

Centre for Ore Deposit and Exploration Studies

CODES KEY CENTRE

Proterozoic sediment-hosted base metal deposits

AMIRA/ARC Project P.384

Supplement to Report No. 1

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Stratigraphy of the McArthur Basin and the Murphy Inlier

PLEASE NOTE: The information presented in the following pages is summarised from:

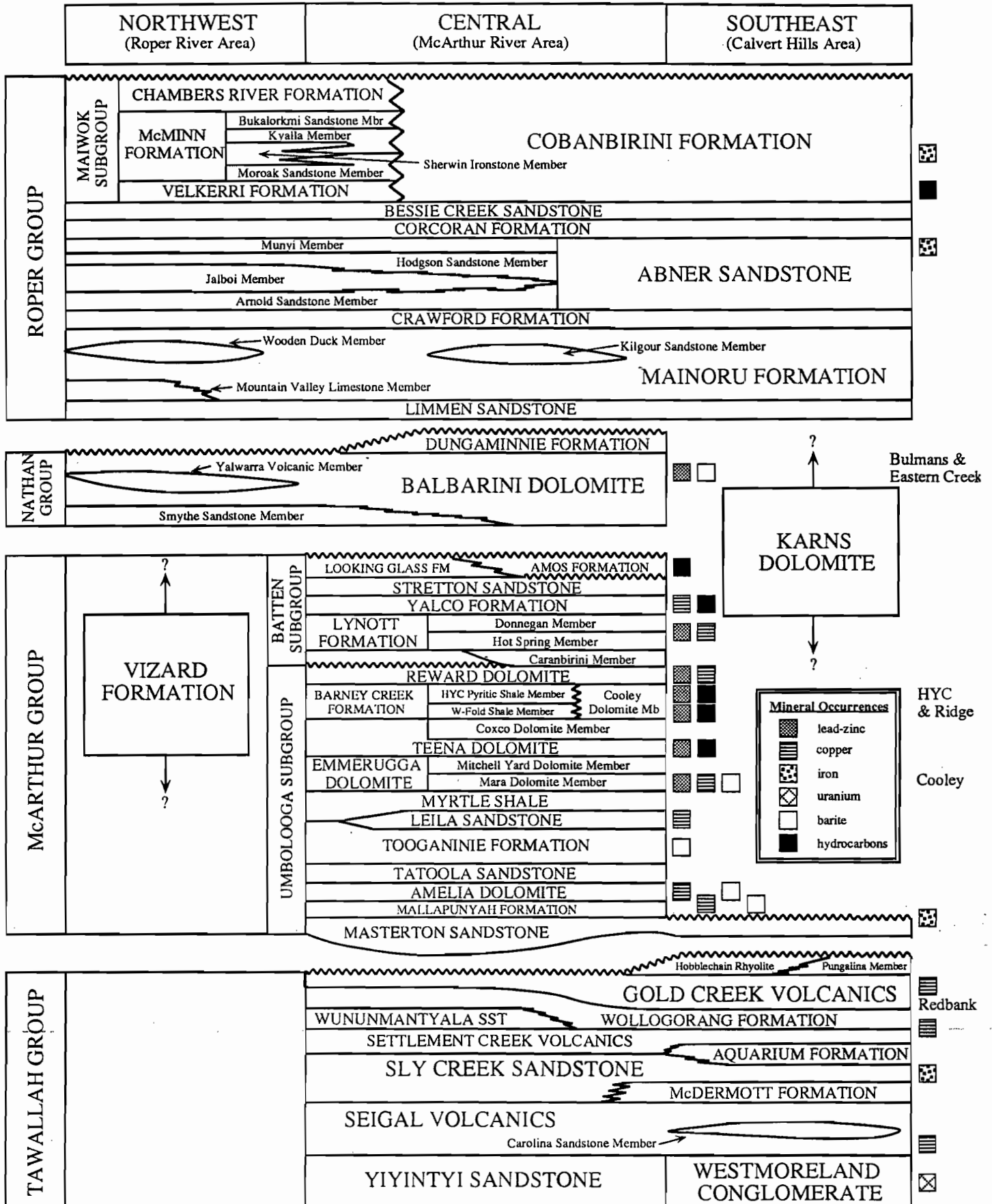
Ahmad, M., and Wygralak, A.S., 1989. Calvert Hills, Northern Territory - 1:250,000 Metallogenic Map Series. Northern Territory Geological Survey Explanatory Notes and Mineral Deposit Data Sheets SE53-8

Jackson, M.J., Muir, M.D. and Plumb, K.A., 1987. Geology of the Southern McArthur Basin, Northern Territory. Bureau of Mineral Resources Australia, Bulletin 220

Pietsch, B.A., Wyche, S., Rawlings, D.J., Creaser, P.M., and Findhammer, T.L.R., 1991. McArthur River Region, Northern Territory - 1:100,000 Geological Map Series. Northern Territory Geological Survey Explanatory Notes SE6065-6165

David Cooke 10/92

McARTHUR BASIN STRATIGRAPHY



BASEMENT

Murphy Metamorphics

A sequence of quartz-albite-muscovite-biotite schists and gneisses are exposed in the Murphy Inlier at the southern margin of the McArthur Basin. Shales, siltstones, greywackes and volcanic units deposited between 2100 and 1900 Ma were subjected to isoclinal folding and greenschist facies metamorphism prior to the emplacement of the Nicholson Granite Complex, probably during the 1855-1890 Ma Barramundi Orogeny.

TAWALLAH GROUP (1800 - 1700 Ma)

Westmoreland Conglomerate

Conglomeritic sandstones, quartz sandstones and conglomerates unconformably overlie the Murphy Inlier in the southeastern portion of the McArthur Basin, varying from 20 to 1900 metres in thickness. The Westmoreland Conglomerate is typically thickly to very thickly bedded and characterised by an absence of interbedded fine grained sandstones and siltstones. Sedimentary structures include trough-crossbeds, channels and upward-fining cycles. This unit is interpreted to have been deposited by braided rivers and debris flows in an alluvial fan environment.

Yiyintyi Sandstone

The Yiyintyi Sandstone crops out on the Mount Young and Bauhinia Downs map sheets as a sequence of medium to thick bedded mature quartz sandstones with a maximum thickness in excess of 3000m. This unit is considered to be the lateral equivalent of the Westmoreland Conglomerate. Well rounded, well sorted white and pink quartz arenites display abundant cross-stratification and ripple marks. The bulk of this formation is thought to have been deposited in a gradually subsiding marine basin by traction currents over a prolonged period.

Seigal Volcanics

Basic volcanics with tholeiitic affinities overlie the Westmoreland Conglomerate in the southeast of the McArthur Basin, and the Yiyintyi Sandstone in the McArthur River region. The Seigal Volcanics are up to 400m thick in the McArthur River region, and between 1000 and 1600 metres thick in the Calvert Hills area. They mostly show subareal features, although in the McArthur River region, hyaloclastite and feldspathic sandstones near the top of the formation suggest at least part of this unit formed in a subaqueous environment. Doleritic feeder sills related to the Seigal Volcanics are recognised in the Yiyintyi Sandstone.

McDermott Formation

Alternating arenite, dolostone, siltstone and chert beds that undergo marked lateral facies variations characterise the McDermott Formation. This unit is restricted to the southern part of the McArthur Basin, where it obtains a maximum thickness of over 400m. Stromatolitic carbonates, cauliflower cherts and hopper halite casts suggest a shallow marginal marine to shoreline facies with a 'sabkha overprint'. The alternation of dolostones and sandstones reflect unstable tectonic conditions in the marginal southern part of the McArthur basin.

Sly Creek Sandstone

Prominently outcropping sandstones and minor conglomerates are exposed in the Tawallah, Batten and part of the Scrutton Ranges, and in the Mallapunyah Dome. A maximum thickness of 900m is attained in the Batten Range; elsewhere, thicknesses range from 100 to 400m. White, grey, pink and red mature medium grained quartz arenites are predominant. Low angle planar cross-stratification is common in the north, whereas ripples and cross-stratification are common in southern outcrops. The depositional environment is interpreted to be shallow marine, with local variations from offshore deeper marine to shoreline beach and associated littoral facies.

Aquarium Formation

Recessive glauconitic sandstones, dolostones and siltstones characterise the Aquarium Formation. Southern exposures are dominated by medium to coarse grained, moderately sorted, laminated glauconitic sandstones with small scale cross bedding and ripple marks. The sandstone content decreases dramatically northwards, so that in the Tawallah & Scrutton Ranges, this unit is characterised by thin-bedded dololite, dolarenite and shale. Shallow marine, slightly reduced low energy conditions are inferred for the Aquarium Formation.

Settlement Creek Volcanics

Recessive mafic and felsic volcanics and minor shales and dolostones of the Settlement Creek Volcanics are present in most areas where the Tawallah Group is exposed. This unit is no more than 100m thick in the McArthur River area. Basaltic lavas are generally thicker and more laterally extensive than their thinly flow banded and autobrecciated rhyolitic

counterparts. Intrusive phases include alkali dolerites, quartz dolerites, microsyenites and dacites. Alteration is extensive throughout the volcanic sequence. Red and brown hematitic shales with minor hematitic ironstones, dolostones and micaceous sandstones are the dominant lithologies in the north. The Settlement Creek Volcanics are interpreted to represent widespread subareal volcanism and high level intrusive activity together with relatively quiet sediment deposition in shallow lakes and lagoons.

Wununmantlyala Sandstone

Fine to medium grained moderately sorted red quartz arenites of the Wununmantlyala Sandstone outcrop in the McArthur River region, attaining thickness of 520m in the Batten Ranges. Hematite occurs as disseminations in the matrix and as rare coarser grains. Red shale clasts are also common. Ripples, low angle foresets, planar and wedge sets are the most common sedimentary structures. The thick, uniform nature of the arenites combined with their regular and laterally persistent stratification suggest deposition in a sublittoral marine environment.

Wollogorang Formation

Recessive dolostones and ridge-forming sandstones characterise the Wollogorang Formation. Diagnostic features include cherty stromatolites, laminated shales and bituminous nodules. Disseminated sulphides (pyrite, chalcopyrite and rare galena) and rare columnar stromatolites occur in a dololite horizon that has a wide lateral extent throughout the southern McArthur basin. The Wollogorang Formation is approximately 100 m thick, with a maximum thickness of 150 m in the far southeast. Six distinct lithofacies are recognisable: I - *red shale facies* (quiet deposition in a saline mudflat or lagoonal environment); II - *crystalline dolomite facies* (shallow water marginal marine carbonate shelf); III - *dololite facies* with evaporite pseudomorphs, algal laminations, ripples, and disseminated copper mineralisation (playa-lake or supratidal environment); IV - *black shale facies* with a varied assemblage of poorly preserved microfossils and disseminated Pb-Zn mineralisation (anoxic quiet water distal lacustrine environment); V - *grey dolostone facies* (shallower high-energy lacustrine environment with an evaporitic overprint); VI - *clastic facies* with abundant K-feldspar and felsic volcanic fragments, and minor copper mineralisation (braided fluvial to open shallow marine environments).

Gold Creek Volcanics

A series of altered basalts and dolerites conformably overlie the Wollogorang Formation, attaining a maximum thickness of 225 m in the Redbank region. Abrupt lateral and lithological facies variations characterise this unit, with basic to intermediate igneous rocks and interbedded volcanoclastics (trachytes, trachyandesites, agglomerate, tuff, dolerite, microsyenite, and tuffaceous and lithic sandstones and siltstones) comprising the dominant lithologies. Pepperites and hyaloclastites have been recognised in the McArthur River region, suggesting emplacement of lava into wet sediment. The Gold Creek Volcanics represent a widespread period of intermediate volcanic activity, represented by quiet eruptions of lavas, explosive eruptions of tuffs and agglomerates, and intrusion of mafic dykes into wet sediments in a shallow lake system.

Hobblechain Rhyolite and Packsaddle Microgranite

Porphyritic flow banded and spherulitic rhyolites conformably overlie the Gold Creek Volcanics in the Calvert Hills area. The Hobblechain Rhyolite is exposed over a total area of 200 km², and is thought to be comagmatic with the intensely hematized porphyritic Packsaddle Microgranite. Rb-Sr age determinations from the Hobblechain Rhyolite and Packsaddle Microgranite yield an age of 1575 ± 120 Ma; this age is considered on stratigraphic grounds to be too young.

McArthur and Nathan Groups

(1600 - 1700 Ma)

Modified after Pietsch *et al.* (1991).

UNIT AND THICKNESS**DEPOSITIONAL ENVIRONMENT****CHARACTERISTIC FEATURES****McARTHUR GROUP (cont.)****UMBOLOOGA SUBGROUP****Reward Dolomite 30-350m**

Dololomite, stromatolitic dololomite, silty dololomite and dolarenite with lesser sandy dolarenite, dolorudite & sandstone; laminated, thin- to massive- and cross-bedded, brecciated and slumped; pseudomorphs after sulphate evaporites; onkoids, ooids, small silica spheroids; pseudomorphs after pyrite

Shallow water (lacustrine) with periods of emergence

Oblate chert nodules and small chert spheroids common

Barney Creek Formation 10-900m+

Thin-bedded to laminated, dolomitic, carbonaceous and pyritic shale and siltstone, dololomite, rare breccia and sandstone; occasional gypsum casts; talus slope breccia adjacent to Emu Fault

Shallow water (saline lake or nearshore lagoon complex)

Orange- to yellow-weathering pyritic carbonaceous black dolomitic shales and common tuff beds

Teena Dolomite**Coxco Dolomite Member 15-70m**

Grey crystalline dololomite with radiating, needle-like gypsum crystal pseudomorphs normal to bedding; rare conical stromatolites; uncommon thin intervals of dolomitic shale and siltstone

Hypersaline lacustrine with alternating shallow water and emergent conditions

Acicular, radiating crystal casts (Coxco needles) after gypsum

Lower Teena Dolomite <60m

Thin-bedded to laminated dololomite, silicified in places; dolomitic shale and sandstone, intraclast breccia and conglomerate, and dolarenite

Emmerugga Dolomite 620m**Mitchell Yard Dolomite Member**

Massive, dark grey, karstic-weathering, crystalline dololomite; lacks obvious internal sedimentary structures

Shallow lagoon and saline lacustrine

Massive, featureless dolostone

Mara Dolomite Member

Dololomite, stromatolitic dololomite, dolomitic siltstone, dolarenite and dolomitic breccia; columnar, domal and conical stromatolites, often forming bioherm series; halite casts and quartz nodules after evaporites

Abundant stromatolites near base; readily weathers to silicified, Mn- and Fe-oxide-stained brecciated chert

Myrtle Shale 40-60m

Thin-bedded to laminated, commonly dolomitic siltstone, shale and fine-grained sandstone (halite casts common); dololomite (in places stromatolitic)

Lacustrine and/or low-gradient alluvial plain

Red or lesser green shale and siltstone beds containing halite casts and enterolithic cherts

Lella Sandstone <10-30m

Dark grey-weathering dolomitic sandstone; fine- to coarse-grained, poorly sorted, thin- to medium-bedded, commonly cross-bedded and rippled; thin interbeds of sandy dolostone

Shallow marine

Dark brown- to black-weathering dolomitic sandstone

Tooganinle Formation 200m

Dololomite, stromatolitic dololomite (stratiform, domal, columnar and conical forms), dolomitic siltstone & shale, ripple-marked and cross-bedded dolarenite and sandstone; common desiccation cracks and pseudomorphs after gypsum & halite; dedolomitisation; breccia beds and ooids in dolarenite

Marginal sabkha to peritidal marine, possibly deepening to the south

Rhythmic interbeds of stromatolitic dolostone, dolomitic shale & siltstone (ribbed patterns on airphotos); buff-pink caliche common over dolomitic units

UNIT AND THICKNESS**DEPOSITIONAL ENVIRONMENT****CHARACTERISTIC FEATURES****McARTHUR GROUP (cont.)****Tatoola Sandstone 80-350m**

Upper: ridge-forming, mainly medium-grained, thin- to medium-bedded and rippled sandstone with shale clasts and evaporite mineral casts and moulds

Lower: flaggy, thin-bedded, usually fine-grained, white quartz sandstone; thin-bedded shale and siltstone (dolomitic in places) and very fine-grained sandstone at base; abundant small-scale cross-beds, pinch and swell, tool marks, ripples and mud clast impressions. Several recessive dolomitic units consisting of dololutite, dolomitic siltstone, stromatolitic dololutite and dolarenite

Changing up-sequence from peritidal to subtidal beach to peritidal

Distinctly light coloured, thin-bedded to flaggy fine-grained sandstone

Amelia Dolomite 50-180m

Recessive; stromatolitic dololutite (stratiform, domal, conical and columnar forms) and silty dololutite with interbeds of dolarenite and infrequent shale and rare fine-grained sandstone; ooid, brecciated and conglomeratic intervals common; localised development of sideritic dololutite after sulphate evaporites

Broad marginal marine sabkha

Extensively stromatolitic, no sandstone

Mallapunyah Formation 100-450m

Mainly recessive; red to purple dolomitic, cross-bedded sandstone interbeds; stromatolitic dolostone, more prevalent in the upper part of the formation; common botryoidal quartz nodules (cauliflower chert), ripples, desiccation cracks, gypsum and halite casts and moulds

Continental and coastal sabkha

Red-brown-purple colour of evaporitic dolomitic shale and siltstone and of overlying soil; well developed botryoidal quartz nodules (cauliflower chert)

Masterton Sandstone 40-650m

Ridge-forming; pink, brown and buff, fine- to medium-grained, moderately sorted quartz arenite; thin- to thick-bedded, cross-bedded (planar and trough) and extensively rippled; very fine-grained sandstone and siltstone form generally recessive minor units; distinctly ferruginous mottled sandstone with halite & gypsum casts and pseudomorphs mainly in uppermost beds; basal sandstone conglomerate common

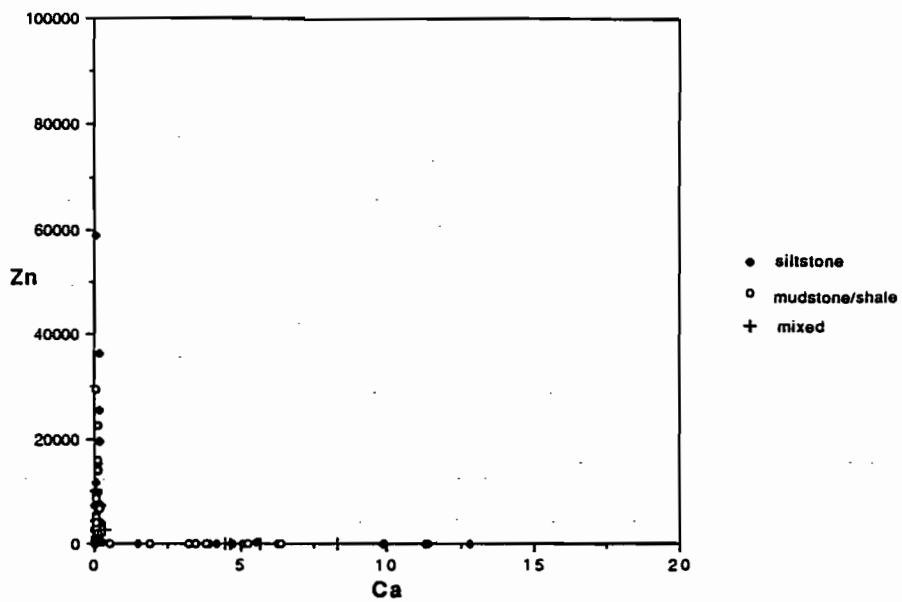
Alluvial fan and braided river base, the remainder very shallow marine and intertidal to supratidal

Extensive ripples and planar cross-beds

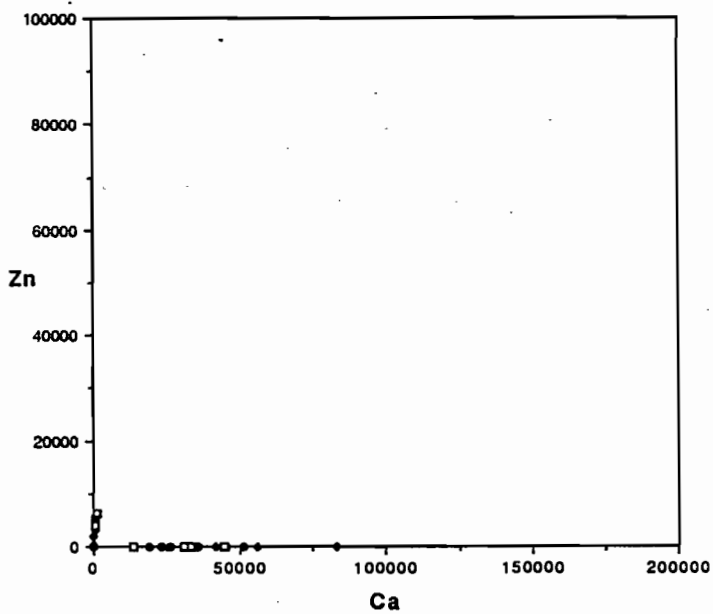
Deposit Halos

Peter McGoldrick

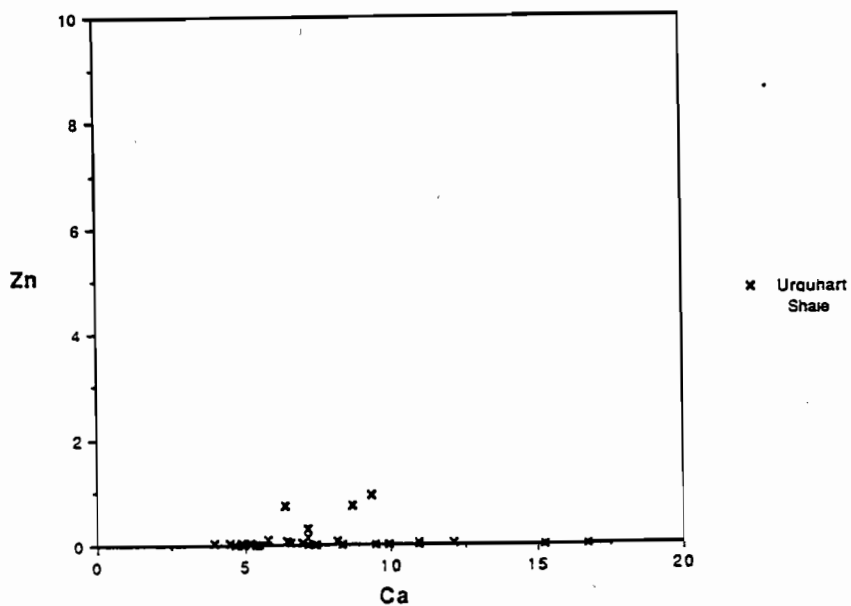
Small Syncline Samples



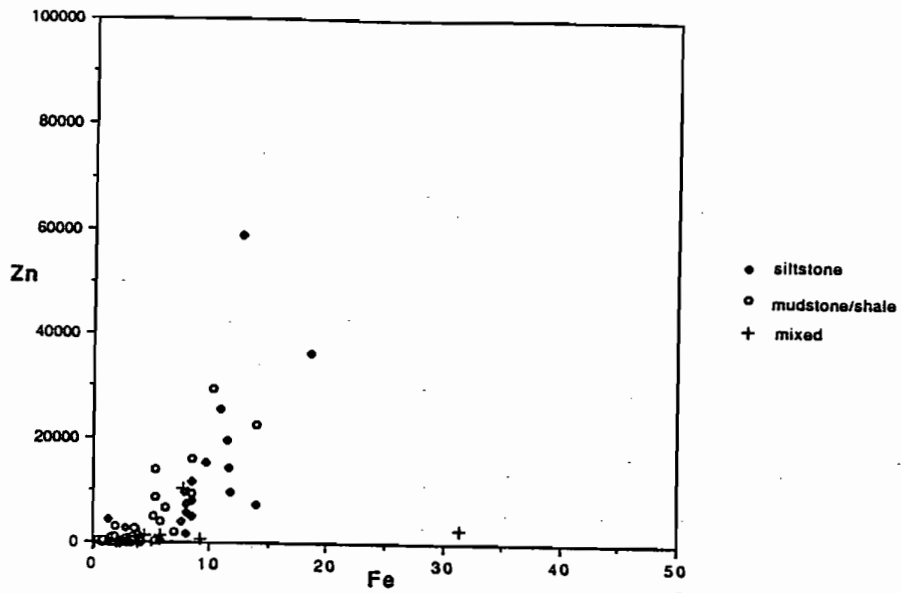
Big Syncline Samples



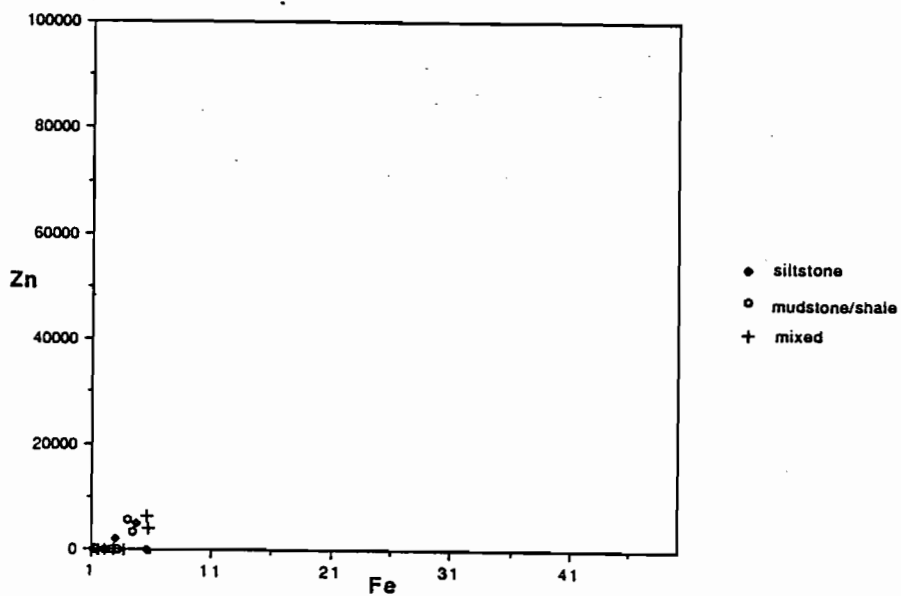
Mount Isa



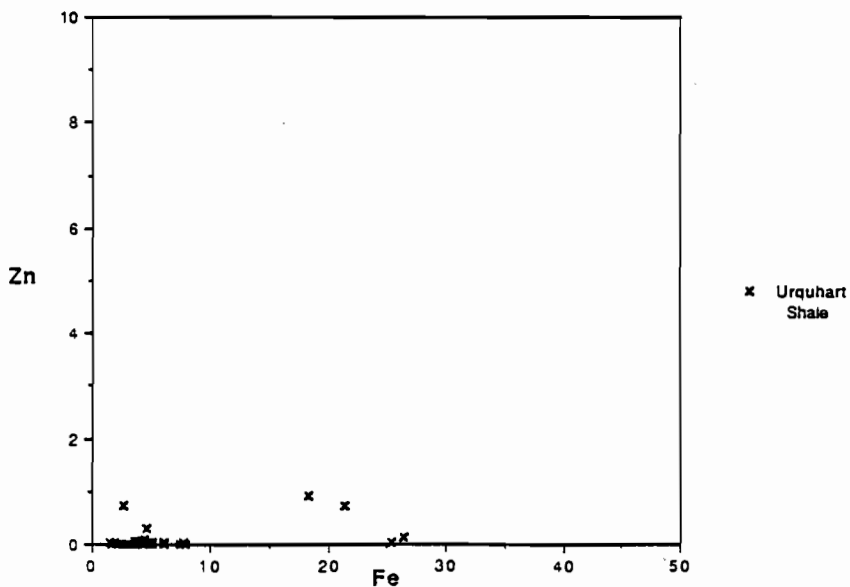
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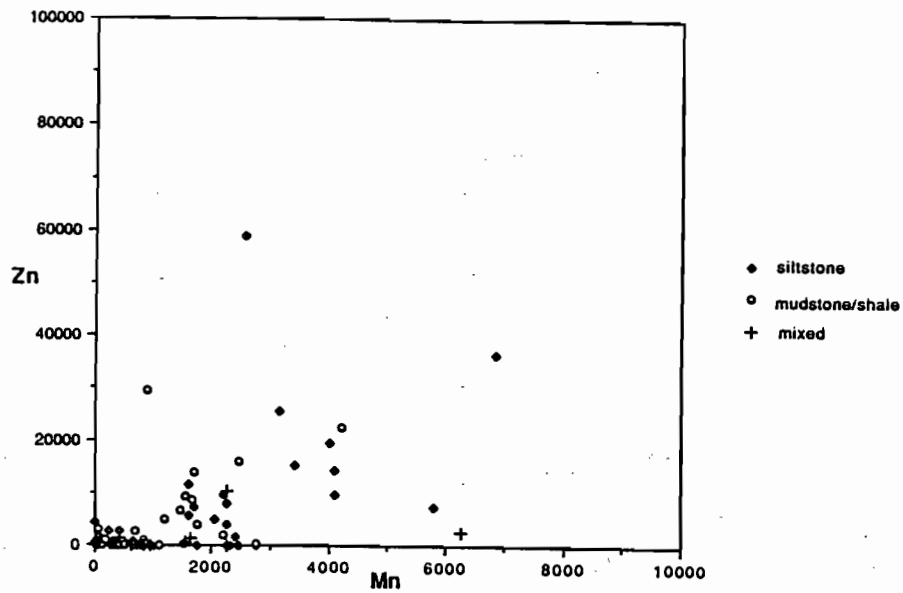
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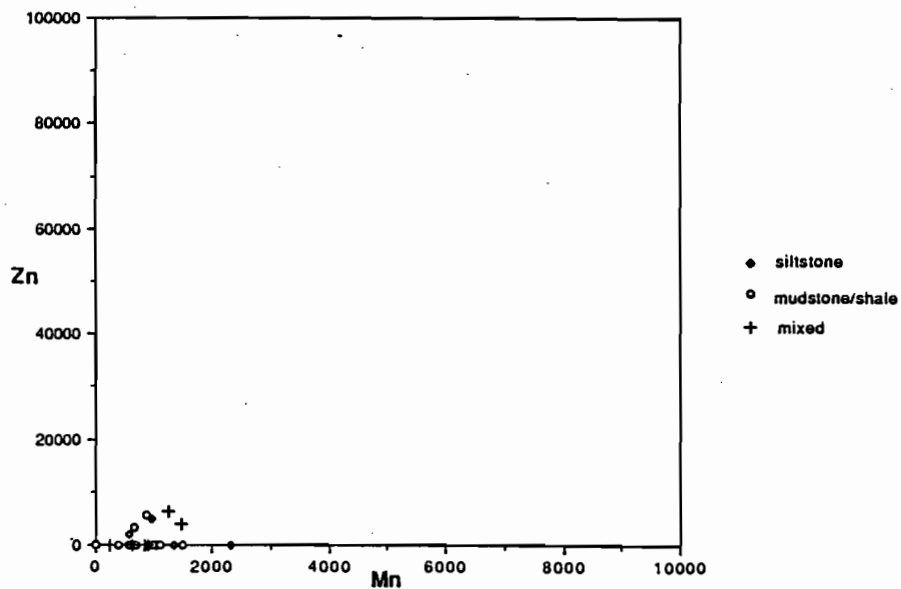
Mount Isa



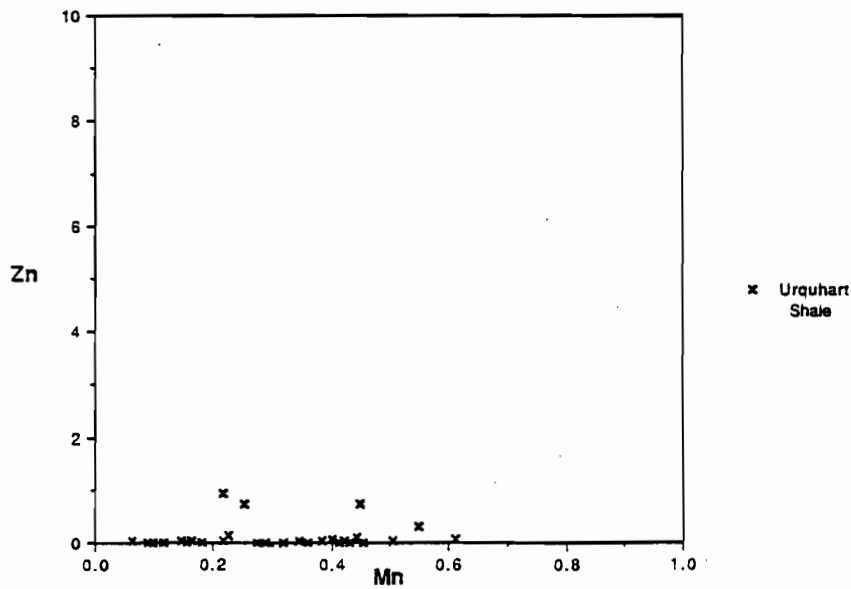
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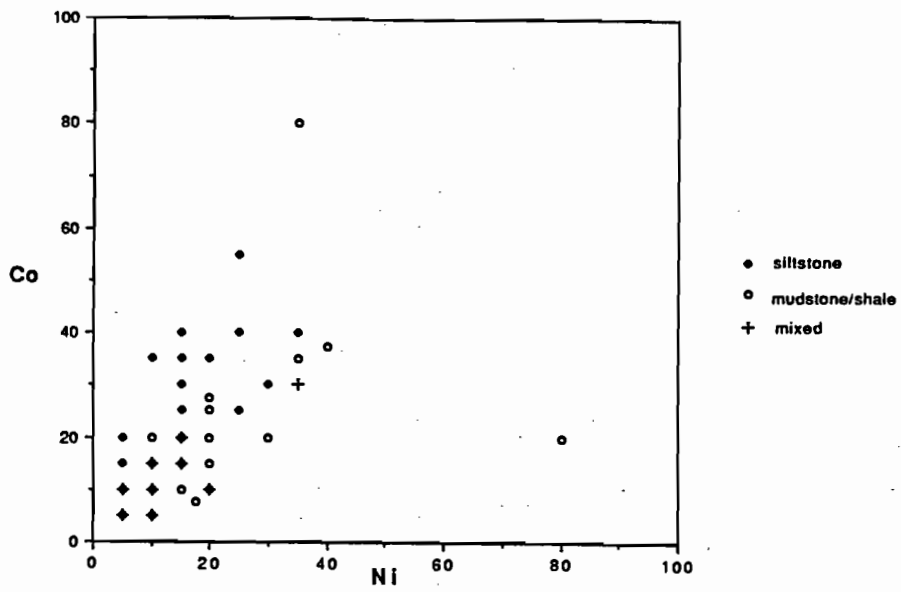
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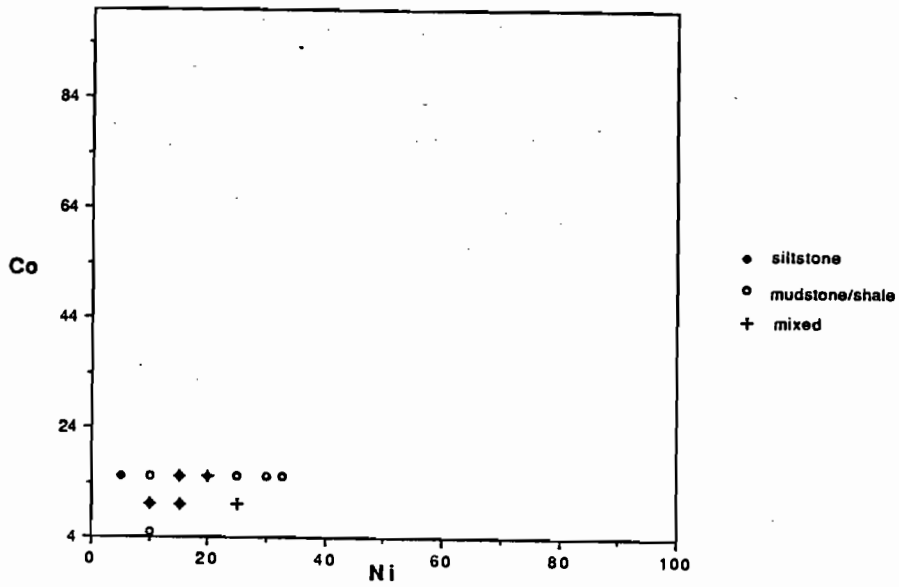
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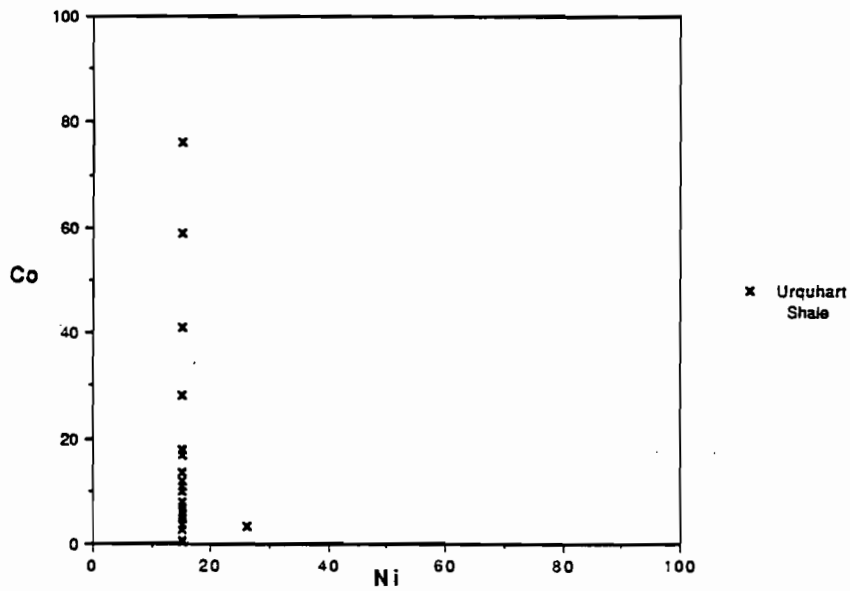
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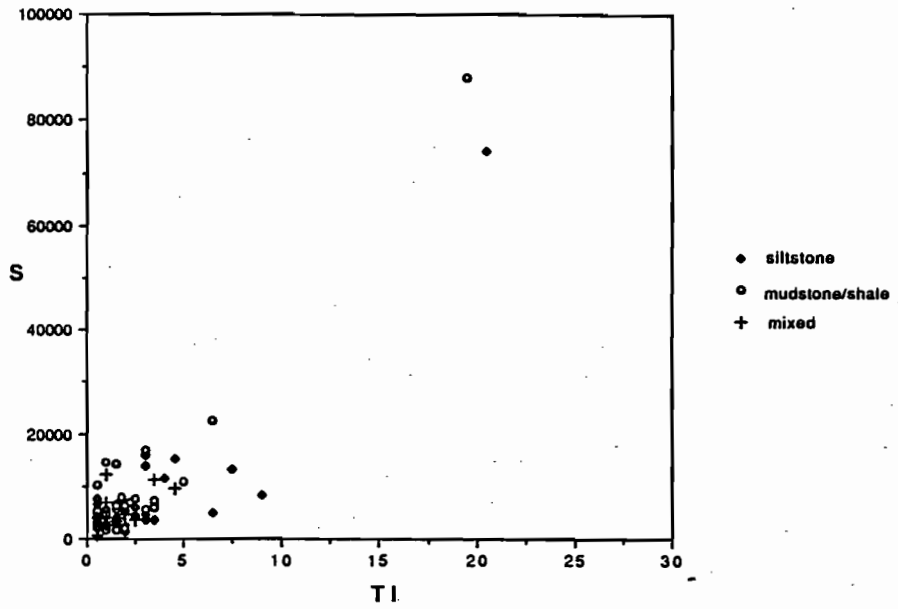
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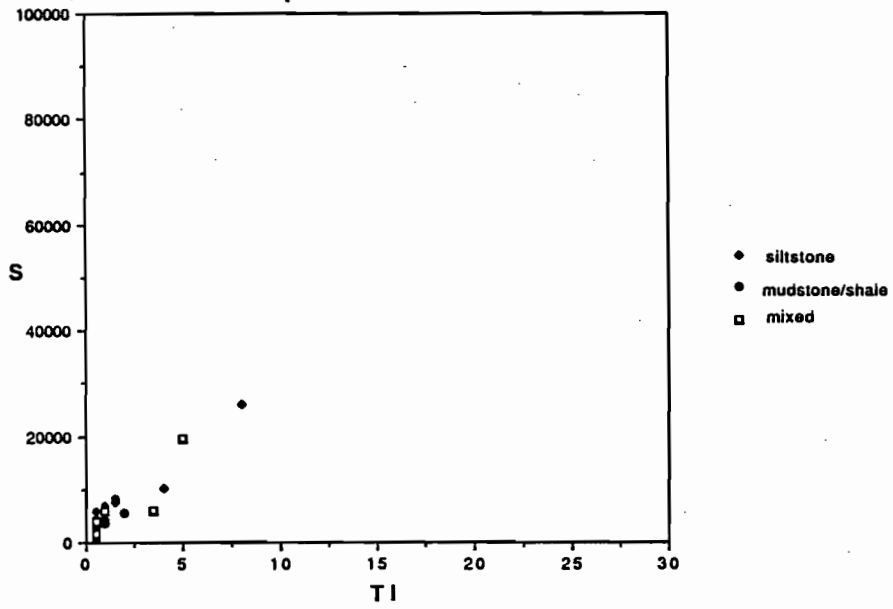
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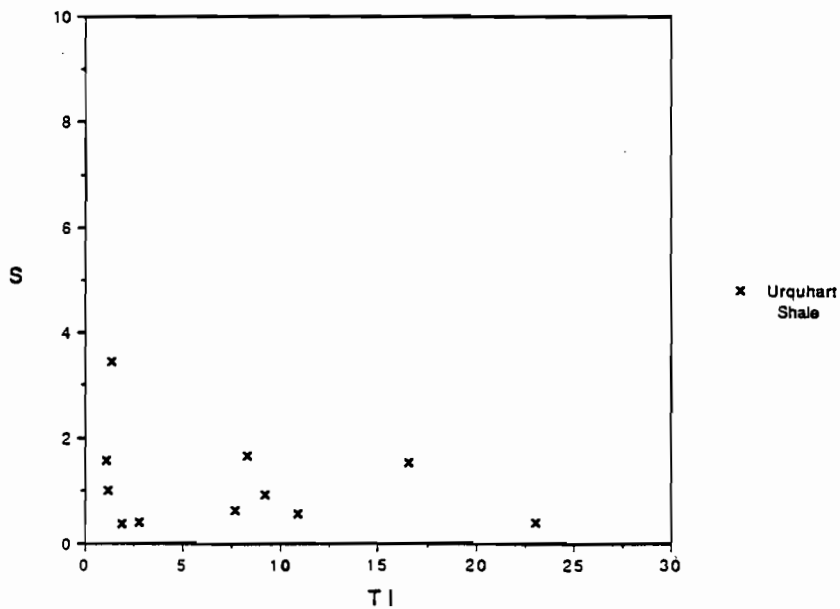
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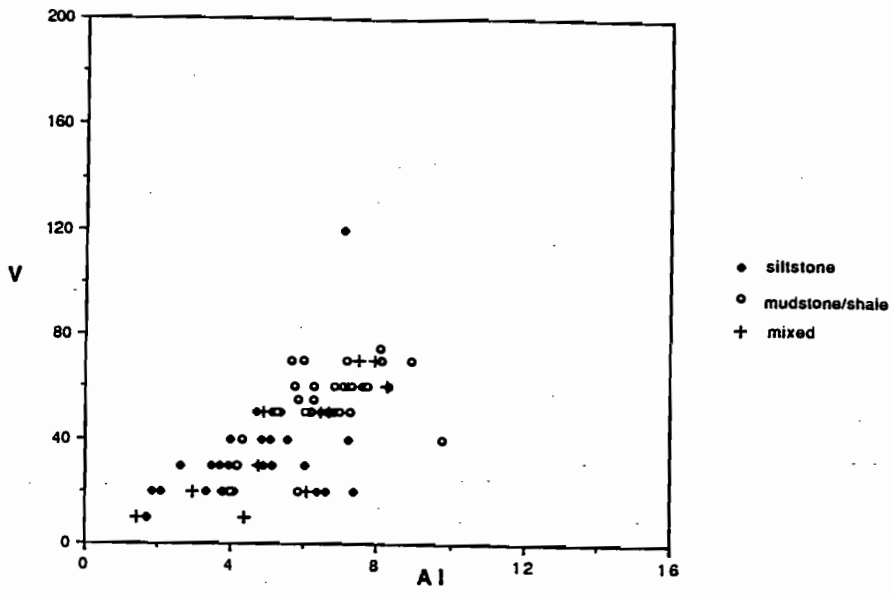
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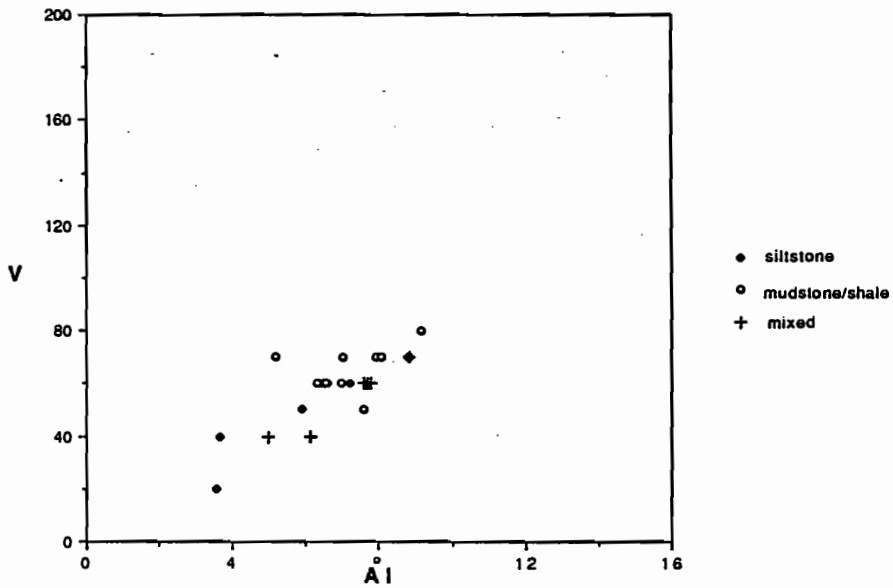
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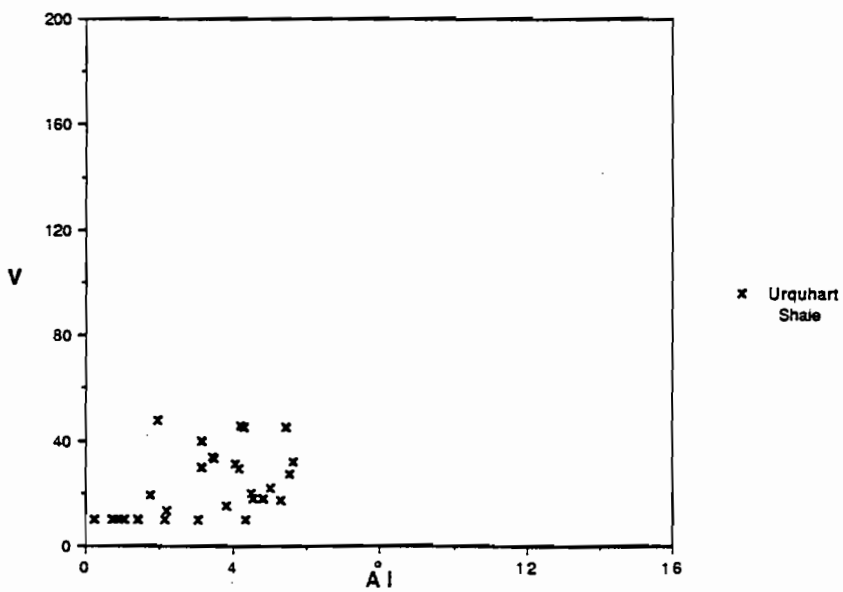
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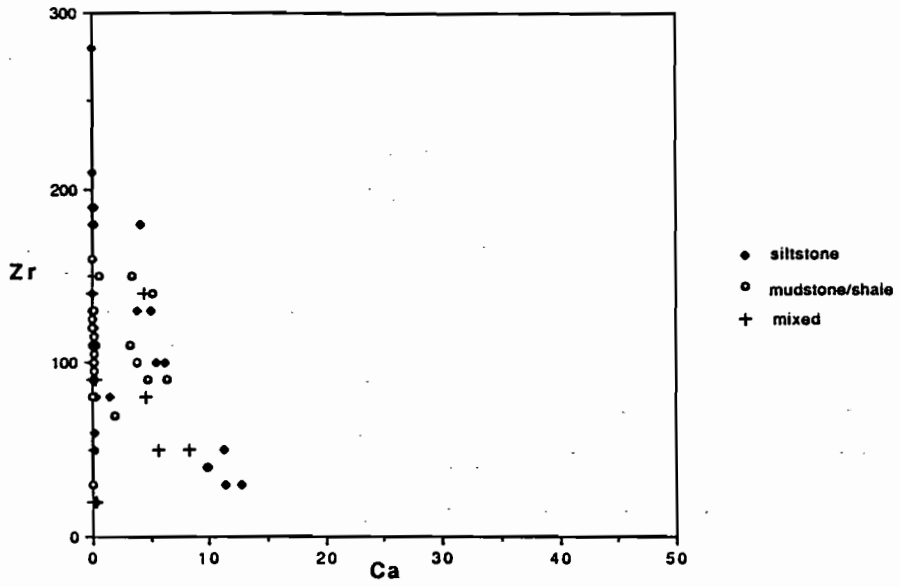
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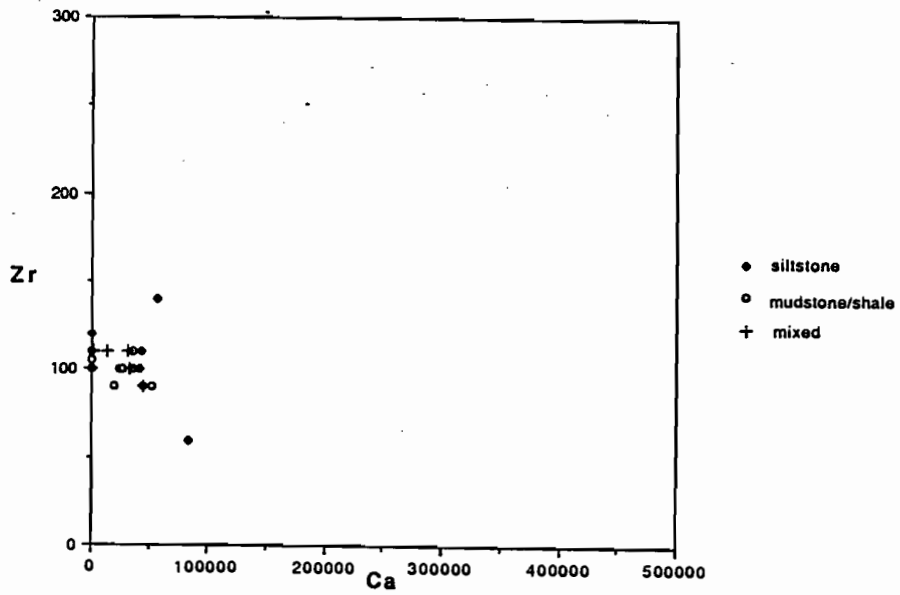
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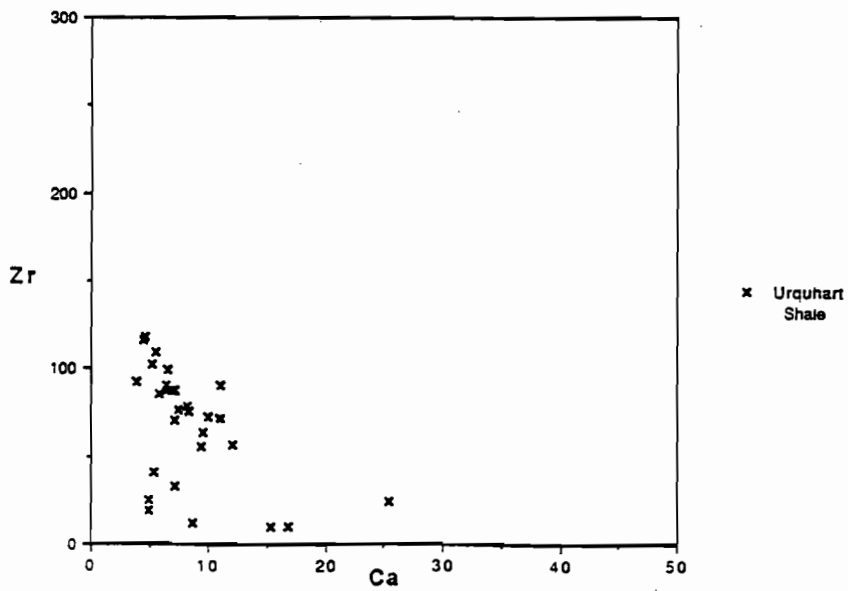
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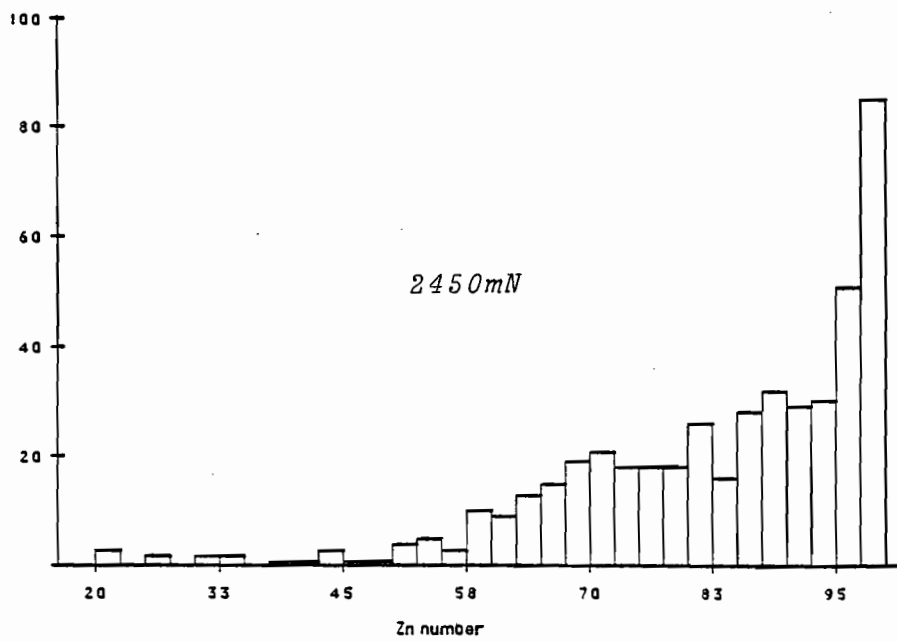
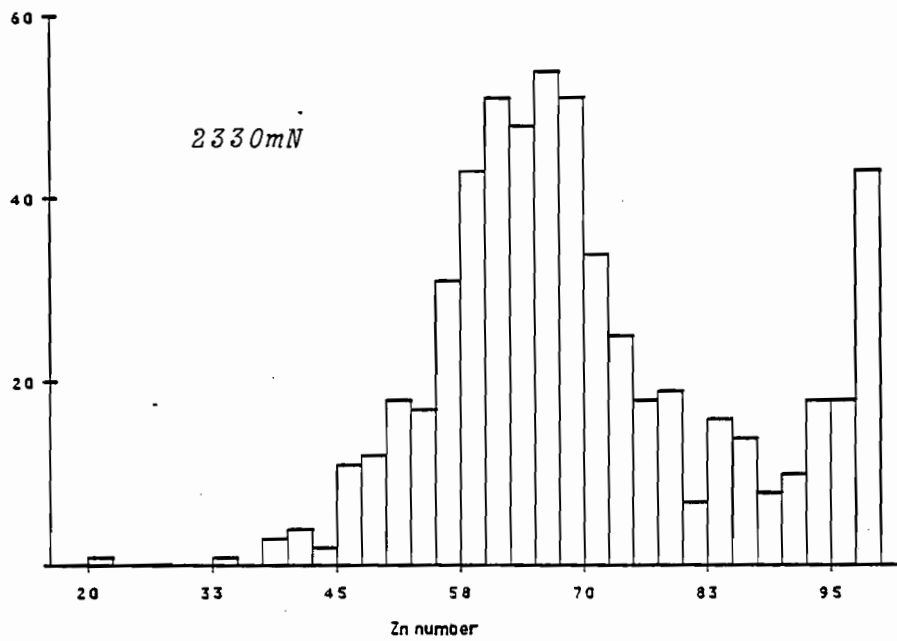
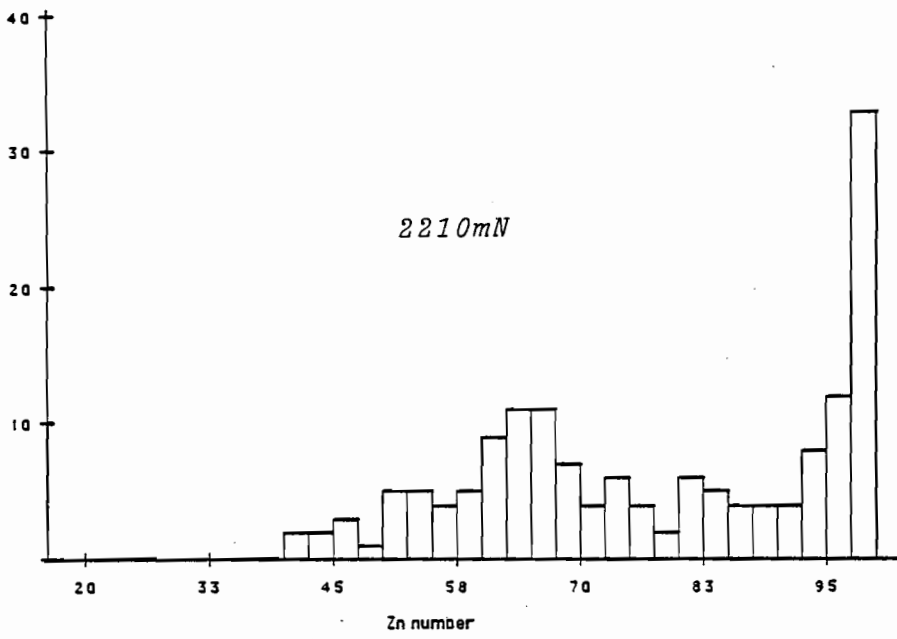


Big Syncline Samples



Mount Isa

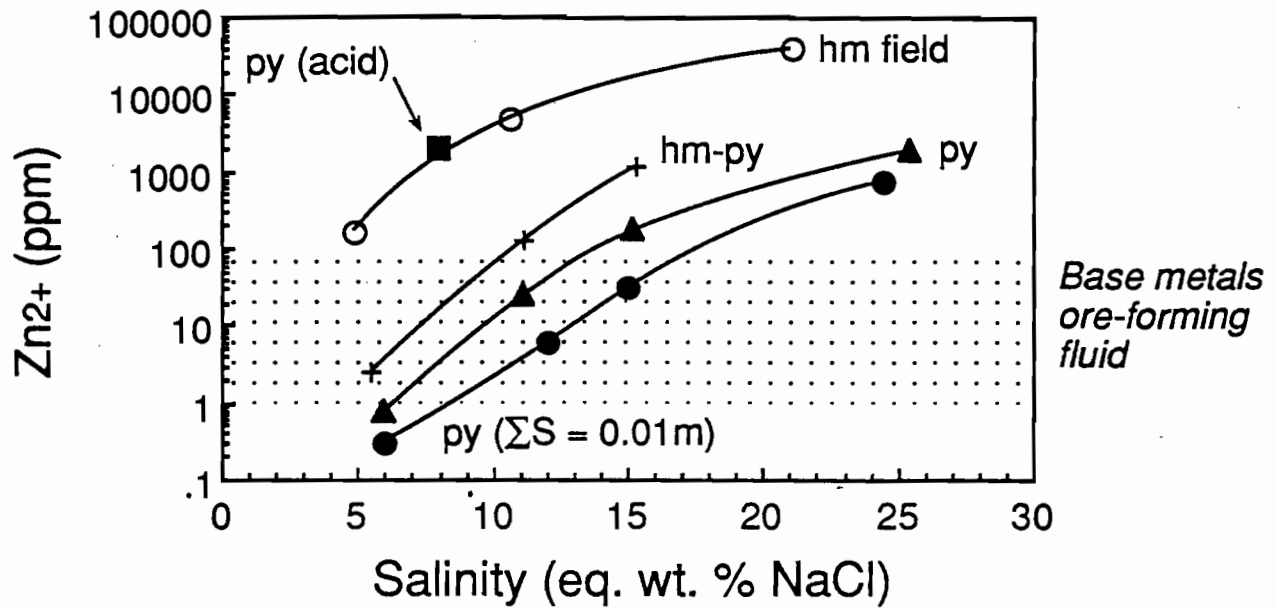




Fluid Modelling

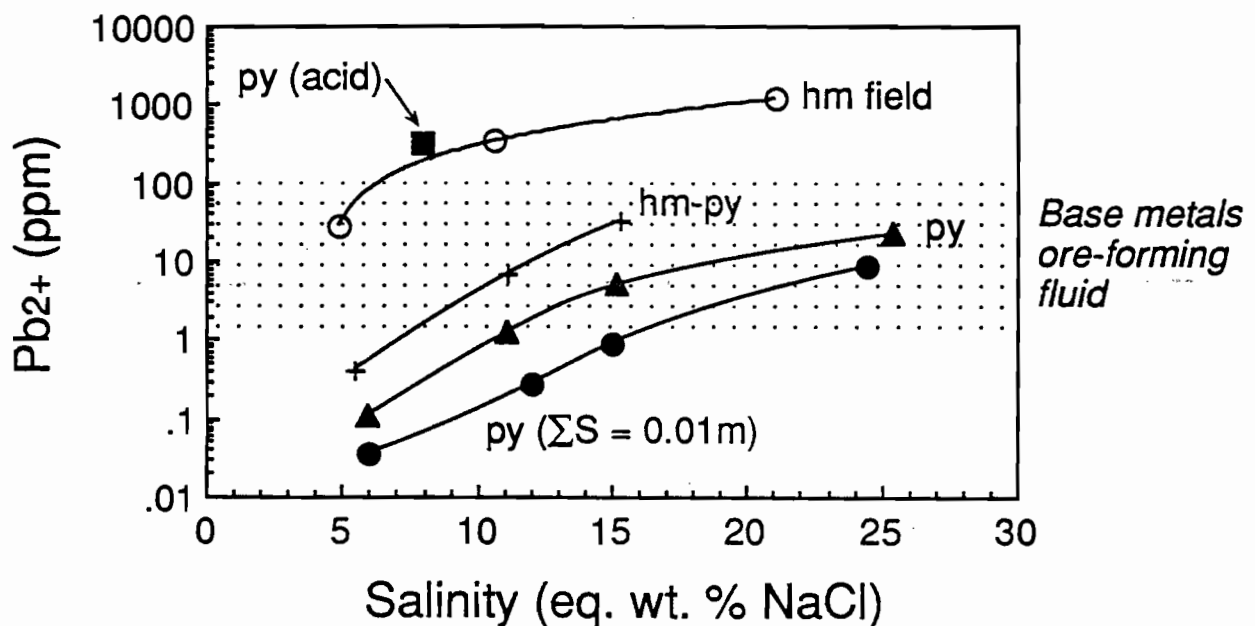
David Cooke

Sedimentary brine (250°) - sphalerite solubility

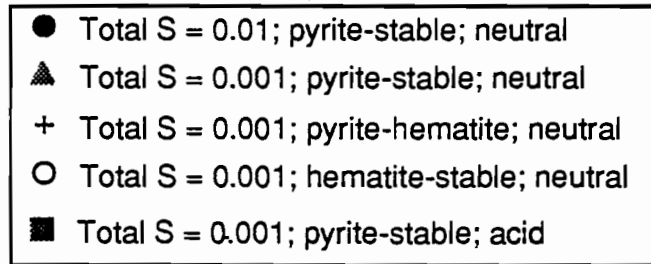
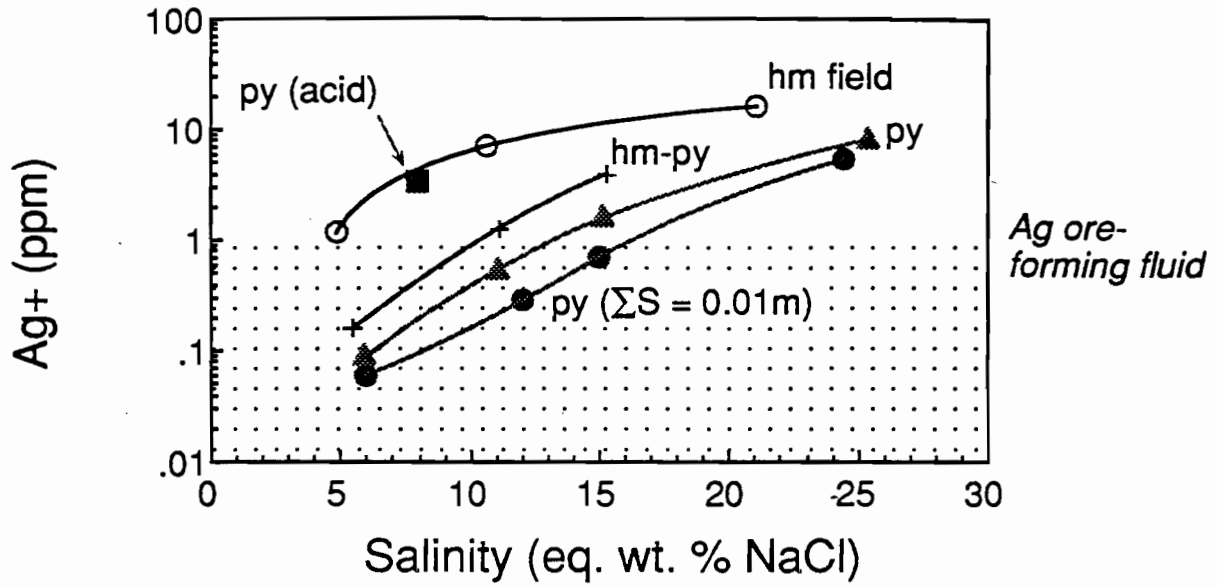


- Total S = 0.01; pyrite-stable; neutral
- ▲ Total S = 0.001; pyrite-stable; neutral
- + Total S = 0.001; pyrite-hematite; neutral
- Total S = 0.001; hematite-stable; neutral
- Total S = 0.001; pyrite-stable; acid

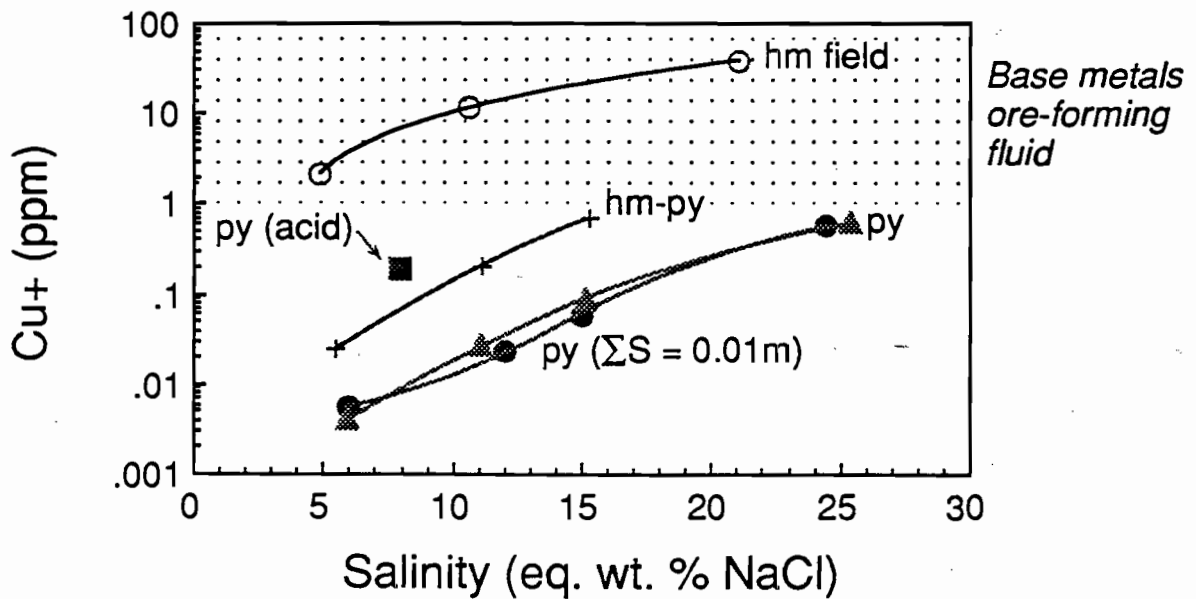
Sedimentary brine (250°) - galena solubility



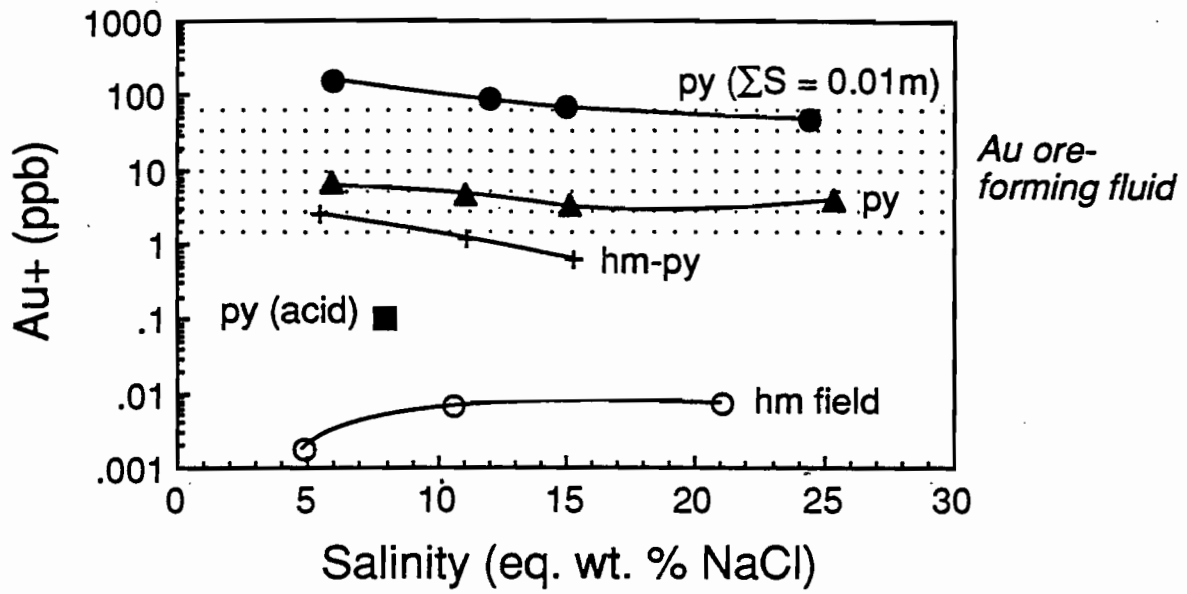
Sedimentary brine (250°) - acanthite solubility



Sedimentary brine (250°) - Cu-sulfides solubility



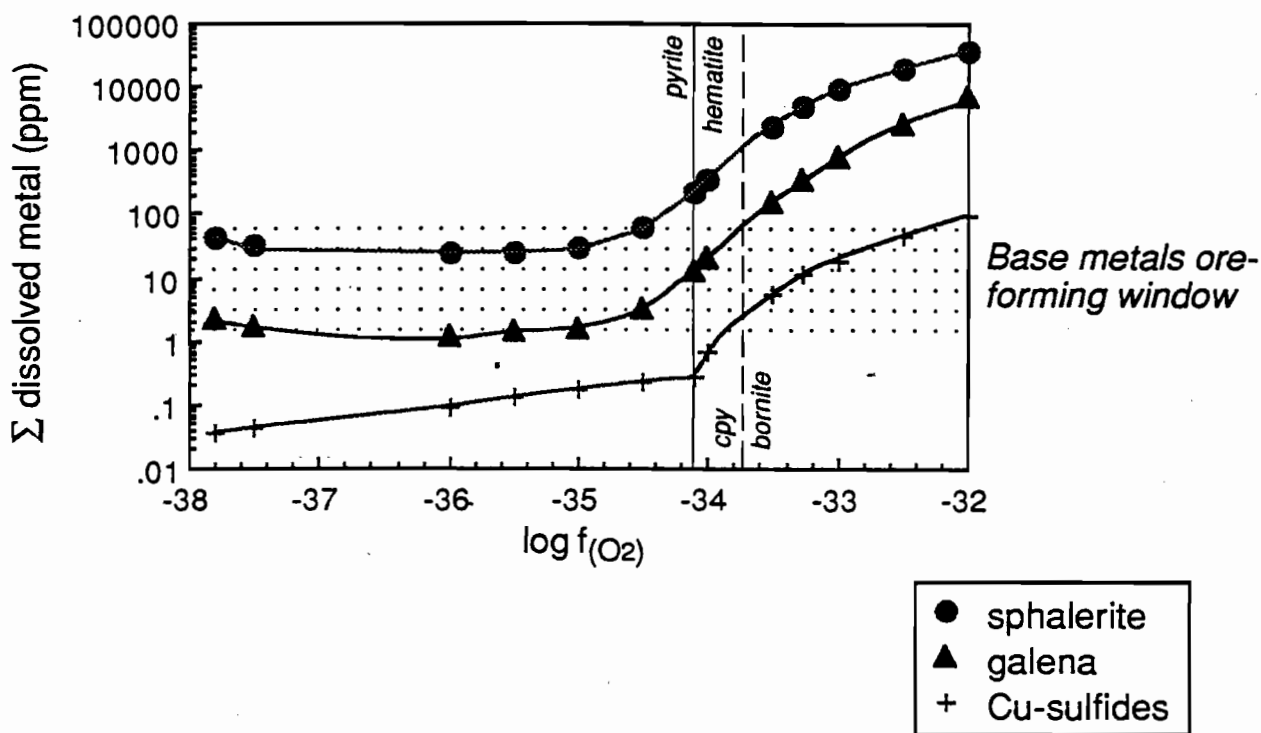
Sedimentary brine (250°) - gold solubility



- Total S = 0.01; pyrite-stable; neutral
- ▲ Total S = 0.001; pyrite-stable; neutral
- + Total S = 0.001; pyrite-hematite; neutral
- Total S = 0.001; hematite-stable; neutral
- Total S = 0.001; pyrite-stable; acid

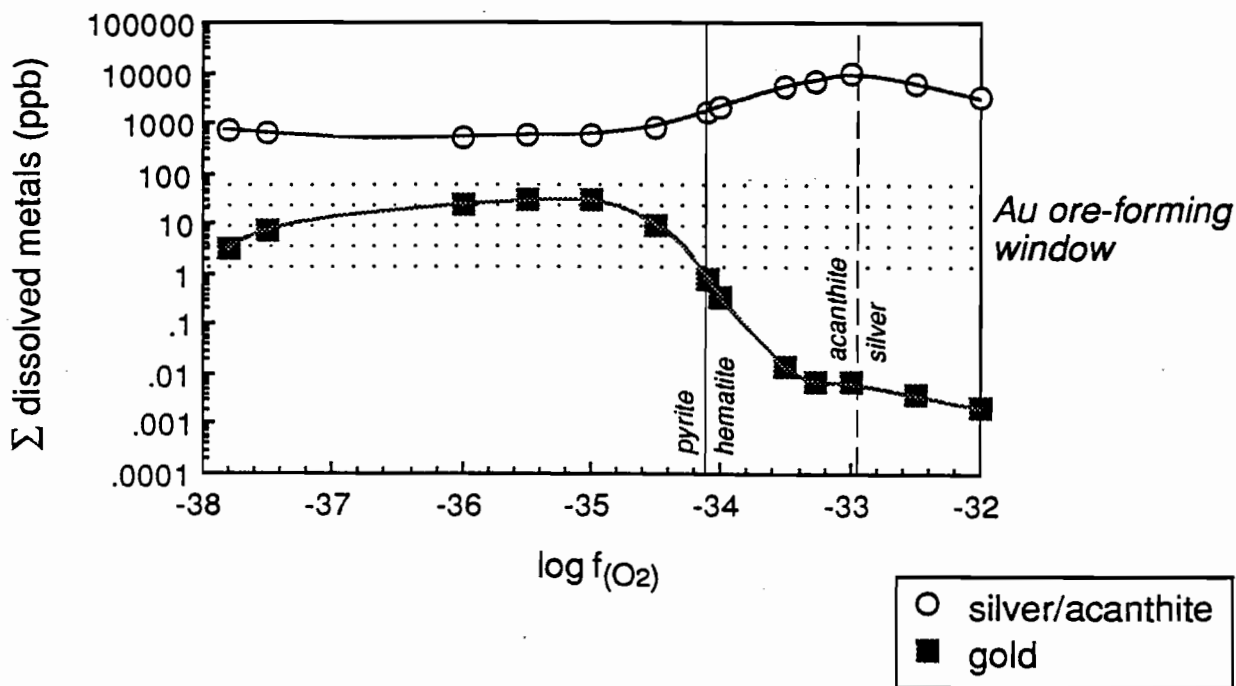
Sulfide solubilities

T = 250°C; pH = 4.96; Salinity = 10.7 eq. wt. % NaCl



Au, acanthite and Ag solubilities

T = 250°C; pH = 4.96; Salinity = 10.7 eq. wt. % NaCl



- METAL TRANSPORT -

SOLUBILITIES OF ORE MINERALS

- All hydrothermal fluids have the capacity to transport some dissolved metal
- Actual quantities are dependent on the chemical nature of the solution
- For base metals, a hydrothermal fluid probably needs to be able to carry at least 1 - 10 ppm Cu, Pb and/or Zn before it has the potential to be an ore-forming fluid
- For gold, concentrations of 1 - 10 ppb are required
- At least 100 ppm silver probably required for an Ag-ore forming fluid

- METAL TRANSPORT -

SATURATION LEVELS

- Three general saturation conditions to be considered
 - 1) Fluids can be incapable of transporting sufficient quantities of a particular metal to form an ore deposit, even when saturated with respect to that metal (low solubility)
 - 2) Fluids can be just capable of carrying sufficient quantities of a metal when saturated to precipitate ore grade mineralisation (moderate solubility)
 - 3) Fluids can be capable of transporting very large quantities of a metal - more than enough to form an ore deposit (high solubility)
- While the 3rd condition has excellent potential for ore-forming fluids, it is also the most likely to suffer from a "source" problem
- If there is insufficient metal in the source environment for the fluid to become saturated, then the fluid could remain significantly undersaturated with respect to that metal
- An effective depositional mechanism is required to force metal saturation and initiate sulfide deposition for condition 3; undersaturated low and moderate solubility fluids will never form economic mineralisation
- High solubility fluids have great potential as transporting agents, but are not necessarily very effective mineralising solutions

- METAL TRANSPORT -

CONCLUSIONS - REDUCED SEDIMENTARY BRINES

- At 250°C and at neutral pH, reduced sedimentary brines are probably capable of carrying sufficient Pb, Zn and Ag to form economic base metal mineralisation, -providing the fluid is saturated or close to saturation with respect to these metals (moderate solubility fluids: Zn, Pb and Ag). Lower ΣS concentrations favour base metal transport.
- The same fluids cannot carry sufficient copper to precipitate economic copper mineralisation (low solubility fluids: Cu)
- Significant gold could be carried in this type of brine, providing ΣS is high enough (moderate to high solubility fluids: Au)
- More acid conditions favour transport of higher concentrations of Pb, Zn, Ag and Cu, and lower concentrations of Au. However, highly acidic conditions are probably geologically unrealistic.

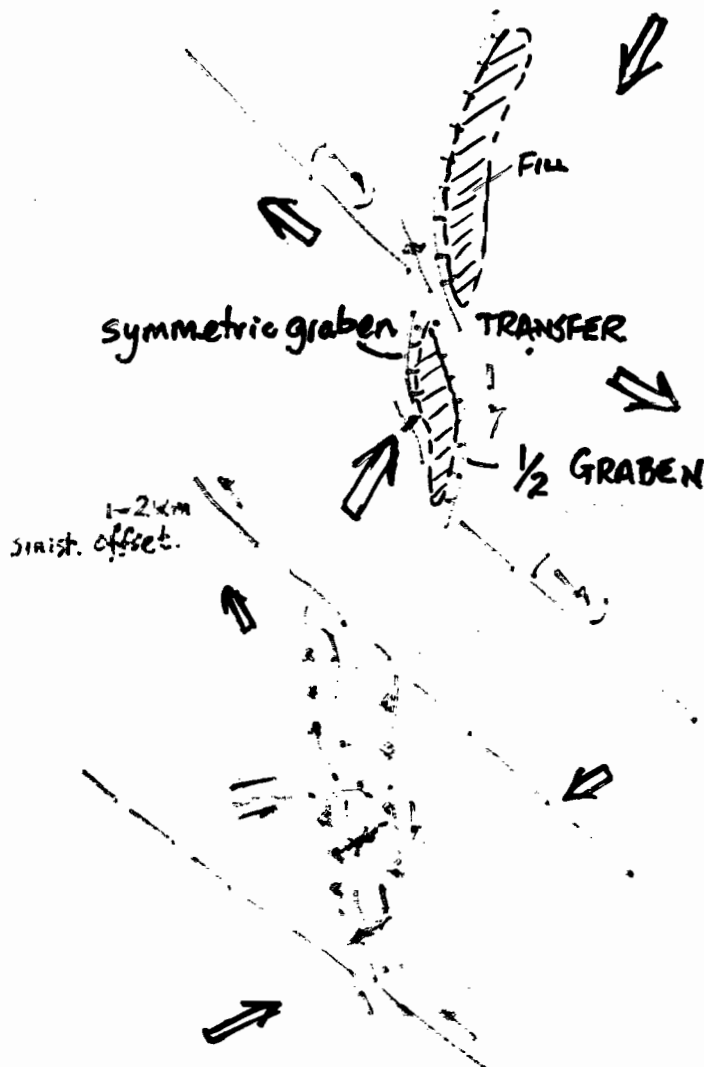
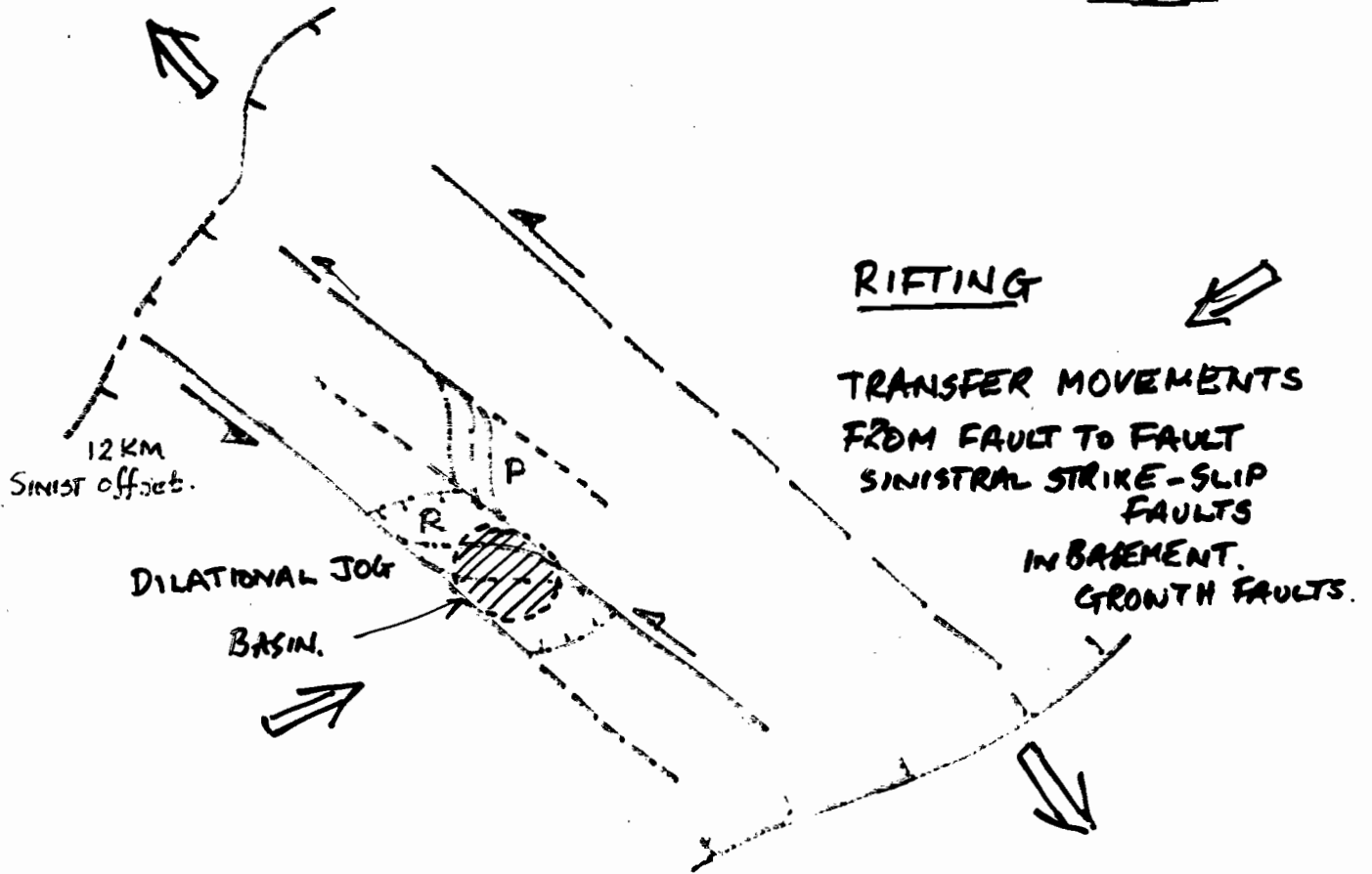
CONCLUSIONS - OXIDISED SEDIMENTARY BRINES

- At 250°C and at neutral pH, oxidised sedimentary brines are capable of carrying large quantities of Pb and Zn in solution (high to moderate solubility fluids: Zn and Pb).
- The same fluids can carry sufficient Cu and Ag to precipitate economic copper and silver mineralisation, provided the fluids are saturated or close to saturation with these metals (moderate solubility fluids: Cu and Ag)
- Gold cannot be transported in sufficient quantities to form ore grade mineralisation if the fluid is hematite-stable (low solubility fluids: Au)

Structures in the Southern McArthur Basin

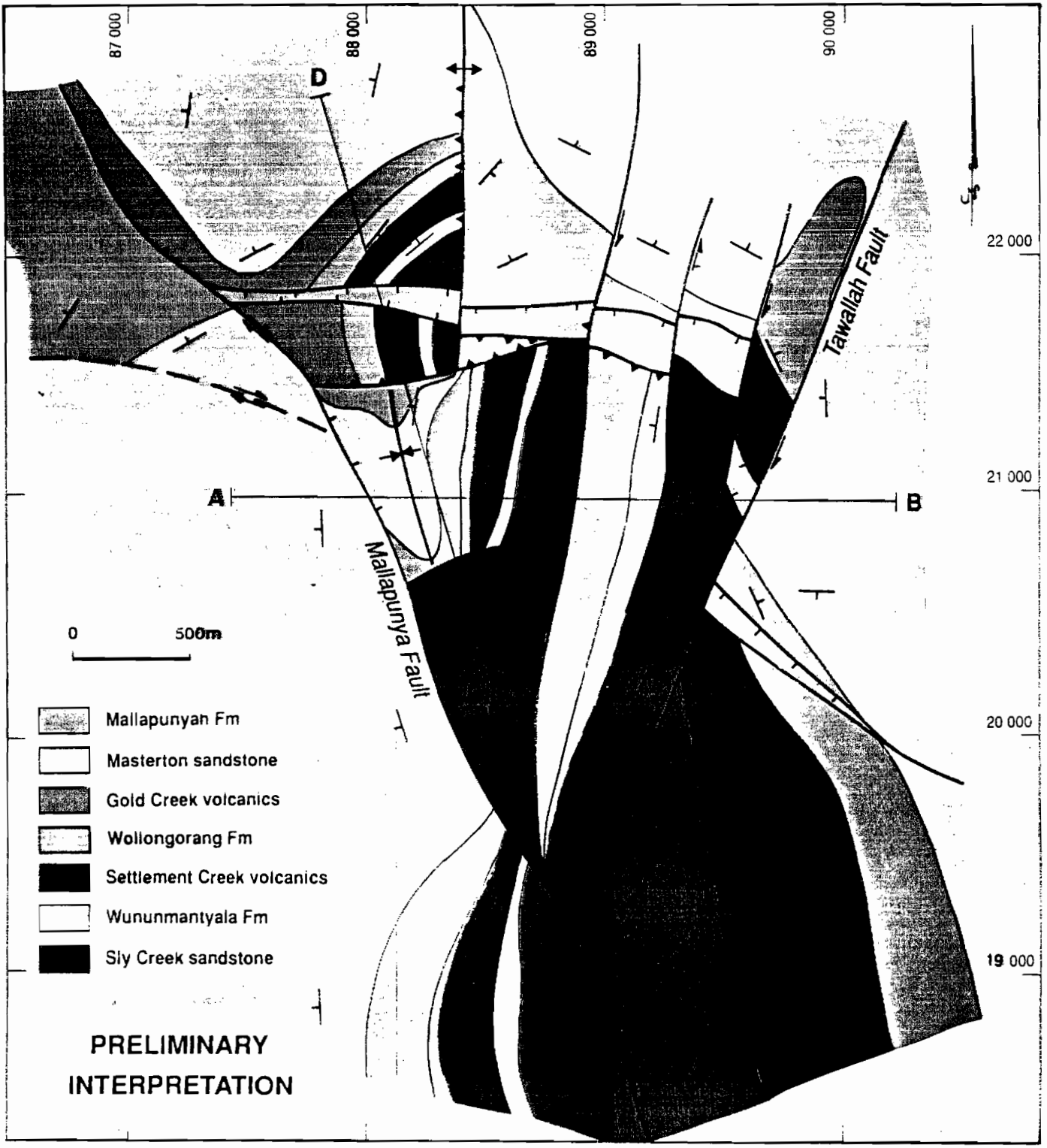
Richard Keele








POSSIBLE MODELS FOR EVOLUTION OF McARTHUR BASIN.



PULL-APART / RIFTING
 MOVEMENT ON BASEMENT
 SHEARS CEASES
 DEXTRAL REACTIVATION?
 GROWTH FAULTS

BASIN INVERSION
 NORMAL FAULTS → THRUSTS
 GRABEN → HORST.



-  Mallapunyah Fm
-  Masterton sandstone
-  Gold Creek volcanics
-  Wollongorang Fm
-  Settlement Creek volcanics
-  Wunnamantyalta Fm
-  Sly Creek sandstone

0 500m

**PRELIMINARY
INTERPRETATION**

Mallapunyah Fault

Tawallah Fault

A

B

D

87 000

88 000

89 000

90 000

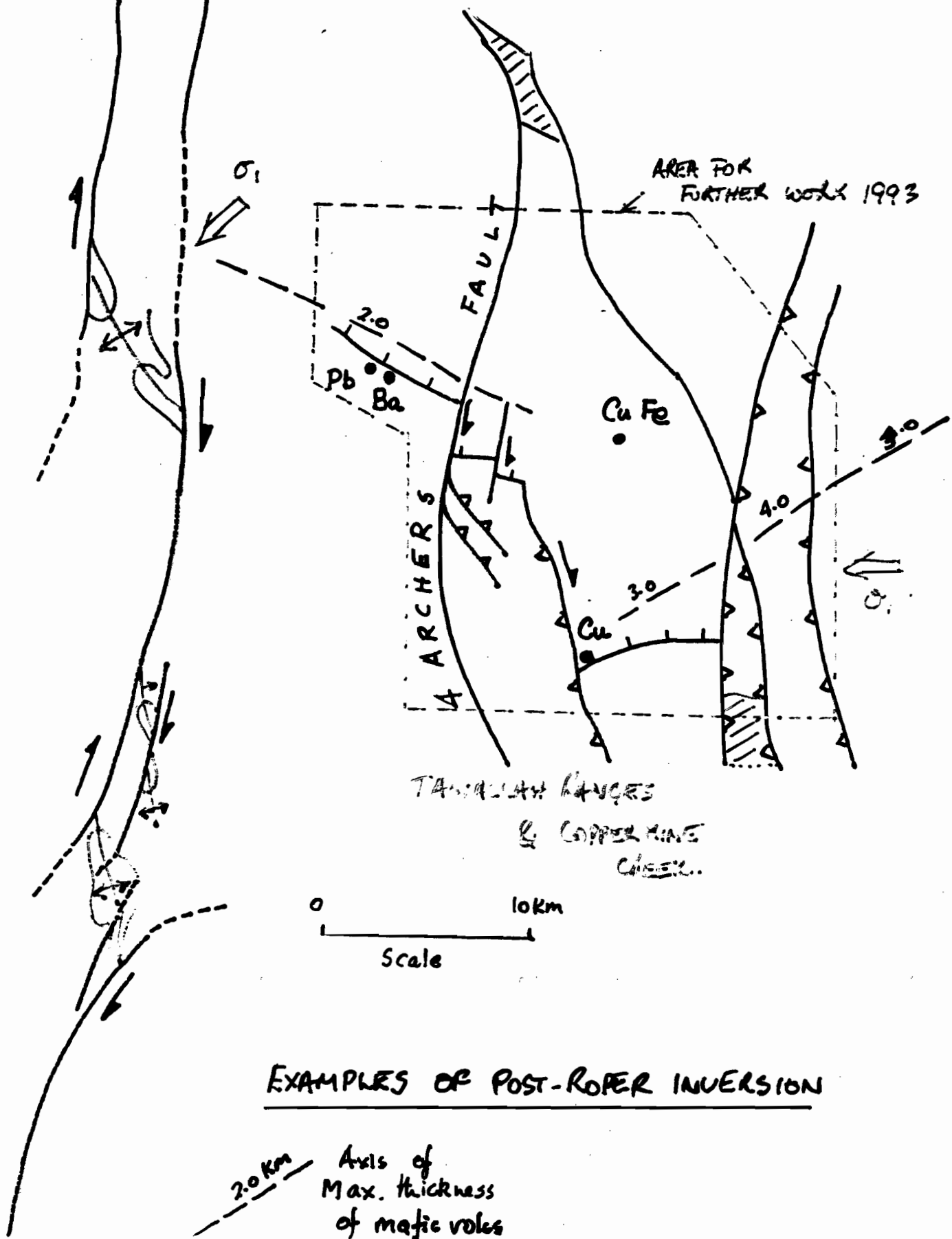
22 000

21 000

20 000

19 000

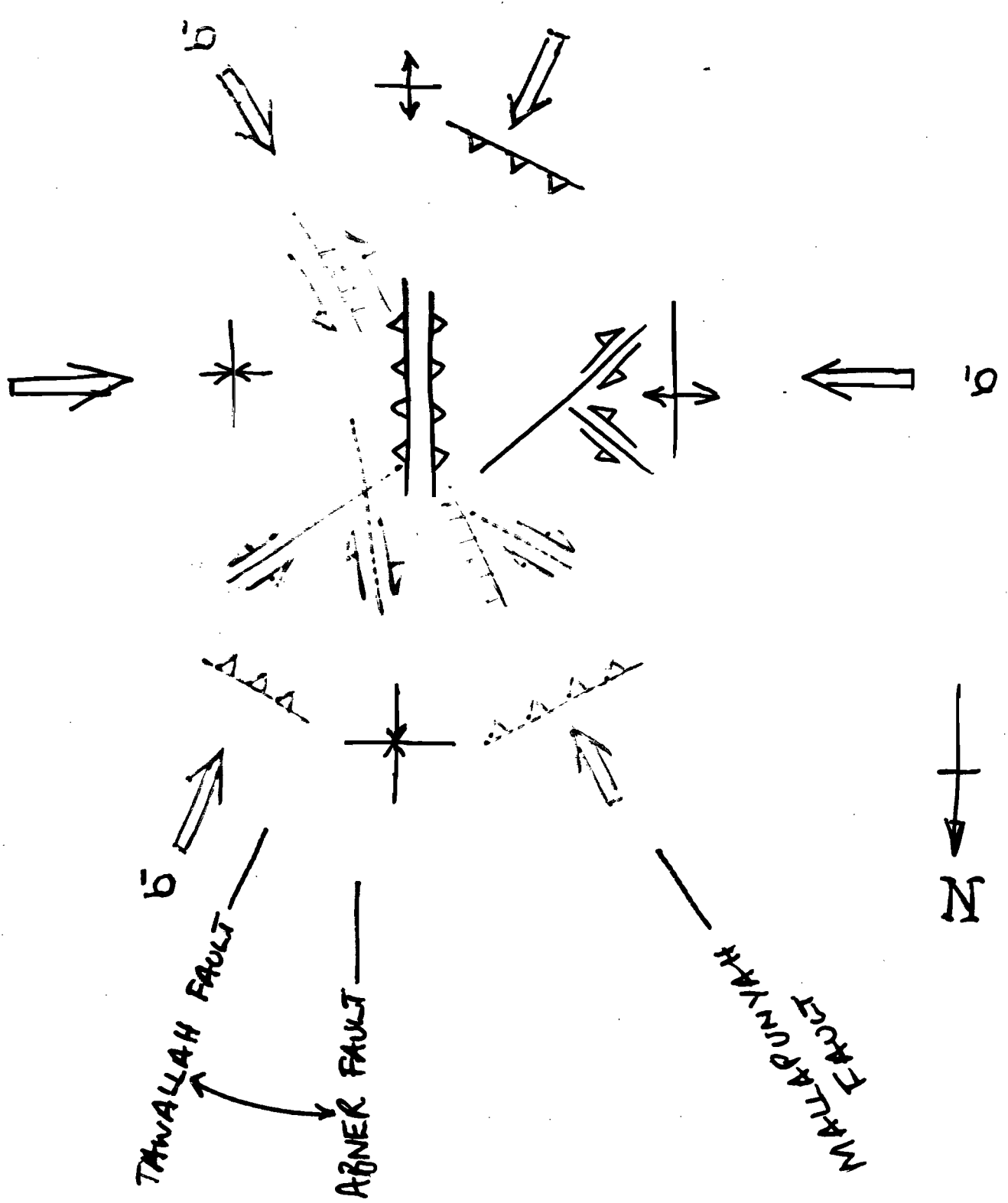
DEXTRAL N-S FAULT ZONE
(WEST ROPER FZ)

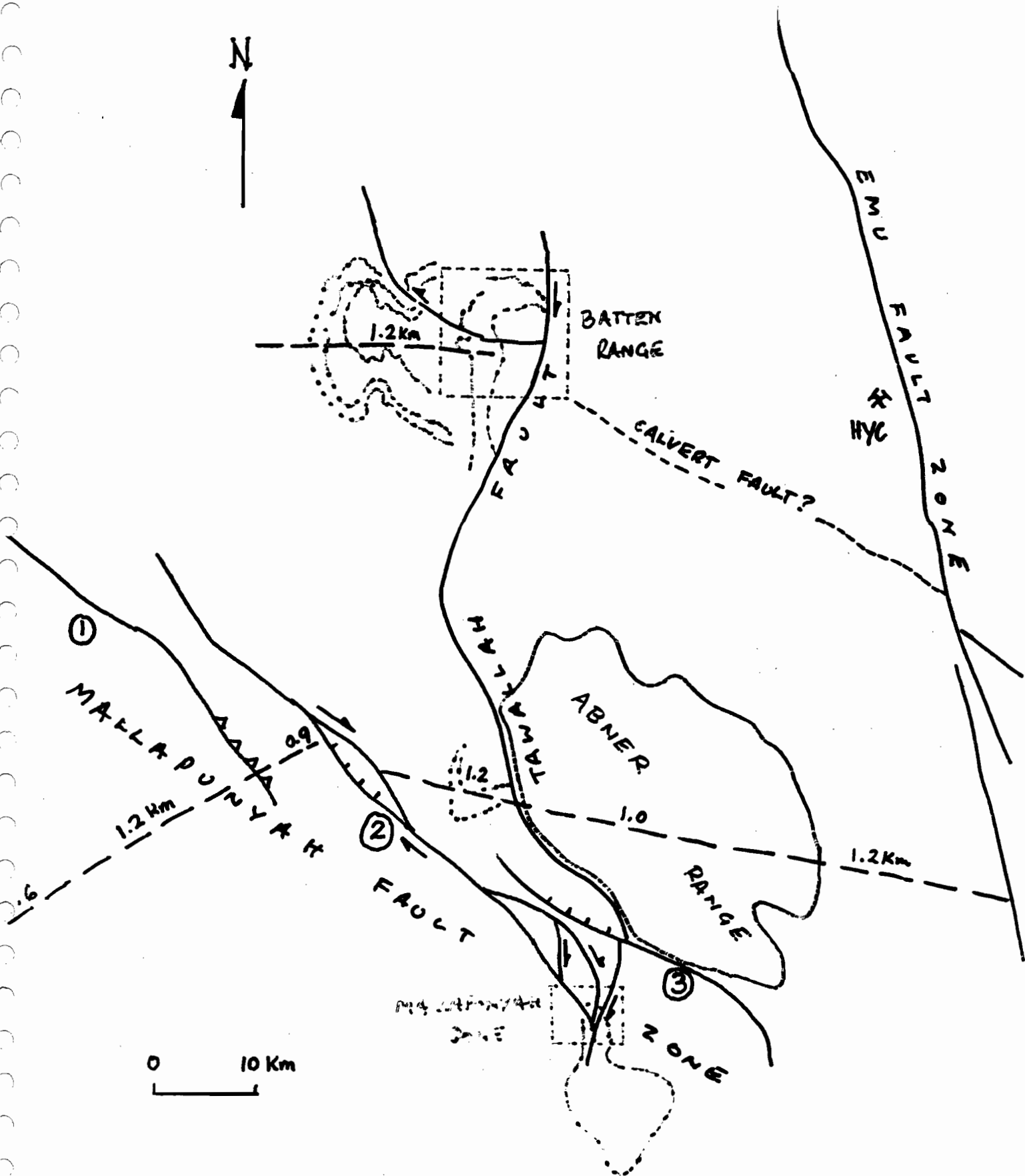


EXAMPLES OF POST-ROPER INVERSION

2.0 km Axis of Max. thickness of mafic volcanics

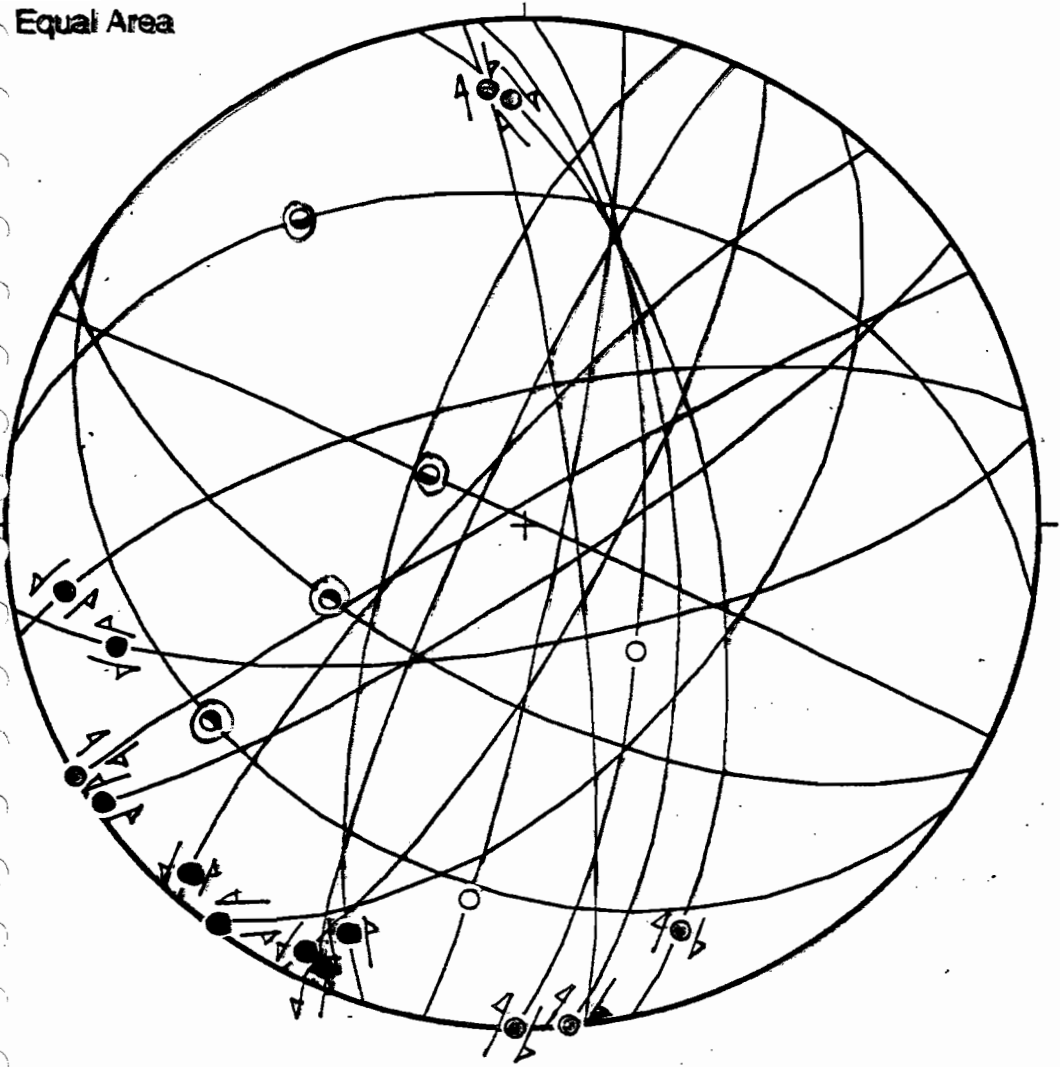
POSSIBLE 3 ORIENTATION STRESS STATES
 IN MATLAPUNYAH DOME.





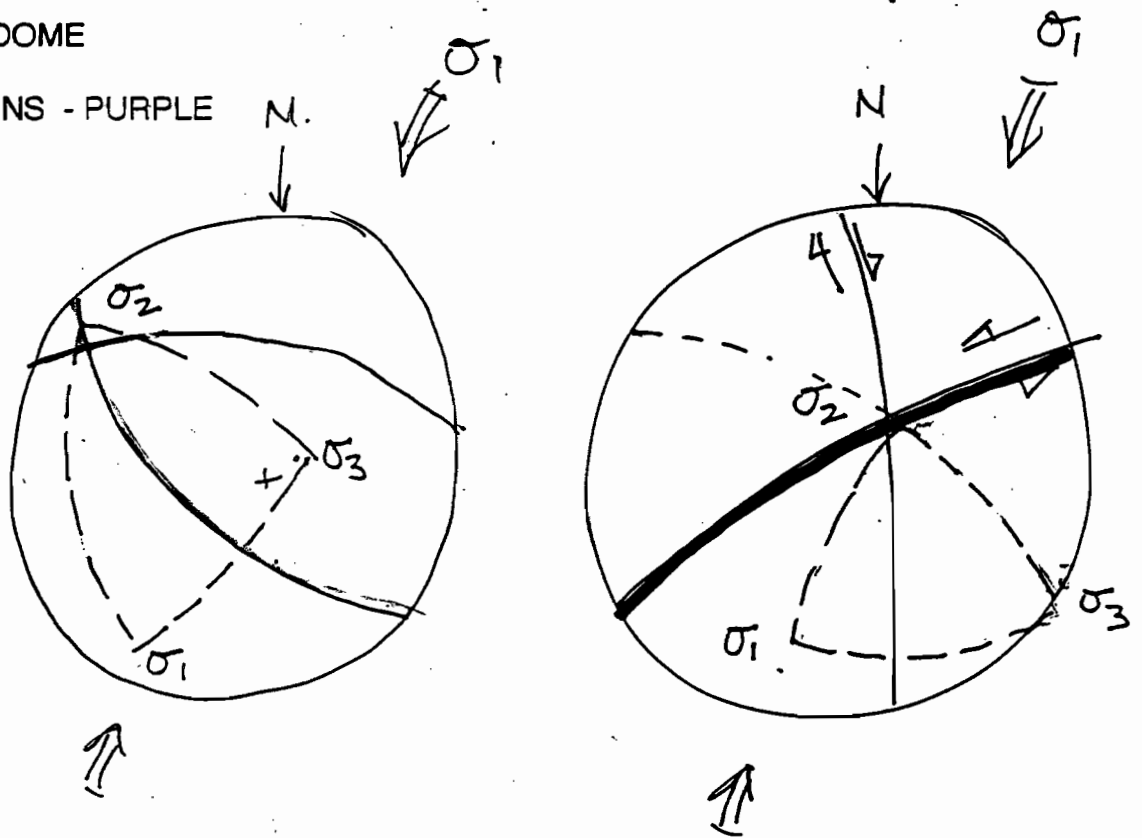
LEFT-STEPPING MALLAPUNYAH FZ & TAWALLAH FAULT.
 SHOWING AXES OF THICKENED U. TAWALLAH MAFIC VOLCS.-----

Equal Area



MALLAPUNYAH DOME

FAULT STRIATIONS - PURPLE



DIP SLIP.

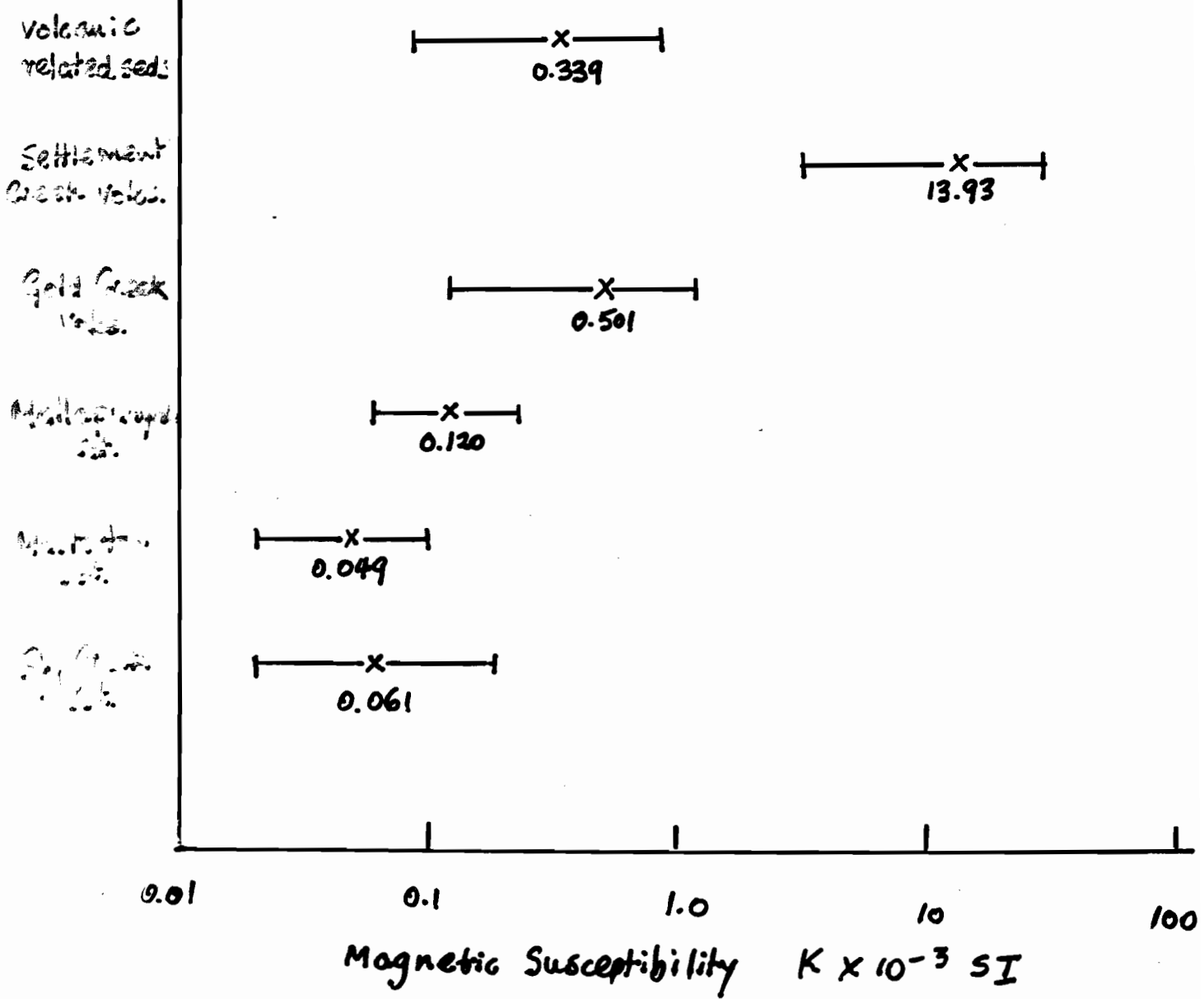
STRIKE SLIP

σ_2 swaps with σ_3
(σ_1 stable).

SUMMARY OF MAGNETIC SUSCEPTIBILITY DATA

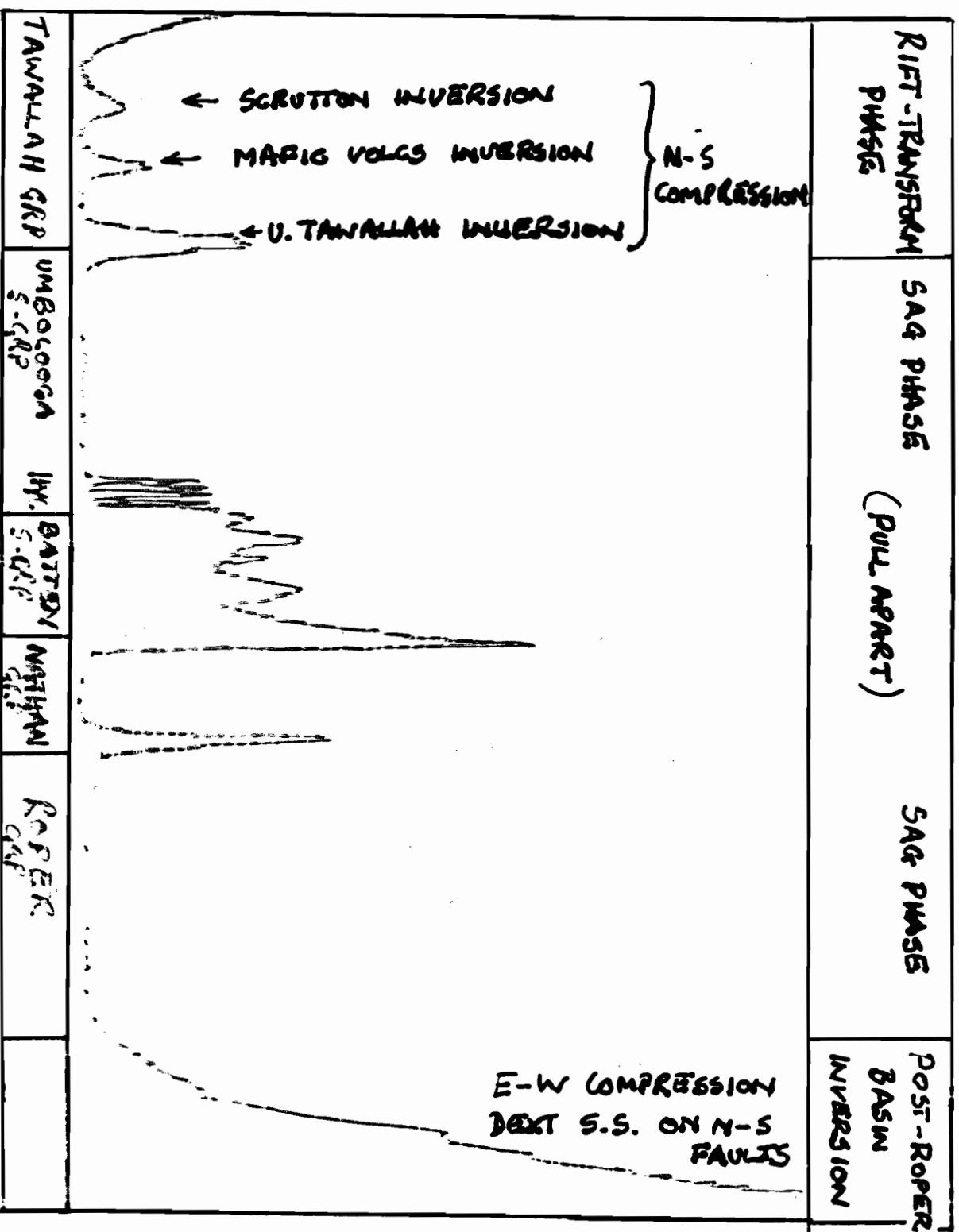
MALLAPUNYAH DOME (S. MEARNS BASIN.)

ROCK TYPE/
STRATIG.



'TETENOQAM' of EVENTS IN S. M. ALTAIR BASIN.

Intensity of tectonic activity. →



**SUMMARY OF RESEARCH FINDINGS
RELEVANT TO EXPLORATION MODELS
FOR STRATIFORM Pb-Zn DEPOSITS**

**ROSS LARGE
CODES**

**Overheads used in November 1992
AMIRA Meeting Project P384**



EXPLORATION MODEL

STRATIFORM SEDIMENT HOSTED Pb-Zn

Developed in 1990 prior to AMIRA project.

TARGET	MINING AND TREATMENT
<ul style="list-style-type: none"> • Large, single deposits are characteristic • Average 60mt at 11% Pb+Zn • High silver credits • e.g. Mt Isa Pb/Zn, McArthur River, Selwyn Basin deposits 	<ul style="list-style-type: none"> • Tabular form and uniform grades allow relatively easy assessment and mining • Some fine grained ores provide treatment difficulties (e.g. McArthur River) • Metamorphosed-recrystallised ores are easier to treat • Smelter penalties are generally low

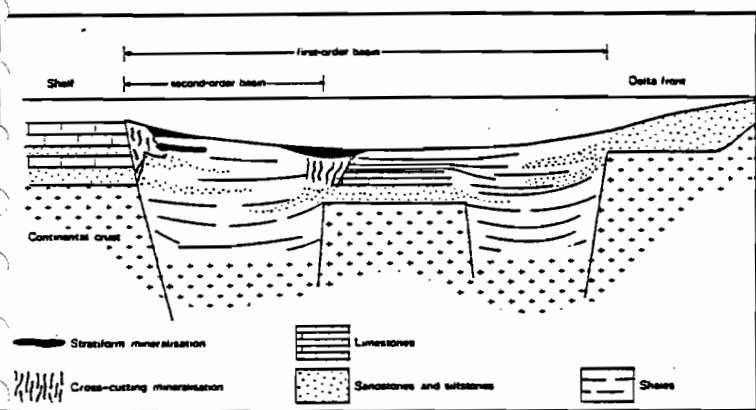


Figure 1.3 Possible geotectonic setting of sediment-hosted massive sulphide Pb-Zn deposits. After Large (1980).

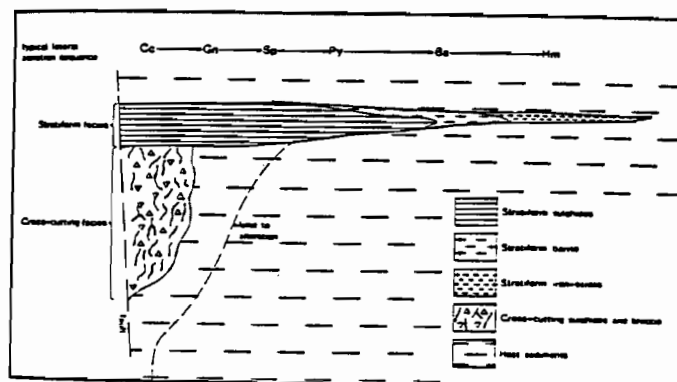


Figure 1.6 Hypothetical model of a sediment-hosted massive sulphide Pb-Zn deposit illustrating some of the features described in the text. Cc-chalcopyrite; Gn-galena; Sp-sphalerite; Py-pyrite; Bc-barite; Hm-hematite. After Large (1980).

GEOLOGICAL CRITERIA	MINERALISATION FEATURES
<ul style="list-style-type: none"> • Rift related intracontinental or continental margin marine basins • Age - peaks in L-M Proterozoic, Cambrian and Carboniferous • Located at edge of sedimentary basin • Adjacent to syn-sedimentary faults • Wide range of marine sedimentary host rocks - shales, evaporites, sandstones, turbidites, conglomerates & breccias. • Exhalites may provide target horizons (e.g. Py shale, chert, barite shale or BIF) • Depth of water varies from shallow evaporite sequences to deep marine clastic sediments • Coarse grained debris flows (breccias) associated with syn-sed faults may overlie or underlie ore lenses • Oxidation of host sediments varies from pyritic shales (e.g. Mt Isa) to oxide facies BIF (e.g. Pegmont and Tynagh) • Link with igneous intrusions is not obvious, although basic intrusions commonly occur in the lower stratigraphy of basins 	<ul style="list-style-type: none"> • Stratiform, banded, stacked lenses are common • Interbanded sediment and sulphides form laterally extensive sheets • Vein style Pb-rich mineralisation may be present in footwall or within the feeder fault • Overall metal zonation is generally outward and upward from the feeder fault Cu → Pb → Zn → ± barite • Pyrite ± pyrrhotite content varies from abundant (e.g. Mt Isa type) to minor (e.g. Broken Hill type) • Stratiform barite often lateral to or stratigraphically above the sulphides
	<p>ALTERATION</p> <ul style="list-style-type: none"> • Some deposits (e.g. Rammelsburg and Sullivan) have footwall alteration pipes • Silicification accompanies FW vein systems • In carbonate bearing hosts the dolomite/calcite ratio increases toward ore • K-feld/albite ratio increases in tuffaceous rocks towards ore

GEOCHEMICAL CRITERIA

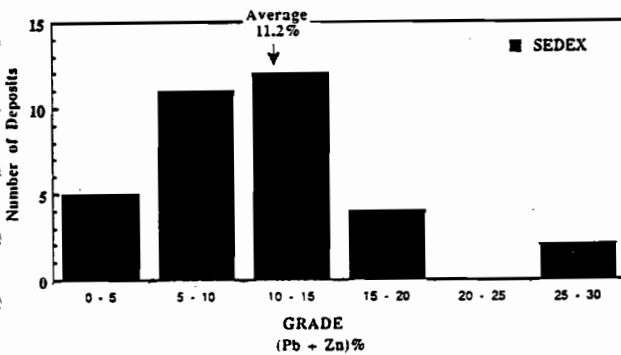
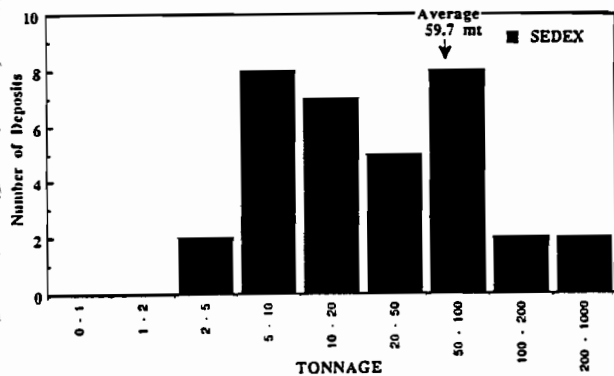
- Host sequence may be anomalous in Zn, Tl±Ba±Mn for many km along strike
- Zinc ratio ($100 \text{ Zn}/[\text{Zn}+\text{Pb}]$) shows three distributions ZR=10 to 20, ZR=40 to 50, ZR=70 to 100
- Trace elements include As, Sb, Tl, Cd, Hg, Ba
- Sulphur isotopes generally vary from -5 to +25‰ and suggest two sources of sulphur (hydrothermal H_2S and reduced seawater SO_4^{2-})
- Pb isotopes give same model age as the host rocks

GEOPHYSICAL CRITERIA

- Regional geophysics (gravity, magnetics) can be used to define basin margins and major syn-sed feeder faults
- Magnetics may locate favourable exhalites
- Magnetics may locate footwall alteration zones (of silification & magnetite destruction)
- Ores are poor to moderate electrical conductors depending on pyrrhotite and pyrite content
- Pyrrhotite-bearing deposits can be targeted with magnetics and electromagnetics

FLUID CHEMISTRY & SOURCE

- High salinity 5-25 wt % NaCl
- Moderate temperature 150-280°C
- Reduced $\text{H}_2\text{S} > \text{SO}_4$
- Source - connate basinal brines
- Metal sulphide deposition due to cooling and mixing of hot basinal brine with ambient seawater



Tonnage Grade Histograms for Sedex deposits world wide.

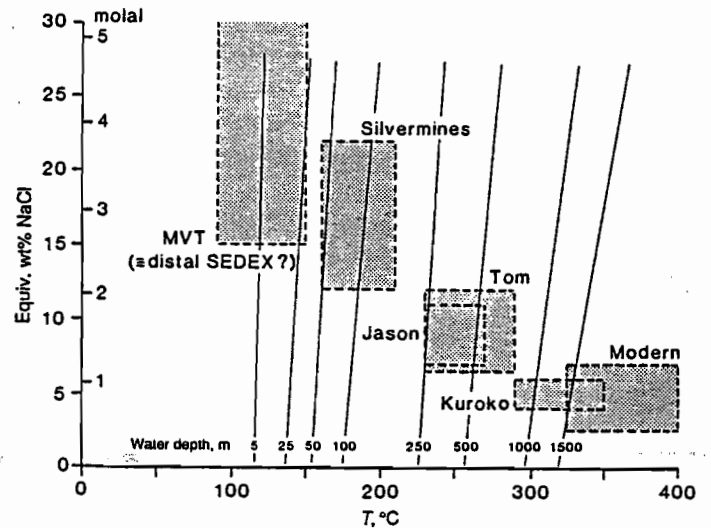


Fig. 19 Relationship between hydrothermal fluids of various temperature-salinity values and minimum water depth required to prevent boiling⁹²

Compiled by Ross Large, CODES, University of Tasmania

References: Sangster (1990), Large, D.E. (1983), Beeson (1990)

POTENTIAL SOURCE ROCKS

- **Sediments** - clay minerals:
Pb, Zn \pm Cu
- **Volcanics** - felsic Pb, Zn
- mafic Cu, Zn
- **Granites** - ? unlikely source
- maybe a heat engine?

SAWKINS MODEL FOR GIANT PROTEROZOIC ORES

Published in *Geology* V.17,p757-660, 1989

Pb-Zn Deposits

- Major Pb deposits appear abruptly after 2,000 m yrs.
- This is related to availability of source rocks.
- Pb substitutes for K⁺ in K-feldspar ~ 25 ppm Pb.
- Highly fractionated magmatic/volcanic rocks contain up to 300 ppm Pb in K-feld.
- Thus the felsic magmatic/volcanic event 1840-1880 m yrs in N.Australia provides a major source for Pb and Zn.
- These volcanics/granites eroded to contribute Pb-Zn rich first cycle clastic sediments (Tawallah Gp)
- These rocks provide a unique source of metals for deep penetrating connate brines that ultimately formed the giant Sed-H Pb-Zn deposits.

Relation to Cu-deposits

- **stratiform Cu**
 - **early stages of rifting.**
 - **subaerial environment.**
 - **evaporate successions.**
 - **oxidised environments.**

- **stratiform Pb/Zn**
 - **in late stages of rifting.**
 - **submarine and reduced environment.**

HOWEVER

- **Nature of volcanism in deep FW is CRITICAL.**
mafic volcanics → Sed-H Cu.
felsic volcanics → Sed-H Pb-Zn.

FLUID TRANSPORT CHEMISTRY

- Connate Brines** - high salinity (10-30wt% NaCl);
neutral pH
- Two Options

OPTION 1

**Reduced,
H₂S > SO₄**

**Moderate Temp
200-250 °C**

- Only Zn, Pb, Ag are transported (±Au).
- Metals near saturation, at low levels.
- Deposition due to **TEMPERATURE** decline.
- Redox boundaries are not important for deposition.
- May have sulphide feeder zones with high Pb/Zn or Cu/Zn ratios.
- Pyrite deposited with galena, sphalerite.
- Preferred fluid type for seafloor massive sulphides (e.g. VHMS and Selwyn Basin, Sedex).

OPTION 2

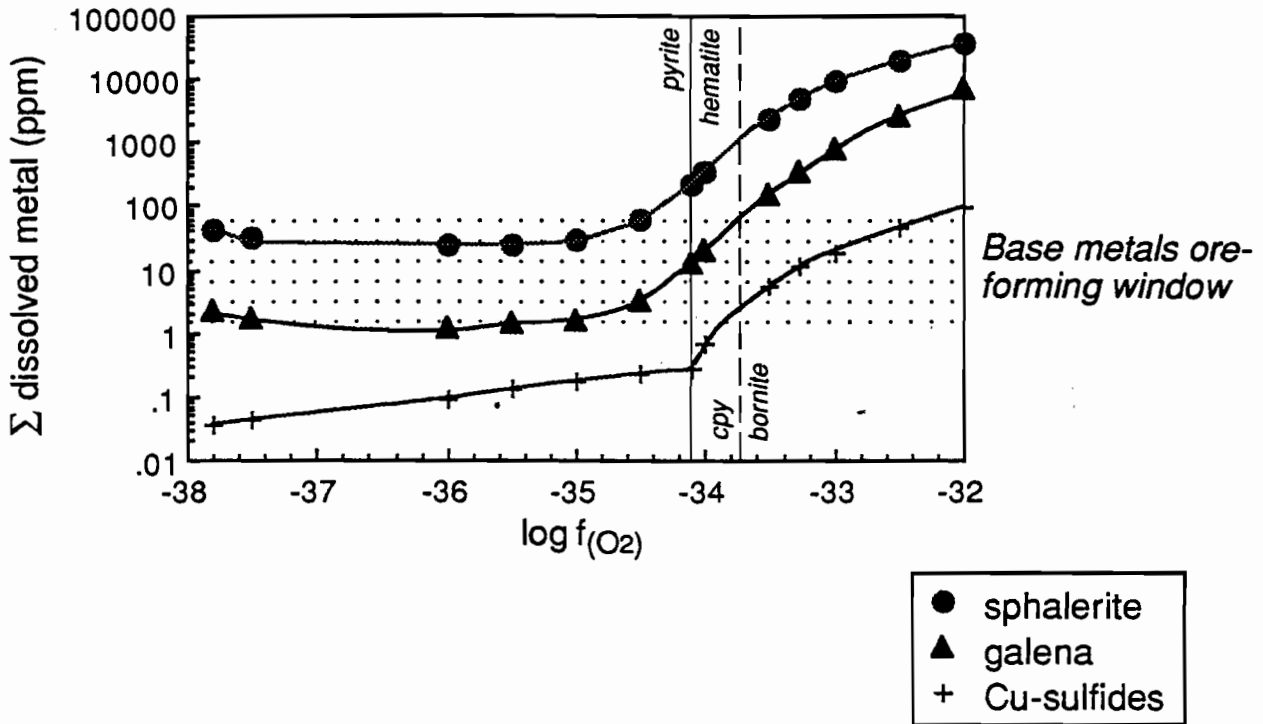
**Oxidised
SO₄ > H₂S**

**Moderate to low Temp
100 - 250°C**

- **Abundant Cu, Pb, Zn and Ag are transported.**
- **Pb and Zn are grossly undersaturated, copper near saturation.**
- **Temperature decrease does not cause mineralisation.**
- **Reduction boundaries are the critical trap.**
- **Successive reduction separates Cu from Pb, Zn.**
- **Cu deposited at first reduction zone.**
- **Pb, Zn only deposited at HIGHER, MAJOR reduction barriers.**
- **Preferred fluid type for sediment hosted Cu deposits.**
- **Possible fluid type for subseafloor stratiform Pb-Zn deposits (e.g. McArthur River, Century).**

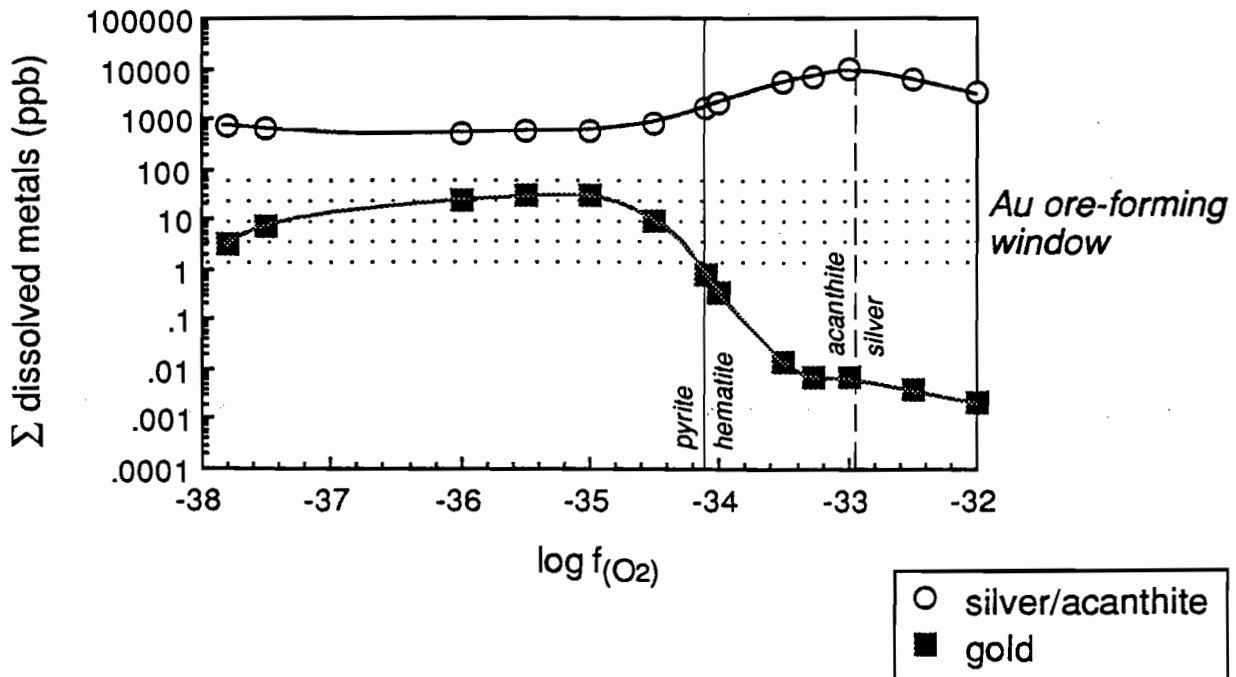
Sulfide solubilities

T = 250°C; pH = 4.96; Salinity = 10.7 eq. wt. % NaCl



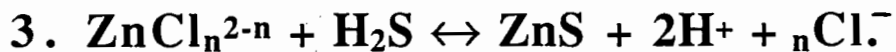
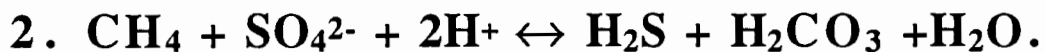
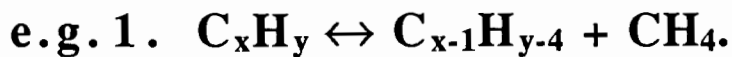
Au, acanthite and Ag solubilities

T = 250°C; pH = 4.96; Salinity = 10.7 eq. wt. % NaCl



TRAP HORIZONS - STRONG REDUCTANTS

- **Barton (1967) and Anderson (1991) argue that sulphate reduction by methane is the most effective method of precipitating Pb and Zn in MVT deposits.**
- **Heat from the hydrothermal fluid causes thermal maturation of organic matter releasing CH₄ which in turn reduces SO₄²⁻ to H₂S, leading to Pb-Zn precipitation.**



- **McGoldrick and Keays (1990) argue that the Mt Isa Cu and Pb-Zn-Ag ores deposited from cool oxidised fluids rather than hot reduced fluids.**
- **Wall and Heinrich (1990) suggest that the Redbank breccia pipe Cu mineralisation forms by reduction of oxidised brines due to interaction with hydro-carbon bearing fluids sourced in the Wollongorang Formation.**
- **Organic rich black shale horizons within the Upper Tawallah Group or the McArthur Group provide the best reductants for stratiform Pb-Zn.**

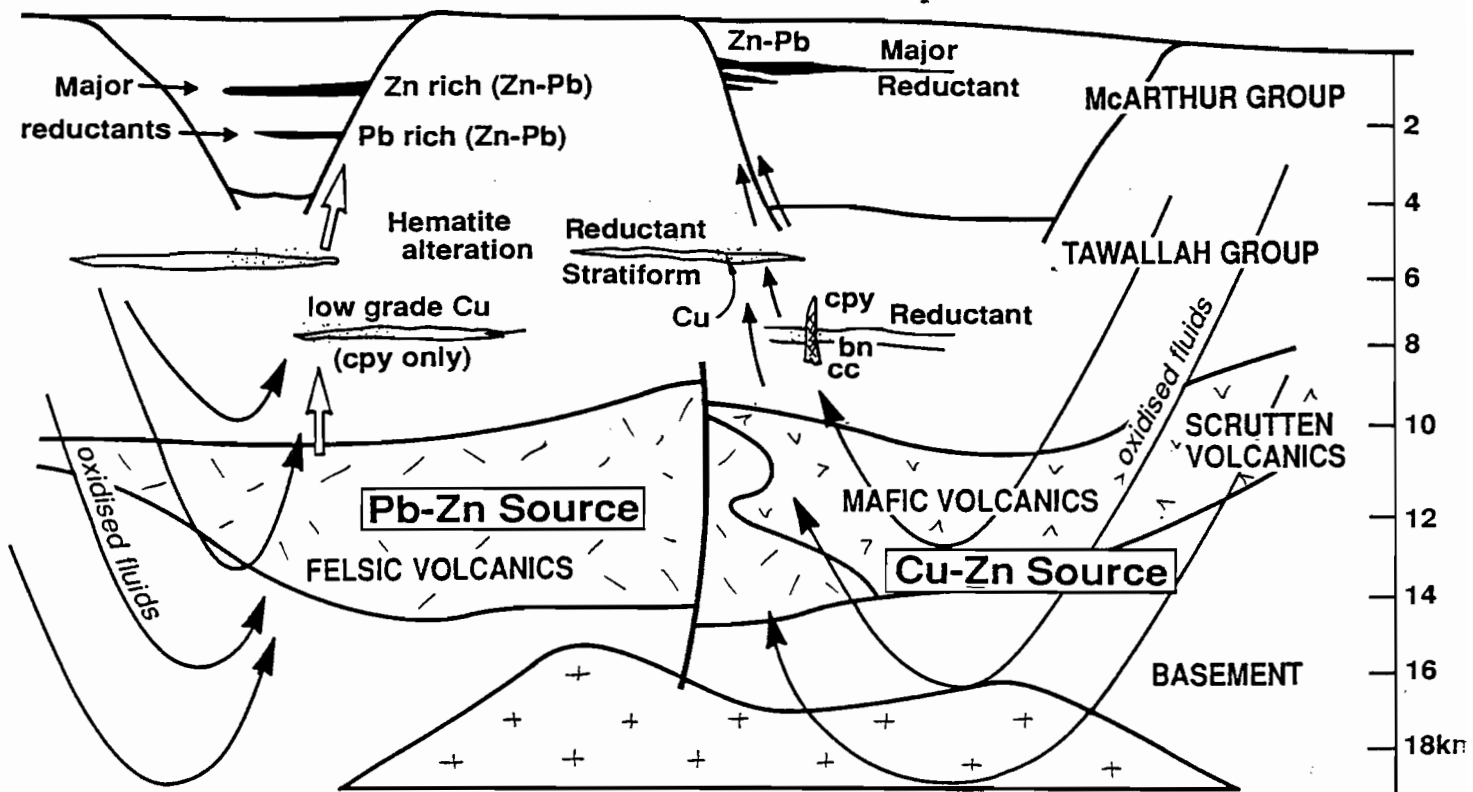
CONCLUSIONS BASED ON OUR RESEARCH

- **Potential exists for both Sed-H Cu and Sed-H Pb/Zn in the McArthur basin.**
 - **Gravity/magnetic modelling which indicates 4 - 6 km thick mafic/felsic volcanic suite in lower McArthur basin, and provides an ideal source for both Cu and Pb/Zn.**
 - **supported by chemical modelling which indicates oxidised fluids are suitable for the formation of both Sed-H Cu and Sed-H Pb/Zn in the same basin.**
- **Stratiform Cu is likely to occur in the Tawallah Gp or lower McArthur Group associated with mild to strong reduction boundaries in an oxidised package.**
- **Stratiform Pb/Zn is more likely higher in the stratigraphy at exceptionally strong reduction boundaries, within the overall reduced package.**
- **Within the more reduced package, Pb-rich ores are more likely in the lower stratigraphy with Zn/Pb ratio increasing upwards (into more reduced environment).**
- **Hematite alteration and zinc-lead depletion is predicted in the lower stratigraphy (Tawallah Group and below). Preliminary field work supports this idea.**

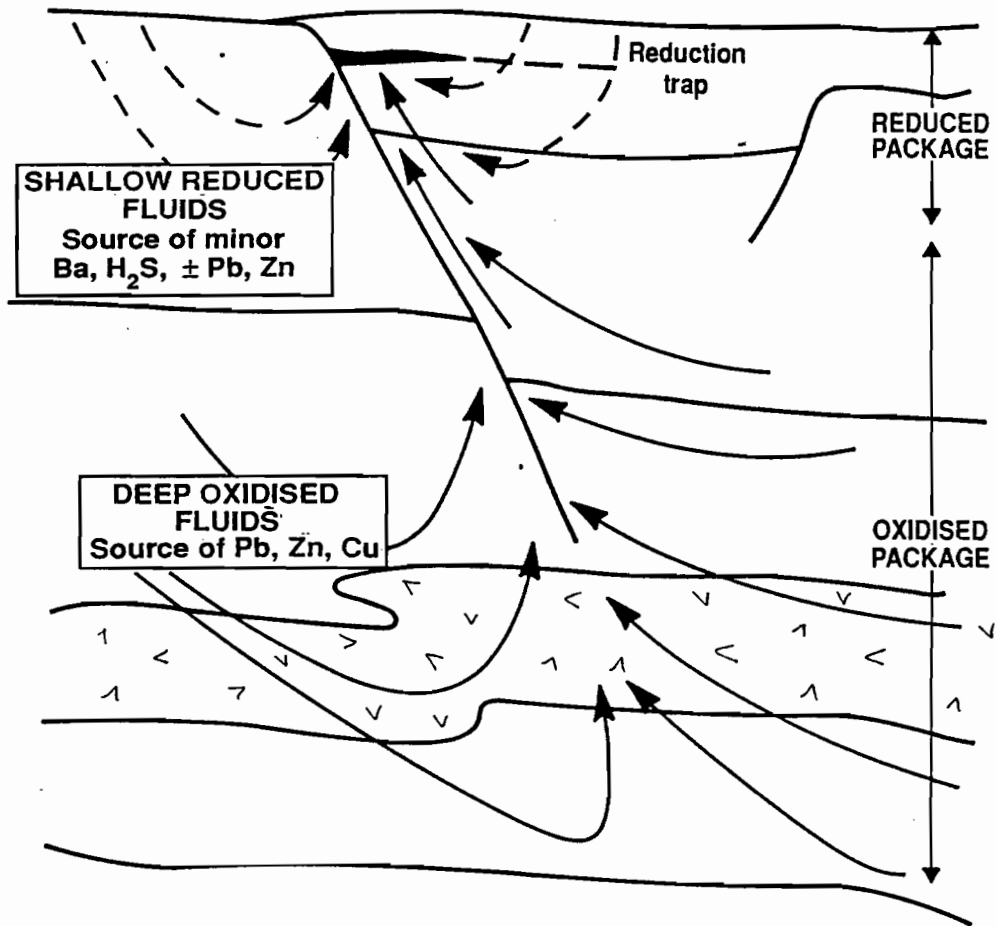
CONCLUSIONS CONTINUED

- **Cu will be dispersed in the lower stratigraphy wherever reduced horizons occur. Organic-rich horizons or sedimentary pyrite horizons will pull Cu out of solution, but not Pb/Zn.**
- **Pb/Zn is more likely to form high grade zones where MAJOR reductants exist - availability of H₂S or CH₄ is critical for deposition.**
- **Temperature changes will have no effect on mineral deposition from oxidised fluids → exhalation on the basin floor will not necessarily cause Pb/Zn deposition.**

WORKING MODEL ; SED-H BASE METAL DEPOSITS FROM OXIDISED FLUIDS



TWO-FLUID WORKING MODEL



SOLOMON & HEINRICH MODEL

Published in Exploration & Mining Geology VI,p85-91, 1992

OUTLINE

- Basin dewatering by sediment compaction does not produce the temperatures or fluid volumes needed to form sedimentary Pb-Zn deposits.
- For ore fluid temperatures $>200^{\circ}\text{C}$, abnormally high geothermal gradients are required.
- Fluid convection cells probably extended into the basement, as demonstrated for the Irish deposits.
- They assume the ore fluid is reduced ($\text{H}_2\text{S} > \text{SO}_4$) and carries about 10 ppm Pb and Zn. Temperatures of $>235^{\circ}\text{C}$ are needed to carry this much metal in a reduced fluid.

NEED FOR A HEAT SOURCE

- **High heat producing (HHP) granite underlies ore at Mt Isa.**
- **They speculate HHP granites underlie the McArthur River deposit.**
- **These granites provide long lived heat to drive fluid circulation responsible for the deposits.**
- **10^{12} - 10^{13} tonnes of ore fluid is required to produce a giant deposit.**

Comments on model

- **Gravity modelling (DEL) indicates granites are probably present below the McArthur basin at 12 - 16 km depth to top.**
- **These maybe basement granite (1830 my series) or the younger HHP granites (1730 my series).**
- **The deep position of these granites may create a problem in maintaining fluid temperatures at $>235^{\circ}\text{C}$ over a thickness of >12 km of sediments and volcanics.**

Anorogenic felsic magmatism, rift sedimentation, and giant Proterozoic Pb-Zn deposits

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ABSTRACT

The giant lead deposits that developed after ~1.8 Ga in Australia, North America, and Africa are absent in the earlier geologic record. These Proterozoic lead (+ zinc) deposits were all preceded by major outbreaks of anorogenic felsic magmatism that brought significant amounts of lead-rich material (>30 ppm) to the surface of Proterozoic cratons. Erosion of these volcanics apparently transferred major quantities of the lead to rift basins where giant lead deposits were generated. All known giant Proterozoic sediment-hosted lead-zinc deposits (more than 50 Mt of lead metal) are explained by a model that is supported by Sm/Nd data relevant to mantle separation ages of volcanics and the metasedimentary source rocks for the lead ores.

INTRODUCTION

Lead ore deposits (>3% Pb) represent the result of processes acting to concentrate lead by a factor of over 2000 times average crustal values (<15 ppm). Galena, the sole sulfide of lead, is present in many hydrothermal metal deposits, but deposits that contain more than 2 Mt (10^6 tonnes) of lead metal are rare and occur as either sediment-hosted Pb-Zn massive sulfide-type deposits (SHLZ) or sandstone- or carbonate-hosted Mississippi Valley-type (MVT) deposits (Sawkins, 1984a). Prominent among the SHLZ type is a group of six giant Middle Proterozoic deposits that account for over 50 Mt of lead metal (Table 1).

Broad consensus has it that both types of deposits are generated by saline brines driven out of compacting sedimentary sequences (see Beales and Jackson, 1966; Cathles and Smith, 1983; Sawkins, 1984b; Oliver, 1986; Lydon, 1986). The lead and zinc are acquired, at least in part, by the brines from phyllosilicate minerals undergoing compaction and heating in accumulating sedimentary sequences (Lydon, 1983). Additional lead is almost certainly acquired by the brines as they move through sand-

stone aquifers in which detrital K-feldspars are present (Doe and Delevaux, 1972; Sverjensky, 1984).

SOURCE ROCKS FOR LEAD DEPOSITS

The high concentration factor involved in generating lead deposits suggests multistage processes of lead enrichment, especially for giant Proterozoic SHLZ deposits. These deposits arrived abruptly on the metallogenic scene after 2000 m.y. of Earth history during which few significant concentrations of lead formed (Klau and Large, 1980; Meyer, 1988).

Lead is a typical large ion lithophile element (LILE) that has an ionic radius of 1.20 Å (Pb^{2+}) as compared to 1.33 Å for K^+ . Pb^{2+} therefore can be incorporated to some extent in the place of K^+ in potassium-bearing rock-forming minerals, especially potassium feldspar. Most potassium feldspars contain between 25 and 30 ppm lead, but can contain up to ~300 ppm if related to late-magmatic concentration processes (Wedepohl, 1978). Crustal melt granites, especially those formed in anorogenic settings, are enriched in lead (Table 2), and related volcan-

ism would thus be a favorable precursor event to the formation of major lead deposits.

EARLY TO MIDDLE PROTEROZOIC FELSIC MAGMATIC EVENTS AND THEIR EROSIONAL PRODUCTS

A widespread (>37000 km²) and well-documented period of felsic volcanism and granite emplacement occurred between 1880 and 1840 Ma in Australia (Wyborn, 1988) (Fig. 1). These igneous rocks are predominantly of I-type, are of uniform composition over large areas, and relative to orogenic igneous suites are consistently enriched in potassium and LILE even at SiO₂ levels as low as 60%–65% (Wyborn, 1988). Intrusive types are mainly granodiorite and monzogranite, whereas volcanic phases are mainly dacite and rhyodacite. The lead content of these igneous rocks is considerably elevated (~30 ppm), as is the lead content of all pristine anorogenic felsic igneous rocks (Table 2).

Given suitable paleogeography and the indicated wide dispersion of the volcanic members of this igneous suite as subaerial ignimbrite sheets (Wyborn, 1988), it seems probable that

TABLE 1. GIANT AND MAJOR PROTEROZOIC LEAD DEPOSITS

Deposit	Location	Age (Ma)	Dominant Lithologies	Pb (Mt)	Reference
Broken Hill	New South Wales, Australia	~1800	Meta-psammite, meta-pelite, ?felsic volcanics	20	Stevens et al. (1988)
Mount Isa	Queensland, Australia	~1680	Pelites, dolomites, psammite, felsic volcanics	8.2	Plumb et al. (1980)
Hilton	Queensland, Australia	~1680	Pelites, psammites	2.7	Plumb et al. (1980)
McArthur River	Northern Territory, Australia	~1680	Dolomites, pelites, psammites	7.9	Walker et al. (1977)
Sullivan	British Columbia, Canada	~1440	Psammites, pelites	10.2	Hamilton et al. (1982)
Aggenys	N. Cape, South Africa	~1330	Meta-pelite, meta-psammite	5.2	Ryan et al. (1986)

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

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No. 5

Organic Maturation and Ore Precipitation in Southeast Missouri

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Abstract

The "sulfate-reduction plus mixing" hypotheses for the formation of Mississippi Valley-type deposits have suffered from an inability to show a plausible mass balance between sulfate, possible reductants, and sulfide ores, and a mechanism for mixing the reduced gas (H_2S) with the metal-bearing fluid. Both these problems are resolved by focusing on the gases (mostly methane) generated from the organic matter in the host carbonate rocks during thermal maturation caused by heat from the hydrothermal solutions. In southeast Missouri, it appears that the volume of the Bonneterre Formation required to produce all the methane needed to reduce enough sulfate to precipitate all the ores is approximately the same as the volume of the brown-rock facies, which hosts most of the ore. Therefore it appears that metal- and sulfate-bearing solutions entered the Bonneterre at Lamotte Sandstone pinchouts, then followed permeability trends, which coincided mainly with the oolitic grainstones associated with the stromatolite reef, most of which are brown. Evolution of methane and other reducing compounds from the brown rock resulted in sulfate reduction and precipitation of sulfides. Several other regional and local factors in the geology of the area are found to be compatible with this idea.

Introduction

THE relationship between organic material and Mississippi Valley-type deposits has been discussed many times, but it is fair to say that the relationship, if any, remains tentative and poorly understood. The problem is essentially twofold: (1) although organic matter is commonly found in the ores and occasionally in fluid inclusions, there is never enough to satisfy the mass balance required if this is to be called upon as a reducing agent for sulfate; and (2) the reduction of sulfate by organic matter in the temperature range established for Mississippi Valley-type deposits has not been unequivocally established. A related problem is that in some Mississippi Valley-type areas (e.g., southeast Missouri) the source of sulfate to be reduced is not obvious.

The central idea in this contribution is that the hot brines associated with mineralization cause thermal maturation of organic material in the adjacent rocks. A principal feature of this maturation is the evolution of hydrocarbon gases (CH_4 , C_2H_6 , C_3H_8 , etc.) which, if trapped, provide a reservoir of reductant for sulfate (producing H_2S for metal precipitation), either present locally as gypsum or anhydrite or dissolved in the mineralizing fluid itself. By focusing on the gases generated rather than on the bitumen, oil, or remaining kerogen in the rocks, the mass balance problem is resolved. The problem of the sulfate source and its

reduction mechanism and kinetics remains, but examination of data on H_2S reservoirs in the petroleum literature indicates not only that the proposed processes are viable but that other, broader features of Mississippi Valley-type deposits, such as their occurrence in carbonates in general and dolomites in particular, fit very well into the overall hypothesis. Therefore although I present data only for southeast Missouri, I feel that the general features of the proposals may be applicable to all Mississippi Valley-type deposits.

In addition to the central idea of methane generation and sulfate reduction, two other themes are developed which are equally important. These are the importance of permeability trends, and the importance of sandstone pinchouts. These and some of the other ideas discussed have been proposed before, but they bear repeating in this context.

- Southeast Missouri Geology

The geologic facts about the environment of the ores in southeast Missouri are too well known to require a summary, but there are a few features which have a direct bearing on the ideas presented here.

Sedimentary facies and permeabilities

Upper Cambrian depositional patterns in Missouri were controlled largely by the tectonic framework which produced the failed Reelfoot rift and the bor-

Are High-Heat-Producing Granites Essential to the Origin of Giant Lead-Zinc Deposits at Mount Isa and McArthur River, Australia?

M. SOLOMON and C.A. HEINRICH

Bureau of Mineral Resources, Geology and Geophysics
G.P.O. Box 378, Canberra, ACT 2601, Australia

Abstract — Giant, sediment-hosted lead-zinc deposits in northern Australia formed during development of Mid-Proterozoic extensional basins that overlie Lower Proterozoic basement. The basement in the Mount Isa area, exposed by folding and faulting, contains fractionated, high-heat-producing granites. These granites generate heat at a rate of about $6\mu\text{Wm}^{-3}$, probably sufficient to form giant lead-zinc deposits either by (a) driving episodic convection of saline basement and basin fluids for periods of 10^5 to 10^6 years at temperatures of about 230°C , or (b) heating basin fluids moving under the influence of topographic relief or fault movement. The presence or absence of such granites may form a vital component of the genetic model. Ore-forming fluid flow was probably initiated by continent-scale, extensional basin fracturing.

Introduction

Giant stratiform, sediment-hosted lead-zinc (sedex) deposits containing > 10 Mt (10^6 tonnes) of both Pb and Zn first appear in the geological record of Australia in host rocks dated at about 1680 Ma, e.g. H.Y.C., Lady Loretta, Hilton, Mount Isa, and Broken Hill (Page, 1988; Page and Laing, 1990). Supposedly older stratiform lead-zinc deposits in the Mount Isa area, e.g. Dugald River, have not been definitively dated and their age is uncertain. Like their younger counterparts in other continents, particularly the Irish lead-zinc province (Hitzman and Large, 1986), the deposits consist of more-or-less stratiform lenses rich in sphalerite and galena, and apparently formed on or just below the basin floor within lacustrine or marine sequences of variable style that developed in epi- or intra-cratonic extensional basins (Gustafson and Williams, 1981; Large, 1983; Lambert, 1983). As Sangster (1990) has noted, individual sedex deposits are similar in size to Mississippi Valley-type (MVT) districts, but differ in being the product of sharply focused fluid flow, commonly in major synsedimentary growth faults. Unlike MVT deposits, sedex ores formed during basin development rather than afterward.

During the last five years there has been considerable discussion regarding the origin of the ore fluids and metals in sedex deposits, and the nature of the sedimentary environment (e.g. Lydon, 1986; Wright et al., 1987; Jackson et al., 1987; Plimer and Lottermoser, 1988; Willis et al., 1988; Sawkins, 1984, 1989). A widely held view is that the ore fluids were derived by episodic basin dewatering (see review in Sangster, 1990), consistent with their occurrence within large, extensional sedimentary basins. These basins are generally of carbonate-shale-sandstone type, and for such basins dewatering as a result of compaction is not a viable process, the thermal and mass fluxes being inadequate to generate the large deposits (Bethke, 1985). These problems disappear for the relatively low-temperature MVT deposits if copious flow is driven by the hydraulic head produced as result of tectonic uplift

of basin margins (Bethke, 1986); the higher temperatures required for forming sedex ores, however, probably require unusually high geothermal gradients and/or deep fluid penetration beneath the basins.

The Irish lead-zinc deposits are unlikely to have formed from basin brines because there is no substantial basin (Andrew, 1986), and Russell (1978) proposed that they formed as a result of convection following extensional basin fracturing. Russell et al. (1981) later extended this model to all giant lead-zinc deposits. In this model the convection cells are interpreted to have extended downward to greater and greater depths through the life of the system. One-dimensional, finite-difference thermal modeling by Strens et al. (1987) indicated that the Russell model might account for giant deposits under favorable conditions such as large catchment area, high thermal gradient, and adequate permeability.

Tectonic movement on faults provides a third possible driving force for ore-fluid movement and sedex mineralization. Seismic activity along fault zones is known to cause major fluid flow, either by the mechanism of seismic pumping (Sibson et al., 1975), or by rupture stopping at dilational jogs (Sibson, 1985).

In this communication we argue on the basis of solubility considerations and geological observation that all three driving mechanisms of fluid flow (the Bethke uplift model, the Russell convection model, and the Sibson fault models) require unusually high thermal inputs to form giant sedex deposits of the size of McArthur River and Mount Isa. We propose that the Australian examples in the McArthur and Mount Isa basins were probably formed as a result of high heat flow in the basement resulting from radioactive decay in Lower Proterozoic granites. Whether the ore fluids were convecting by thermal buoyancy, or being driven by a hydraulic head related to topography and/or fault tectonics, is not yet clear although we consider the convection model most likely. We examine the geology of the McArthur and Mount Isa areas, the former yielding information on basin structure and growth, the latter, being much more severely