report for Job No: 8AD3153.

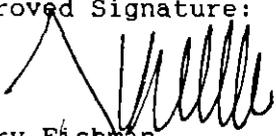
*Rock Chips
- trace elements.*

Report Dist'n: Carbon Copies(CC), Electronic Media(EM), Magnetic Media(MM)

Type	Recipient	Location	Date	Copies
MM	SHELL	DEVONPORT	12-OCT-88	1

Approved Signature:

for


Harry Fishman
Managing Director.
CLASSIC COMLABS LTD

(Please address any enquiries to Mr. Trevor Francis)

This report relates specifically to the sample(s) tested in so far as that the sample(s) is truly representative of the sample source as supplied.



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Analytical Laboratories (INC. IN WA)

305 South Road, Mile End South, South Australia, 5031
Telephone: (08) 43 5722 Fax: (08) 234 0321 Telex: LABCOM AA89323



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Job: 8AD3153

O/N: 11638/LD51/JPR

608031

030

ANALYTICAL REPORT

SAMPLE	Ba	Sr	Rb	La	Zr	Nb	Y	AMQ
5900N 11675E 14380 ✓ <i>CvLa</i>	1020	100	130	40	200	10	22	402310, 5406330
" 12485E 14381 ✓	550	16	165	40	135	13	32	402980, 5405890
5750N 12440E 14382 ✓	560	4	125	70	250	17	44	402860, 5405790
" " 14383 ✓	510	5	125	60	240	16	40	" , "
" " 14384 ✓	560	6	160	60	300	22	52	" , "
" " 14385 ✓	460	5	125	50	200	16	34	" , "
" " 14386 ✓	640	5	150	70	280	19	34	" , "
5650N 12370E 14387 ✓	430	14	150	50	150	15	12	402750, 5405750
5600N 12300E 14388 ✓	530	17	180	50	150	14	14	402660, 5405740
5525N 12260E 14389 ✓	135	5	86	50	175	13	18	402590, 5405700
5510N 12150E 14390 ✓ <i>Cvrdq</i>	420	16	150	60	230	12	22	402490, 5405750
5480N 11975E 14391 ✓ <i>Cvrdq</i>	850	16	125	50	220	12	22	402330, 5405820
5500N 11860E 14392 ✓ <i>Cvld</i>	480	20	190	60	300	13	22	402240, 5405900
5470N 11690E 14393 ✓ <i>CvLa</i>	620	24	185	70	290	18	30	402080, 5405970
Track E of Cuvlin 14394 ✓	290	6	160	60	300	17	26	---
5730N 11640E 14395 ✓ <i>CvLa</i>	250	7	180	80	270	16	32	402190, 5406210
9710N 9590E 14396 ✓	380	8	155	60	320	19	34	---
9600N 10200E 14397 ✓	280	10	88	20	220	12	16	403120, 5410220
9280N 10500E 14398 ✓	135	4	92	70	290	19	32	403180, 5409790
10600N 11440E 14399 ✓	220	3	200	50	250	17	28	404690, 5410380
10600N 11640E 14400 ✓	260	3	110	40	270	19	24	404900, 5410250
10470N 11770E 16001 ✓	320	32	120	50	250	14	28	403010, 5410250
10800N 11890E 16002 ✓	440	20	115	60	320	18	34	405180, 5410300
10940N 11900E 16003 ✓	330	16	94	90	250	17	32	405270, 5410410
20160N 51310E 16004 ✓	340	11	130	50	220	17	24	---
UNITS	ppm							
SCHEME	XRF1							



031

ANALYTICAL REPORT

SAMPLE	Ba	Sr	Rb	La	Zr	Nb	Y	E	N
20430N 51280E 16005 ✓ <i>silty</i>	660	26	195	50	165	16	18	405400, 5411380	
20630N 50840E 16006 ✓ <i>fine gr. calc</i>	370	26	160	40	140	14	16	404860, 5411730	
20580N 50620E 16007 ✓ <i>calc</i>	440	20	155	80	145	14	6	404560, 5411850	
20540N 50570E 16008 ✓ <i>block</i>	760	18	165	40	150	12	16	404510, 5411860	
20530N 50550E 16009 ✓ <i>cup</i>	830	2	94	40	110	8	14	404480, 5411850	
20600N 50430E 16011 ✓ <i>calc</i>	195	7	105	50	130	9	14	404410, 5411970	
20660N 50400E 16013 ✓	270	7	150	40	195	10	22	404420, 5412030	
20800N 50320E 16014 ✓	430	11	135	50	210	10	24	-	
20890N 50160E 16015 ✓	670	8	230	50	230	10	24	-	
Two Hummocks 16016 ✗	250	10	190	50	165	14	26	-	
" " 16017 ✓	440	9	195	60	180	15	22	-	
" " 16018 ✗	740	16	280	60	290	13	26	-	
" " 16019 ✓	185	8	195	60	220	16	26	✓	

UNITS SCHEME	ppm XRF1						
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Job: 8AD3153
O/N: 11638/LD51/JPR

032

ANALYTICAL REPORT

SAMPLE	Ce
14380	50
14381	60
14382	100
14383	110
14384	80
14385	80
14386	80
14387	70
14388	50
14389	60
14390	70
14391	70
14392	80
14393	100
14394	70
14395	80
14396	100
14397	50
14398	90
14399	50
14400	50
16001	80
16002	90
16003	110
16004	70
UNITS	ppm
SCHEME	XRF1



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Job: 8AD3153

O/N: 11638/LD51/JPR

ANALYTICAL REPORT

033

SAMPLE	Ce
16005	50
16006	40
16007	90
16008	50
16009	40
16011	40
16013	60
16014	80
16015	70
16016	80
16017	70
16018	80
16019	70
UNITS	ppm
SCHEME	XRF1



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Telephone: (08) 43 5722 Fax: (08) 234 0321 Telex: LABCOM AA89323

034

File
LD51
846

Mr. David Hall
Billiton Australia Ltd
30 Mersey Main Rd
Spreyton
DEVONPORT
TAS 7310 Australia

JOB NUMBER: 8AD2392.

Your Reference: 11635/LD51/JPR

Date Received: 18-JUL-1988

Turnaround 36 days

Date Relayed: 23-AUG-1988

Date Reported: 23-AUG-1988

Number of Samples: 31

Report Analyte Codes

N.A. - Not Analysed.

L.N.R. - Listed But Not Received.

I.S. - Insufficient Sample for Analysis.

Report Comprising: Cover Sheet
Pages 1 to 6

Comments:

CRD 88-1
White Rock
+ Sr Ba Zr Rb

Report Dist'n: Carbon Copies(CC), Electronic Media(EM), Magnetic Media(MM)
Type Recipient Location Date Copies

Approved Signature:

for

Harry Fishman
Managing Director.
CLASSIC COMLABS LTD
(Please address any enquiries to Mr. Trevor Francis)

This report relates specifically to the sample(s) tested in so far as that the sample(s) is truly representative of the sample source as supplied.



035

Job: 8AD2392
O/N: 11635/LD51/JPR

ANALYTICAL REPORT

SAMPLE	Fe2O3	MnO	TiO2	CaO	K2O	P2O5	SiO2
REV 8F-1 40-4/m 17610	2.98	0.12	0.41	2.40	3.44	0.08	64.7
50-51/m 17620	3.00	0.13	0.38	1.39	2.88	0.06	69.0
60-61/m 17630	2.92	0.18	0.35	3.10	1.79	0.06	65.4
70-71/m 17640	3.52	0.10	0.39	0.80	3.04	0.07	64.1
80-81/m 17650	3.94	0.15	0.42	1.97	3.66	0.07	63.3
90-91/m 17660	2.92	0.13	0.39	1.77	4.62	0.05	69.0
100-101/m 17669	1.64	0.05	0.21	0.66	4.12	0.02	75.2
110-111/m 17679	2.14	0.03	0.23	0.15	3.56	0.02	75.4
120-121/m 17689	1.53	0.04	0.23	0.76	5.30	0.01	74.4
130-131/m 17699	1.81	0.10	0.20	1.18	3.24	0.02	74.0
139 8-140-61-17708	6.20	0.22	0.48	3.40	1.95	0.07	64.5
150-151/m 17719	2.36	0.13	0.24	1.65	4.82	0.04	73.3
160-161/m 17729	1.70	0.11	0.25	1.67	3.50	0.03	73.4
170-171/m 17739	5.10	0.13	0.47	0.97	5.35	0.11	66.5
179 4-180-17748	10.8	1.41	0.14	21.8	1.45	0.03	21.8
185-186/m 17754	2.36	0.11	0.27	2.04	5.00	0.05	71.0
220-221/m 17761	2.94	0.07	0.28	0.51	4.30	0.03	71.8
230-231/m 17771	4.70	0.09	0.45	1.18	5.15	0.11	67.1
242-243/m 17783	3.04	0.11	0.28	1.34	2.86	0.04	72.3
247-248/m 17788	4.78	0.12	0.45	1.86	4.62	0.12	66.4
255-256/m 17796	2.90	0.07	0.24	0.65	5.05	0.03	74.5
265-266/m 17806	6.35	0.48	0.24	7.90	3.08	0.03	55.7
292-293/m 17813	3.88	0.33	0.18	5.00	3.42	0.01	63.2
30/m 17815	3.28	0.06	0.28	0.16	3.80	0.06	74.3
310/m 17816	3.22	0.12	0.29	1.13	2.90	0.08	72.5
UNITS	%	%	%	%	%	%	%
SCHEME	XRF4	XRF4	XRF4	XRF4	XRF4	XRF4	XRF4



036

Job: 8AD2392
O/N: 11635/LD51/JPR

ANALYTICAL REPORT

SAMPLE	Fe2O3	MnO	TiO2	CaO	K2O	P2O5	SiO2
30m 17817	2.76	0.06	0.36	0.98	6.10	0.07	70.0
200m 17818	7.10	0.22	0.50	7.85	2.14	0.13	48.6
210m 17819	8.30	0.15	0.57	4.20	2.46	0.14	52.2
275m 17820	4.74	0.13	0.45	2.70	4.00	0.13	65.9
285m 17821	4.04	0.07	0.52	1.16	5.45	0.14	66.3
305m 17822	5.75	0.13	0.44	1.52	4.36	0.12	65.1
UNITS	%	%	%	%	%	%	%
SCHEME	XRF4	XRF4	XRF4	XRF4	XRF4	XRF4	XRF4



Job: 8AD2392
O/N: 11635/LD51/JPR

037

ANALYTICAL REPORT

SAMPLE	Al2O3	MgO	Na2O	LOI
17610	16.7	0.89	4.04	4.00
17620	14.6	1.18	4.14	3.16
17630	15.1	1.28	4.72	4.96
17640	17.7	2.38	4.32	3.46
17650	15.9	1.46	3.82	4.82
17660	13.3	1.31	2.58	3.82
17669	12.3	0.66	2.40	2.56
17679	12.9	0.89	2.52	2.14
17689	12.5	0.62	1.59	2.92
17699	11.5	1.79	2.84	2.96
17708	10.6	3.48	0.97	8.00
17719	10.7	1.01	2.00	3.26
17729	11.2	0.91	2.76	3.58
17739	13.9	1.44	2.10	3.92
17748	3.78	8.05	0.06	30.1
17754	11.8	1.23	2.14	3.92
17761	12.9	1.21	2.88	2.74
17771	13.8	1.64	2.92	2.82
17783	11.9	1.31	3.12	3.44
17788	13.8	1.54	2.48	3.70
17796	11.6	1.24	0.70	2.84
17806	9.20	3.18	0.72	13.0
17813	10.5	2.22	2.52	8.75
17815	12.9	0.64	2.46	2.02
17816	12.4	0.98	3.48	2.84
UNITS	%	%	%	%
SCHEME	XRF4	XRF4	XRF4	XRF4



Job: 8AD2392
O/N: 11635/LD51/JPR

038

ANALYTICAL REPORT

SAMPLE	Al2O3	MgO	Na2O	LOI
17817	14.4	1.10	1.05	3.00
17818	12.3	7.55	2.62	10.9
17819	14.5	7.00	2.90	7.50
17820	13.3	1.81	2.26	4.40
17821	15.3	1.60	2.04	3.34
17822	13.5	2.56	2.78	3.74
UNITS	%	%	%	%
SCHEME	XRF4	XRF4	XRF4	XRF4



Job: 8AD2392
O/N: 11635/LD51/JPR

039

ANALYTICAL REPORT

SAMPLE	Sr	Ba	Zr	Rb
17610	125	640	270	140
17620	155	490	260	130
17630	130	290	230	98
17640	120	860	250	150
17650	105	820	240	165
17660	64	1320	230	195
17669	42	1080	180	165
17679	50	620	195	150
17689	42	1240	190	210
17699	62	490	175	130
17708	30	320	145	64
17719	36	650	190	120
17729	32	540	220	115
17739	56	1040	200	175
17748	110	230	34	62
17754	54	1000	170	115
17761	48	950	220	140
17771	68	1560	185	125
17783	70	490	220	105
17788	66	1120	180	145
17796	34	850	190	180
17806	105	440	140	105
17813	54	590	165	105
17815	60	890	200	105
17816	82	570	195	76
UNITS	ppm	ppm	ppm	ppm
SCHEME	XRF1	XRF1	XRF1	XRF1



040

Job: 8AD2392
O/N: 11635/LD51/JPR

ANALYTICAL REPORT

SAMPLE	Sr	Ba	Zr	Rb
17817	20	760	220	195
17818	280	970	72	64
17819	105	860	92	68
17820	80	800	180	125
17821	66	890	210	175
17822	98	810	175	130
UNITS	ppm	ppm	ppm	ppm
SCHEME	XRF1	XRF1	XRF1	XRF1

APPENDIX 2

Lead Isotope Compositions. Report by CSIRO

042

Sirotope



CSIRO
AUSTRALIA

608043

Division of Exploration Geoscience

Delhi Road, North Ryde, NSW. Postal Address: PO Box 136, North Ryde NSW 2113
Telephone (02) 887 8666. Telex AA25817. Fax (02) 887 8909

Chief: Dr BJJ. Embleton

REPORT TO SHELL AUSTRALIA

ON

THE Pb

ISOTOPE COMPOSITIONS

OF

EXPLORATION SAMPLES

FROM THE Mt READ VOLCANICS

NORTHWEST TASMANIA

GRAHAM R. CARR
21/10/88

R e s e a r c h A d v a n c i n g A u s t r a l i a

Floreat Park

Location: Underwood Avenue, Floreat Park
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Telephone: (09) 387 4233
Telex: AA92178
Fax: (09) 387 6046

Lindfield

Location: Bradfield Road, Lindfield
Postal Address: PO Box 218, Lindfield NSW 2070
Telephone: (02) 467 6733
Telex: AA26296
Fax: (02) 467 1902

SUMMARY

THE Pb ISOTOPE COMPOSITIONS OF EXPLORATION SAMPLES FROM THE CATTLEY RANGE ARE CONSISTENT WITH DERIVATION FROM FLUIDS WITH A SIMILAR ORIGIN TO THOSE RESPONSIBLE FOR THE FORMATION OF THE CAMBRIAN MASSIVE SULFIDE DEPOSITS OF THE REGION. IN CONTRAST, LAKESIDE, MURCHISON MINE SITE AND THE STERLING VALLEY MINE ALL HAVE A HIGH PROBABILITY OF BEING RELATED TO DEVONIAN THERMAL EVENTS.

1. AIM

The aim of this study has been to determine the Pb isotopic compositions of geological exploration samples from the Cattley Range, Lakeside, Murchison Mine site and Sterling Valley Mine site in northeastern Tasmania and compare them with the known signatures for volcanogenic mineralization associated with the Mt Read Volcanics and vein mineralization associated with Devonian thermal events.

2. SAMPLES

A total of 13 samples from the 4 prospects were received for analysis (Table 1). The Pb contents varied from 650ppm to over 30%.

3. TARGET SIGNATURES

The Pb isotopic signature of mineralization from this region has been thoroughly studied over the past decade. Massive sulfide mineralization such as Rosebery, Que River and Hellyer have homogeneous isotopic compositions. On Figures 1 and 2 the data from each of these deposits are represented by 95% confidence ellipses which plot as overlapping fields. Devonian vein mineralization on the other hand is generally far less homogeneous in any one deposit (see for e.g the range for Queen Hill mineralization in Figs. 1 and 2) and there is broad range of distributions with $^{206}\text{Pb}/^{204}\text{Pb}$ values of between about 18.43 to over 18.7.

4. METHODS

A 0.1g subsample of the pulverised drill core material was leached in a solution of 7N HNO_3 + 7N HCl in sealed Savillex teflon beakers. The solutions were centrifuged and passed through

anion exchange resin columns prior to electroplating onto Pt electrodes. The two galena samples were dissolved in HNO_3 prior to electroplating as above. The purified Pb was analysed for its isotopic composition on a VG Isomass 54E solid source mass spectrometer in fully automated mode. The precision estimates of the method are presented graphically in the top left hand corner of the accompanying diagrams and are based on over 1000 analyses of standards.

5. RESULTS

1. Of the 6 samples from the Cattley Range prospect, 5 form a homogeneous cluster which overlaps the Cambrian massive sulfide signatures (Table 2, Figs 1 and 2). Sample Cattley 3 (10400N, 11792E) contains a higher proportion of radiogenic Pb (i.e. higher $6/4$ etc.) and plots outside the Cambrian signature and at the least radiogenic end of the Devonian fields.

2. The Lakeside and Murchison mine site samples have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of greater than about 18.6. On both Figures 1 and 2 they plot in or near the field for Devonian mineralization at Queen Hill.

3. The Sterling Valley mine site samples plot between the Cambrian massive sulfide and the Queen Hill signatures. Other Devonian mineralization such as Mt Farrell have similar isotopic compositions.

6. DISCUSSION AND CONCLUSIONS

1. The Pb isotopic composition of the Cattley Range mineralization is consistent with derivation from fluids with a similar origin to those responsible for the formation of the

Cambrian massive sulfide deposits of the region. The single Cattley Range sample which contains more radiogenic Pb than the the Cambrian Massive sulfides may indicate overprinting by Devonian vein mineralization or it may result from radiogenic addition of Pb since the Cambrian due to higher than normal U contents. Whichever explanation is correct, this single enigmatic result does not detract from the relatively high exploration priority that is assigned to this prospect.

The possibility that the Cambrian signature at Cattley Range is related to the intrusion of granitoids can only be addressed indirectly. There is no information in the SIROTOPE database on mineralization that has been definitely ascribed to the Cambrian granitoids. Mineralization such as at Lake Selina which may be related to plutonic rather than volcanic events has similar isotopic compositions to the massive sulfide signatures. We would expect there to be some isotopic contrast between two such events, especially in the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios. Until we have hard information on the isotopic composition of the granites we can only suggest that mineralization that has the massive sulfide signature and can be seen to be associated with the Mt Read Volcanics is unlikely to be related to Cambrian granites.

2. Mineralization at Lakeside, Murchison Mine site and Sterling Valley mine site all have a high probability of being related to Devonian thermal events and as such would be considered to have only a low probability of representing significant base metal resources.

047

TABLE I

LEAD ISOTOPE SAMPLES

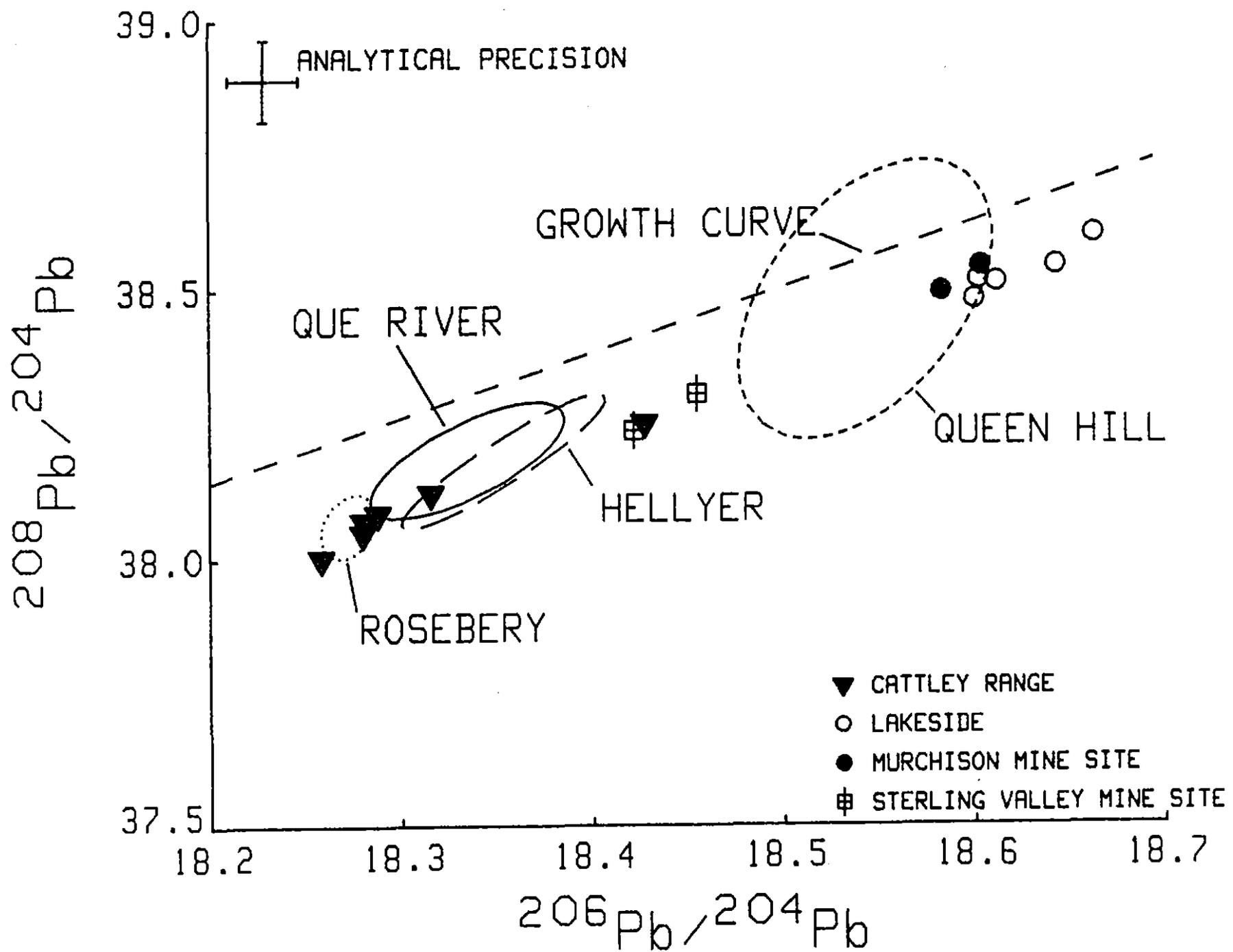
<u>PROJECT</u>	<u>LOCATION</u>	<u>SAMPLE NO</u>	<u>SAMPLE TYPE</u>	<u>PB ASSAY</u>
CATTLEY RANGE	10400N 11757.5E		Costean	1020ppm
	2 10400N 11792E		Costean	1040ppm
	3 9600N 11105E		Costean	880ppm
	4 10600N 11750E		Auger	910ppm
	5 10400N 11750E		Auger	650ppm
	6 CRD86-1 191.8-193.8m	13526	Drill Core	1700ppm
LAKESIDE	RED 87-3 112-113m	14055	Drill Core	0.23%
	RED 87-6 118.6-119.9m	13832	Drill Core	0.71%
	RED 86-1 126.05-126.9m	13631	Drill Core	30.7%
MURCHISON	Mine Site	MP30-250	Drill Core	3250
		MP32-323.6	Drill Core	1850
STERLING VALLEY	Mine Site	3036	Rock Chip	2.72%
		3039	Rock Chip	12.43%

Table 2. Lead isotope ratios of Mt Read Volcanic samples - Billiton.

Sample	$\frac{208 \text{ Pb}}{206 \text{ Pb}}$	$\frac{207 \text{ Pb}}{206 \text{ Pb}}$	$\frac{206 \text{ Pb}}{204 \text{ Pb}}$	$\frac{207 \text{ Pb}}{204 \text{ Pb}}$	$\frac{208 \text{ Pb}}{204 \text{ Pb}}$	Pb(ppm)
<u>CATTLEY RANGE</u>						
CATTLEY 1	2.0813	0.8523	18.280	15.581	38.048	85
CATTLEY 2	2.0757	0.8468	18.428	15.604	38.250	87
CATTLEY 3	2.0825	0.8524	18.281	15.583	38.069	85
CATTLEY 4	2.0813	0.8527	18.258	15.569	38.000	88
CATTLEY 5	2.0813	0.8515	18.316	15.596	38.121	99
CATTLEY 6	2.0824	0.8528	18.288	15.596	38.084	1,01
<u>RESIDE</u>						
L'SIDE 14055	2.0703	0.8396	18.603	15.619	38.515	
L'SIDE 13832	2.0672	0.8373	18.644	15.611	38.541	
L'SIDE 13832R	2.0681	0.8375	18.663	15.631	38.599	
L'SIDE 13631	2.0690	0.8387	18.612	15.610	38.509	
L'SIDE 13631R	2.0686	0.8388	18.601	15.603	38.477	
<u>MURCHISON MINE SITE</u>						
MURCHISON 30	2.0713	0.8401	18.584	15.612	38.492	
MURCHISON 32	2.0716	0.8401	18.604	15.629	38.540	
<u>STERLING VALLEY MINE SITE</u>						
STERL V 3036	2.0755	0.8458	18.455	15.609	38.305	
STERL V 3039	2.0756	0.8464	18.422	15.592	38.236	

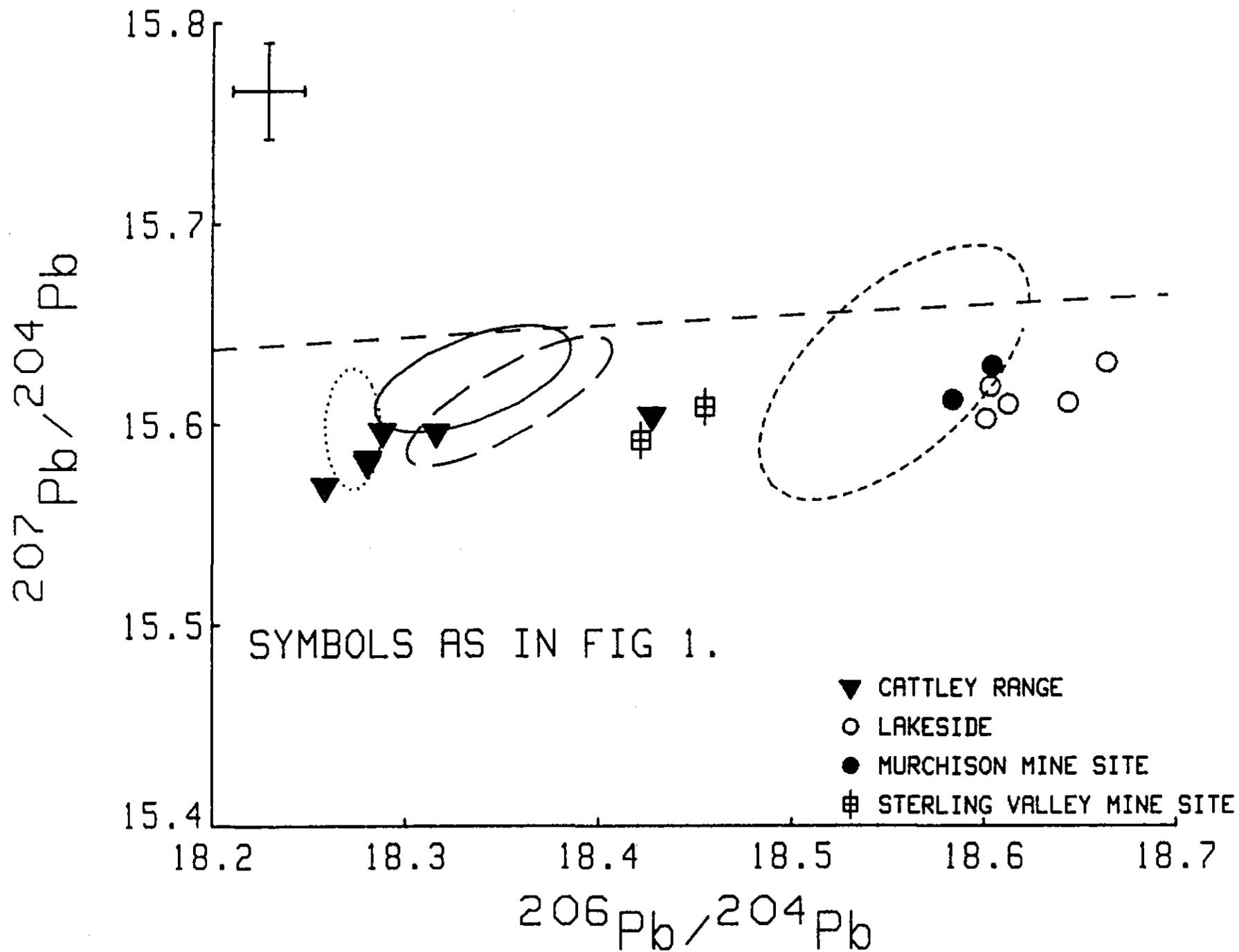
"R" denotes repeat analysis.

Pb contents for Cattley Range determined by isotope dilution.



049

608050



050

608051

APPENDIX 3

Oxygen Isotope & Petrological Investigation of
altered Rocks in the Cattley Range Area



MINES CONSULTANCY SERVICES

**Oxygen isotope and petrological
investigation of altered rocks in the
Cattley Range area, north-west Tasmania
: A report for Billiton Australia**

Author: GEOFFREY R. GREEN

Date: MARCH 1989

TASMANIA DEPARTMENT OF MINES

Oxygen isotope and petrological investigation of altered rocks in the Cattley Range area, north-west Tasmania : A report for Billiton Australia

by G. R. GREEN, B.Sc (Hons), Ph.D.

SUMMARY AND CONCLUSIONS

$\delta^{18}\text{O}$ values from drill hole CRD 86-1 show an increase from the margins of the dacite intrusive (approximately 14‰) to 16 and 18‰, corrected for phenocryst quartz in rocks 17 m and 80 m from the contact. These high $\delta^{18}\text{O}$ values reflect alteration at low temperatures of less than 100°C if seawater ($\delta^{18}\text{O}=0\text{‰}$) was the altering fluid, or about 170°C for a fluid with a typically magmatic $\delta^{18}\text{O}$ value of 7‰. Temperatures in the contact zone of the dacite would have been 135°C or 250°C for these respective cases.

Rocks from CRD 86-1 have pervasively sericitised and carbonated feldspars. The alteration and mineralisation in the drill hole preceded cleavage development, and some textural evidence suggests it was probably syndiagenetic. Rocks with $\delta^{18}\text{O}$ values of 14‰ or more around massive sulphide deposits are in the fringes of the alteration system, and show negligible alteration of feldspar. It is suggested that the alteration and minor mineralisation intersected in CRD 86-1 was a local feature related to the dacite intrusive. This is consistent with the low pyrite content of the rocks, the distribution of the minor base metal mineralisation, and the whole rock geochemical data.

Rocks from CRD 88-1 display only very minor alteration of feldspars. $\delta^{18}\text{O}$ values of 12.1 to 13.7‰ probably reflect alteration under lower water/rock ratio conditions than in the area of CRD 86-1.

Some comparisons have been made of the more mafic rocks from CRD 88-1 with the regional units mapped by Pemberton and Vicary (1988).

INTRODUCTION

At the request of Mr J. P. Randell of Billiton Australia Limited an investigation of alteration

in rocks in the Cattley Range area, drilled by the company in 1986 and 1988, was made. The investigation involved examination of core, petrography and oxygen isotope analysis of seven whole-rock samples. To avoid unnecessary repetition, most of the theory is covered in Appendix 3 (pp. 407-410, fig. 6).

RESULTS

1. Core Examination

Only a cursory examination was made of the core, and in the main the observations, particularly those relating to the facies of the sequence in both holes, agree well with those of Jeff Randell. In hole CRD 86-1 minor sphalerite and galena was observed in the contact zone of the dacite body (89.2-90.6 m). When I looked at the core, I suspected that the main dacite body (90.6-191.8 m) might be a lava, mainly on the basis of 10 mm rounded clasts of chert and black mudstone in the basal 150 mm. Critical information on the basal contact is obscured by slickensided quartz-chlorite veining. However, Billiton's geochemical results are more consistent with Jeff Randell's interpretation that the body is an intrusive. The breccia-volcaniclastic unit from 204.8 to 239 m is regarded as a single depositional unit.

In hole 88-1, a coarsening of grain size discernible under the hand lens in the "andesite lava" between 187.0 and 196.3 m suggests that this body could be a dyke. The textures in the thin section at 214.3 m are consistent with this proposal (Appendix 2).

2. Petrography

A few specimens were selected for possible oxygen isotope analysis. Polished thin sections of these rocks were prepared and examined to determine their suitability for isotope analysis, and to investigate the timing of alteration with

respect to rock deformation and cleavage formation.

The necessity of the second approach is obvious: all massive sulphide deposits in the Mount Read Volcanics and associated alteration systems were produced in the Cambrian, and therefore pre-date the major Devonian deformation events in the Mount Cattley area. A necessary condition for Cambrian alteration is that it should be affected by later cleavage and deformation: this should be detectable at the thin section scale.

The first approach is designed to determine the nature and extent of mineralogical interferences which are likely to cloud interpretation of oxygen isotope data. Some minerals preserve their oxygen isotope values through alteration events. In the content of rocks in the Mount Cattley area the main problem is likely to be quartz. Quartz, once formed, is very slow to exchange oxygen isotopes. Therefore, in order to understand the extent of Cambrian alteration, it is necessary to estimate the proportions of the following:

1. Phenocryst quartz ($\delta^{18}\text{O}$ of about 8‰, unaffected by alteration)
2. Precambrian detrital quartz—common in some greywacke in the area
3. Post-cleavage veins.

In practice it was found that only phenocryst quartz was significant. It is relatively simple to correct for this effect in the rocks by the equation:

$$\delta m = X \cdot \delta qz + (1 - X) \delta alt$$

where δm is the measured $\delta^{18}\text{O}$ values of the rock

X is the fraction of phenocryst quartz

δqz is the $\delta^{18}\text{O}$ value of phenocryst quartz (8‰)

δalt is the $\delta^{18}\text{O}$ values of the rock that may be related to alteration processes.

Descriptions of polished thin sections of rocks looked at in detail in this study are listed in Appendix 1. Brief notes on thin sections borrowed from Billiton are given in Appendix 2.

The main conclusions are as follows:-

1. Rocks examined from drill hole CRD 86-1 have undergone much more alteration than those from CRD 88-1. In 86-1 feldspars are totally destroyed, being altered to fine-grained sericite variably overprinted by carbonate.
2. The alteration, and the mineralisation developed locally around the contacts of the

porphyry in CRD 86-1, predate cleavage development in the rock. In general, the cleavage development and alteration in CRD 88-1 are too weak to determine relative timing. One specimen of silicified siltstone (CRD 88-1 at 217.2 m) has minor carbonate veinlets which are folded. The axial surfaces of the folds are parallel to bedding, suggesting that the alteration and veining developed during early diagenesis.

3. Textures in the mafic rocks in CRD 88-1 (at 143.8 and 214.5 m) are doleritic. Comparisons with rocks collected by John Pemberton show that these are identical to his Em unit (feldspar-pyroxene-chlorite-quartz bearing ophitic-textured mafic to intermediate rock). Only the sample at 298.4 m looks like a dacite or andesite, and this is similar to the pink hornblende-feldspar porphyry (Efh) mapped by Pemberton.

4. The nature of the mineralisation in hole 86-1 is dissimilar to stockwork veining associated with massive sulphide deposits, but appears to be localised around the porphyry intrusive. The whole-rock geochemical analyses that Billiton carried out support this—localised kicks in Fe, Mn, Mg and Ca near the contacts reflect local pyrite and more intense carbonate veining associated with the mineralisation. The lack of base metal sulphides associated with pyrite away from the contact (even as minute inclusions in pyrite) is similar to other low temperature, barren alteration zones (e.g. Boco).

3. Oxygen Isotope Results

DDH	m	Rock type	$\delta^{18}\text{O}_1$	$\delta^{18}\text{O}_2$
86-1	92	Dacite	14.1	14.1
86-1	190	Dacite	13.9	13.9
86-1	209	Crystal-rich epiclastic	14.7	16.2
86-1	272.15	Altered volcaniclastic	16.1	18.1
88-1	90.6	Pumiceous pyroclastic?	13.7	13.7
88-1	183.5	Quartz-feldspar porphyry	12.4	12.9
88-1	298.4	Granophyre	12.1	12.1

$\delta^{18}\text{O}_1$ = measured $\delta^{18}\text{O}_{\text{SMOW}}$ value (‰)
 $\delta^{18}\text{O}_2$ = measured $\delta^{18}\text{O}_{\text{SMOW}}$ value (‰) corrected for phenocryst quartz

The oxygen isotope data clearly indicate the difference in the Cattley Range alteration system from that around the Kuroko deposits (Green *et al.*, 1983) or around Tasmanian massive sulphide deposits (Rosebery, Que River, Hellyer). In the massive sulphide systems there is a decrease in whole rock $\delta^{18}\text{O}$ values towards the ore body and footwall alteration zone (as determined by parameters such as Na_2O

depletion, degree of feldspar destruction, pyrite content etc.). In fact the more altered rocks in CRD 86-1 have higher $\delta^{18}\text{O}$ values than those in CRD 88-1. On the limited sampling from 86-1 there is a suggestion of declining $\delta^{18}\text{O}$ values towards the margins of the dacite intrusive.

On the other hand the oxygen isotope data from the Kuroko deposits (Appendix 3) and the Tasmanian massive sulphides show values of less than 10‰ in the most intensely altered rocks, with values increasing outward. Values of around 10 to 11‰ may occur in rocks with carbonated feldspars around the fringes of an alteration pipe. However these rocks do not display the total carbonation and sericitisation seen in the samples from CRD 86-1 and are generally more pyritic, with inclusions of base metal sulphides being common in the pyrite. Rocks with $\delta^{18}\text{O}$ values of 14‰ or more commonly display very little textural evidence of alteration; in the Kuroko deposits features such as oscillatory zoning in plagioclase are preserved.

The patterns discussed above are typical of the great majority of massive sulphide deposits, and are consistent with an ore fluid with a $\delta^{18}\text{O}$ value in the range -1 to 4‰, centred around the seawater value of 0‰. A number of exceptions exist, such as the giant Kidd Creek deposit in Ontario, which formed from a fluid with a $\delta^{18}\text{O}$ value between 6 and 9‰; and the Raul mine, Peru, which apparently formed from fluids with $\delta^{18}\text{O}$ values of +7 to +12‰. Both deposits have some unusual features.

The Kidd Creek deposit is unusual for its mammoth size (140 Mt) and the fact that it has been Canada's largest tin producer-tin values, dominantly as cassiterite, locally reach 3%. Beatty, Taylor and Coad (1988) believe that the high $\delta^{18}\text{O}$ values for the fluid are the result of convective circulation of seawater high in ^{18}O as the result of evaporation. However, the values are also consistent with a magmatic fluid, a postulate more consistent with the high tin values in the ore and the occurrence of fluorite and tourmaline as gangue minerals. There is no evidence for these in the Cattley Range area.

Raul consists of a number of semi-massive concordant mantos and stringer, disseminated and vein copper ores in a bedded sequence of andesite lavas and pyroclastics, greywacke and siltstone metamorphosed to amphibolite facies during post-ore granodiorite intrusion. It should be noted that the high $\delta^{18}\text{O}$ values calculated for the ore fluid were based on isotope fractionation between quartz-magnetite pairs; on the other hand fluid inclusions extracted from pyrite and chalcopyrite had $\delta^{18}\text{O}$ values close to 0‰ (Ripley and Ohmoto, 1977; 1979). It is therefore

possible that the magnetite (which shows "recrystallisation" textures) could have been introduced, with pyrrhotite, during post-ore granitoid emplacement, a situation analagous to that in the southern part of the F lens at Rosebery.

A number of possible scenarios are consistent with the oxygen isotope, petrological and geochemical data from the Cattley Range.

1. Involvement of magmatic fluids from the dacite porphyry intrusive in the mineralisation locally developed near the contacts, with temperatures declining from about 250°C in the margins of the porphyry and at its contacts to about 170°C 80 m below the contact.
2. Alteration by a seawater-dominated fluid with a $\delta^{18}\text{O}$ value of near 0‰ would imply much lower temperatures (about 135°C near the contacts declining to less than 100°C).
3. A third possibility, more complicated but consistent with the petrographic evidence, is that there are two independent alteration events:
 - (a) Early sericitisation, associated with seawater circulation.
 - (b) Carbonate alteration, associated with emplacement of the dacite porphyry and minor mineralisation. This is the later event.

Even if this interpretation was correct, the oxygen isotope data indicates that the earlier event in the vicinity of CRD 86-1 occurred at low temperatures.

Whether all of the alteration in the drill hole is related to the porphyry intrusion is difficult to determine. The extreme sericitisation and carbonation of feldspars could be part of the localised system related to the porphyry, or could be part of a larger alteration complex. The increase in $\delta^{18}\text{O}$ values away from the porphyry in CRD 86-1 is consistent with the former proposal. Rocks with $\delta^{18}\text{O}$ values as high as 14-18‰ are known from the outer parts of massive sulphide-related alteration zones in Japan and Tasmania, but do not show the extreme alteration effects (feldspar destruction, Na_2O depletion), again suggesting that the alteration is more probably a local feature.

All of the possible scenarios carry one important common feature. The extreme depletion in elements such as Na and Sr strongly indicates that alteration around CRD 86-1 occurred under water-dominated conditions. This implies the the oxygen isotope data reflect temperatures

of alteration. For each of the three possible cases, temperatures of alteration away from the porphyry body are too low to generate significant massive sulphide mineralisation ($\sim < 200^{\circ}\text{C}$).

In contrast, the distinctly less severe alteration of feldspars in CRD 88-1 suggest that fluid/rock interaction in this area may have occurred under rock-dominated conditions. That is, it is possible that the lower $\delta^{18}\text{O}$ values in this hole reflect higher temperatures of alteration, but it is more probable that alteration occurred at lower water/rock ratios than in the area of CRD 86-1 at comparable or even lower temperatures (see Appendix 3, fig. 6).

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APPENDIX 1

Description of polished thin sections prepared for this study

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100679 Field No.: Co. No.:

Location : Billiton Mount Cattley D.D.H. 86-1 92 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Relict feldspar phenocrysts (10%) to 2 mm long in snowflake texture groundmass (micropoikilitic quartz grains \sim 0.2 mm across with minute inclusions of feldspar now sericitised : a common high temperature devitrification texture in intrusives, lavas and welded tuffs).

Mineralogy (and estimated proportions) :

\sim 60% quartz, 25% white mica, 15% carbonate.

Mineralisation (relation to cleavage) :

Very minor subhedral and rare framboidal pyrite to 80 μ m (\sim 0.05%).
Very minor rutile, some after Fe-Ti oxides. No cleavage apparent.

Alteration (inclusions in feldspars, veining etc.):

Feldspars totally altered to white mica rimmed or studded by carbonate Patches of secondary carbonate and quartz to 5 mm in diameter with carbonate grains showing strain extinction-veinlets of carbonate plus quartz \sim 1 mm wide.

CONCLUSION: Feldspar prophyry dacite

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 14.1 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100681 Field No.: Co. No.:

Location : 86-1 190 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Feldspar phenocrysts ~ 10% of rock to 2.5 mm long in mainly snowflake texture groundmass. Patches of the groundmass lack snowflake texture, have a fine grained groundmass. In one of these there is a rounded (now totally sericitised) rock fragment 1.5 mm in diameter.

Mineralogy (and estimated proportions) :

Quartz 50%, Carbonate 30%, White mica 20%

Mineralisation (relation to cleavage) :

0.1% fractured pyrite grains to 80 μ m. Minor rutile.

Alteration (inclusions in feldspars, veining etc.):

Most feldspars totally altered to carbonate, a few are partly sericite. A few irregular carbonate veinlets to 0.5 mm across, fine grained carbonate patches 0.2 to 0.4 mm across are common in the groundmass. Less secondary quartz, more carbonate than in 100679.

CONCLUSION: Strongly sericitised and carbonated feldspar porphyry dacite.

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 13.9 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100683 Field No.: Co. No.:

Location : CRD 86-1 209 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Crystal-rich (50%), approximately equal proportion of broken and embayed quartz phenocrysts (to 1.5 mm) and strongly altered rock fragments and sericitised shards in fine grained siliceous matrix.

Mineralogy (and estimated proportions) :

Quartz 60%, including 15-20% phenocryst quartz, 25% carbonate, 15% white mica. Trace sphene, zircon.

Mineralisation (relation to cleavage) :

0.2% pyrite to 160 μ m. Pressure shadows around some of coarser grains. Similar amount of well crystallised rutile, some of which is associated with carbonate.

Alteration (inclusions in feldspars, veining etc.):

Feldspars totally altered to sericite + carbonate \pm quartz, as are rock fragments and coarser shards. Patches of poikilitic secondary carbonate, some 76 mm across, are common. Veinlets of fine grained quartz \pm carbonate \pm white mica are present.

CONCLUSION: Quartz feldspar phyric epiclastic sandstone, strongly altered.

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 14.7 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100685 Field No.: Co. No.:

Location : CRD 86-1 272.15

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Very few primary textures discernible. About 20% embayed- and fractured quartz phenocrysts up to 3.5 mm across. Some probable feldspars replaced by carbonate.

Mineralogy (and estimated proportions) :

Quartz 60%, white mica 25%, carbonate 15%. Few grains of zircon.

Mineralisation (relation to cleavage) :

Minute trace ultrafine pyrite (10 to 20 μm). Very minor fine grained rutile, mostly associated with sericite.

Alteration (inclusions in feldspars, veining etc.):

Few recognisable feldspars replaced by carbonate. Quartz strongly fractured, fractures healed by deformed fibrous carbonate. Fractured perpendicular to well defined cleavage. Matrix fine grained cherty quartz with small carbonate grains and 70-100 μm quartz grains; in places totally sericitised.

CONCLUSION: Strongly sheared volcanoclastic, strongly altered and subsequently deformed.

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 16.1 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100686 Field No.: Co. No.:

Location : CRD 88-1 90.6 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Pumiceous pyroclastic or epiclastic with 30% plagioclase phenocrysts to 2 mm, dense lithic clasts, including snowflake texture dacite, and tube pumice fragments to 5 mm in fine grained cherty quartz, greenish white mica groundmass - probably original glass dust.

Mineralogy (and estimated proportions) :

Albite 30%, quartz 45%, sericite + chlorite (minor) 25%.

Mineralisation (relation to cleavage) :

Minor pyrite to 800 μm . Trace chalcopyrite blebs to 160 x 30 μm associated with sericite-chlorite patches and crystalline rutile. One case the chalopyrite replaces pyrite. Some of the rutile is in aggregate of 30 μm crystals 400 x 170 μm replacing iron-titanium oxides.

Alteration (inclusions in feldspars, veining etc.):

Very minor carbonate and lesser sericite alteration of albitised plagioclase. Carbonate veinlets present.

CONCLUSION: Despite the traces of chalcopyrite, weakly altered pumiceous epiclastic.

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 13.7 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

063

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

608064

Mines Dept. No.: 100688 Field No.: Co. No.:

Location : CRD 88-1 183.5 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Quartz-feldspar porphyry: about 10% of both quartz and albitised plagioclase phenocrysts to 3 mm. Felsitic groundmass with quartz and fine tabular feldspar crystals, some small spherulitic textures ~ 40 μ m across.

Mineralogy (and estimated proportions) :

10% of each of phenocryst quartz and albite. Difficult to determine quartz/feldspar proportion in groundmass. ~ 5% sericite, 2% carbonate, trace sphene, zircon, apatite.

Mineralisation (relation to cleavage) :

Very minor, relatively coarse grained pyrite; subhedral, generally spongy, 50 to 250 μ m long. Patches of coarsely crystalline rutile (Fe-Ti oxide replacements).

Alteration (inclusions in feldspars, veining etc.):

Very minor sericite inclusions in plagioclase. A few quartz minor albite veinlets, carbonate veinlets, seams of sericite along fractures. Patches of carbonate and sericite.

CONCLUSION: Negligibly altered quartz feldspar porphyry.

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 12.4 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

MRVP - ISOTOPE & ALTERATION STUDY
PETROGRAPHY

Mines Dept. No.: 100694 Field No.: Co. No.:

Location : CRD 88-1 298.4 m

Hand Specimen

Primary textures :

Mineralogy and alteration :

Thin section

Primary textures :

Feldspar-porphyry-granophyre. Patchily textured rock in which plagioclase phenocrysts to 3.5 mm long together with minor chloritised ferromagnesian, quartz phenocrysts and relict iron oxides are set in a groundmass of randomly oriented plagioclase laths surrounded by devitrified felsic glass with granophyric or spherulitic habit.

Mineralogy (and estimated proportions) :

Albite-oligoclase 45%, alkali feldspar 10%, quartz 20%, chlorite 15%, carbonate 5%, sericite 2%, opaques 3%. Trace zircon, sphene, apatite.

Mineralisation (relation to cleavage) :

Moderate amounts of rutile both as discrete grains ($\sim 50 \mu\text{m}$) and as grain aggregates after Fe-Ti oxides. No sulphides seen in section.

Alteration (inclusions in feldspars, veining etc.):

Minor sericitisation of plagioclase phenocrysts. Patches of coarse grained secondary quartz to 1.5 mm. Minor quartz-carbonate veins and veinlets.

CONCLUSION: Granophyre-texturally similar to unit on MRV Map 8 termed Efh (feldspar hornblende porphyry, generally pink, spherulitic).

$\delta^{13}\text{C}$ $\delta^{18}\text{O}$ 12.1 $\delta^{34}\text{S}$ Probe :

Whole rock analysis

Notes on Billiton thin sections

13577—CRD 86-1, 192.8 m

A coarse-grained pyrite vein associated with sphalerite, galena, chalcopyrite and traces of tetrahedrite with gangue of carbonate, chlorite, white mica and quartz appears to have been the locus for introduction of mineralising fluids. Fine to medium-grained pyrite occurs as lobate fronts spreading out from the vein for 10–20 mm, and is associated with minor chalcopyrite, sphalerite and galena between and within pyrite grains. The sulphides appear to have grown in favoured laminae, particularly carbonaceous siltstone, and pyrite grain size appears to be partly lithologically controlled, although in some laminae pyrite grain size increases towards the feeder vein. The mineralisation does not favour carbonate laminae.

Both the vein and disseminated sulphides have been deformed. In a number of places, areas of coarse-grained pyrite have been pulled apart and the ends of the respective massive pyrites show a jigsaw fit, with the intervening space being filled with fibrous chlorite and white mica, and more massive quartz and carbonate. Mica pressure shadows and fringes commonly occur around pyrite grains in the semi-massive laminae in the adjacent siltstone, and are particularly pronounced at the outer limits of the pyritic lobes. The main vein and minor veins pinch and swell irregularly, and one veinlet shows changes in direction where it crosses a carbonaceous lamina. The lamina changes in thickness at this point.

These features indicate that veining and mineralisation occurred when the sediments were semi-consolidated, i.e. it was syn-diagenetic.

13578—CRD 86-1, 189.8 m

Very similar to Mines Department sample 100681 (at 190 m). A few of the altered feldspars have sericite cores with carbonate rims, suggesting that carbonation has overprinted sericitisation.

13579—CRD 86-1, 206.25 m

Quartz phenocryst-rich epiclastic sandstone with an average grain size of about 2 mm. Fine-grained sericite replaces feldspar and shards. A few mudstone clasts are present. One 2 mm pyrite grain is probably clastic; it has a fibrous sericite beard.

13580—CRD 86-1, 218.2 m

Coarse-grained epiclastic rock with quartz up to 5 millimetres. About half of the slide consists of a granular carbonate matrix, but contains inclusions of cherty and sericitic volcanic fragments and quartz phenocrysts. This probably reflects post-depositional, pre-cleavage carbonation. The rest of the rock has a quartz-sericite groundmass with sericitised relic shards and feldspars recognisable. A few siltstone clasts are present.

13581—CRD 86-1, 238.36 m

Quartz (to 4.5 mm) phenocryst-rich epiclastic sandstone, with calcareous siltstone fragments to 5 millimetres. Some quartz-rich siltstone clasts are subrounded. Feldspars are altered to fine-grained sericite, but have generally retained their euhedral shape. The fine-grained sericite is variably overprinted by carbonate. Some cherty and volcanic rock fragments are present.

13582—CRD 86-1, 256.65 m

Coarse-grained epiclastic sandstone with sericitised feldspar more abundant than quartz, and slate fragments to 5 millimetres. Minor chert fragments. Some sericite is partly overprinted by carbonate. Minor patches and veinlets of chlorite and carbonate are pre-cleavage. Zones of strong sericite development are present. The texture is similar to, but not as well developed as, 13583.

13583—CRD 86-1; 264.2 m

Shard-rich epiclastic sandstone with quartz greater than feldspar originally. Shards are altered to sericite and the interstitial material to very fine grained quartz. Most feldspar is altered to carbonate. A few clasts of slate to 3 mm are present. One patch of SPHALERITE (outlined by thick blue line) is present. It is cut by seams of coarse-grained white mica (coarser than the sericite replacing the shards). Extensive patches of carbonate alteration and pre-cleavage carbonate veining.

13584—CRD 86-1, 271.85 m

Coarse-grained breccia with fragments to 10 mm+ identifiable by changes in groundmass texture. Difficult to identify former feldspar sites—some altered to quartz + sericite. No chlorite. Numerous pre-cleavage carbonate veinlets.

13585—CRD 86-1, 278.8 m

Rock has coarse fragmental texture, originally feldspar much more abundant than quartz. All feldspar totally altered to sericite or carbonate. Groundmass fine-grained quartz-sericite with carbonate clots, very strongly cleaved, some carbonaceous material. Fragments to 2 mm+.

CRD 88-1, 33.8 m

Feldspar-minor quartz crystal-lithic epiclastic. Feldspar and matrix moderately sericitised.

CRD 88-1, 49.1 m

Coarse-grained lithic-crystal breccia with rhyolite fragments to 8 mm, welded tuff fragments. Most rocks feldspar-phyric. Most feldspars show weak to moderate sericitisation and carbonation. Some alteration may have preceded sedimentation.

CRD 88-1, 69.8 m

Coarse-grained crystal-lithic epiclastic. Weak to moderate sericitisation, carbonation of feldspar. Pumice and lithic clasts are dominantly felsic, some basalt clasts. Minor chlorite after ferromagnesian.

CRD 88-1, 99.0 m

Mainly vitric ash with beautifully preserved shards. Quartz and feldspar to 0.3 mm. Very weak sericitisation of feldspar, mesh-type sericitisation in groundmass. A few carbonate patches are present.

CRD 88-1, 127.3 m

Strongly sericitised rock with fine-grained quartz-sericite matrix with mesh texture. Some

rock fragments, quartz crystals and strongly sericitised feldspars to 0.3 mm. Shards not discernable. A more altered version of the rock at 162.4 m.

CRD 88-1, 143.3 m

Dolerite with sub-ophitic texture. Moderate sericitisation of plagioclase, total chloritisation of pyroxene. Patches and veins of carbonate.

CRD 88-1, 162.5 m

Vitric crystal tuff with very indistinct shards to 0.5 mm. Fine-grained felsitic groundmass. Feldspar, very weakly carbonate altered and quartz to 0.5 mm.

CRD 88-1, 167.7 m

Pervasively fractured rock with veining by fine-grained micas and later quartz-carbonate. Originally a quartz-feldspar porphyry with snowflake texture. Feldspar totally sericitised. Near a fault zone.

CRD 88-1, 214.5 m

Ophitic dolerite. Randomly orientated, weakly sericite and/or carbonate altered plagioclase to 2 mm long, pyroxenes altered to chlorite and carbonate, skeletal magnetite? and minor quartz in groundmass.

CRD 88-1, 217.2 m

Silicified siltstone with secondary silica ovoids. Some early diagenetic and later fracture-fill veining of carbonate and pyrite. One carbonate vein is folded with the axial surface trace of the folds parallel to bedding.

APPENDIX 3**Whole-rock oxygen isotope distribution in the Fukazawa-Kosaka area,
Hokuroku District, Japan, and its potential application to mineral
exploration.**

by GEOFFREY R. GREEN, HIROSHI OHMOTO, JIRO DATE, AND TOSHIO TAKAHASHI

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Whole-Rock Oxygen Isotope Distribution in the Fukazawa-Kosaka Area, Hokuroku District, Japan, and Its Potential Application to Mineral Exploration

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Abstract

Oxygen isotope analyses of 151 samples of Miocene volcanic and sedimentary rocks from a 20 × 15-km area of the Hokuroku district, Japan, show a consistent relationship between alteration assemblages and $\delta^{18}\text{O}$ values of whole rocks. Excluding quartz-rich sandstones, which are resistant to hydrothermal alteration, the $\delta^{18}\text{O}$ values of all types of igneous rocks (dacite, andesite, basalt) and sedimentary rocks (tuff and mudstone) lie within the ranges of 16.9 ± 2.7 (1 σ value) per mil in the zeolite zone, 11.1 ± 2.5 per mil in the montmorillonite zone, and 6.7 ± 1.3 per mil in the sericite-chlorite zone. Essentially, all the Miocene rocks in the Hokuroku district are altered to zeolite or higher grade zones.

Concentric zoning patterns of the whole-rock $\delta^{18}\text{O}$ values and of alteration minerals are particularly well developed in the footwall volcanics around the Fukazawa Kuroko deposit. The $\delta^{18}\text{O}$ values of the whole rocks gradually increase from less than 8 per mil in the sericite-chlorite zone that extends about 0.5 km outside of the ore zone, to 8 to 14 per mil in the montmorillonite zone, a 1- to 3-km-wide zone occurring outside the sericite-chlorite zone, to mostly greater than 14 per mil in the peripheral zeolite zone.

In the hanging-wall rocks above the Fukazawa deposit, $\delta^{18}\text{O}$ and mineralogical zonations extend at least 400 m above the ore horizon (i.e., to the present-day surface), but these zones gradually contract upward. Such features together with the radiometric ages of the igneous rocks suggest that the Fukazawa mine was the site of discharge of high-temperature ($T > 200^\circ\text{C}$) hydrothermal fluids for a period of over 3 million years, although the hydrothermal activity may have been episodic and decreased in intensity with time.

Comparison of the spatial variation of $\delta^{18}\text{O}$ values of the footwall rocks in the Fukazawa area with that of Na, K, Mg, Ca, Sr, Cu, Pb, Zn, and S contents and of the magnetic susceptibility shows that the areal extent of the $\delta^{18}\text{O}$ anomaly is much larger than that of other geochemical anomalies, and that the variability of $\delta^{18}\text{O}$ values within a site is much less than that of the elemental compositions. This suggests that the analysis of whole-rock $\delta^{18}\text{O}$ values is a useful method of exploration for volcanogenic massive sulfide deposits (and also for vein deposits occurring in submarine volcanic sequences) during the reconnaissance stage whereas other geochemical methods are more suitable in the development stage. In fact, 18 of 21 drill sites where low $\delta^{18}\text{O}$ (<8‰) rocks were discovered in this study are located within 1 km of known Kuroko-type or vein-type deposits. Analyses of whole-rock $\delta^{18}\text{O}$ values are also useful in the exploration for these types of deposits in metamorphosed and deformed terrains, because the oxygen isotope zoning is less likely to be destroyed than the alteration mineral zoning during regional metamorphism.

The $\delta^{18}\text{O}$ values of the altered volcanic rocks around the Kuroko deposits and their correlation with alteration assemblages can be interpreted as a result of interaction between the rocks and

seawater at different temperatures (25°–200°C for the zeolite zone, 150°–300°C for the montmorillonite zone, and 200°–400°C for the sericite-chlorite zone) under water-dominated (i.e., water/rock > 1) conditions. This interpretation also explains most of the hydrogen isotope data of the whole-rock samples ($\delta D = -34$ to -80%) from the Hokuroku district.

Introduction

PREVIOUS stable isotope studies of volcanogenic massive sulfide deposits have been aimed principally at determining the origin of the ore-forming fluids through analyses of fluid inclusions or of gangue minerals from orebodies (e.g., Ohmoto and Rye, 1974; Hattori and Sakai, 1979; Ripley and Ohmoto, 1979; Kowalik et al., 1981) and have paid scant attention to the surrounding rocks. However, the recognition of well-defined $\delta^{18}O$ halos in whole rocks around mineralized zones in other types of ore deposits, particularly the epithermal gold-silver deposits (Taylor, 1974; Casadevall and Ohmoto, 1977), has prompted us to extend this approach to volcanogenic massive sulfide deposits with the aims of establishing a new exploration guide for this type of

deposit and of determining some of the hydrological characteristics, such as the size, temperature, and fluid/rock ratio of the fluid discharge zone.

Area of Study

The area of this study is an approximately 20-km (north-south) \times 15-km (east-west) portion of the eastern part of the Hokuroku district of Japan, which roughly coincides with the area subjected to a detailed geological study by Guber and Green (1983). This area contains two major groups of Kuroko deposits, the Fukazawa and Kosaka mines, and numerous Cu-Zn-Pb-Ag-Au vein deposits of younger age, including: Takarakura, Yamadate, Saruma, and Kanehata (see Tanimura et al., 1983).

The $\delta^{18}O$ values of 149 whole-rock samples were analyzed, of which 103 samples came from 26 drill holes within 5 km of the Fukazawa mine, 43 samples from 14 drill holes within 5 km of the Kosaka mine, and 3 samples from other parts in the area (see Table

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TABLE 1. Oxygen Isotope Composition and Alteration Mineralogy of Samples from the Hokuroku District

Drill hole no.	Location ¹		Depth (m)	Rock unit ²	$\delta^{18}O$ (‰)	Alteration zone ³	Mineral assemblage ⁴
	X	Y					
J4	-118.9	228.9	62	T ₁	18.2	1	q, fs, mord, mt, anhy, chl, mont
			288	T ₂	18.7	1	q, mord, fs, anhy, mt, dol, mont, chl
			373	D ₃	17.9	1	q, fs, mord, chl, mont
			448	B ₃ (?)	12.0	2	q, fs, mont, chl, anhy, ht
			640	Men	10.3	2	
			712	Men	11.9	2	
HO12	-129.5	253.7	203	T ₁	9.7	2	
			339	T ₂	11.3	2	
			427	M ₂	10.4	2	
			505	D ₃	9.5	2	
HO33	-123.7	265.3	238	An ₁	8.0	2	
			320	T ₁	8.3	2	
			390	T ₂	8.7	2	q, fs, mont, ser, chl
			478	T ₃	5.5	3	q, fs, mont, ser, chl, ka, anhy, gy, py
			490	T ₃	5.8	3	
			570	T ₃	4.6	3	q, fs, ser, chl
TK188	-106.4	271.3	592	T ₃	5.6	3	q, fs, ser, chl, anhy, gy
			60	T ₀	18.2	1	fs, crist, mont, py, mord
			180	T ₁	19.6	1	q, fs, mont, mord
			360	T ₁	16.6	2	q, fs, ka, mont
			510	D ₀	9.5	2	q, fs, chl, mont
TK141	-116.7	276.8	690	D ₃	9.9	2	q, fs, chl, ser, mont, anhy
			30	M ₀	12.1	2	q, gy, mont, py
			270	T ₂	7.8	3	q, fs, ser, chl, dol, gy, py
			440	D ₂	6.0	3	q, fs, ser, chl, py
			610	D ₂	8.0	3	q, fs, ser, chl, cal, py

TABLE 1—(Continued)

Drill hole no.	Location ¹		Depth (m)	Rock unit ²	$\delta^{18}O$ (‰)	Alteration zone ³	Mineral assemblage ⁴
	X	Y					
HO30	-133.7	277.0	255	D ₀	7.6	3	
			347	D ₁	7.4	3	
			516	D ₁	6.0	3	q, ser, chl, anhy, py
			645	T ₂	6.2	3	q, ser, chl, py
			766	T ₂	7.2	3	q, ser, chl, fs, py
			851	T ₂ (?)	7.1	3	
TK168	-117.9	282.6	120	T ₁	19.1	1	q, fs, crist, mont
			400	D ₀	8.6	2	q, fs, mont
			475	T ₂	15.6	2	q, dol, gy, mont
			562	T ₂	10.7	2	q, ser, py, ka
			680	D ₂	7.6	3	q, fs, ser, py
TK58	-120.6	286.3	120	T ₁	10.6	4	q, fs, ser, chl, dol, py, mont
			150	M ₁	10.0	4	q, fs, ser, chl, dol, py, mont
			240	T ₂	6.2	4	fs, ser, chl, cal, py
			380	B ₂	6.8	4	q, fs, ser, chl, cal, dol
			500	D ₂	5.5	3	q, ser, chl, py
TK26	-125.8	288.3	30	T ₀	7.0	3	q, fs, ser, chl
			120	T ₁	6.9	3	q, fs, ser, chl, py
			270	M ₂	6.0	3	q, fs, chl, py
			290	M ₂	5.1	3	fs, chl
			310	B ₂	6.1	3	q, ser, chl, cal, py
			350	B ₂	6.4	3	q, chl, py
			410	T ₂	6.5	3	q, ser, chl, py
HO8	-115.7	289.9	436	T ₂	15.7	2	
			468	T ₂	10.5	2	q, fs, ser, chl, mont, dol, cal, gy, py
			497	D ₂	8.8	2	q, ser, mont, anhy, py
TK45	-131.7	293.0	65	T ₀	10.1	2	q, fs, ser, chl, mont, py
			305	T ₁	11.1	2	q, fs, mont, py
			480	D ₂	6.5	3	q, ser, chl, py
TK190	-156.9	294.2	381	D ₂	7.6	3	q, ser, chl, fs, dol
			569	D ₂	6.3	3	q, ser, chl, fs, mont, cal, py
HO47	-89.4	295.0	262	B ₂	12.5	2	
			434	T ₂	8.6	2	
			557	B ₂	10.5	2	
OE5	-109.3	297.6	46	T ₁	19.4	1	
			340	D ₂	14.3	1	q, fs, mord, mont, ba
TK118	-134.5	300.3	60	T ₀	13.1	2	q, fs, gy, mont
			180	T ₁	20.6	1	q, fs, mont, mord
			320	T ₂	13.0	2	q, ser, fs, gy, py, mont
			410	D ₂	12.5	2	q, fs, ser, chl, cal, py
HO26	-161.5	300.8	477	T ₂	10.1	3	q, fs, ser, chl, py
			527	D ₂	11.6	2	q, fs, ser, chl, mont, cal, anhy
			700	D ₂	10.5	3	q, fs, ser, chl, cal, ba
			749	D ₂	13.6	2	q, fs, ser, chl, mont, anhy
HO29	-103.2	301.0	55	T ₂	22.4	1	
			259	D ₂	19.7	1	
			384	D ₂	18.7	1	
			512	D ₂	14.9	1	
TK161	-140.0	305.2	150	D ₀	12.2	2	q, fs, anhy, ka, mont
			250	T ₁	17.6	1	q, ka, mont, mord
			310	T ₂	15.2	1	q, fs, cal, ka, mont, anal
			510	M ₂	13.3	2	q, fs, dol, ka
			690	D ₂	14.0	2	q, fs, sid, dol

TABLE 1—(Continued)

Drill hole no.	Location ¹		Depth (m)	Rock unit ²	$\delta^{18}\text{O}$ (‰)	Alteration zone ³	Mineral assemblage ⁴
	X	Y					
HO34	-106.0	307.3	54	T ₁	21.2	1	
			240	D ₃	19.3	1	
			323	D ₂	17.0	1	
			591	D ₂	13.9	1	
HO42	-121.7	308.0	243	T ₂	13.3	2	
			357	D ₂	11.8	2	q, fs, mont, ser, chl, anhy, ep(?)
TK181	-106.7	317.8	110	T ₁	15.7	1	
			284	T ₂	15.4	1	
			381	D ₂	14.4	1	
HO39	-152.8	319.4	204	T ₂	15.2	1	q, fs, ill, mont, anal, ht(?)
			296	T ₂	8.3	2(?)	
			353	T ₂	15.0	1	q, fs, anal, mont, chl, cal, mt, anhy
			498	D ₂	14.7	1	q, mont, chl, anhy, fs, cal, gy, anal
			515	D ₂	12.5	2	q, fs, ser, chl, mont, gy, anhy, cal
			545	D ₂	11.2	2	q, fs, anal, mont, ser, chl, cal, anhy
TK180	-142.9	322.1	60	T ₁	16.8	1	q, fs, ka, mont, mord
			120	T ₁	17.8	1	q, ka, mont, mord
			164	T ₂	16.6	1	q, ka, mont, anal, mord
			240	T ₂	14.1	2	fs, cal, ka, mont
			340	T ₂	15.4	2	q, fs, mont
			390	D ₂	15.7	1	q, fs, cal, mord
MR1333	-95.6	325.1	85	T ₁	13.1	2	q, fs, chl, mont, ser, cal, dol, py, anhy, gy
			307	T ₂	10.6	2	
TK183	-132.5	335.4	361	D ₂	11.6	1	q, mord, anal, dol
			431	D ₂	16.8	2	q, fs, ser, chl, mont
			439	Dol	9.0	2	q, fs, ser, mont
Kosaka area							
K17	-89.6	340.0	211	T ₁	8.2	2	
			428	D ₂	8.1	2	
			499	T ₃ (?)	6.5	2(?)	
MR1258	-103.1	342.8	60	T ₂	12.2	2	
			216	M ₂	9.5	2	
			492	D ₂ (?)	9.2	2	
			567	D ₂	7.6	2(?)	
MR1161	-67.7	351.9	253	T ₂	7.5	3	q, chl, ser, ka
			284	T ₂	6.3	3	q, ser, py
MR953	-53.2	365.0	545	SS _{ms}	9.8		
MR1338	-86.2	366.7	133	T ₁	12.6	2	
			200	T ₁	7.5	2	
			351	D ₂	9.2	2	
			478	D ₂	7.9	2	
MR1317	-39.4	378.4	67	T ₂	20.5	1	fs, mont, mord, calc
			207	D ₂	9.1	2	
			360	T ₂	12.1	2	
			399	T ₂	11.3	2	q, fs, ser, mont, chl, py
			419	D ₂	12.0	2	q, fs, ser, mont, cal, ht
			479	M ₂	9.7	2	q, fs, mont, chl
			525	SS	13.3	2	q, fs, chl, ser, anhy, py
MR1345	-69.7	384.6	184	Qtz from D ₂	8.6		

TABLE 1—(Continued)

Drill hole no.	Location ¹		Depth (m)	Rock unit ²	$\delta^{18}\text{O}$ (‰)	Alteration zone ³	Mineral assemblage ⁴
	X	Y					
MR983	-86.0	389.3	147	D ₃	16.4	1	q, fs, mord, clino, mont, anhy, cal
			270	T ₄	12.7	2	q, fs, ka, mont, ser, cal, dol
			301	T ₃	13.1	2	q, mont, chl, fs, cal, py
MR1224	-25.3	388.4	715	T ₃	8.5	2	
MR1241	-26.0	392.2	338	T ₁	12.8	2	
			416	T ₁	13.4	2	
			508	An ₃ (?)	11.8	2	q, fs, chl, mont, cal, anhy
MR1248	-37.4	398.8	100	T ₄	8.7	2	q, fs, ser, chl, mont, py, anhy
			128	T ₁	8.6	2	q, fs, chl, ser, mont, anhy
			169	An ₄	6.9	2	
			326	T ₃	4.9	3	q, ill, chl, fs, cal, anhy, py
			384	T ₂	10.7	2	q, fs, chl, ser, mont, ka
			388	SS _{ma}	8.7	2	q, ill, mont, py, ht, cal, anhy
MR959	-84.0	400.9	80	T ₃	14.7	1	q, fs, anal, py, anhy, mont, dol
			105	T ₃	14.0	2	q, fs, ser, mont, cal, anhy, py
			200	T ₃	16.8	2	q, fs, mont, chl, cal, gy
T6	-37.8	415.5	237	T ₃	9.5	2	q, fs, chl, ser, anhy, py, ba, mont
			397	T ₃	7.5	2	
			416	SS _{ma}	4.3		
H048	-158.7	427.5	408	D ₂	15.6	2	
				Qtz from above	7.6		
KH8	-88.0	471.8	351	SS _{ma}	6.3		
(JU78SF101)Surface, Fukazawa			O.Q.D.	7.1			
			Qtz from above	6.8			

¹ The coordinates X (E-W) and Y (N-S) are those used by the Dowo Mining Company, Ltd.; see Figure 4 for reference points; samples are arranged from south to north

² Rock unit code is as follows: An = andesite, B = basalt, D = dacite or rhyolite, Dol = dolerite, M = mudstone, Men = Menaichizawa Formation, O.Q.D. = Ohtaki (quartz) diorite, Qtz = quartz, SS = Sasahata Formation, T = tuff or tuff breccia; subscript ma refers to muddy matrix or pelitic clastic material; subscript numbers refer to the relative age: 0, the youngest, to 3, the oldest; the Kuroko ore horizon lies between (T₃ or D₃) and (T₂, M₂, or B₂)

³ Alteration zones are based on the study by Date et al. (1983) and this study: 1 = zeolite zone, 2 = montmorillonite zone, 3 = sericite-chlorite zone, and 4 = Na montmorillonite zone

⁴ Mineral abbreviations are as follows: anal = analcime, anhy = anhydrite, ba = barite, cal = calcite, chl = chlorite, clino = clinoptilolite, crist = cristobalite, dol = dolomite, ep = epidote, fs = feldspar (mostly plagioclase), gy = gypsum, ht = hematite, ill = illite, ka = kaolinite, mont = montmorillonite, mord = mordenite, mt = magnetite, py = pyrite, q = quartz, ser = sericite, sid = siderite

1 for sample locations). Our efforts were concentrated around the Fukazawa mine since excellent background information exists in the form of whole-rock chemical and mineralogical data (Date and Tanimura, 1973, 1974; Ishikawa et al., 1976; Date et al., 1979, 1983). Previous investigations of the whole-rock oxygen isotope distributions around massive sulfide deposits have focused on preore sequences (Beatty and Taylor, 1980a and b; Hattori and Muehlenbachs, 1980; Kowalik et al., 1981). However, the occurrence of well-defined alteration halos both below and above the Kuroko deposits has encouraged us to devote equal attention to both pre- and postore rocks.

The immediate footwall (i.e., preore) rocks of the Kuroko deposits are essentially identical in the Kosaka and Fukazawa mine areas and are composed of dacitic tuff breccia and tuffs (T₃ and T₄ units) and nearly contemporaneous flows and domes of dacite (D₃ and D₄ units). The T₃, T₄, D₃, and D₄ units are collectively called the Uwamuki Formation in the Kosaka area and the Yukisawa Formation in the Fukazawa area (see Tanimura et al., 1983). In the following interpretation of the hydrology of ore-forming systems, the important differences between the two areas are the thickness of these volcanic units and the lithology and thickness of units underlying them. In the Kosaka area, the Uwa-

muki Formation is only 50 to 300 m in thickness and is underlain by the thin (0–150-m-thick) Sasahata Formation, a conglomerate and sandstone unit derived from basement quartzite, schist, and slate (Tanimura et al., 1983), lying unconformably on the Paleozoic basement rocks. In the Fukazawa area, the Yukisawa Formation is 350 to 650 m in thickness and is underlain by at least 300 m of the Menaichizawa Formation, a stratigraphic equivalent of the Sasahata Formation, but which consists predominantly of andesite flows and tuff breccia. Within a few kilometer radius of the Fukazawa mine, the Paleozoic basement rocks have not been encountered by any drill hole.

The hanging-wall (i.e., postore) rock sequence is similar between the two areas and is comprised mostly of interbedded dacitic tuffs (T_2 , T_1 , and T_0 units) and mudstones (M_2 , M_1 , and M_0 units) except in some areas in the Fukazawa mine, where the ores are directly overlain by an approximately 30-m-thick basalt flow (B_2 unit). Except for the local basalts, the post-Kuroko igneous activity is characterized by a general lack of flows but by an abundance of intrusives of dacite (D_2 , D_1 , and D_0 units), andesite (An_2 and An_1 units), and dolerite (Tanimura et al., 1983).

Analytical Techniques

For oxygen isotope analyses of whole-rock samples and quartz separates, finely powdered samples were reacted with BrF_3 at $600^\circ \pm 30^\circ C$ in nickel reaction vessels for a minimum of 12 hours (Clayton and Mayeda, 1963). The liberated O_2 was then converted to CO_2 by reaction with hot graphite discs. For hydrogen isotope analyses, water from rock samples was liberated by induction heating in vacuo to melting. Any hydrogen produced in this process was converted back to H_2O by reacting with CuO at $450^\circ C$. Water was then converted to H_2 through reaction with uranium at $800^\circ C$, following the method of Godfrey (1962). Isotope analyses were performed on either a 3-inch (for O and H) or a 6-inch (for O) radius mass spectrometer equipped with dual inlet and double collector systems and constructed by the Nuclide Corporation. All isotope analyses are reported as per mil deviation from the SMOW standard. Overall precision of analyses was about ± 0.1 per mil for $\delta^{18}O$ and ± 1 per mil for δD values.

Many of the samples analyzed in this study are those previously investigated by one of us (J.D.) for alteration assemblages and for major and trace element contents (reported in Date and Watanabe, 1979; Date et al., 1979, 1983). An additional 20 samples were analyzed for major and trace element contents by X-ray Assay Laboratories, Ontario, and for Cl by M. E. Campbell for the U. S. Geological Survey, Reston, Virginia. Thin sections were made from approximately 100 samples and examined by the senior author for mineralogy and textures.

Results and Interpretation

The $\delta^{18}O$ values of 149 whole-rock samples range from 4.3 to 22.4 per mil, three samples of quartz separated from dacites range from 6.8 to 8.6 per mil, and the δD values of six whole-rock samples range from -56.2 to -100.9 per mil (Tables 1 and 2). The most significant trends in the data are discussed below.

Correlation of $\delta^{18}O$ values with alteration mineralogy

The existence of a correlation between the whole-rock $\delta^{18}O$ values and alteration mineralogy and a trend of increasing $\delta^{18}O$ values toward the alteration zones of lower temperature was first reported by us (Green et al., 1980) and was based on the analyses of approximately 70 samples from the Fukazawa area. Additional data obtained since then from the Kosaka area as well as the Fukazawa area are in accordance with these findings.

Several schemes have been proposed for division of alteration zones around the Kuroko deposits (e.g., Iijima, 1974; Shirozu, 1974; Izawa et al., 1978; Utada et al., 1981). In this paper we have followed a simple classification presented in the preceding paper by Date et al. (1983): zone I or zeolite zone, characterized by mineral assemblages of clinoptilolite + mordenite + Mg·Na-type montmorillonite \pm cristobalite or analcime + Mg·Na-type montmorillonite + quartz \pm calcite \pm sericite \pm Fe-rich chlorite; zone II or montmorillonite zone, characterized by Mg·Ca-type montmorillonite + quartz \pm kaolinite \pm calcite \pm sericite \pm Fe-rich chlorite; and zone III or sericite-chlorite zone, characterized by quartz + sericite \pm Mg-rich chlorite.

An important characteristic of the alteration associated with the Kuroko deposits is the change in the alteration features of plagioclase. As noticed by many previous investigators (e.g., Iijima, 1974; Shirozu, 1974; Date et al., 1983) and also in this study (see Table 3), primary plagioclase is usually unaltered in the zeolite

TABLE 2. Hydrogen Isotope Composition of Whole-Rock Samples from the Hokuroku District, Japan

Drill hole no.	Depth (m)	Rock unit	δD (‰)	Alteration zone
HO33	478	T_2	-56.2	2
	490	T_3	-68.6	3
HO39	204	T_2	-82.9	1
	296	T_3	-100.9	2(?)
	353	T_3	-84.6	1
	545	D_3	-72.9	2

See Table 1 for the locations and classifications of rock units and alteration zones.

TABLE 3. Major Element and Petrographic Data of Whole-Rock Samples from the Fukazawa Area¹

Sample number	m ± ore horizon ²	Rock unit	Alteration zone ³	Plagioclase alteration ⁴	TiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	ΣFeO	MnO	TiO ₂	P ₂ O ₅	H ₂ O
TK26-225	+204	T ₂	3	ab	73.7	12.4	0.19	3.86	1.69	2.46	2.45	0.15	0.27	0.04	2.3
TK26-340	+89	B ₂	3	ab	50.9	15.9	0.73	8.65	1.94	1.22	11.4	0.50	1.30	0.11	4.5
TK26-460	-31	D ₂	3	d → q	77.0	10.4	0.07	1.64	<0.01	2.94	4.03	0.06	0.18	0.02	1.4
TK26-514	-85	D ₂	3	d → q	72.7	10.9	0.22	3.63	<0.01	2.56	5.18	0.16	0.18	0.02	2.7
TK45-47.3	+351	T ₀	2		72.4	12.7	0.17	2.26	2.24	3.46	2.80	0.22	0.35	0.05	2.0
TK45-86	+312	T ₀	2	c + ab	67.7	14.1	0.24	3.04	1.48	5.74	3.60	0.23	0.51	0.08	2.6
TK45-329.4	+69	T ₂	2	ab + c	71.5	13.7	1.26	1.55	3.05	2.37	2.79	0.13	0.39	0.05	1.0
TK45-481.6	-84	D ₂	3	d → q	69.8	13.8	0.14	2.69	<0.01	3.81	4.40	0.05	0.23	0.03	2.7
TK58-48.2	+398	T ₁	4	K	74.3	12.6	0.57	2.40	0.58	3.12	2.24	0.10	0.29	0.03	2.5
TK58-222.7	+223	T ₂	4	K	78.1	10.2	1.45	1.34	0.76	2.73	1.94	0.09	0.33	0.05	1.5
TK58-331.6	+114	tuff in M ₂	4	ab + c	69.1	13.8	2.24	2.38	2.67	2.19	3.07	0.15	0.56	0.11	2.2
TK58-453	-7	D ₂	3	d → q + py	72.0	14.0	0.36	2.02	<0.01	4.14	2.09	0.02	0.23	0.03	2.5
TK118-67.5	+222	T ₀	1 (or 2)	p, i	66.6	14.1	2.47	1.88	3.10	1.30	3.44	0.08	0.39	0.06	3.5
TK118-174.2	+114	T ₁	1	p, i	71.5	13.0	1.37	1.84	2.09	3.12	2.56	0.05	0.30	0.04	2.0
TK118-387	-98	D ₂	2	K + c, a + g	73.9	13.4	0.37	1.14	4.70	1.68	2.63	0.06	0.22	0.03	1.5
TK118-443	-154	D ₂	2	a → g ± c	71.9	12.3	2.37	1.30	2.39	2.56	2.58	0.09	0.22	0.03	2.0
TK180-41.5	+287	T ₁	1	p	70.3	12.7	1.82	1.16	3.54	1.58	2.48	0.10	0.33	0.05	3.5
TK180-170.8	+157	T ₂	1	p	76.5	10.8	0.56	1.05	1.43	5.08	1.70	0.06	0.28	0.04	2.0
TK180-353.3	-25	D ₂	1 (or 2)	p	74.3	13.7	0.65	0.82	6.15	1.41	1.54	0.04	0.16	0.02	1.1
TK180-407	-79	D ₂	1 (or 2)	p	79.8	9.85	0.76	0.86	3.01	2.50	1.62	0.04	0.12	0.01	0.9

¹ Analyses by X-ray Assay Laboratories, Don Mills, Ontario, Canada; weight percent values² Height of sample with respect to ore horizon (top of T₃) in meters³ 1 = zeolite zone, 2 = montmorillonite zone, 3 = sericite-chlorite zone, 4 = Na montmorillonite zone⁴ Alteration products of plagioclase: ab = albite, d → q, py = plagioclase dissolved, void infilled with quartz and pyrite, c = carbonate, K = K-feldspar, p = primary plagioclase, i = incipient clay alteration, a = anhydrite, g = gypsum

zone; is replaced by albite, K-feldspar, calcite, and anhydrite (or gypsum) in the montmorillonite zone; and is mostly dissolved and replaced by quartz in the central part of the sericite-chlorite zone. Replacement of plagioclase by K-feldspar, a feature commonly observed in the intermediate alteration zone of many other Kuroko deposits (e.g., Iijima, 1974; Utada et al., 1981), has not been observed in the Fukazawa area until this study. Its absence has been used by some investigators (e.g., Utada et al., 1981) as evidence to suggest that the alteration zones around the Fukazawa Kuroko deposits were related to the younger vein mineralization. However, our discovery of K-feldspar replacement of plagioclase in the montmorillonite zone suggests that the alteration zones around the Fukazawa deposit are similar to those in the other Kuroko deposits.

The $\delta^{18}\text{O}$ values of whole rocks, excluding those of the Sasahata sandstone, are compared to the alteration mineralogy in Figure 1. Date et al. (1983) have recognized a fourth alteration zone (Na montmorillonite zone), which occurs in a restricted area in the hanging-wall rocks in the Fukazawa mine. We have included the data from zone IV in zone II, because the rocks in zone IV are similar in mineral assemblage to those in zone II except for the type of montmorillonite, because only a small number of zone IV samples were analyzed, and because their $\delta^{18}\text{O}$ values are generally indistinguishable from those of zone II rocks. Figure 1 shows a trend of higher values and a broader range of $\delta^{18}\text{O}$ values from the higher to the lower temperature alteration zones. Within an alteration zone, the $\delta^{18}\text{O}$ values among dacites, basalts, andesites, tuffs, and mudstone are indistinguishable. The average and the standard deviation (1σ) of the $\delta^{18}\text{O}$ values are as follows: zeolite zone, 16.9 ± 2.7 per mil ($n = 34$); montmorillonite zone, 11.1 ± 2.5 per mil ($n = 74$); and sericite-chlorite zone, 6.7 ± 1.3 per mil ($n = 31$).

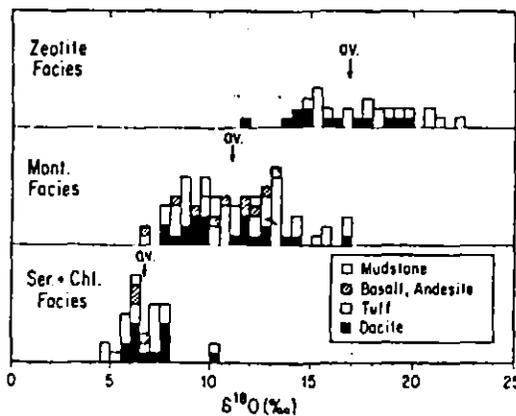


FIG. 1. Whole-rock $\delta^{18}\text{O}$ values of Miocene volcanic and sedimentary rocks from the Hokuroku district, grouped by alteration zones. Each square represents one sample. Mont. = montmorillonite, ser. = sericite, chl. = chlorite, av. = average.

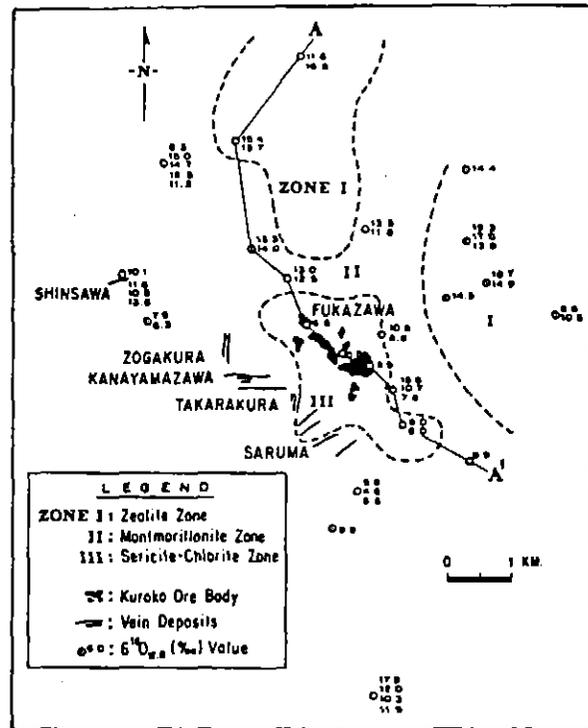


FIG. 2. Areal distribution of the whole-rock $\delta^{18}\text{O}$ values of footwall volcanic rocks in the Fukazawa area. The boundaries for the alteration zones are modified from Date et al. (1983).

Spatial distribution of $\delta^{18}\text{O}$ values

Comparisons between the spatial distribution of the $\delta^{18}\text{O}$ values and the alteration mineral assemblages in the Fukazawa area are made in Figures 2 and 3a and b. These figures show that the alteration zones in both the footwall and hanging-wall rocks change from I to II and then to III approaching the ore zone. The correlation between the $\delta^{18}\text{O}$ values and the alteration mineralogy is excellent in north, northwest, east, and southeast directions from the Fukazawa mine. In both the footwall and the hanging-wall rocks, the $\delta^{18}\text{O}$ values of rocks in the sericite-chlorite zone fall within a range of 5.1 to 8 per mil, gradually increase outward to 8 to 14 per mil in the montmorillonite zone, and to values greater than 14 per mil in the outermost zeolite zone. The fact that the low $\delta^{18}\text{O}$ sericite-chlorite alteration zone contracts in the hanging-wall rocks (Fig. 3a and b) suggests that the overall intensity of hydrothermal activity decreased with time. However, the existence of the sericite-chlorite and montmorillonite zones throughout the >400-m hanging-wall-rock sequence suggests that high-temperature hydrothermal activity persisted over a long period of time, perhaps over a 3-m.y. period according to the radiometric ages of dacites (Tanimura et al., 1983), possibly not continuously, but intermittently according to the thermal

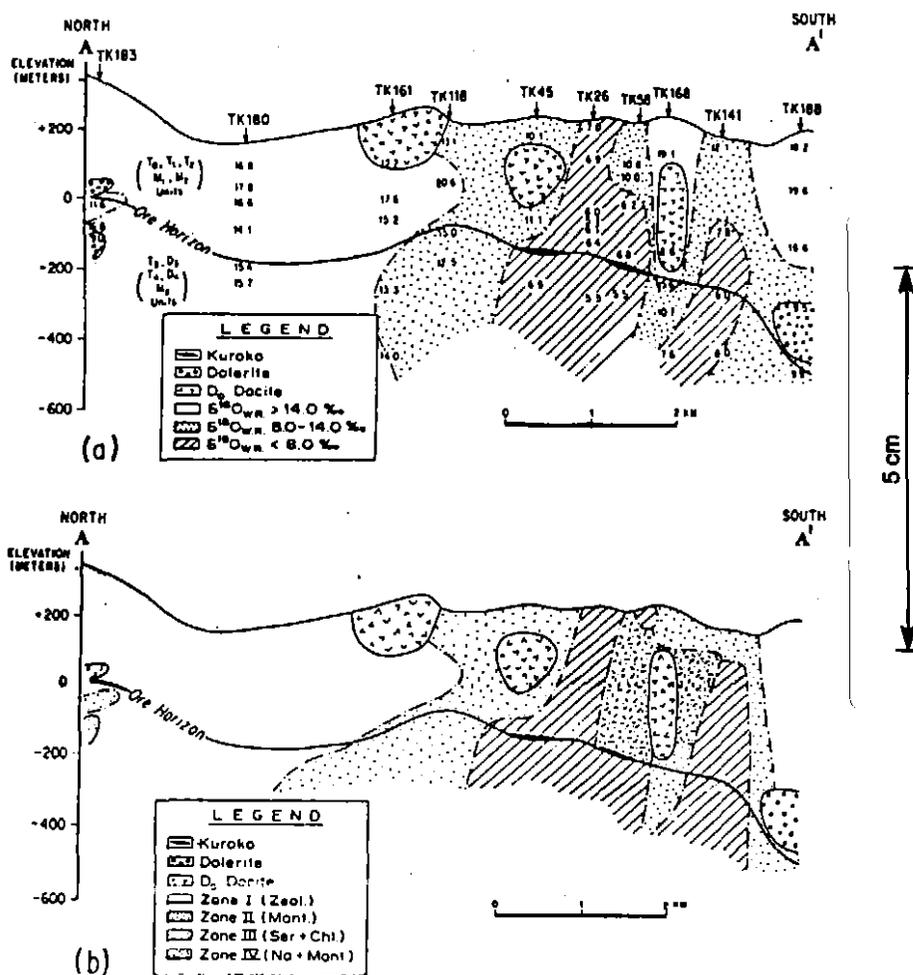


FIG. 3. (a) Whole-rock (w.r.) $\delta^{18}\text{O}$ values of pre- and postore rocks in drill holes along section A-A' in Figure 2. (b) Alteration zones along the same cross section as (a). Modified from Date et al. (1983).

history reconstructed by Pisutha-Arnond and Ohmoto (1983).

The $\delta^{18}\text{O}$ zoning and its correlation with the alteration mineral zoning are not as well defined in the western part of the Fukazawa area (see Fig. 2). In this area, some of the rocks in the montmorillonite zone show $\delta^{18}\text{O}$ values less than 8 per mil. However, the fact that these abnormal samples come from a north-west-southwest trending zone which hosts many younger vein deposits, such as the Shinsawa, Zogakura, Kanayamazawa, Takarakura, and Saruma deposits, suggests that these low $\delta^{18}\text{O}$ values were produced by hydrothermal activity related to the younger vein formation.

In Figure 4, the minimum $\delta^{18}\text{O}$ value of felsic volcanic rocks (excluding D₀) from each drill hole in the entire area studied is compared with the sites of known Kuroko deposits, of younger vein deposits, and of heavy metal mineralization encountered by drilling. In most drill holes, the $\delta^{18}\text{O}$ values gradually decrease down-

ward and the minimum value occurs in the lowest part. However, the alteration boundaries are often irregular (e.g., TK141 in Fig. 3a), and the minimum $\delta^{18}\text{O}$ value may sometimes occur in the hanging-wall rocks. Figure 4 shows that 18 of the 21 drill holes in which the minimum $\delta^{18}\text{O}$ values are less than 8 per mil are situated within 1 km of known mineralization. This supports the idea that the low $\delta^{18}\text{O}$ halos are associated with the sites of mineralization and that the investigation of whole-rock $\delta^{18}\text{O}$ values is indeed an excellent method of exploration for massive sulfide and vein deposits that occur in submarine volcanic sequences. It also suggests the presence of yet undiscovered Kuroko-type or vein-type mineralization in three other drill hole areas where the $\delta^{18}\text{O}$ values are less than 8 per mil.

Comparison of $\delta^{18}\text{O}$ and other geochemical halos

Previously known geochemical halos around the Fukazawa mine are those of the major elements (Na, K,

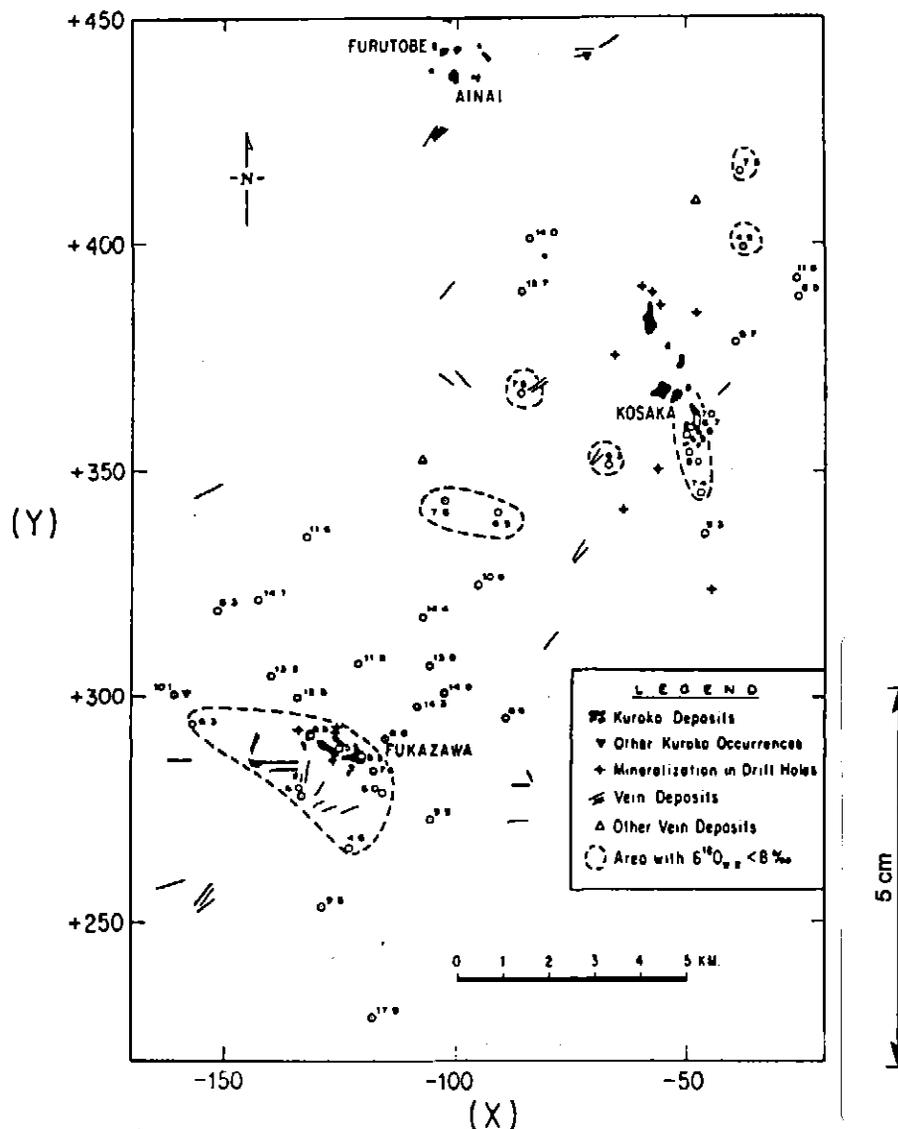


FIG. 4. Minimum $\delta^{18}O$ values of drill hole samples of felsic volcanic rocks, excluding D_0 from the eastern Hokuroku district compared with the sites of known mineralization. Six data points in the Kosaka mine are those from Hattori and Muehlenbachs (1980). See Table 1, footnote 1, for meaning of X and Y.

Mg, Ca), the heavy metals (Cu, Pb, Zn), sulfur contents, the Fe^{+3}/Fe^{+2} ratio, and the magnetic susceptibility to the footwall and hanging-wall rocks (Date and Tanimura, 1973, 1974; Date et al., 1979, 1983; Izawa et al., 1978; Ishikawa et al., 1976; Yamada and Hashiguchi, 1982). In addition to the $\delta^{18}O$ halo, this study has identified a zone of Sr depletion around the Fukazawa deposit, a feature noted in the massive sulfide deposits at Woodlawn, Australia (Petersen and Lambert, 1979), and Rosebery, Australia (Green et al., 1981).

In Figure 5a to k, the variations in the $\delta^{18}O$ values of footwall dacite (D_3 unit) in the drill holes along a section transecting the Fukazawa deposit from north to southeast are compared with those in other geo-

chemical parameters. The values of Sr content in Figure 5f are from those in Table 4, but the data on other elements are based on analyses by the Dowa Mining Company of 10 to 30 samples from each drill hole. Some of the prominent features in these results are as follows:

1. The Na_2O content of the footwall dacite increases from 2.3 ± 0.6 wt percent in the zeolite zone to 3.5 ± 1.5 wt percent in the montmorillonite zone and decreases markedly to less than 0.1 wt percent in the central part of the sericite-chlorite zone.

2. The K_2O content decreases from 3.0 ± 1.5 wt percent in the zeolite zone to 2.0 ± 1.0 wt percent in the montmorillonite zone and increases to as high as

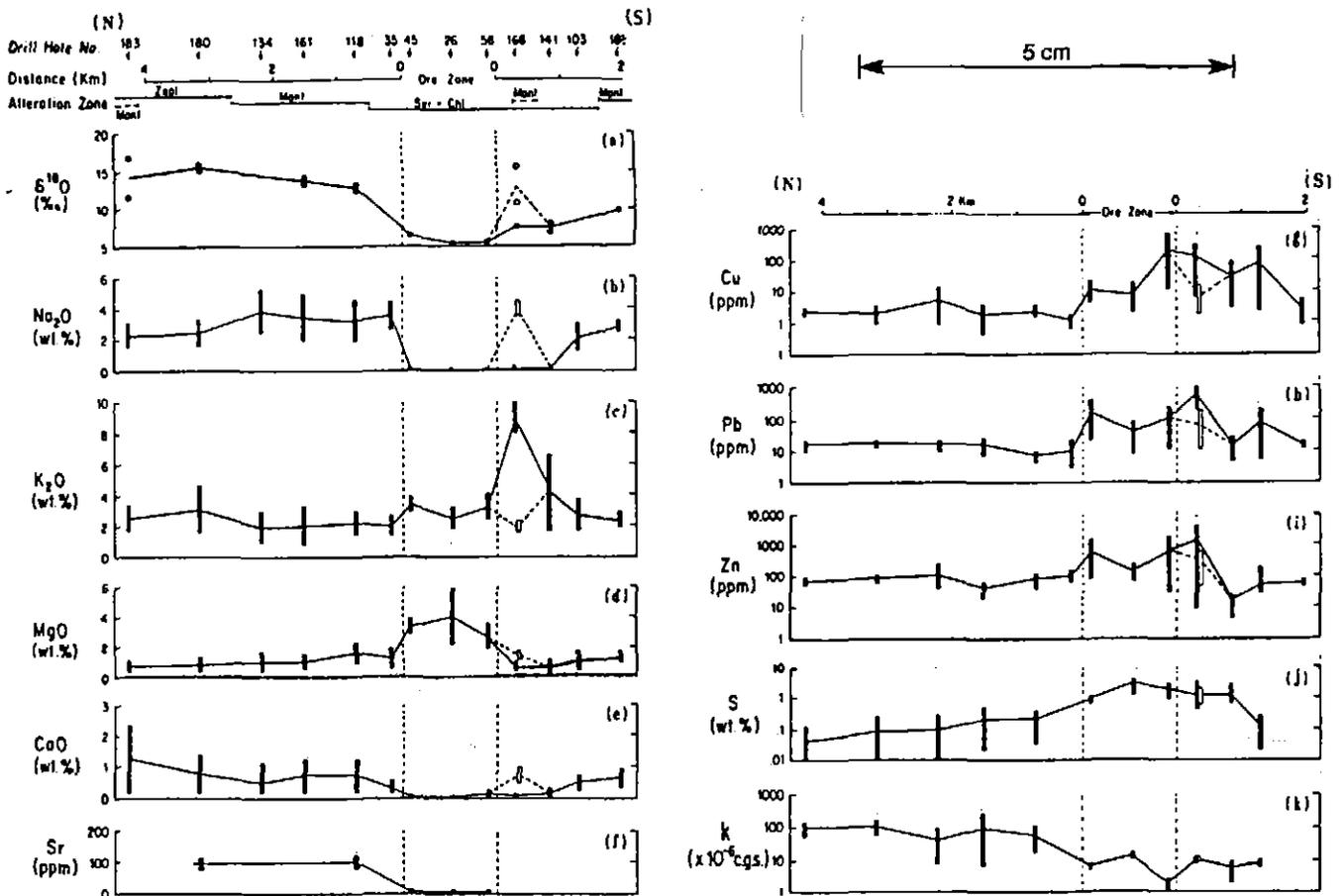


FIG. 5. Comparisons of the $\delta^{18}\text{O}$ values of footwall dacite, alteration zones, and other geochemical halos along section A-A' in the Fukazawa area (Fig. 2). Circles represent the values obtained in this study (1975 and 1976) and open symbols represent the values of other geochemical parameters (e.g., Na_2O , MgO , Cu , magnetic susceptibility) of 10 to 30 samples per drill hole analyzed by the Dowo Mining Company (unpub. data); open symbols are for rocks in the Na montmorillonite zone in drill hole 168; lines connect the average values; k is the magnetic susceptibility of whole rock; note the logarithmic scale for (g) through (k).

10 wt percent in the sericite-chlorite zone. However, the rocks with the highest K_2O contents occur outside of the ore zone, as in TK168 and TK141 in Figure 5c.

3. The MgO content increases gradually from 0.7 ± 0.4 wt percent in the zeolite zone to about 1.0 ± 0.5 wt percent in the montmorillonite zone and to 2 to 6 wt percent in the ore zone of the sericite-chlorite zone. However, outside the ore zone some rocks in the sericite-chlorite zone have MgO contents as low as those in the zeolite zone (see data of TK168 and TK141 in Fig. 5d).

4. The CaO content decreases gradually from 1.2 ± 1.0 wt percent in the zeolite zone to 0.7 ± 0.5 wt percent in the montmorillonite zone and to less than 0.1 wt percent in the sericite-chlorite zone.

5. The Sr content decreases from about 100 ppm in the montmorillonite zone to less than 10 ppm (i.e., detection limit) in the sericite-chlorite zone.

6. The above changes in the major element and Sr contents are what one would expect from the changes

in the mineral assemblages: decreasing abundance of primary plagioclase (i.e., loss of Na, Ca, and Sr) and increasing abundances of sericite (i.e., increase in K) and Mg-rich chlorite (i.e., increase in Mg) from rocks in the zeolite zone to those in the sericite-chlorite zone.

7. The heavy metal contents in the zeolite zone are fairly uniform: 2.8 ± 1.5 ppm for Cu, 17 ± 7 ppm for Pb, and 79 ± 36 ppm for Zn. The average metal contents in the montmorillonite zone are similar to those in the zeolite zone, but the variations are larger. The average metal contents and the variations in the sericite-chlorite zone are much higher than those in the montmorillonite zone. Some rocks in the sericite-chlorite zone are depleted, rather than enriched, in the heavy metals.

8. The sulfur content in the zeolite zone ranges from 0.01 to 0.1 wt percent gradually increases in the montmorillonite zone, and reaches values greater than 0.5 wt percent in the sericite zone.

9. The magnetic susceptibility of rocks in the zeolite

TABLE 4. Volatile and Minor Element Contents of Whole Rocks from the Fukazawa Area

	CO ₂	S	Cl	Zr	Rb	Sr	Cu	Pb	Zn
TK26-225	<0.1	0.19	18	130	40	50	3	12	100
TK26-340	0.3	8.13	15	50	<10	20	11	16	190
TK26-460	<0.1	2.31	12	120	60	<10	4	24	130
TK26-510	0.1	2.64	22	150	70	<10	3	12	49
TK45-47.3	0.1	0.43	18	140	50	30	69	320	1330
TK45-86	<0.1	0.24	36	100	70	60	10	16	160
TK45-329.4	0.8	0.39	45	140	40	80	3	12	56
TK45-481.6	0.1	2.70	19	170	80	<10	12	200	190
TK58-48.2	0.4	0.72	29	100	50	10	4	20	91
TK58-222.7	1.4	0.43	18	100	60	30	3	8	25
TK58-331.6	1.5	0.09	13	110	60	100	4	8	66
TK58-453	<0.1	1.61	19	210	110	<10	140	36	38
TK118-67.5	0.1	0.21	16	130	60	180	6	20	72
TK118-174.2	0.1	0.20	13	120	30	100	2	16	69
TK118-387	0.1	<0.10	17	180	40	90	1	8	61
TK118-443	1.1	0.89	18	140	70	110	<1	12	53
TK180-41.5	0.2	0.18	13	140	<10	240	3	12	51
TK180-170.8	0.1	0.25	12	80	90	40	7	24	62
TK180-353.3	0.1	0.02	16	150	10	80	1	12	64
TK180-407	0.3	0.05	12	100	60	100	1	12	46

Cl analyses by E. Campbell, U. S. Geological Survey, Reston, Virginia; other analyses by X-ray Assay Laboratories, Ontario, Canada; concentration units are weight percent for CO₂ and S and ppm for the others

zone is $(100 \pm 30) \times 10^{-6}$ cgs, is similar in average value but shows a larger variation in the montmorillonite zone, and decreases to less than 18×10^{-6} cgs in the sericite-chlorite zone.

10. The above trends—increasing contents of the heavy metals and sulfur, decreasing magnetic susceptibility, as well as increasing Fe⁺³/Fe⁺² toward the sericite-chlorite zone (Date et al., 1983)—are also what one would expect from the reactions of the metal- and sulfur-bearing hydrothermal fluids with the magnetite-bearing dacite at high temperatures.

There are two important differences between the $\delta^{18}\text{O}$ halo and the other geochemical halos. One is that the $\delta^{18}\text{O}$ halo extends over a much larger area. For example, rocks with $\delta^{18}\text{O}$ values less than 14 per mil may occur 1 to 2 km away from the edge of the ore zone, whereas the zones of low Na, high Mg, low Ca, low Sr, and high metal contents can be recognized only in an area less than 1 km from the ore zone. The second characteristic is that the magnitude of variation in the $\delta^{18}\text{O}$ values among rocks from a drill hole is generally less than that in the elemental concentration, particularly for heavy metals. These two characteristics of the $\delta^{18}\text{O}$ halo reflect the fact that there is an excellent correlation between the $\delta^{18}\text{O}$ values and the alteration mineral assemblage, that the variation in the $\delta^{18}\text{O}$ values within an alteration zone is less than ± 2.5 per mil, and that the montmorillonite zone extends much farther than the areas with elemental anomalies. These char-

acteristics of the $\delta^{18}\text{O}$ halo then suggest that the analysis of oxygen isotope composition of whole-rock samples is particularly useful during a reconnaissance stage of exploration of volcanogenic massive sulfide deposits. The analysis of only a few samples may define a potential area, while many more analyses of heavy metal contents are required to identify a potential area. On the other hand, other geochemical investigations are more useful in locating a specific target.

The existence of a strong correlation between the $\delta^{18}\text{O}$ values and the alteration mineral zoning around the Kuroko deposits may indicate that a study of alteration mineral assemblages, which is certainly much easier than a study of $\delta^{18}\text{O}$, is a more practical method of exploration of volcanogenic massive sulfide deposits. This may be true of exploration for younger and unmetamorphosed deposits but not for exploration of this type of deposit in metamorphosed terrains.

Terrains containing volcanogenic massive sulfide deposits commonly have been subjected to greenschist facies or higher grade metamorphism. This activity could destroy evidence of zeolite and montmorillonite zone rocks. Some subtle clues for the fringe zone of alteration, such as the replacement of plagioclase by K-feldspar and carbonate, may persist in rocks metamorphosed to greenschist facies (e.g., Green et al., 1981), and a weak trend in some elements such as Mg and Ca might remain, but these effects might well escape cursory examination. However, the oxygen isotope zonation would likely be preserved because re-

gional metamorphism is generally a process operating under low water/rock ratios. The generally smooth oxygen isotope profiles around the Kuroko deposits suggests sampling every two hundred meters or so across strike would be sufficient. Because the $\delta^{18}\text{O}$ values generally decrease toward the footwall rocks, more detailed sampling might even provide evidence of the facing direction of volcanic sequences and evidence of faulting, which are often difficult to establish in deformed and metamorphosed volcanic terrains.

Of particular importance to exploration for massive sulfide deposits in metamorphosed terrains, the Fukazawa case study has shown that the oxygen isotope halo is well defined both in the footwall and hanging-wall volcanic sequences. This comes from the apparent longevity of hydrothermal systems having consistent $\delta^{18}\text{O}$ values of water (see later). The effects of alteration in the postore rocks are not as clearly shown by the other geochemical parameters. Thus oxygen isotope analyses may have particular application in terrains where the recognition of a host-rock horizon for massive sulfide mineralization is difficult.

For successful application of the technique, it should be realized that rock mineralogy can exert a major influence on the oxygen isotope composition of bulk-rock samples. For example, quartz is resistant to isotopic exchange (see later). Therefore, rocks containing a high proportion of quartz phenocrysts or quartz-rich xenoliths should be avoided. In addition, allowance must be made for different rock-water fractionation factors among different minerals. For example, a mineral assemblage rich in quartz will have a higher $\delta^{18}\text{O}$ value under equivalent conditions of temperature and water/rock ratio than a rock dominated by chlorite (e.g., Taylor, 1979). This effect may account for the sharp change in $\delta^{18}\text{O}$ values between the dacites and basalts from drill hole J-4 (Table 1).

Origin of the alteration zones

Phenocryst quartz is not abundant in the rocks from the Hokuroku district, but three samples of igneous quartz show a $\delta^{18}\text{O}$ range of 6.8 to 8.6 per mil (see Table 1). These values, together with the equilibrium isotope fractionation factors between quartz and other igneous materials at magmatic temperatures (Taylor, 1979) and with the commonly observed feature in altered volcanic sequences that quartz is resistant to subsequent isotopic exchange with hydrothermal solutions (Clayton et al., 1968; Taylor, 1979) suggest that the unaltered dacite in the Hokuroku district had $\delta^{18}\text{O}$ values of about 6 to 8 per mil. These values are also typical of unaltered felsic volcanic rocks in Japan (Matsuhisa, 1977). Thus the variations in the $\delta^{18}\text{O}$ values of whole rocks observed in the Hokuroku district must have been caused by isotopic exchange reactions between rocks and hydrothermal fluids. An example of

the inertness of quartz to isotopic exchange and a change in the whole-rock $\delta^{18}\text{O}$ value is shown by one sample of D₂ dacite which shows 7.6 per mil for quartz and 15.6 per mil for whole rock.

According to the fluid inclusion analyses by Pisutha-Arnond and Ohmoto (1983), the CO₂ content in the hydrothermal fluids involved in the Kuroko mineralization and later vein mineralization was less than 0.3 moles/kg H₂O. Therefore, the oxygen isotope exchange reaction between fluids and rocks in the Hokuroku district may be considered as simple water-rock interaction. The change in the $\delta^{18}\text{O}$ value of rock due to water-rock interaction can be evaluated from the following equation:

$$\delta^{18}\text{O}_r^i \cdot X_r^i + \delta^{18}\text{O}_w^i \cdot X_w^i \\ = \delta^{18}\text{O}_r^f \cdot X_r^f + (\delta^{18}\text{O}_r^f - \Delta_w^f) \cdot X_w^f \quad (1)$$

(see Sheppard et al., 1969, and Taylor, 1971, for similar equations) where superscripts *i* and *f* refer respectively to the initial state (i.e., before water-rock interaction) and the final state (i.e., after interaction), subscripts *r* and *w*, respectively, to rock and water, *X* to the atomic fraction of oxygen in rock or water with respect to the total number of oxygen atoms in the rock + water system, and Δ_w^f to the isotopic fractionation factor between rock and water in the final state.

If the amount of H₂O transferred between rock and water during reaction is negligible (i.e., $X_w^i = X_w^f$ and $X_r^i = X_r^f$), the final $\delta^{18}\text{O}$ value of rock can be expressed as

$$\delta^{18}\text{O}_r^f = \frac{\delta^{18}\text{O}_r^i + (\delta^{18}\text{O}_w^i + \Delta_w^f) \frac{w}{r}}{1 + \frac{w}{r}} \quad (2)$$

where *w/r* is the water/rock ratio expressed in atom proportion of oxygen which is approximately twice the water/rock mass ratio for most systems (Ohmoto and Rye, 1974).

The most serious problem in the application of equation (2) to natural systems is the selection of Δ_w^f values, because rocks are composed of more than one mineral phase and the mineral-water fractionation factors can be either equilibrium or kinetic isotopic fractionation factors. The common approaches have been to use the equilibrium fractionation factors of plagioclase-H₂O (e.g., Taylor, 1979) or muscovite-H₂O (e.g., Spooner et al., 1977) for the Δ_w^f values. Cathles (1983) has adopted the smectite-H₂O fractionation factors determined by Cole (1980) for interpretation of the oxygen isotope history of water and rock in the Hokuroku district.

In this study, we have followed Taylor's approach (e.g., 1979) and used the equation:

$$\Delta_w^l = \frac{2.68 \times 10^6}{T^2} - 3.53 \text{ (O'Neil and Taylor, 1967), (3)}$$

where T is in Kelvin.

One of the reasons for this approach is that the overall fractionation factors between rocks and water in the experimental system granite-NaCl solutions at $T = 200^\circ$ to 300°C , computed from the abundance of individual alteration minerals and the mineral-water fractionation factors, were found by Cole (1980) to be similar to the plagioclase- H_2O fractionation factors. At temperatures below about 100°C , it does not make much difference to the calculated results whether plagioclase- H_2O or smectite- H_2O fractionation factors are used, because they are very similar. The extrapolations of the plagioclase- H_2O and smectite- H_2O curves give Δ_w^l values around 27 per mil at 25°C . The $\delta^{18}\text{O}$ values greater than 20 per mil and as high as 27 per mil are also common among the altered oceanic basalts obtained by the Deep Sea Drilling Project (e.g., Muehlenbachs, 1980; Friedrichsen and Hoernes, 1980). The reasonable agreement between the extrapolated mineral-water fractionation factors and the observed differences in the $\delta^{18}\text{O}$ values of these basalts to seawater may be used as more evidence to support our equilibrium model.

The rocks in the zeolite zone with a mineral assemblage of clinoptilolite + mordenite + $\text{Mg} \cdot \text{Na}$ -type montmorillonite \pm cristobalite have been commonly interpreted to have undergone only diagenetic alteration (i.e., $T \approx 25^\circ\text{C}$), whereas those containing analcite have undergone slightly higher temperature alteration (Iijima, 1974; Utada et al., 1981; Izawa et al., 1978). Temperatures of mordenite formation at Wairakei, New Zealand, are around 100°C (Ellis, 1979). Analcite and mordenite are forming in a temperature range of 85° to 135°C in the Niigata oil field (Iijima and Utada, 1971), which is located approximately 300 km southwest of Fukazawa and at temperatures up to 200°C at Reykjanes, Iceland (Tomasson and Kristmannsdóttir, 1972), and at Yellowstone Park (Bargar and Beeson, 1981). Therefore, the entire temperature range for zeolite alteration may be considered to be between 25° and 200°C . Pisutha-Arnond and Ohmoto (1983) have suggested formation temperatures of 150° to 300°C for the montmorillonite zone and 200° to 400°C for the sericite-chlorite zone, based on fluid inclusion filling temperature measurements, and on the calculated stability relationships among montmorillonite, sericite, chlorite, K-feldspar, and calcite, which were estimated by using the thermodynamic data of these minerals and the chemical compositions of fluid inclusions.

Using equations (2) and (3), changes in the $\delta^{18}\text{O}$ values of rock with an initial value of 7 per mil were computed as a function of T and w/r under three

different conditions of the $\delta^{18}\text{O}_w^l$ values, +6, 0, and -8 per mil. Comparisons of the calculated $\delta^{18}\text{O}_w^l$ values in Figure 6a to c with the mineralogical temperatures indicate the following possible conditions for the formation of zeolite rocks with $\delta^{18}\text{O}$ values of 15 to 21 per mil in a temperature range of 25° to 200°C :

$$\delta^{18}\text{O}_w^l = 6\text{‰} \text{ and } w/r > 0.5 \quad (\text{Z-1})$$

or

$$\delta^{18}\text{O}_w^l = 0\text{‰} \text{ and } w/r > 0.7. \quad (\text{Z-2})$$

In fact any water with $\delta^{18}\text{O}$ values between 0 and 6 per mil at $w/r > 0.7$ can satisfy the conditions. If the $\delta^{18}\text{O}_w^l$ was much lower than 0 per mil, it must imply that all the zeolite rocks studied had undergone isotopic exchange with water at temperatures much less than 100°C .

The sericite-chlorite-zone rocks with $\delta^{18}\text{O}$ values of 5 to 8 per mil can be produced in a temperature range of 200° to 400°C under the conditions of:

$$\delta^{18}\text{O}_w^l = 0\text{‰} \text{ and } w/r > 1$$

(i.e., water dominated) (S-1)

or

$$\delta^{18}\text{O}_w^l = -8\text{‰} \text{ and } w/r < 0.2$$

(i.e., rock dominated). (S-2)

The $\delta^{18}\text{O}_w^l$ values of +6, 0, and -8 per mil represent, respectively, the "pristine" values of three types of water that could have interacted with the rocks in the Hokuroku district: magmatic water, seawater, and meteoric water. The role of meteoric water was important only after the district became subaerial, i.e., several million years after the Kuroko mineralization (see Tanimura et al., 1983). However, it is important to keep in consideration that the $\delta^{18}\text{O}_w^l$ value of water involved in the water-rock interaction in natural systems may or may not have retained the pristine value and may not be used as an indicator for the origin of fluid. As shown by Ohmoto and Rye (1974), Cathles (1983), and Pisutha-Arnond and Ohmoto (1983), any water, regardless of the origin, may end up with the same $\delta^{18}\text{O}$ value, if the w/r ratio was much less than 1 (i.e., rock dominated). For example, a magmatic water may attain a $\delta^{18}\text{O}$ value around 0 per mil if it was buffered by an igneous rock of 7 per mil at temperatures around 250°C . This water, now with a $\delta^{18}\text{O}_w^l$ value of 0 per mil, may be involved in the water-rock interaction at lower temperature conditions. Only when the w/r ratio of the system is much greater than 1 (i.e., water dominated) can the $\delta^{18}\text{O}_w^l$ value estimated from the $\delta^{18}\text{O}_w^l$ value be used to identify the origin of fluid. Therefore, any combination of the above conditions, such as (Z-1) and (S-1) or (S-2), or (Z-2) and (S-1) or (S-2), could theoretically produce the observed $\delta^{18}\text{O}$ zoning in the Hokuroku district. (Note that the montmorillonite zone with $\delta^{18}\text{O}$ and temperature values inter-

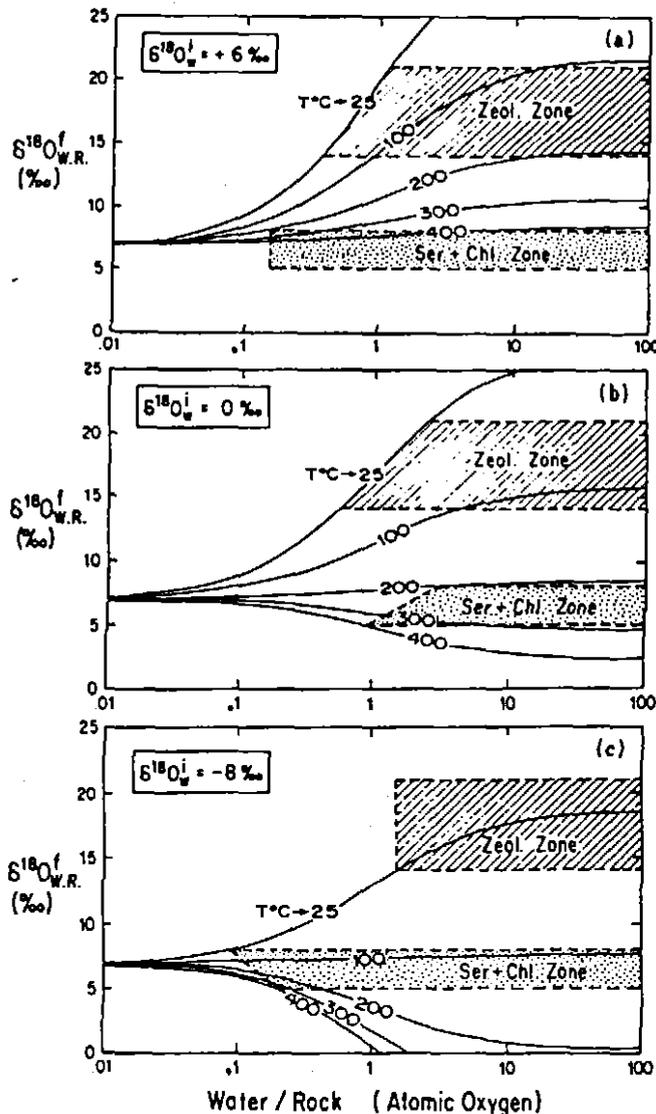


FIG. 6. Calculated changes in the $\delta^{18}\text{O}$ values of volcanic rocks ($\delta^{18}\text{O}_i = 7.0\text{‰}$) as a result of equilibrium oxygen isotope exchange with waters of different initial compositions. The shaded areas represent the $\delta^{18}\text{O}$ ranges of rocks in the zeolite and the sericite-chlorite zones.

mediate to the zeolite and the sericite-chlorite zones can also be satisfied at any of the above conditions.) However, a specific combination of the conditions requires a specific set of hydrologic features.

For example, the combination of (Z-1) or (Z-2) with (S-2) implies that per unit mass (or area) of rock there was more fluid flow in the zeolite zone than in the sericite-chlorite zone. Such a hydrothermal system is difficult to imagine. The combination of (Z-1) and (S-1) may be possible if the rocks in the zeolite zone and those in the sericite-chlorite zone interacted with large amounts ($w/r > 1$) of magmatic water and seawater, respectively. This is geologically unrealistic, the opposite relationship being more likely.

The combination which is geologically most rea-

sonable is (Z-2) and (S-1). That is, the rocks in both the zeolite and the sericite-chlorite zones (and also the montmorillonite zone) have undergone oxygen isotope exchange with large amounts ($w/r > 1$) of seawater at different temperatures. This suggestion is in support of the model of the seawater origin of the Kuroko ore-forming fluids, first presented by Ohmoto et al. (1970) and later substantiated by other papers in this volume (e.g., Pisutha-Arnond and Ohmoto 1983; Ohmoto et al., 1983b). Based on the Mg and Ca balance between rocks and solutions, Ohmoto et al. (1983) have also reached the conclusion that the minimum water/rock mass ratios were about 20 in the sericite-chlorite zone. Similarity in the $\delta^{18}\text{O}$ values among different rock types within the same alteration zone, particularly between basalts and dacitic tuffs which differ greatly in porosity, can only be explained by oxygen isotope exchange under water-dominated conditions.

This conclusion of water-dominated conditions for the hydrothermal systems associated with the Kuroko deposits might, at first sight, appear contradictory to the suggestion made in other papers in this volume (e.g., Cathles 1983; Mizukami and Ohmoto 1983; Pisutha-Arnond and Ohmoto 1983; Ohmoto et al., 1983). However, we must realize that we are comparing processes that took place in different time scales (see Ohmoto and Rye, 1974). According to the calculations by Cathles (1983) and by Ohmoto et al. (1983), the time it took for a given packet of seawater to enter the underlying rock sequence, be heated, convect, and discharge at the seafloor was probably less than 500 years and certainly less than 20,000 years. This water must certainly have interacted with more than its mass of rocks along its circulation path. In other words, for a given packet of water, the system was always rock dominated and the chemical and isotopic characteristics were controlled by the rocks. On the other hand, the water/rock ratios obtained in this study are an integrated record of the total amount of water that passed through the rock over a 3-m.y. period.

The δD values of two samples from drill hole HO33 in the Fukazawa area, which lies in the boundary zone between the montmorillonite and the sericite-chlorite zones, are -56 and -69 per mil (see Table 2). These values are similar to the values of between -34 and -63 per mil obtained by Hattori and Muehlenbachs (1980) for 17 samples of the montmorillonite and the sericite-chlorite zones in the Kosaka area. In comparison to the much lower δD values of two samples from HO39 in the Fukazawa area, which lies in the zone between the zeolite and the montmorillonite zones, are much lower at -73 to -101 per mil.

In a temperature range of about 200° to 300°C , the $\Delta_{\text{H}_2\text{O}}^{\text{mineral}}$ values for the hydrogen isotope systems are about -30 to about -50 per mil for chlorite- H_2O and muscovite- H_2O (Suzuoki and Epstein, 1976; Taylor, 1979). Therefore, the δD values of around -30 to -50

per mil for the sericite-chlorite and the montmorillonite zones are consistent with the suggestion made from the oxygen isotope study that the isotopic composition of the rocks in the alteration zones around the Kuroko deposits were essentially buffered by seawater at different temperatures. The hydrogen isotope fractionation factors between hydrous minerals and H₂O at temperatures below about 200°C are not well established. If the trend of decreasing $\Delta_{\text{H}_2\text{O}}^{\text{mineral}}$ value with decreasing temperature continued, the values around -80 per mil may not be unreasonable for the zeolite facies rocks formed in equilibrium with seawater at around 100°C. The δD values lower than -80 per mil may have been caused by isotopic exchange with post-Miocene meteoric water.

Dimensions of the hydrothermal system

The areal extent of the ore zone in the Fukazawa Kuroko mine is about 1.5 km in the northwest-southeast direction and about 1 km in the northeast-southwest direction, that of the sericite-chlorite zone where the discharging fluid temperatures reached higher than about 200° is about 3 km (northwest-southeast) × 1.5 km (northeast-southwest), and that of the montmorillonite zone where the discharging fluid temperatures were greater than about 150°C and where $\delta^{18}\text{O}$ and some geochemical anomalies are detectable is conservatively 5 km (northwest-southeast) × 3 km (northeast-southwest). The areal extent of various geochemical halos around the Kosaka area is similar to that in the Fukazawa area.

An important question for the dimensions of a Kuroko hydrothermal system is the depth of seawater circulation through the underlying rocks. Hattori and Muehlenbachs (1980) obtained $\delta^{18}\text{O}$ values of 8.3 to 16.3 per mil for four samples of the Sasahata sandstone formation and 18.0 and 19.0 per mil for a phyllite and a chert of the Paleozoic basement rocks in the Kosaka area. They concluded that the sharp upward decrease in $\delta^{18}\text{O}$ values from the Sasahata Formation to the overlying volcanic rocks (mostly less than 9‰) corresponded to the effective depth limit (less than 200 m) of the ore-forming hydrothermal system at Kosaka.

Our petrographic examination of several rocks from the Sasahata Formation has, however, revealed abundant evidence of hydrothermal alteration in the form of chloritization of phyllitic clasts and the common presence of euhedral pyrite. Up to 70 percent of the rock is composed of quartz, quartzite, and quartz-mica schist clasts. These rock types, which probably had initial $\delta^{18}\text{O}$ values of around 19 per mil, would be more resistant to subsequent isotopic exchange, as shown, for example, by detrital quartz subjected to temperatures of 320°C in the Salton Sea geothermal area (Clayton et al., 1968). Thus a direct comparison of the $\delta^{18}\text{O}$ values of samples from the Sasahata Formation with the overlying volcanic rocks is likely to give a

misleading impression of the degree of hydrothermal alteration of the former.

In a few samples of Sasahata conglomerate, an attempt was made to drill out pelitic clasts and matrix to concentrate the material most susceptible to isotopic exchange. Although it could not be ensured that clastic quartz was excluded from these samples, their relatively low $\delta^{18}\text{O}$ values of 4.3 to 9.8 per mil (see Table 2), which are similar to the $\delta^{18}\text{O}$ values of the overlying volcanic rocks, suggest that the high-temperature hydrothermal system encompassed at least the Sasahata Formation and probably the basement rocks. This suggestion is in accord with the lead isotope data obtained by Fehn et al. (1983).

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February 1, 1983

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APPENDIX 4

Percussion Drill Logs CRP 88-1, 2, 3

BHMET SYSTEM
METRIC
DECIMAL POINTS AS REQUIRED

The Shell Company of Australia Limited
METALS DIVISION
DRILL LOG SHEET
CONTINUATION SHEET

PROJECT CATTLEY RANGE	HOLE NAME CRP 98-1
LOGGED BY J. RANDELL	TOTAL DEPTH 70m

DISTANCE FROM COLLAR		CORRECTION	SAMPLE NO	CORE ANGLE	ROCK TYPE	DIA	RSEC CODE	GRAPHIC LOG	DESCRIPTIVE LOG
TO TOP	TO BOTTOM								
50	52								<p>fine grained, non amygdaloidal, trace pyrite As above 70% as above 30% medium brown sediment Matrix weakly amygdaloidal</p> <p>↓</p> <p>70% grey clay 30% fine grained basalt OWEN CONGLOMERATE - predominantly quartz + fine pebbles with rounded pebbles, cobbles</p> <p>Hole continuously cased, jamming etc.</p>
52	54								
54	56								
56	58								
58	60								
60	62								
62	64								
64	66								
66	68								
68	70								
END OF HOLE									

AREA INFORMATION

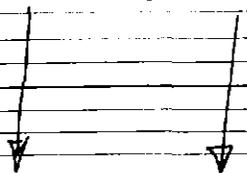
087

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SHELLMET SYSTEM
METRIC
DECIMAL POINTS AS REQUIRED

The Shell Company of Australia Limited
METALS DIVISION
DRILL LOG SHEET
CONTINUATION SHEET

PROJECT <i>CATTLEY RAN66</i>	HOLE NAME <i>CRP 88-2</i>
LOGGED BY <i>J. RANDALL</i>	TOTAL DEPTH <i>82m</i>

DISTANCE FROM COLLAR		SAMPLE NO	CORE ANGLE	ROCK TYPE	DIAM	DESC CODE	GRAPHIC LOG	DESCRIPTIVE LOG
TO TOP	TO BOTTOM							
50	52							<i>Fire grained weakly amygdaloid</i>  <i>As above + yellow quartz amygdaloid.</i> <i>As Above.</i> <i>As above + 20% grey clay.</i> <i>70% grey clay 30% fine grained basalt</i> <i>OWEN CONGLOMERATE - predominantly</i> <i>quartz, quartzite, rounded pebbles. Generally</i> <i>mainly pebbles to rubble size.</i> <i>Hole continuously caving, can't wash out</i> <i>pebbles.</i>
52	54							
54	56							
56	58							
58	60							
60	62							
62	64							
64	66							
66	68							
68	70							
70	72							
72	74							
74	76							
76	78							
78	80							
80	82							
END OF HOLE								

ASSAY INFORMATION

680

060809

BHMET SYSTEM
METRIC
DECIMAL POINTS AS REQUIRED

The Steel Company of Australia Limited
METALS DIVISION
DRILL LOG SHEET
CONTINUATION SHEET

PROJECT <i>CATTLEBY RANGE</i>	HOLE NAME <i>CRP 88-3</i>
LOGGED BY <i>J. RANDELL</i>	TOTAL DEPTH <i>72m</i>

DISTANCE FROM COLLAR	TO TOP		TO BOTTOM		SAMPLE NO	CORE ANGLE	ROCK TYPE	DIAM	RECORD	GRAPHIC LOG	DESCRIPTIVE LOG
	1	2	3	4							
	50		52								<i>Dark brown wet clay + weathered basalt.</i>
	52		54								
	54		56								
	56		58								
	58		60								
	60		62								
	62		64								
	64		66								
	66		68								
	68		70								
	70		72								
<i>END OF HOLE</i>											

*STRONG
WIPPER
FURN.*

*As above + bleached siliceous? pitstone
As above
OWEN CONGLOMERATE - predominantly
hematitic siliceous chips, 10-20% quartz,
illite-saponite sands, often rounded with
iron pebbles to cobbles.*

Hole caving, unable to reach end hole

ASSAY INFORMATION

091

608092

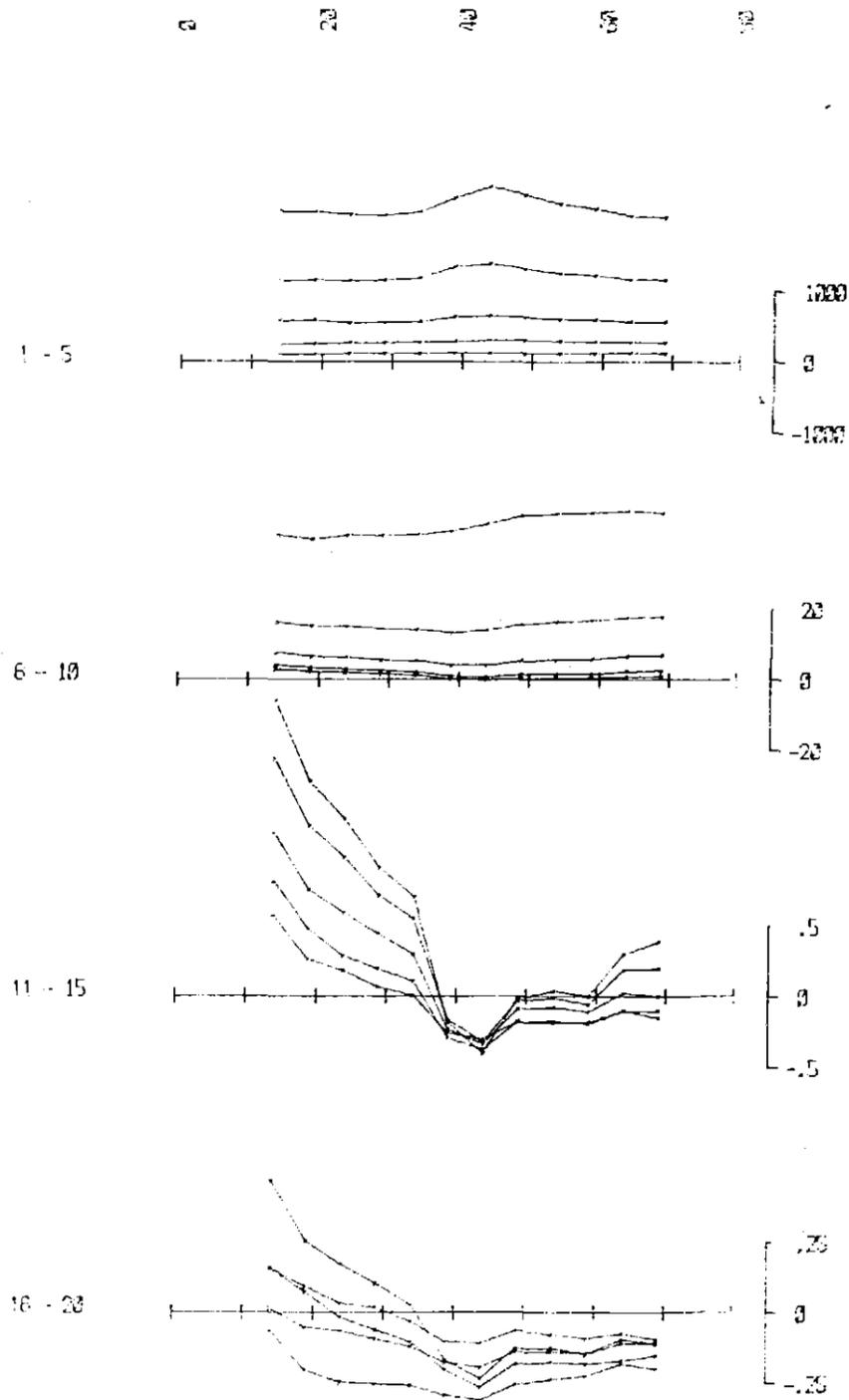
092

608093

APPENDIX 5

Down Hole EM Profiles CRD 88-1, GRP 88-3

AXIAL COMPONENT B_z (Z)



EM-37

BOREHOLE SURVEY

ELECTROMOTIVE FORCE INDUCED BY SECONDARY FIELD

TIME DERIVATIVE OF FLUX DENSITY (Z)

5 cm

Approved to pub. amp metre surveyed

TX LOOP SIDES : 13550N 13590E
 : 13650N 13490E
 TX LOOP SIZE : 100 m X 100 m
 TX TURN OFF TIME : 120 microseconds.
 FIRST GATE TIME : 38.5 microseconds.
 CURRENT : 23.2 amps.
 FREQUENCY : 25 Hz.
 INTEGRATION TIME : 256 cycles
 SYNC MODE :
 HORIZONTAL SCALE : 1:1000
 SURVEYED BY : SOBC
 DATE : 04/03/1999

	SURVEYED AND COMPILED BY		PROJECT NO.
	GEOTREX PTY. LTD.		4-138

CLIENT : BILLITON AUSTRALIA
 PROJECT : CATTLE RANGE
 AREA : WARATAH TASMANIA
 BOREHOLE : CRP685
 TX LOOP : 1

10000

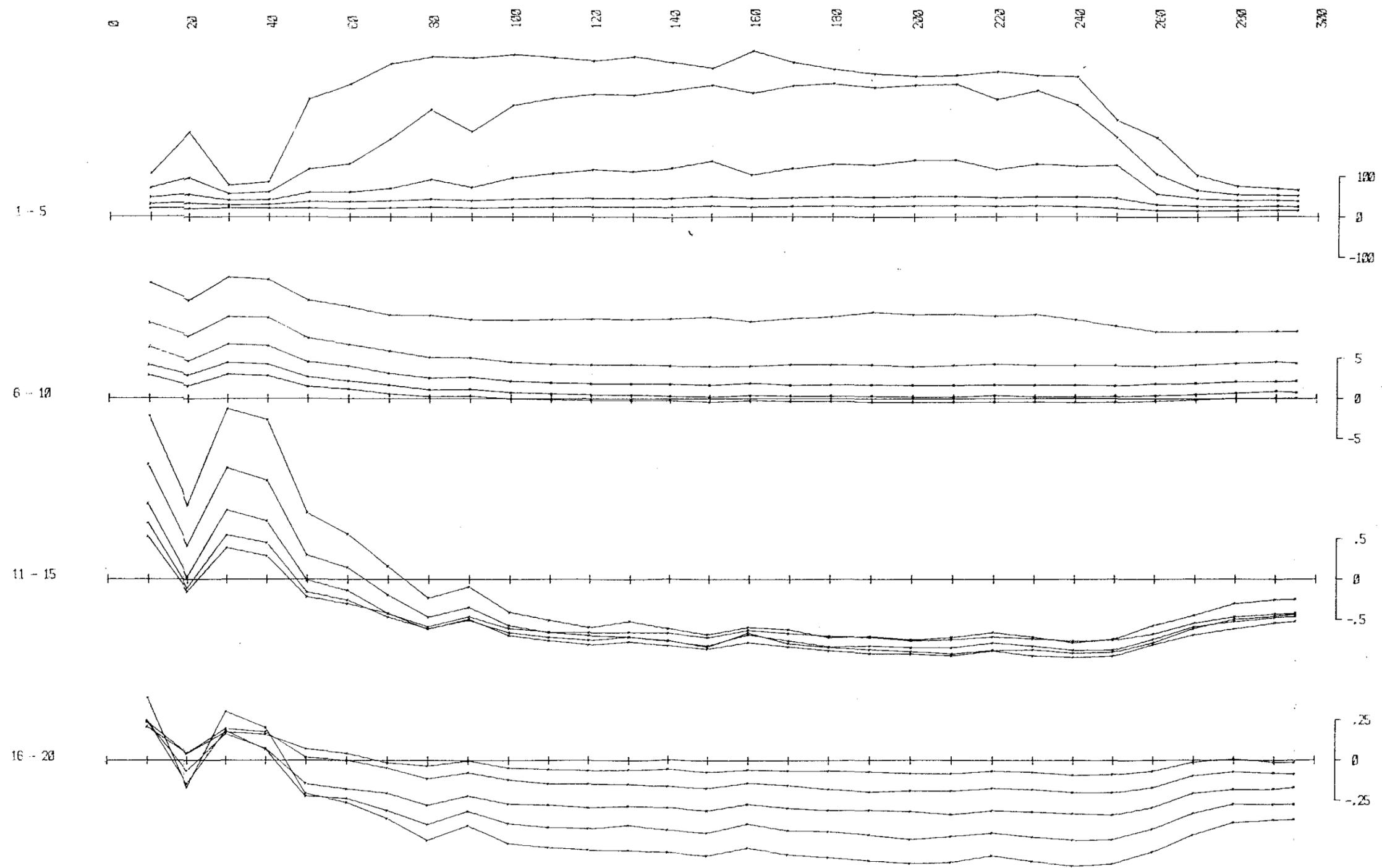
AXIAL COMPONENT \dot{B} (Z)

608095

EM-37

BOREHOLE SURVEY

ELECTROMOTIVE FORCE INDUCED BY SECONDARY FIELD
TIME DERIVATIVE OF FLUX DENSITY (B)



nanovolts per amp metre squared

5 cm

TX LOOP SIDES : 06000N 11950E
 : 05000N 12150E
TX LOOP SIZE : 200 m X 200 m
TX TURN OFF TIME : 220 microseconds.
FIRST GATE TIME : 98.5 microseconds.
CURRENT : 24.2 amps
FREQUENCY : 25 Hz.
INTEGRATION TIME : 1024 cycles
SYNC MODE :
HORIZONTAL SCALE : 1:1000
SURVEYED BY : SDBG
DATE : 04/03/1989

	SURVEYED AND COMPILED BY	PROJECT NO.
	GEOTREX PTY. LTD.	4-103

CLIENT : BILLITON AUSTRALIA
PROJECT : CATTLEY RANGE
AREA : WARATAH TASMANIA
BOREHOLE : CRD331 A
TX LOOP : 2

095

608090

APPENDIX 6

Max-Min EM Profiles & Brief Interpretation Report

MEMORANDUM

TO : BXH Devonport
FROM : BXN/MLB
DATE : 5/11/88
RE : CATTLEY RANGE MAX-MIN

Max-Min profiles for 10600N, 10400N are attached.
Anomaly positions as shown.

The anomaly on line 10600N fits with the conductor on the EM 37 line at 10550E (slight displacement due to different line position?).

The anomaly on line 10400N corresponds to a low resistivity zone on an old IP line (Plan no. LD 01/1016, 1985).

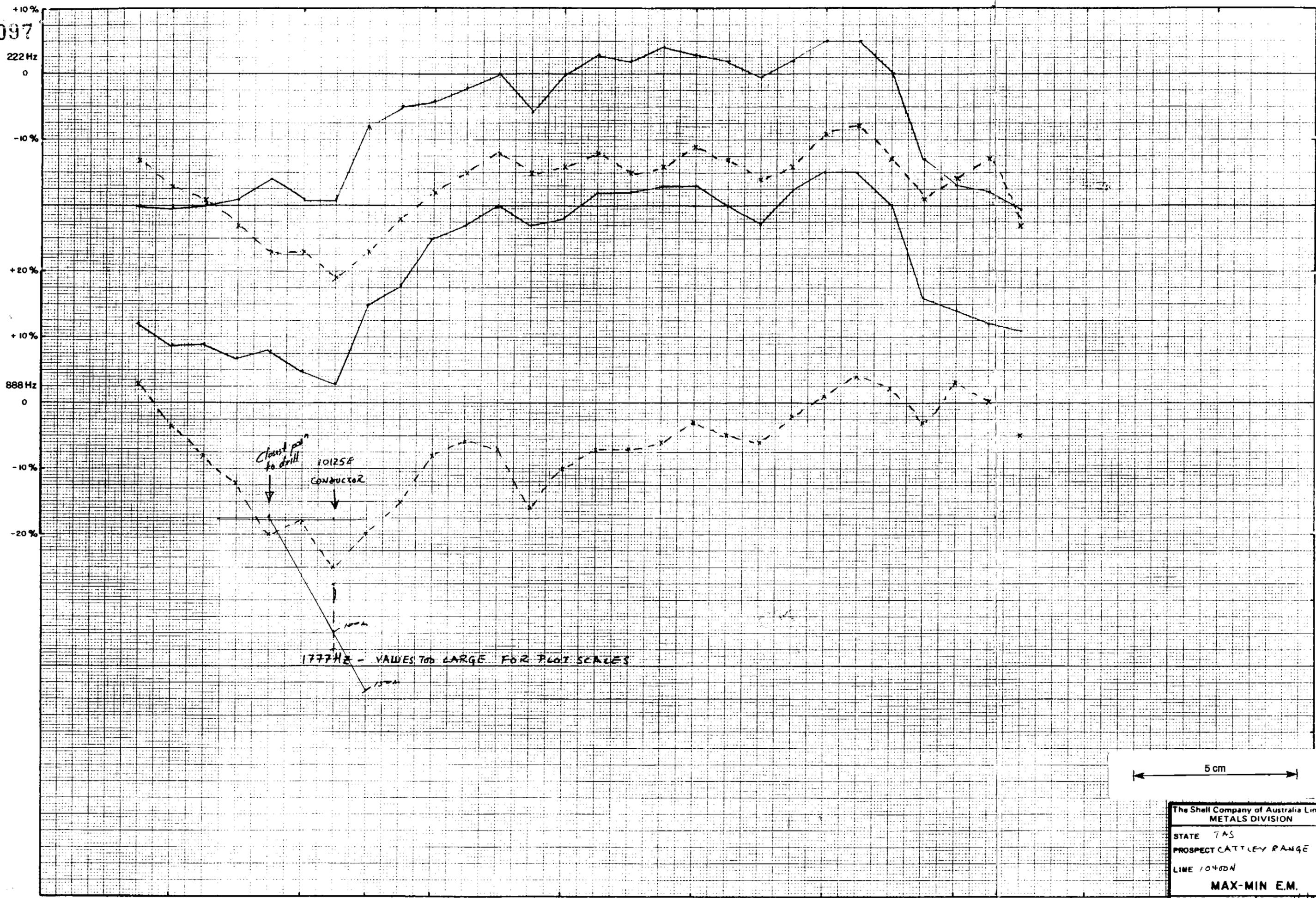
Both anomalies are due to strong conductors, most probably originating from the basalt, but nonetheless worth a drill test.

The anomaly on line 10400N is conveniently close to the road for drilling. I can't do any quantitative work on the profiles since the InPhase results are pretty useless. There may be an east dip on 10600N, but this is less obvious on 10400N.

The western ends of the lines suggest basalt may be thinning out (at the creek), so you could end up drilling quite a thick section of basalt before hitting Cambrian rocks.

Target position (50-100m?) beneath 10400N/10125E.

097



10050E 10100E 10200E 10300E 10400E 10500E 10600E

100 metres

Coil Separation = 100m?

—●— In Phase

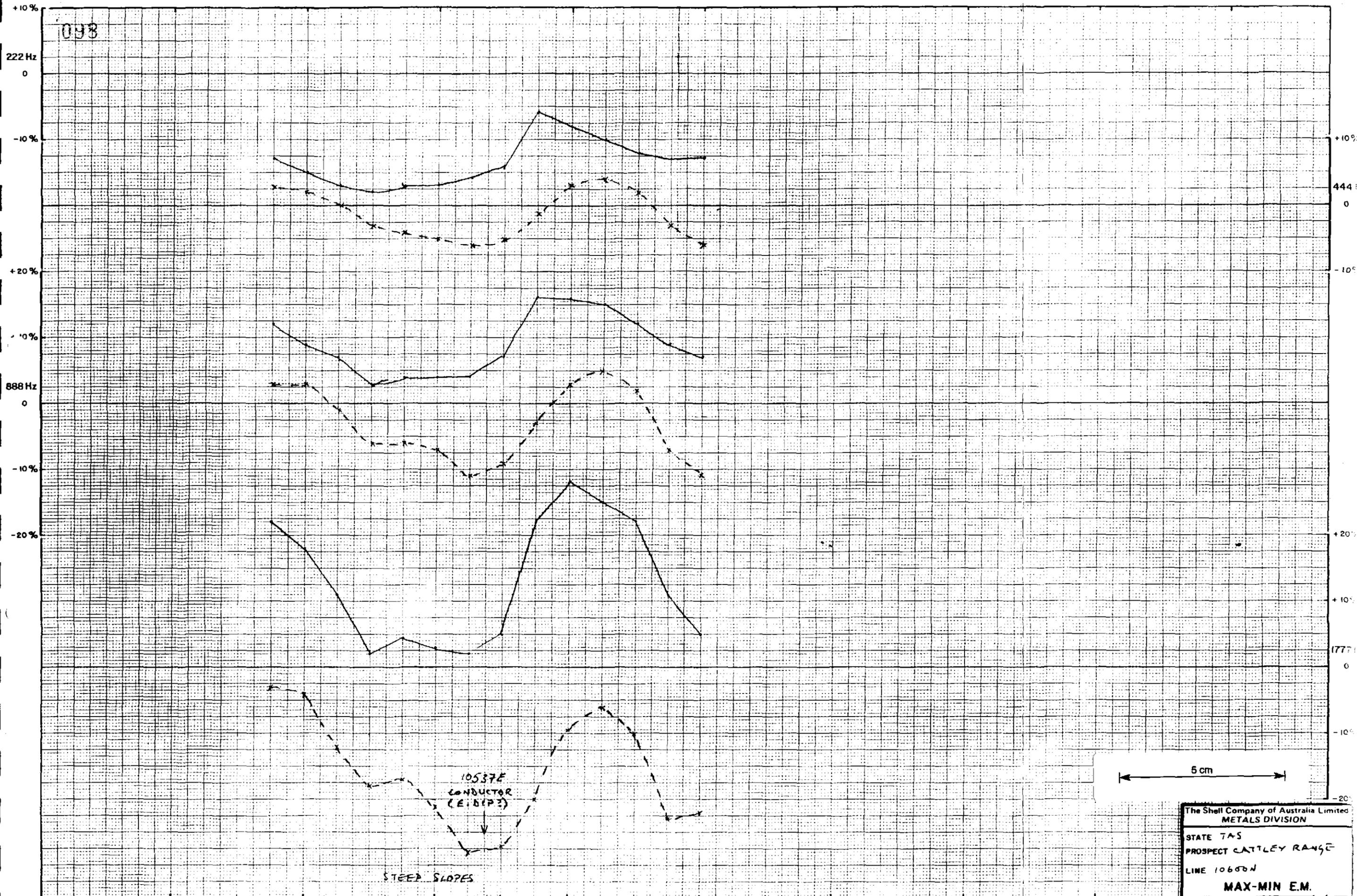
- - - - - Out of Phase

5 cm

The Shell Company of Australia Limited METALS DIVISION	
STATE TAS	
PROSPECT CATTLE RANGE	
LINE 10400N	
MAX-MIN E.M.	
SCALE 1:2500	DATE 4/1/88
AUTHOR RD	DRAWN MH
OFFICE AHO	REP No
DRG No	FIG No

608098

098



10300 10400 10500 10600 10700 E
 100 metres Coil Separation = 100m

—●— In Phase
 - - - - - Out of Phase

The Shell Company of Australia Limited METALS DIVISION	
STATE TAS	
PROSPECT CATTLEY RANGE	
LINE 10600N	
MAX-MIN E.M.	
SCALE 1:2500	DATE 10/11/87
AUTHOR RS	DRAWN NW
OFFICE AHO	REP NO
DRG No	FIG No

608099

Figure 2

**STRATIGRAPHIC DIAGRAM FOR DUNDAS GROUP
IN QUE - HELLYER AREA**

TASMANIA DEPARTMENT OF MINES REPORT 1, MT READ VOLCANICS PROJECT
AUTHORS K.D. CORBETT & P. KOMYSHAN

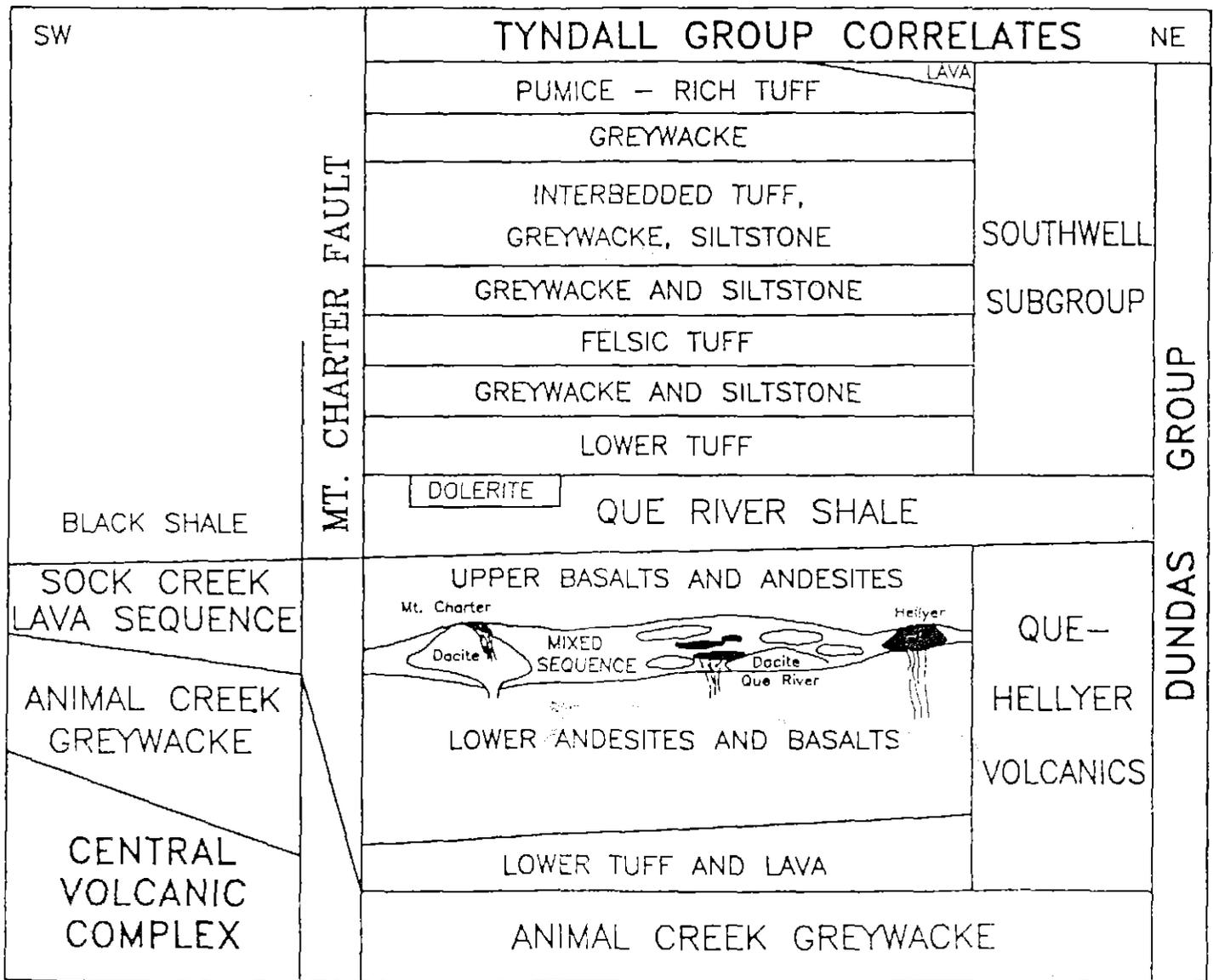
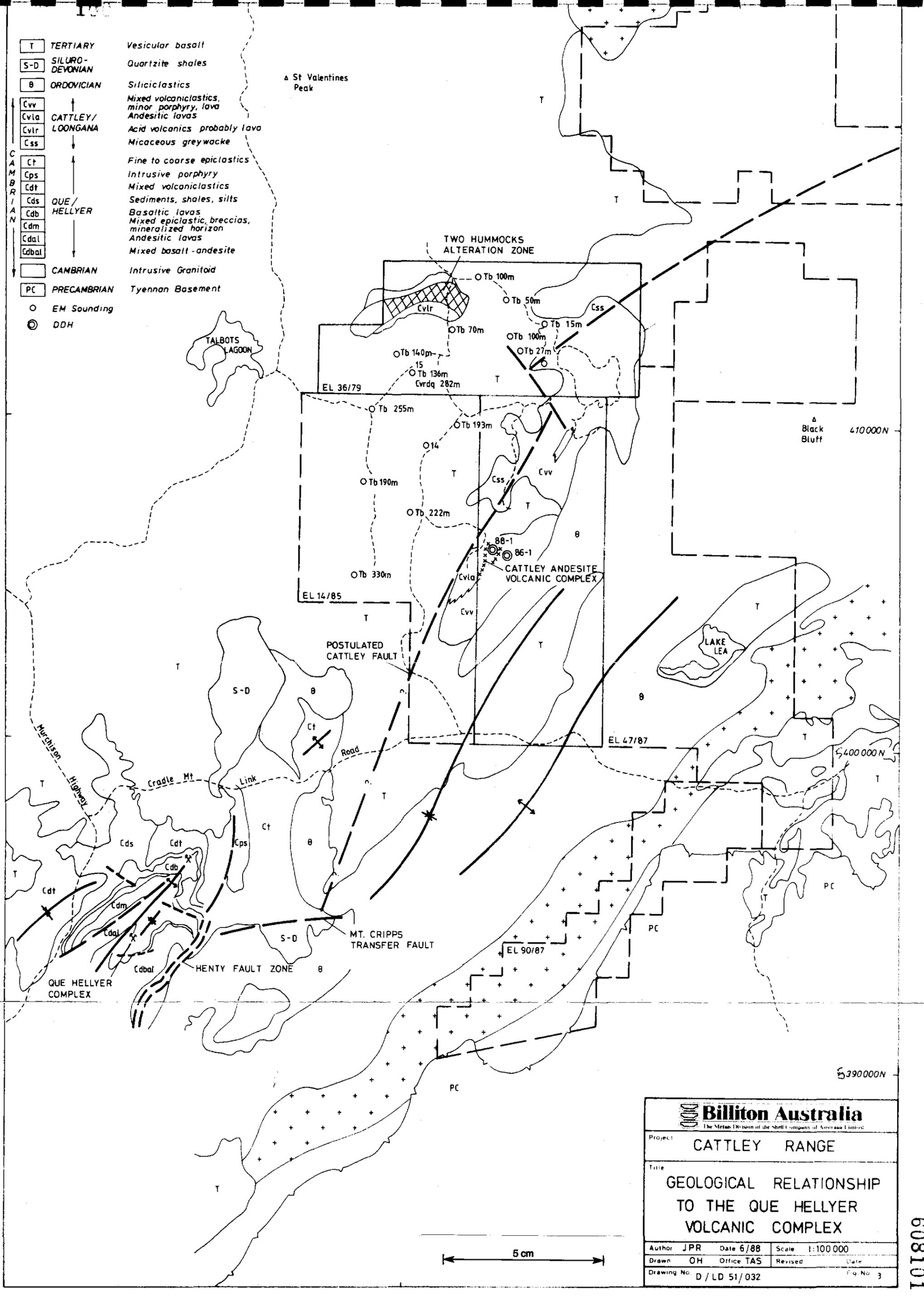


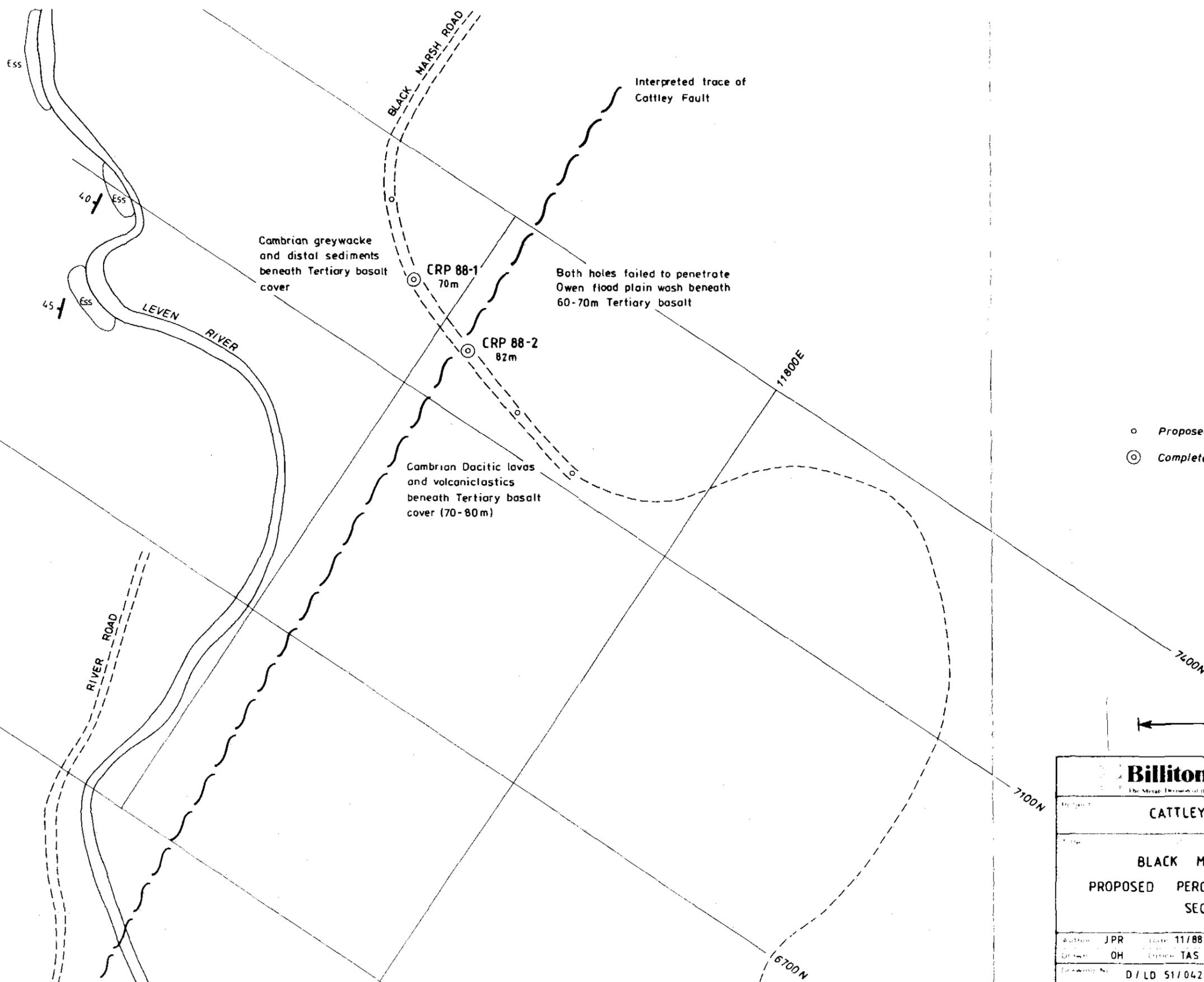
FIG. 2

- T TERTIARY Vesicular basalt
- S-D SILURO-DEVONIAN Quartzite shales
- θ ORDOVICIAN Siliciclastics
- Cvv CATTLEY/LOONGANA Mixed volcanoclastics, minor porphyry, lava
- Cvla Acid volcanics probably lava
- Cvlr Micaceous greywacke
- Ct Fine to coarse epiclastics
- Cps Intrusive porphyry
- Cdt Mixed volcanoclastics
- Cds QUE/HELLYER Sediments, shales, silts
- Cdb Basaltic lavas
- Cdm Mixed epiclastic, breccias, mineralized horizon
- Cdal Andesitic lavas
- Cdbal Mixed basalt-andesite
- CAMBRIAN Intrusive Granitoid
- PC PRECAMBRIAN Tyennan Basement
- EM Sounding
- ⊙ DDH



Billiton Australia <small>The Metals Division of the Shell Company of Australia Limited</small>			
Project		CATTLEY RANGE	
Title			
GEOLOGICAL RELATIONSHIP TO THE QUE HELLYER VOLCANIC COMPLEX			
Author	JPR	Date	6/88
Scale	1:100 000		
Drawn	OH	Office	TAS
Revised			
Drawing No.	D / LD 51 / 032		Fig. No. 3

608101



- Proposed drill hole
- ⊙ Completed drill hole

5 cm

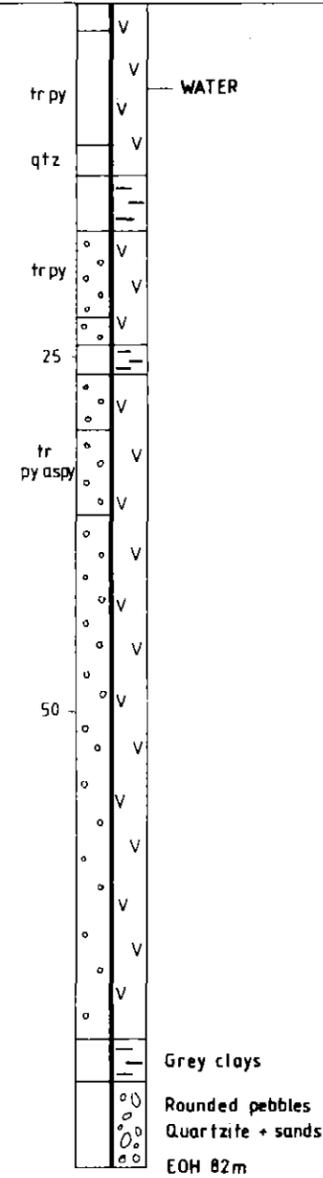
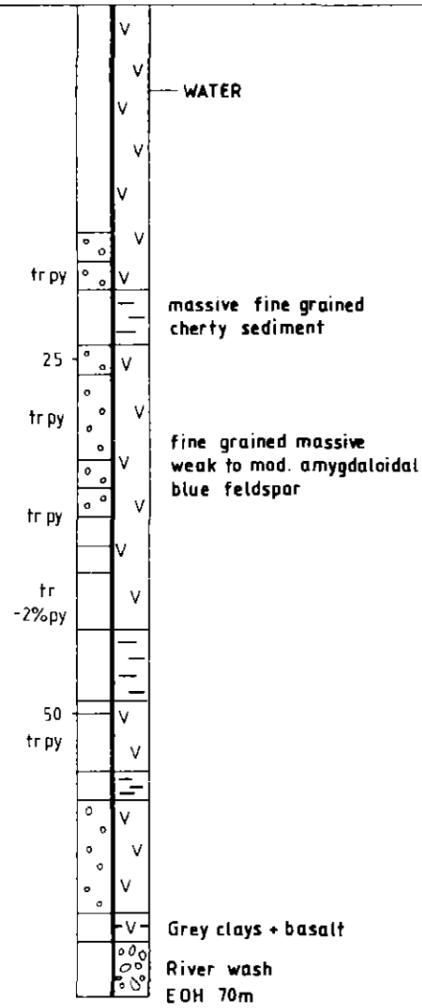
Billiton Australia <small>The Metal Division of the Shell Companies of Australia Limited</small>			
CATTLEY RANGE			
BLACK MARCH ROAD PROPOSED PERCUSSION DRILLING SECTION			
Author: JPR	Date: 11/88	Scale: 1:5000	
Drawn: OH	Entered: TAS	Released:	Sheet:
Drawing No: D/LD 51/042			Fig. No: 4

102

608103

CRP 88-1
(7260N)

CRP 88-2
(7230N)

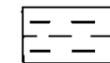


Flood Plain Wash causing hole collapse and jammed rods

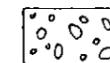
LEGEND



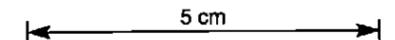
TERTIARY BASALT - fine grained massive variably amygdaloidal.



TERTIARY CLAYS - amorphous clay or fine grained sediments.



ORDOVICIAN CONGLOMERATE - rounded pebbles to cobbles quartzite sandstone minor siltstone



Billiton Australia

The Metals Division of the Steel Company of Australia Limited

CATTLEY RANGE

PERCUSSION DRILL SECTION
BLACK MARSH ROAD

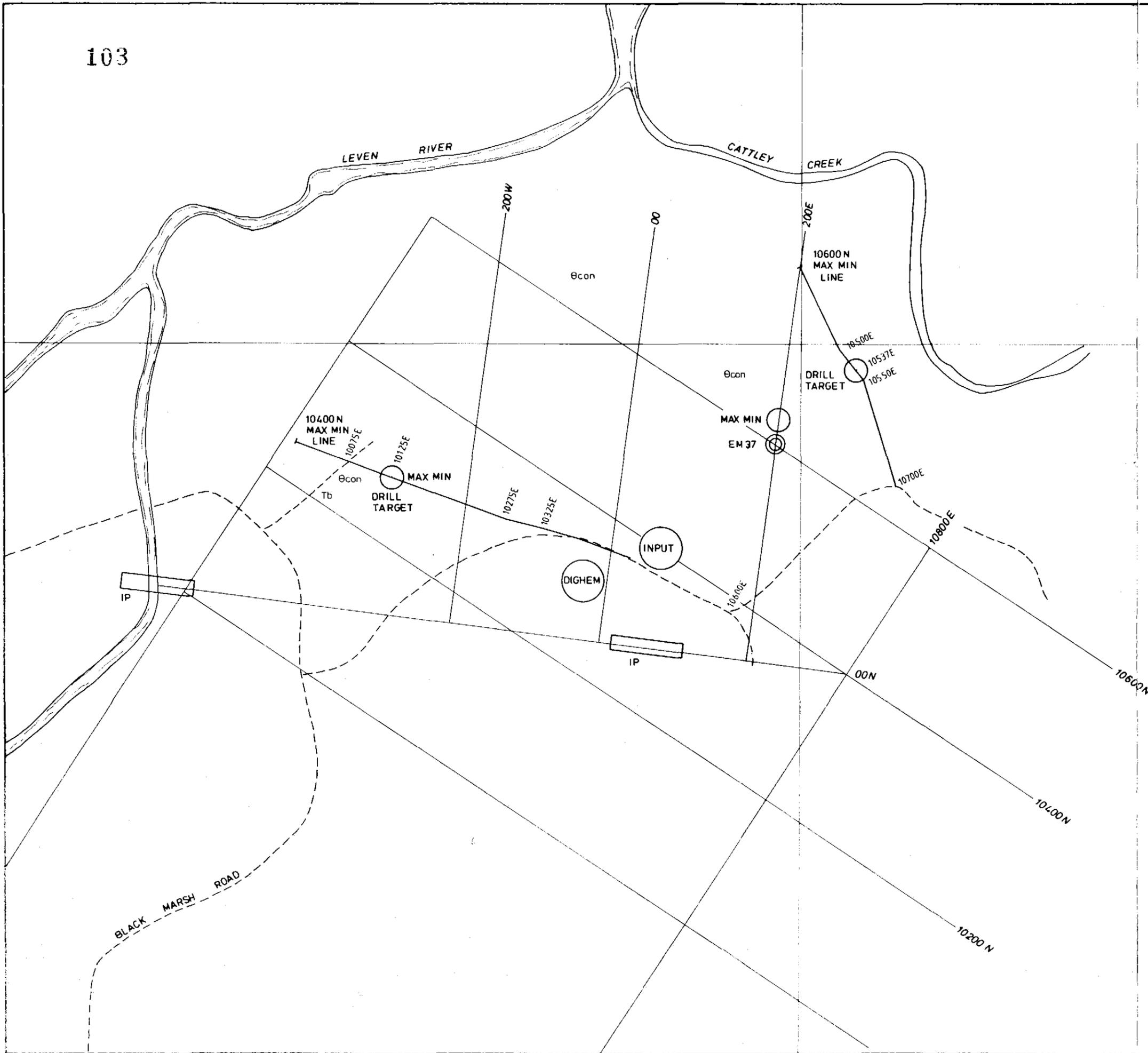
Author: JPR Date: 11/88 Scale: 1:500

Drawn: OH Office: TAS

Drawn No: D/LD 51/044

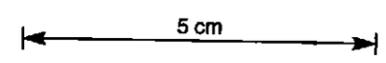
103

608104



EL 36/79

EL 39/83



Billiton Australia <small>The Mineral Division of the Steel Companies of Australia Limited</small>			
CATTLEY RANGE			
MAX MIN EM ANOMALY POSITIONS AND PROPOSED DRILL TESTS			
Author	JPR	Date	11/88
Scale	1:5000	Drawn	OH
Project	TAS	Checked	
Drawing No.	D/LD 51/041		Page No. 6

104

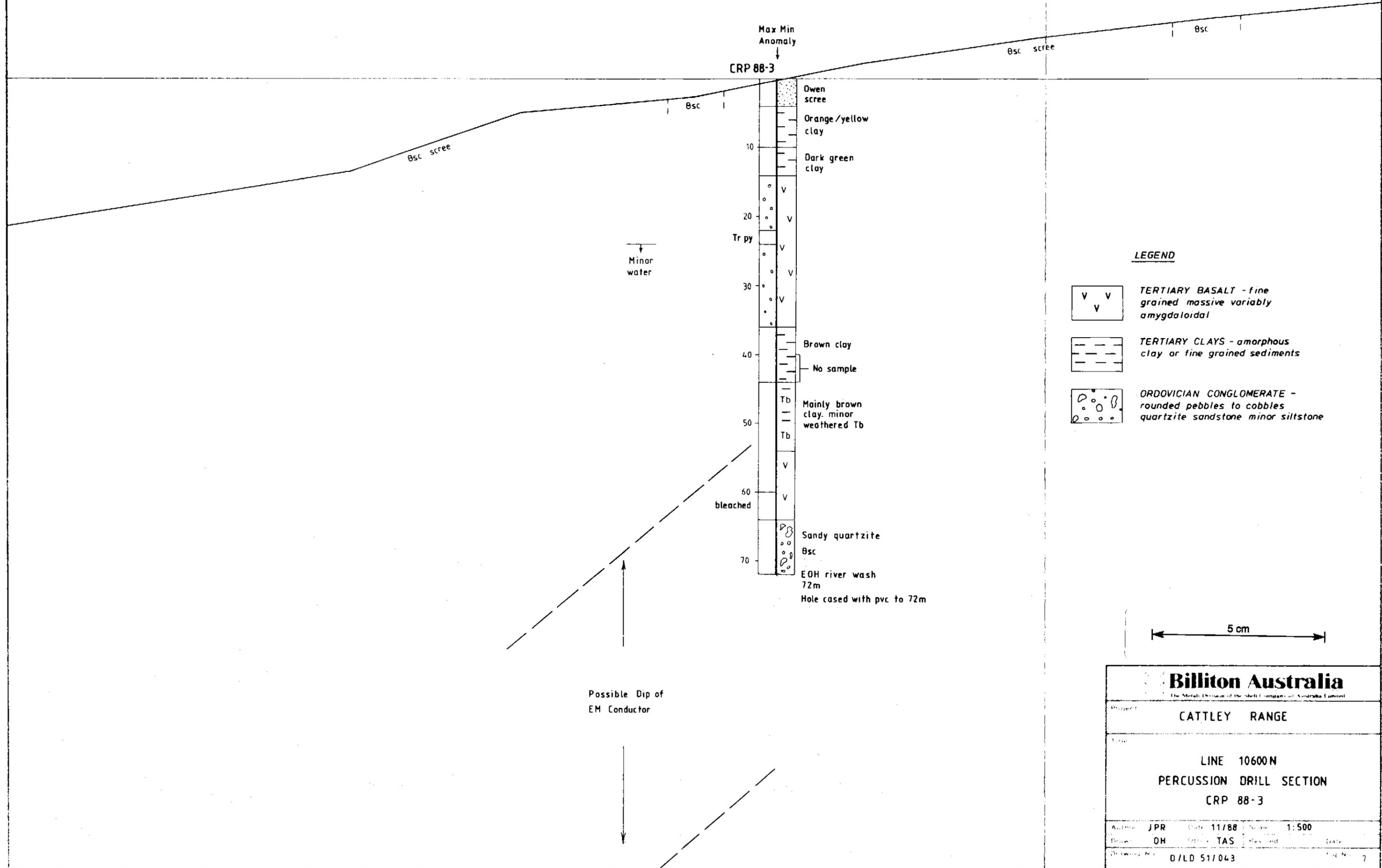
10450E

10500E

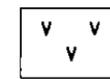
10550E

10600E

608105



LEGEND



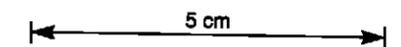
TERTIARY BASALT - fine grained massive variably amygdaloidal



TERTIARY CLAYS - amorphous clay or fine grained sediments



ORDOVICIAN CONGLOMERATE - rounded pebbles to cobbles quartzite sandstone minor siltstone



Billiton Australia
The Metals Division of the Shell Company of Australia Limited

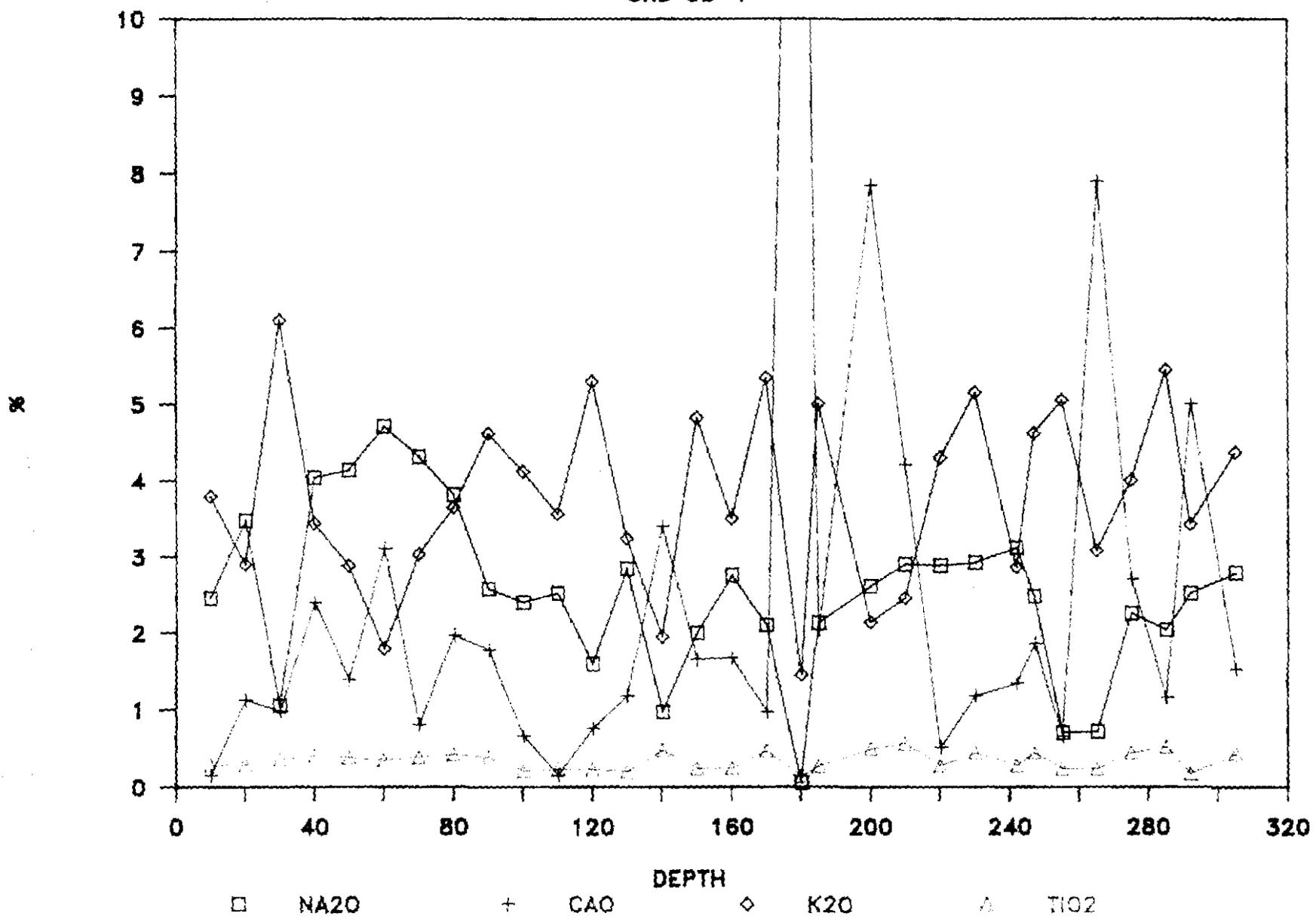
CATTLEY RANGE

**LINE 10600N
PERCUSSION DRILL SECTION
CRP 88-3**

Author: JPR	Date: 11/88	Scale: 1:500
Drawn: OH	Site: TAS	Res. Cont.
Drawing No: 0/LD 511/043	Page No: 7	

CATTLEY RANGE

CRD 88-1



105

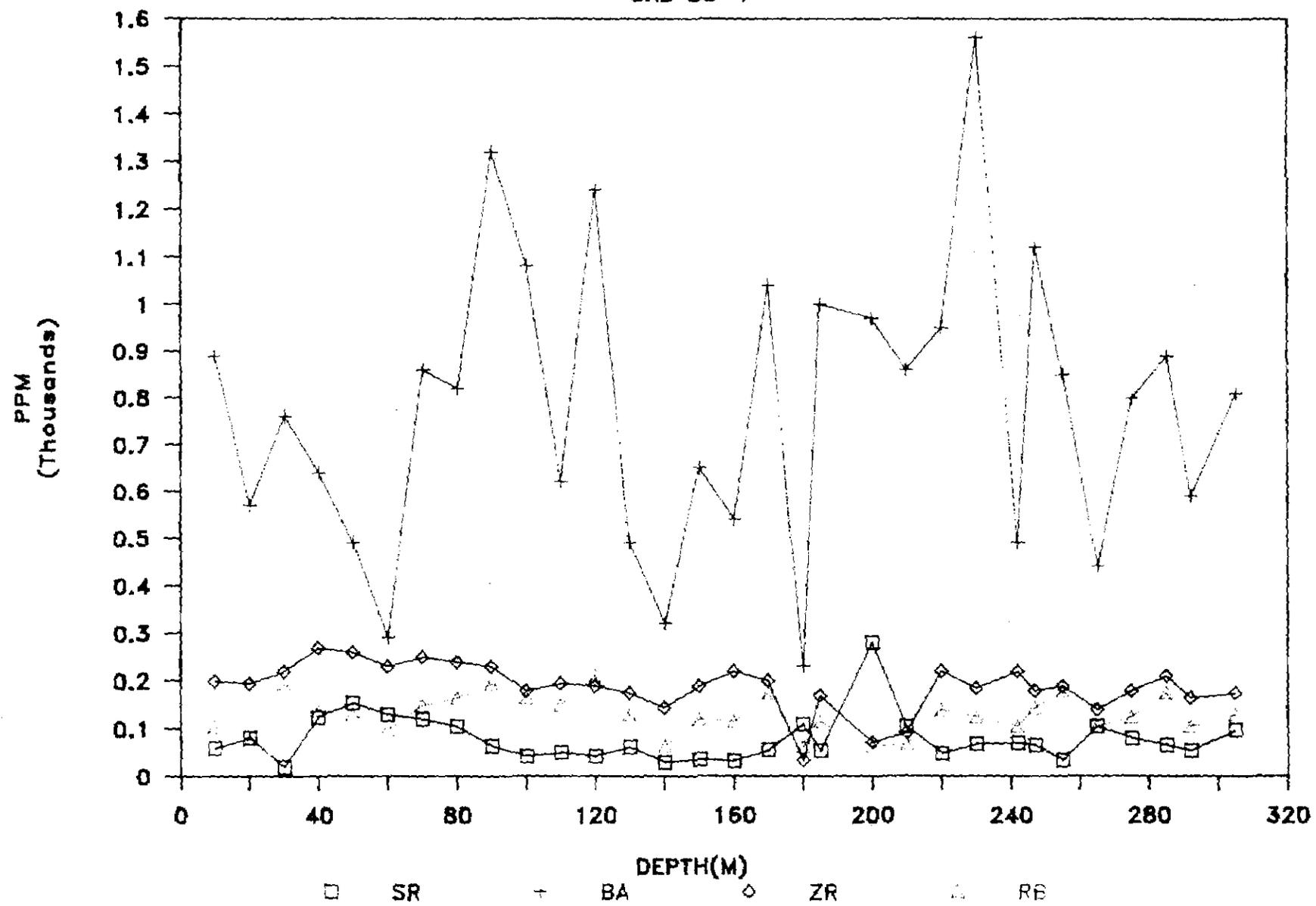
608106

FIG 8

CATTLEY RANGE

CRD 88-1

106



608107

FIG 9