

Centre for Ore Deposit and Exploration Studies



# Proterozoic sediment-hosted base metal deposits

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Report No.2



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## Summary of Research Findings

### REGIONAL GEOPHYSICS AND BASIN ARCHITECTURE

This report describes further advances in the regional basin architecture study

Some revisions and refinements of previously reported material within the Battern Trough are included. The extension of the interpretation southward into the Wallhallow region and eastward onto the Wearyan Shelf is also described. This new work generally confirms the implications of the original study and suggests that the Battern Trough has had a long and complex history. The first two stages of its evolution include large-scale volcanism and irregular extension and uplift. The structural environment of the Wearyan Shelf is shown to be distinct.

Most refinements of the Batten Trough study relate to additional peripheral studies, either reported here or under way, and involve small variations in presented diagrams or additional diagrams. The latter include one omitted from the original report and a detailed version of the distribution of basement granitoids. The few seismic sections available have also been reviewed in light of the implications of the gravity-magnetics interpretation and found consistent with it.

Some readers of the first report were concerned that the inferences concerning substantial, differentiated and concealed volcanic piles might be suspect. Since this pre-Tawallah Group aspect of the interpretation may ultimately prove crucial to an understanding of the basin, its evolution and its mineralisation, it is necessary to demonstrate that feasible alternatives do not exist. An example of such analysis is included here. This shows that the potential field data do not leave much conceptual uncertainty although many details remain to be worked out. Thick, deep volcanic sections do exist in the McArthur Basin.

Others have noted that some interpretation fits were less than ideal and that as a consequence the entire interpretation might be suspect. Lack of fit perfection may result from the nature of the regional data sets and their subsampling for evaluation purposes, the scale of the analysis, and the amount of time actually spent on each analysis. Irrespective of any deficiencies in these factors, an outline of the very rigorous interpretation criteria actually used is included. This outline, and the discussion of volcanic piles, shows that any imperfections are not of consequence at the scale of this study and any refinements are either not justified or not meaningful.

The implications of these findings have yet to be appraised and the significance of the Battern Trough, its margins and structures such as the Emu Fault await completion of interpretation across the Bauhinia Shelf. This study will be described in the next report.

However, it is evident that a coherent history for the basin and its deep volcanic sequences is evolving. The stratigraphic implications are contrasted with the observed relationships in the nearby Isa Inlier. A future study will test the possible correlations across the Murphy Inlier, South Nicholson Basin and Lawn Hill Platform.

### GOLD METALLOGENY AND THE Cu-Au ASSOCIATION OF THE AUSTRALIAN PROTEROZOIC — Results of research from a previous Proterozoic Cu-Au project

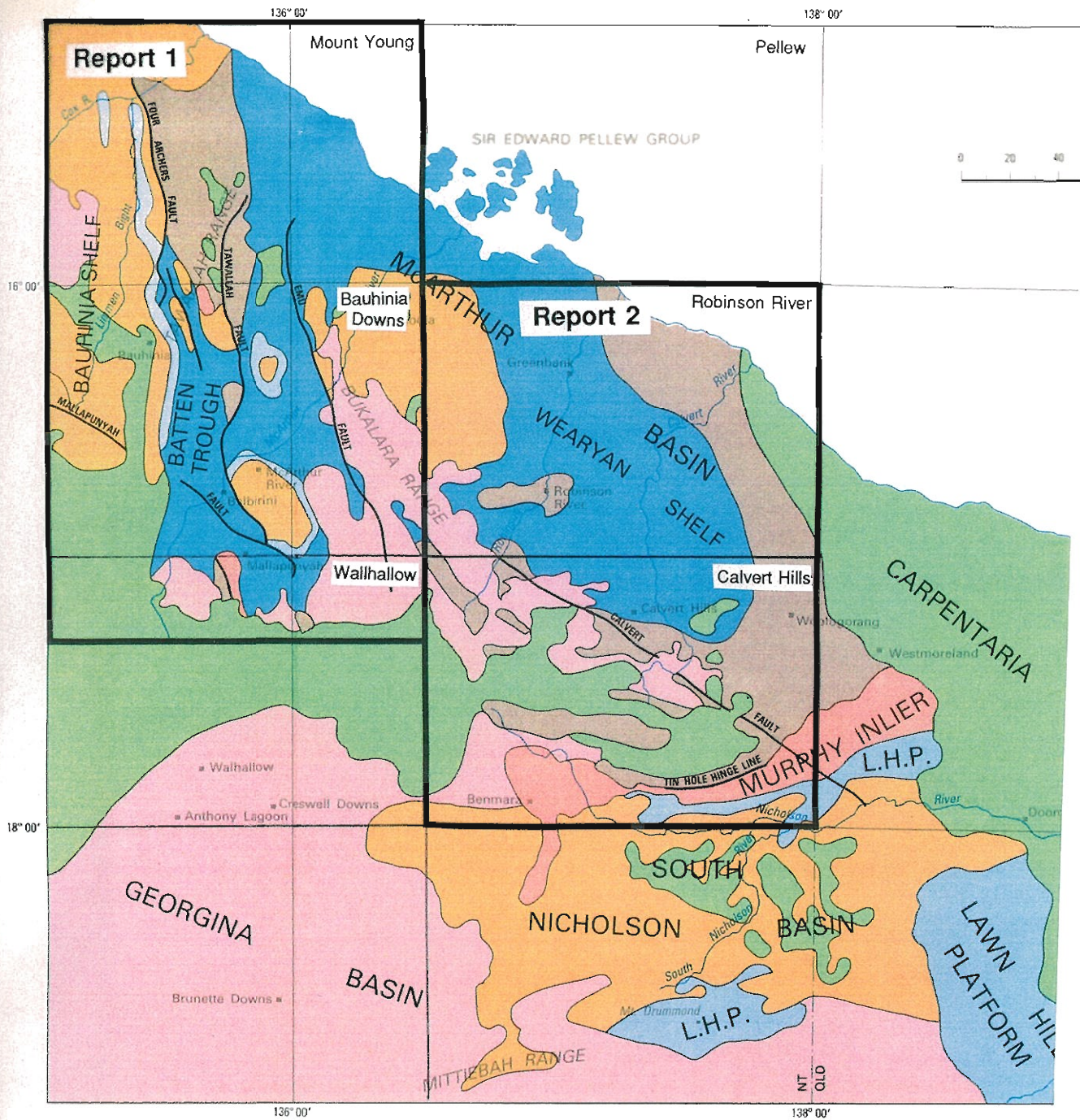
Australian Proterozoic copper-gold deposits, emplaced mainly at 1.6 to 2.0 Ga, are divided into the following categories: (1) breccia-hosted iron oxide-dominated Cu-U-Au-REE deposits spatially associated with fractionated felsic intrusions (273t Au); (2) Au ± Cu-bearing iron formations (128t Au);



(3) unconformity-style U ± Cu/PGM/Au deposits (53t Au); (4) iron-oxide-dominated pipes hosted within shears and folds (147t Au); (5) Broken Hill and volcanic-hosted massive sulphides (150t Au); (6) iron-sulphide-dominated veins and replacement zones spatially related to felsic intrusions (148.7t Au), and (7) iron-sulphide-dominated veins and replacement zones spatially related to elements of regional deformation (147t Au). Categories (1) to (4) are mainly confined to Proterozoic rocks, constituting an association in which Au and Cu are commonly present together, with variable amounts of U, Bi, Co, W, Se, Te and REE. Most examples in categories 1 to 4 fall into either of two groups: Cu–Au–magnetite±hematite types formed at relatively high temperature (300 to 450° C), and Cu–U ± Au –hematite types formed at 150 to 300° C. We postulate that these ores formed from a common high salinity (15–35 wt. % NaCl equiv.), low total sulphur ( $a\Sigma S = 10^{-3}$  to  $10^{-2}$ ), high  $fO_2$  fluid-type, in which metal transport was dominated by chloride-complexing. The most effective method of metal deposition was fluid mixing, achieving a synchronous decrease in  $fO_2$  and temperature. This unusual oxidised fluid association was favoured in high heat-flow extensional settings containing oxidised and/or oxidised-evaporitic sedimentary sequences. The intrusion of oxidised fractionated granites, which are commonly temporally associated with metal emplacement, acted in some places to heat and focus basinal fluids, and in others was the ultimate source of metals.

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GEOLOGIC AND STRUCTURAL SETTING









EARLY CRETACEOUS



EARLY CAMBRIAN



PROTEROZOIC

-  Roper and South Nicholson group
-  Nathan Group
- Middle**
  -  Lawn Hill Platform sequence
  -  McArthur Group
  -  Tawallah Group
- Early**
  -  Murphy Inlier sequence

Geologic and structural setting of study areas (from NTGS 1:250 000 metallogenic map series, Calvert Hills, 1989).

## REGIONAL GEOPHYSICS — BASIN ARCHITECTURE

### 2. Batten Trough Region — Update and Further Analysis

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Centre for Ore Deposit and Exploration Studies

A detailed analysis of the Batten Trough region of the McArthur Basin was provided in Report 1 for the project (Leaman, 1992).

Some minor errors were overlooked during preparation of that report and one figure was replaced by another.

The report also referred to BMR seismic data in the region. Full panels of this data have now been inspected and compared with the implications of the gravity and magnetic interpretation.

This report is in two parts. The first presents the omitted diagram and discussion of the available seismic data with particular reference to implications of the potential field interpretation. Several other diagrams have been represented with minor updates as a result of a comprehensive study of the Wearyan Shelf to the east. The Wearyan study will be reported when complete.

The second part extends the analysis of the Batten Trough south across the Wallhallow 1:250 000 map sheet.

#### PART 1. ADDENDA TO FIRST REPORT — BATTEN TROUGH

Figure 9 (labelled figure 1 here), discussed in the original text and captioned to imply that it represented isopachs for the felsic Scrutton Volcanics, in fact presented the combined thickness of Scrutton and deep mafic volcanics. Many of the features described in the text can be recognised in this figure due to the influence of the felsic rocks in many parts of the region and thus the error might not have been noted.

The correct diagram for figure 9 is attached to this addendum.

This is a very striking and important diagram since it stresses the differences between the areas north and south of the Calvert Fault system during the deposition of the basal volcanics. Normal to this trend are a series of NE-trending troughs filled with felsic volcanics and the entire pattern is suggestive of modern rift and transform patterns. The HYC

mineralised field lies on such a pile and may lie on its active southern margin near the confluence with the NW systems. Clearly a sensitive and important site. And now seen always to have been so.

The omission arose from too many diagrams and many attempts to understand and present the relationships in the deep basin. Experience with the diagrams presented shows that normal isopachs coupled with some sections offer the best form of presentation and demonstration of basin history and depositional patterns.

Some minor errors are largely restricted to the diagrams:

*Fig. 3.* Upper part. Total distance should be 50 000

*Fig. 4.* Upper part. Total depth should be 25 000

*Figs 4, 5.* Ignore ? marks on base of depth axis.

*Fig. 6.* For consistency the four Archers and Tawallah



Faults should be shown as heavy lines into the volcanic pile.

Figs 4, 5, 6. Curve fit parameters should be shown in all diagrams as neutral (within noise of the gravity data, and < 10 nT magnetics).

Fig. 10. Contour value error north of Bauhinia Downs: 15 km SW of copper show and 15 km N of B. Downs should be a 4.

Examination of relationships derived in the Wallhallow and Wearyan regions suggests that the interpreted form of basement granitoids may be as important to appreciation of basin history as their location. The forthcoming Wearyan Shelf report will discuss this issue by providing contrasting information with that deduced for the Batten Region.

Figure 2 (Fig. 7 of the original report) presents structure contours on the upper surface of the basement granitoids. The roof forms stress NE and N-S trends which dominate more modern geology. Either these plutons were intruded with this structural bias or it has been imposed by subsequent extension. The latter solution would imply a general granitic content within basement which has been sundered. No judgment is feasible until a wider distribution of granite patterns is available. NW-SE trends are not evident although the northern limit of the granites may be controlled by such a trend.

The diagram shows the location of the anomalous granites inferred. These appear to penetrate the Tawallah Group by extending more than 5 km above the general roof of the basement masses. No mass trade-off involving denser, or patchy, shallower volcanics can account for the anomalies observed.

Figure 3 (Fig. 10 of original report) presents an updated version of the isopachs of the major mafic unit beneath the Tawallah Group. The variations are subtle, limited to the margins and reflect further analysis to both south and east.

## CORRELATION WITH SEISMIC DATA

The short sounding traverses completed some years ago were reported by Collins (1983). The profiles are too short to offer much indication of lateral continuity or disturbance of reflectors and those picked may not be truly representative. Only four of the available soundings can be compared with the current gravity and magnetic interpretation.

In each case reflectors have been picked and listed. Then, using likely minima and maxima for velocities in this region the possible depth of these horizons has been estimated and compared with the indications of the regional interpretation.

Some assistance may be offered by the implication of thick volcanic sequences which may be expected to present very high velocities — at least locally or in

parts of their section. This almost always leads to "ringing" or loss of character. These features are recognisable in the records. Similarly, the ultimate basement may be expected to present a substantial contrast to basin rocks in many cases. This is especially likely where the basement granites directly underlie the basin sequences.

### Traverse 2: HYC (fig. 4)

The gravity-magnetics model for this site predicts a complex 3D situation but a package of Tawallah Volcanics at about 2.5 km and top of a mafic pile at some 4 km; the Scrutton pile lies between 7 and 11 km.

Reflections occur at approximately 1.2, 1.8, 2.3, 3 with ringing, 6, 7 and 11.5 seconds.

If we assume a velocity of 4000 m/s to the top mafics; i.e., the velocity in the Tawallah Group, then the Tawallah Volcanic package should reflect at about 1 to 1.3 seconds depending on surface effects and the top mafics at about 1.8 to 2 seconds.

If the velocity is assumed to be 5000 m/s within the volcanics then the top Scrutton should occur at about 3.2 seconds and its base at about 5 seconds.

These interpretations are consistent within the assumptions stated.

### Traverse 3: O.T. Downs (fig. 5)

The G-M model implies a depth of 3 km to the Tawallah Volcanic packages and 4 km to the top of the main mafic pile with the Scruttons between 12 and 14 km.

This is a poor record with ringing, especially from 3.7 seconds with a ring restart at about 4.8 seconds and another event at 7 seconds.

Using the same velocity assumptions as above this leads to a predicted Tawallah reflector at about 1.5 seconds and the top of the mafics at about 2 seconds. The Scrutton should appear between 5.3 and 6.3 seconds. The complex ringing within the predicted mafic pile is consistent with expectations and the deep ringing is also consistent with the placement of the felsic pile.

### Traverse 4: Borroloola (fig. 6)

The G-M interpretation indicates Tawallah Volcanics at 2 km, top mafic pile at 3 km and the Scrutton pile between 9 and 13 km.

Reflectors may be noted at about 1.8, 1.95, 2.2, 2.95, 3.8, 4.7, 5 with ringing, 10 and 12 seconds. Reflectors above 5 seconds appear to dip.

Assuming a velocity pattern as above, Tawallah Volcanics should appear at about 1 to 1.3 seconds and the top of the mafic pile at 1.5 to 1.8 seconds. The

Scrutton Volcanics should appear at 4 to 5.6 seconds, or perhaps 3.8 to 5 using slightly higher velocities. Feasible velocities could explain the ringing, to basement?, noted at 5 seconds. The reflection at 2.95 seconds, within the inferred mafics, may indicate a break or lithological change. Such a break could be expected within the Peters Creek or Eastern Creek Volcanics of this part of Australia since each formation contains a marked break and is in two parts.

#### Traverse 8: Starvation Hill (fig. 7)

The G-M model predicts Tawallah Volcanics at 2.5 km with the top of the mafic pile at about 7 km with the Scrutton pile between 9 and 12 km.

The record is poor in part with little information at low times and a complex response from 2.5 to 3.5 seconds, a reflector at 5.4 seconds, further mush, then events at 8.8, 9.8 and 10.5 seconds.

Using the same velocity assumptions the G-M interpretation would predict reflections at about 1.3, 3.4, 4.2 and 5.3 seconds with ringing or "mush" up to 3.4 seconds and ringing after 5.3 seconds.

The correlation is very good.

It may be concluded from these crude correlations that the two data sets MAY be consistent. Certainly, within reasonable assumptions, they appear so. The reflection conclusions must be affected by the limited traverse length and character definition while the G-M inferences may be affected by 3D effects as well.

But, the general estimates of the gravity-magnetics interpretation may be sustained.

#### REFERENCE

- Collins, C.D.N., 1983. Crustal structure of the southern McArthur Basin from deep seismic sounding. *BMR Journal Geology & Geophysics* 8: 19-34.



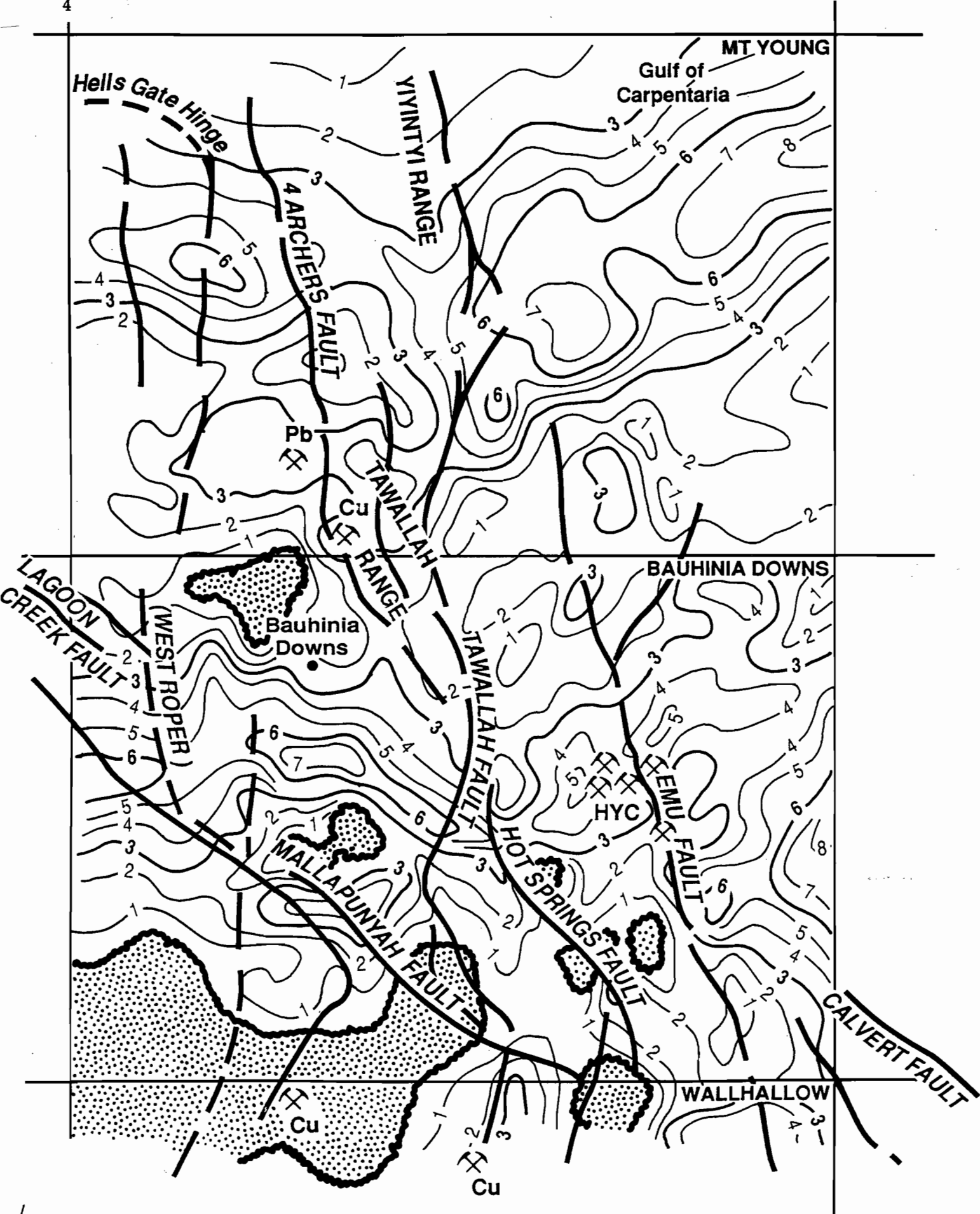


Figure 1 — Interpreted thickness of felsic Scrutton Volcanics. Note the general E-W and NE-SW trends of the formative rifts and the general thickness of the unit near the Tawallah Range.

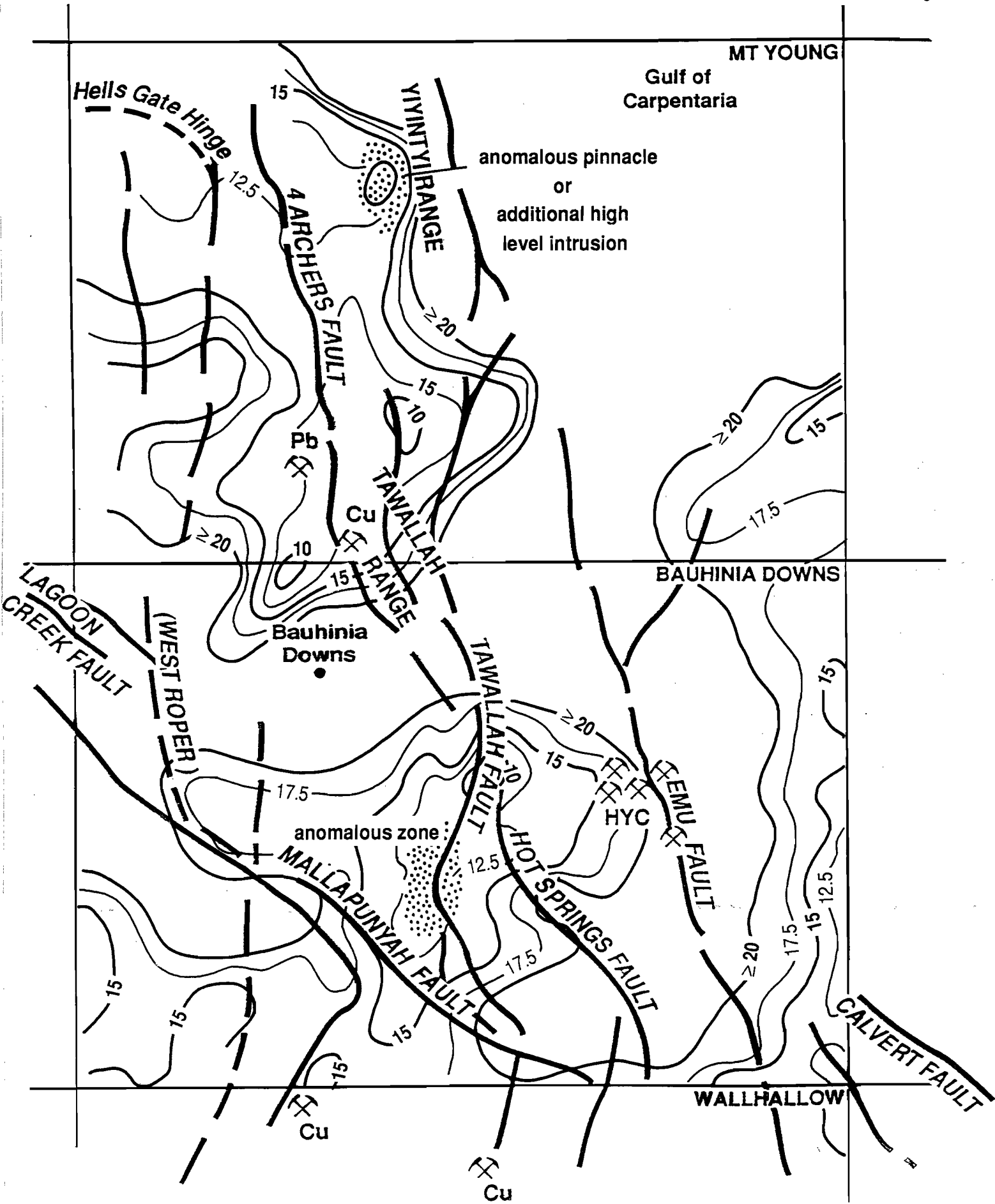


Figure 2 — Contours of estimated depth to upper surface of granites within the basement complex of the Batten Trough region. Note that resolution is limited at depths greater than 20–22 km using the methods applied and that the precision of depth estimates is subject to the assumptions outlined in the text.

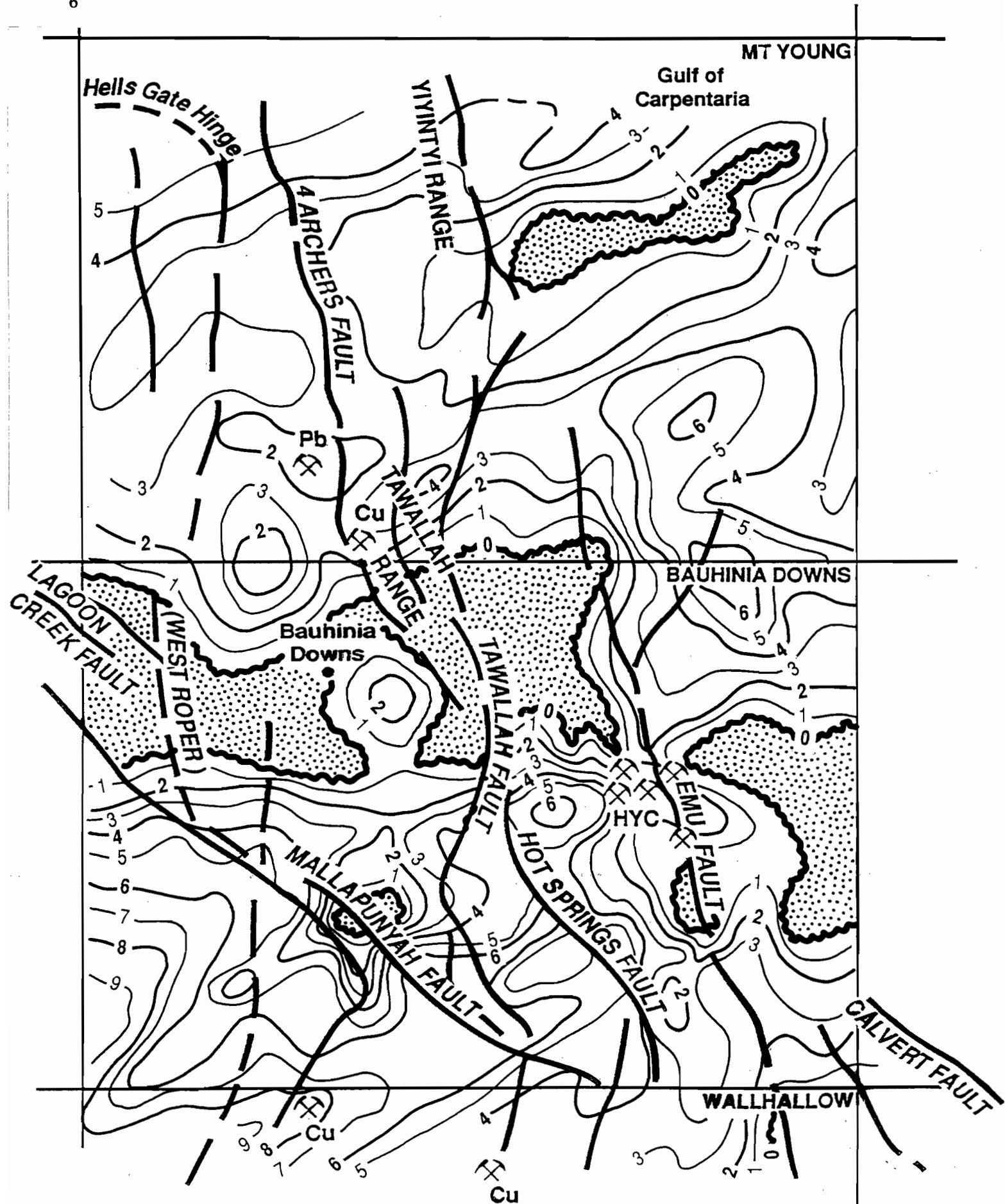
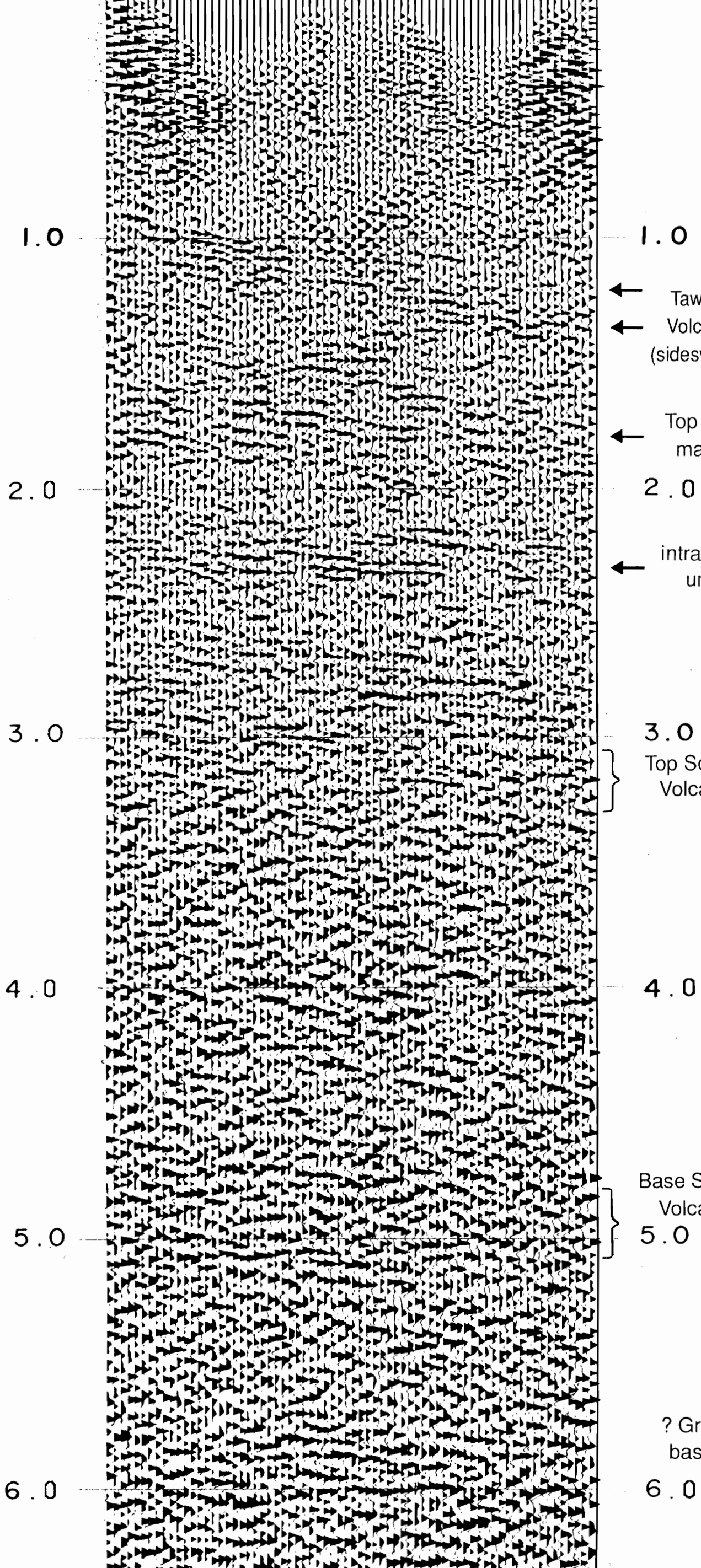


Figure 3 (revised)—Interpreted thickness of major mafic volcanic units which post-date the Scrutton Volcanics. These rocks may correlate with the Seigal or Eastern Creek Volcanics of other regions. Note the strong E-W and NE bias in the deposition and the clear presence of a proto-Emu Fault. The Tawallah Range region was high during formation.

FIELD STATIC | -43 | -46 | -44 | FIELD STATIC

SPN 0.0 48 30 13 0.0 SPN



← Tawallah  
 ← Volcanics (sideswipe ?)  
 ← Top thick mafics  
 ← intra mafic units  
 } 3.0 Top Scrutton Volcanics  
 } 5.0 Base Scrutton Volcanics  
 ? Granite in basement

Figure 4 — SEISMIC TRAVERSE 2

HYC  
16°28';136°3'  
BMR data

Figure 5 — SEISMIC TRAVERSE 3

O.T. Downs  
16°44';135°12'  
BMR data

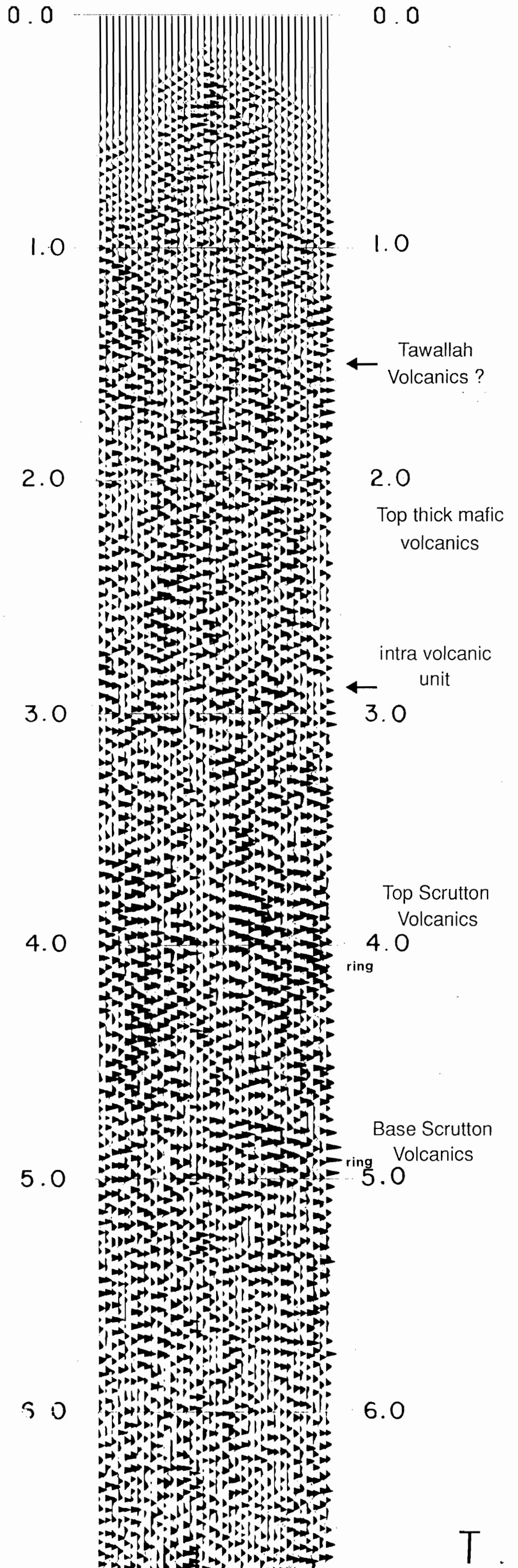
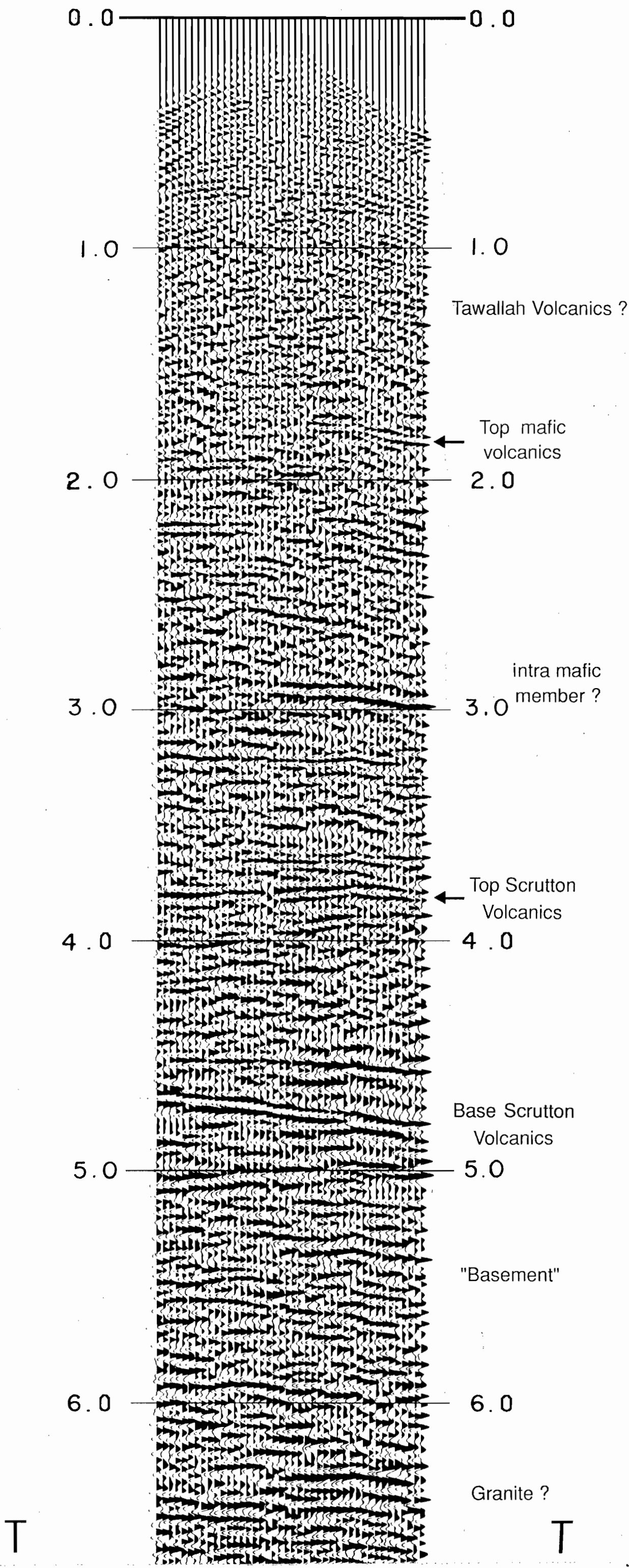


Figure 6 — SEISMIC TRAVERSE 4

Borroloola  
16°2';136°18'  
BMR data



FIELD STATIC

FIELD STATIC

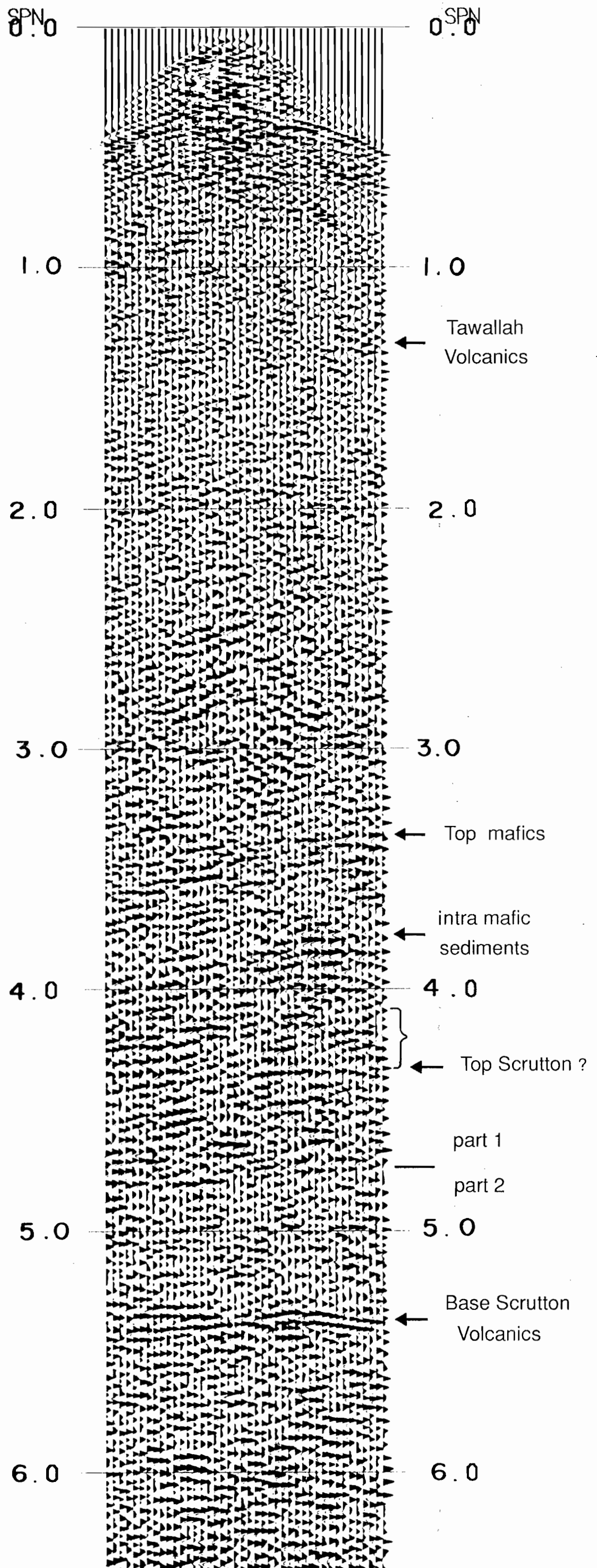


Figure 7 — SEISMIC TRAVERSE 8

Starvation Hill

16°18';136°5'

BMR data

## PART 2 — DOWN WALLHALLOW WAY

Analysis of the style reported for the Batten and Tawallah Range region has been extended south to the Barkly Tableland within the Wallhallow 1:250 000 sheet (Plumb et al, 1965).

The methodology has been as explained in Leaman (1992) although many lateral issues have been reviewed to ensure that no generally misleading conclusions have been derived.

The Wallhallow region has been sampled by profiles 3, 6, 7, 8, HYC of Leaman (1992), extensions of profiles 25, 26, 38, 39, 40, 47 and 51 of the Wearyan project and specific profiles 60–69.

Figure 8 presents a geological base map (Plumb, 1988) and the location of illustrated profiles. Review of the regional data sets (figs 9, 10) will show that these profiles sample all major elements and gradients and enable some appraisal of them.

Figure 9 shows the regional compilation of the magnetic field (BMR 1:1 000 000 compilation). Some broad scale elements are evident, such as the extension of elevated field values from the southern part of Bauhinia Downs to the SW of Wallhallow. This broad sweep of the field may be contrasted with the more variable patterns in the SE part of the sheet. Discontinuous NW–SE and N–S gradients are evident and many appear to coalesce. No strong NE component is evident although some ENE-trending segments may be observed in the SE part of the sheet.

Figure 10 presents the regional Bouguer anomaly distribution for the region (BMR 1:1 000 000 compilation). A general positive extension from NE to SW is evident and the field is much more negative where the magnetic field is reduced and disrupted. A marked negative anomaly occurs in the NW corner of the sheet within an area wholly covered by Tertiary and Cretaceous sediments.

Figures 11 and 12 provide examples of the profile interpretation and illustrate the type of relationships inferred within the region.

Profile 51 (Fig. 11) indicates the nature of the regional magnetic anomaly in the western part of the area. The gravity response is not remarkable in comparison. A reduced anomaly step is evident in profile 60 due to its glancing orientation.

Neither model includes shallow volcanics such as exposed near the Mallapunyah Dome near the centre of line 60 since these have been shown not to yield

any long wavelength response and cannot be controlled due to lack of exposure and regional cover. Some of the spikes noted in the regional map (Fig. 9) and profiles are almost certainly due to small fold and fault disruptions of these Tawallah Group members. Detailed patterns thus allow fault tracing even though the displacements may be less than 200 m. Such units, however, do not contribute significantly to the regional field pattern. This has also been demonstrated for line 34 on the Wearyan Shelf (Leaman, 1993).

The fine balance between magnetic units depends on the fitting of the line array. Three dimensional effects are also evident but the general style can be accepted.

Profile 60 (Fig. 11) supports these conclusions and indicates a thick mafic cover. The structure is disrupted near the Emu Fault Zone. A granitic basement is general.

Profile 60 samples two of the more local negative gravity anomalies. Each can be explained by a fold or sub basin fill of Roper Group rocks and both are located along strike from established blocks of these units.

Profiles 62 and 64 (Fig. 12) present generally north–south aspects of the region and generally confirm the broadscale volcanic cover on a largely granitic basement. The generally smooth fields sampled by profile 62 are very testing in terms of structure and lithological content. The spikes observed at the southern end of profile 60 have not been modelled completely but each is due to roof irregularities in the main mafic slab — not to any unit above or below it. The base of the slab cannot yield the frequencies required. Note that the large spike is generated wholly by modest regional relief of the upper surface. No thin, shallower unit can generate this response style. Similar, but subtler patterns may be recognised along profile 64 but these are difficult to restrain during modelling since the shapes are critical and not easily defined to suit the profile which is a profile sampling of three dimensional forms. The relief must be low but associated with a large volume of magnetic material to generate these responses.

Figures 13, 14 and 15 summarise the interpretation.

Figure 13 presents the distribution and form of the basement granites. There are suggestions of broad



NE–SW trends in this compilation which is quite unlike that for the Batten–Tawallah Range region to the north (Fig. 2). Apart from the NE part of the sheet area granite is massive and universal. Disruption or intrusion is thus restricted only to a part of the Wallhallow sheet — north of the Barkly Tableland.

Figure 14 presents isopachs for the inferred felsic volcanics; or volcanics of reduced contrast. The figure emphasizes some E–W and NE–SW elements with a major podding and axis of deposition extending from the centre of the region to the northeast.

The Mallapunyah Dome lies above a local thickening of these units where this variation in thickness is associated with a major E–W junction which had been active during deposition. A major NW trending feature extending from the SE corner of the region also intersects the dome area. All these elements are defined by thickness variations within these volcanics, but not by any basement element such as the granitoids.

Figure 15 presents isopachs for the mafic volcanic sheet which blankets most of the older rocks of the region. This sheet thickens to north and west and provides a primary explanation of the gravity and magnetic fields. NE trends are evident but displaced from those sites defined by the felsic volcanics and NW trends are obscured. Gross E–W trends are present, however, much as defined by figure 3 in the Batten Region. The Mallapunyah Dome is located on the east side of a local thickening of these volcanics. It might be expected, therefore, that the uplifts recorded represent a response to older sub basin evolution.

Figure 16 summarises trends observed in the raw data sets and those inferred after analysis of causative structures and units. These patterns may be linked to the mapped fault distribution in the northern part of the sheet.

The Emu Fault Zone is represented by a region in which NNW elements are present as a group although no single feature is dominant. No such restriction applies to the Hot Springs Fault which is shown to curl south east toward the western exposures of the Murphy Inlier. None of the other mapped faults can be traced far into the region although it is apparent that other structures are present. Some of these, with NNE trends have influenced some faults west of the Mallapunyah Dome and have re-aligned the Hot Springs Fault itself.

Little is known of the mineral potential of the Wallhallow region due to post Cambrian cover. The present work, however, suggests that this cover is generally very thin and not much in excess of a few hundred metres anywhere. In much of the area the cover may be less than 100 m thick. Detailed resolution of cover issues has not been possible using regional profiles and regional data sets.

Two copper prospects are shown in figure 8 (Yah-Yah, Kilgour). With so few sites known it is not possible to derive absolute conclusions about the origin or siting of the deposits. But there are some very suggestive relationships.

Both sites may be considered to lie along, or near, a major E–W feature which was fundamental during formation of the felsic pile (see Fig. 14). Additionally each can be associated with the highest relief margins of the local mafic piles; i.e., where the greatest rate of change in thickness has been defined. In each case local to regional trends are ENE to NE. In each case some kinking of the older trend can be implied. If major fracture intersections are relevant then the Kilgour site is the more important.

If a linkage between deposit, deposit composition and volcanic accumulations in critical zones is accepted then there is clearly some potential in the Wallhallow region.

Lead–zinc may be associated with the central felsic pile which is clearly associated with some old structure. Similar possibilities exist to the SE toward the end of the Murphy Inlier (to the east). If the associations inferred for HYC are valid (Leaman, 1992) then the reentrant cross structure SE of Kiana and west of Corkwood Creek (refer fig. 8) may be most significant. This may lie upon an extension of the eastern branch of the Hot Springs Fault.

Copper potential, however, would appear to be restricted to the NW and SW quadrants of the region.

Host rocks may limit possible deposition. The analysis has not required insertion of any anomalous units such as the McArthur Group. The gravity solutions fit comfortably without any such requirements and this would suggest that dolomitic units of McArthur type are either thin or absent generally.

This is consistent with the general shelving of all units to the west from the Batten Range toward the Bauhinia Shelf — a structure which will be discussed in a later report.

## REFERENCES

- Leaman, D.E., 1992. 1. Batten Trough Region. Report 1, CODES-AMIRA P384.
- Leaman, D.E., 1993. Do volcanic piles really exist? Report 21. CODES-AMIRA, P384.
- Plumb, K.A., 1988. Geology of the McArthur Basin. 1: 1 000 000 geological map. AGSO.
- Plumb, K.A., Rhodes, J.M., Randal, M.A., & Nichols, R. A., 1965. Wallhallow geological map sheet. 1: 250 000. AGSO.

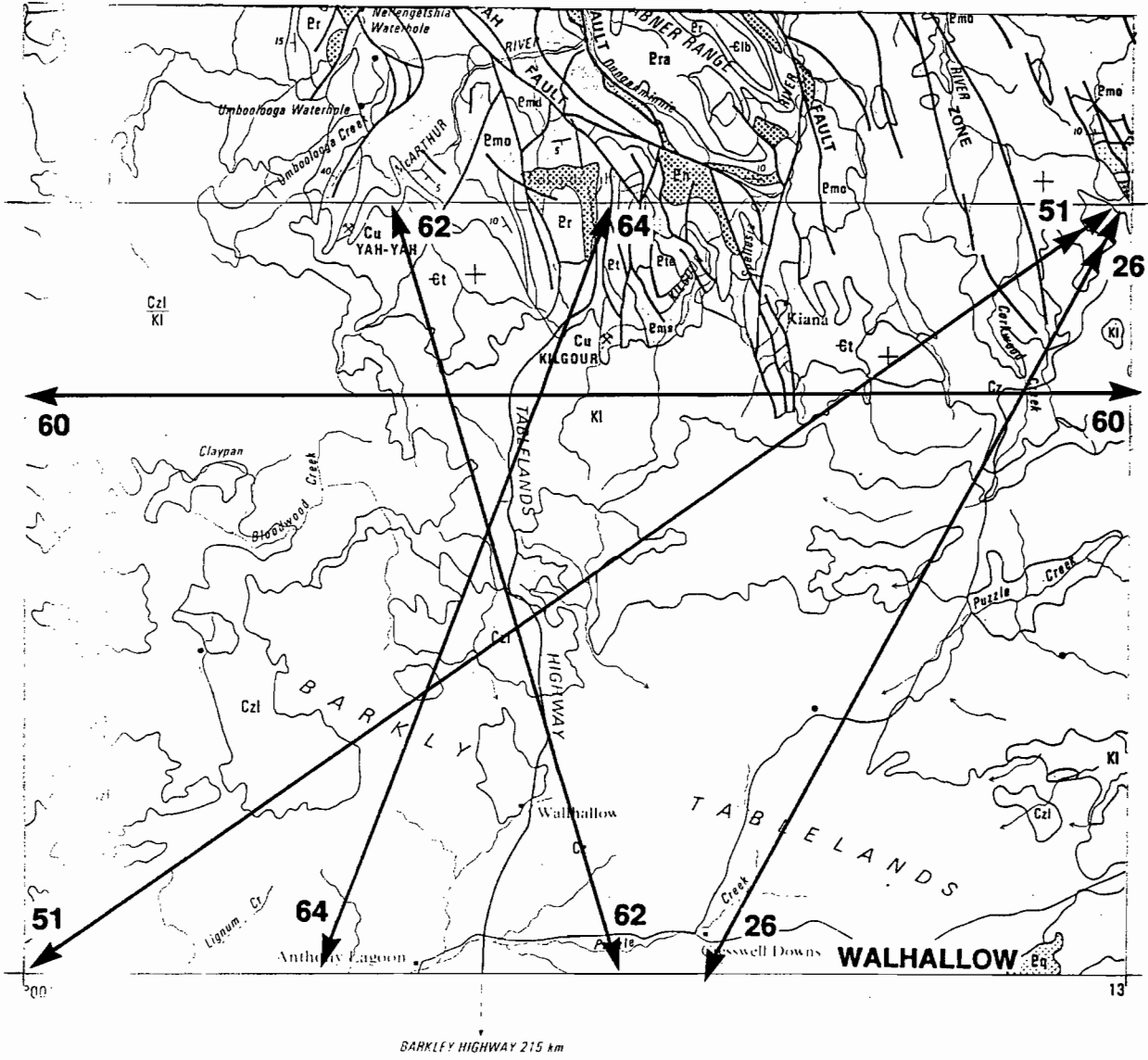


Figure 8 — Geological base map of the Wallhallow region (Plumb, 1988). Position of discussed profiles is superimposed.



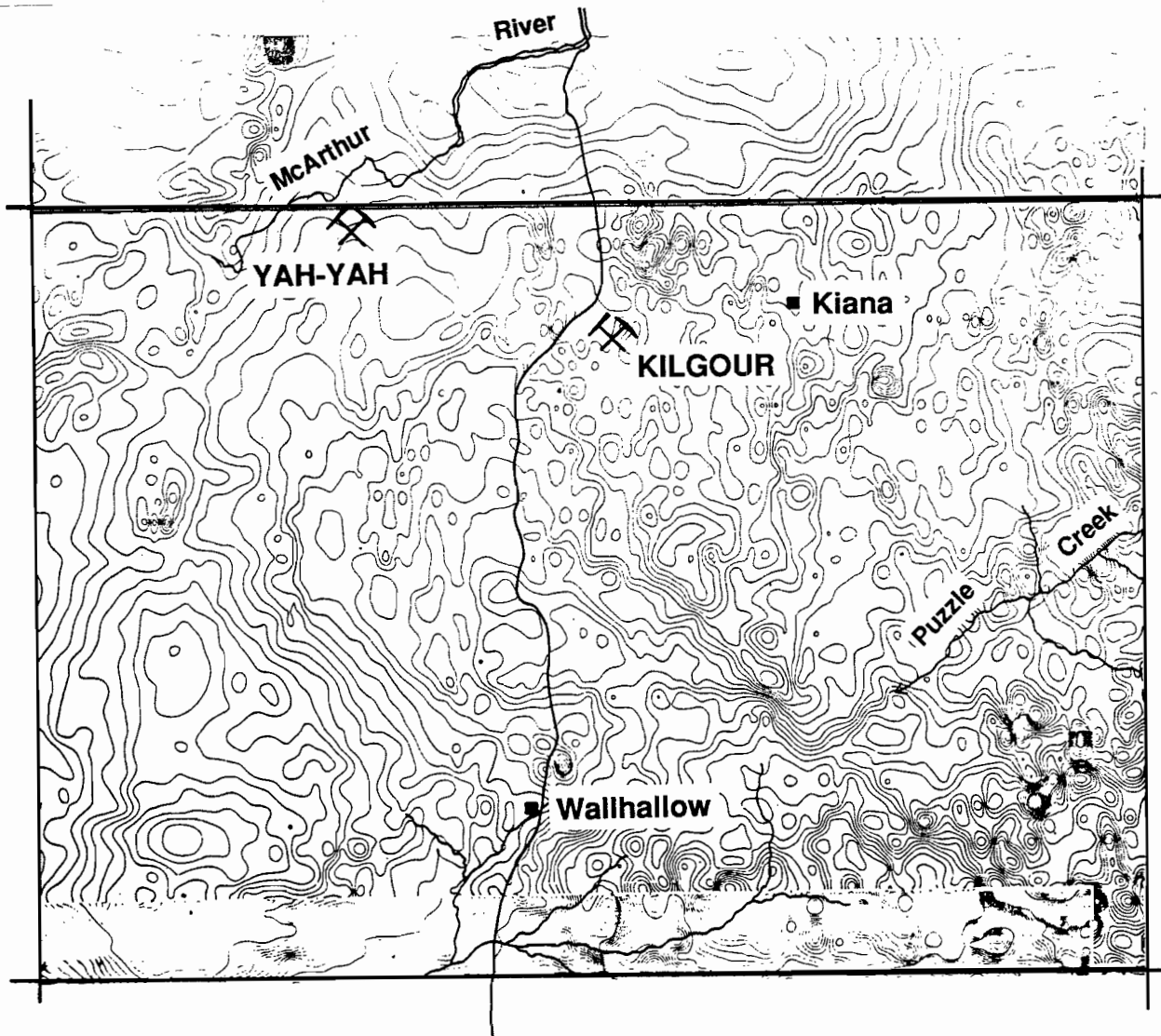


Figure 9 — Regional magnetic field in the Wallhallow region. Data and compilation from AGSO.

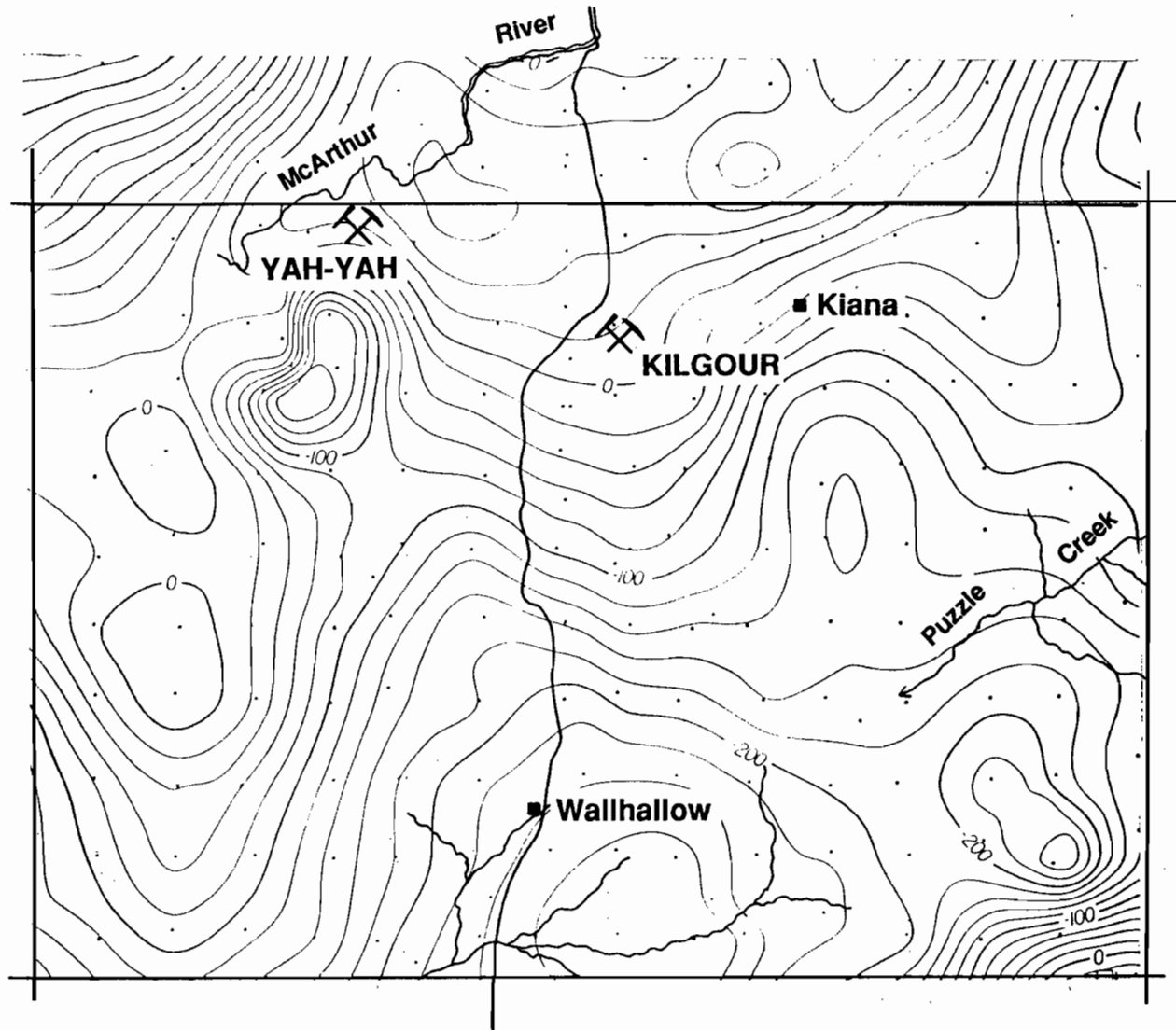


Figure 10 — Regional compilation of Bouguer anomalies in the Wallhallow region (density 2.67 gm/cc). Data and compilation by AGSO.



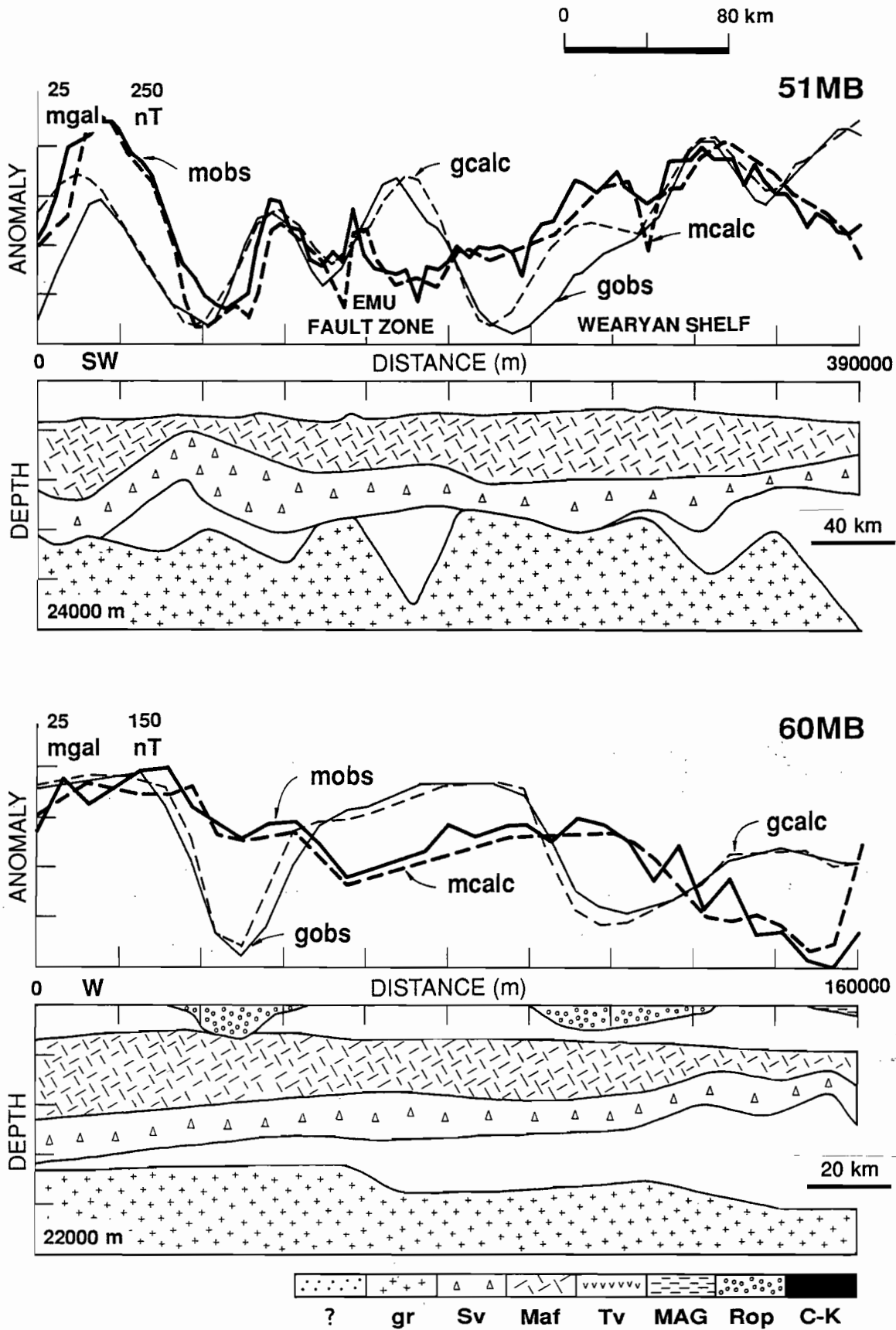


Figure 11 — 2D magnetic and gravity models for profiles 51 and 60.

? = unknown, gr = granite, Sv = Scrutton Volcanics, Maf = mafic volcanic component, Tv = Tawallah Volcanics, MAG = McArthur Group, Rop = Roper Group, C-K = Cambrian-Cretaceous

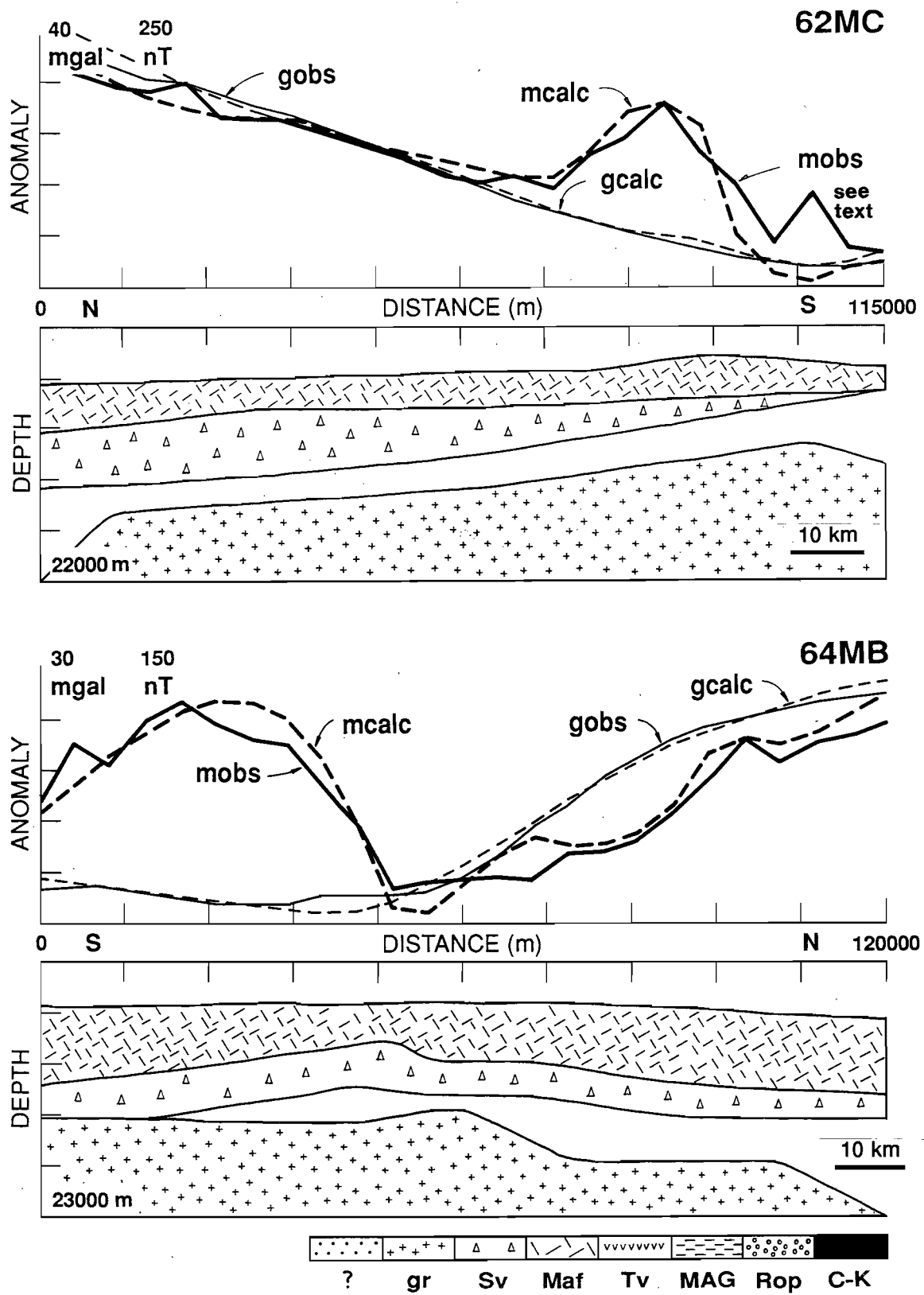


Figure 12 — 2D magnetic and gravity models for profiles 62 and 64.



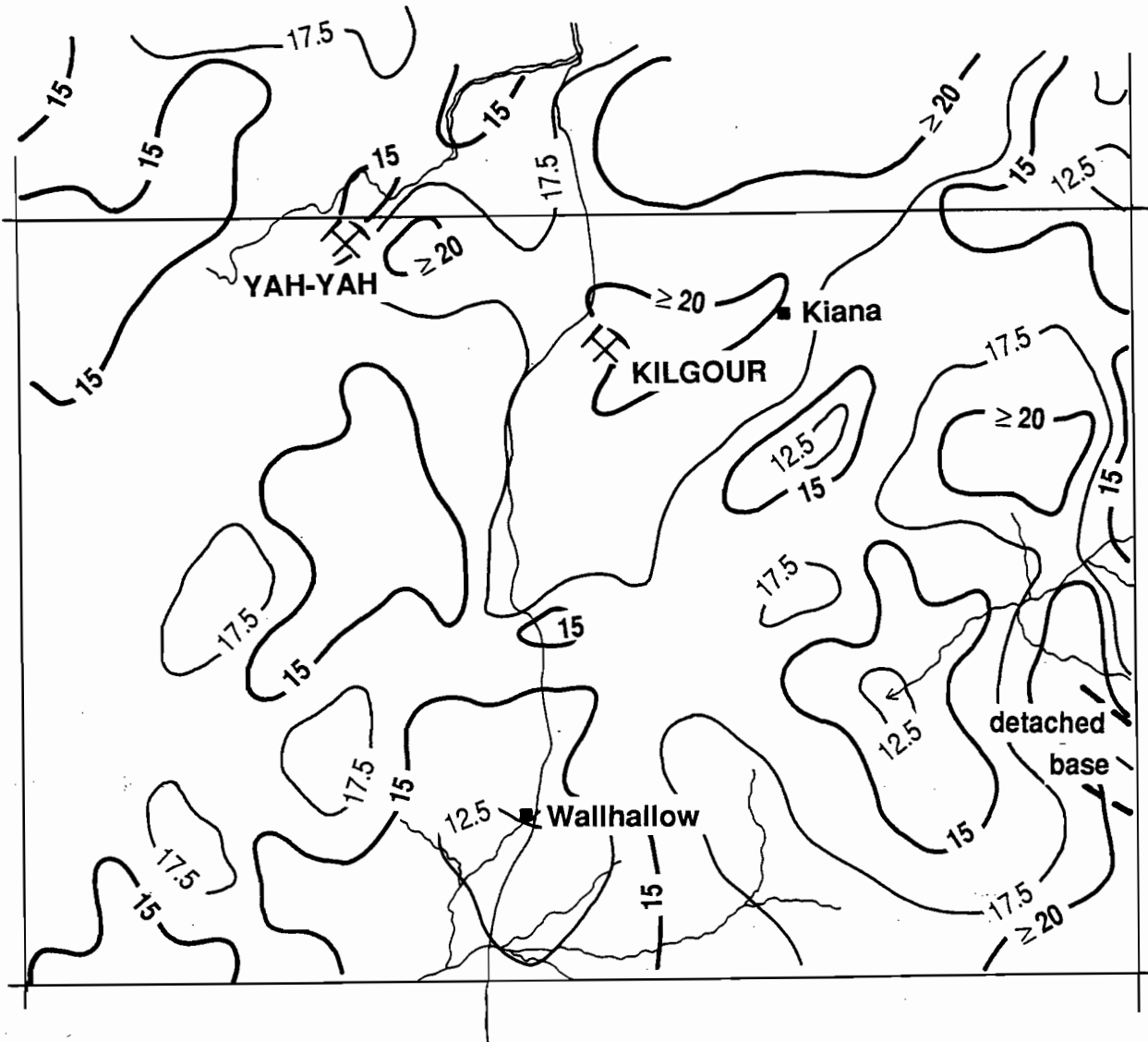


Figure 13 — Contours of estimated depth to upper surface of granites within the basement complex of the Wallhallow region. Note that resolution is limited below 20 km and that limitations may exist in respect of the precision of surface definition.

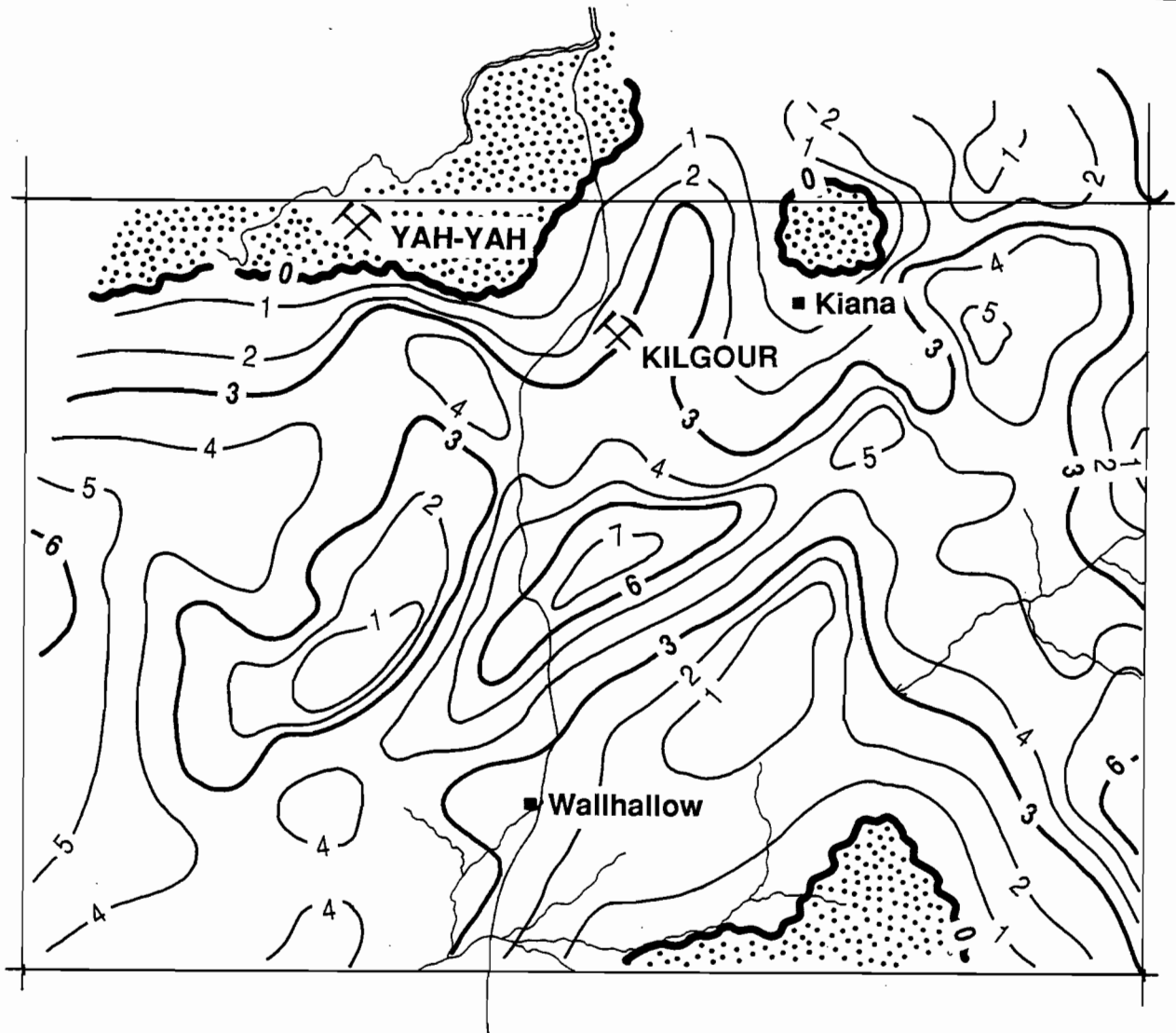


Figure 14 — Thickness of inferred felsic volcanic pile within the Wallhallow region. Contours in km.



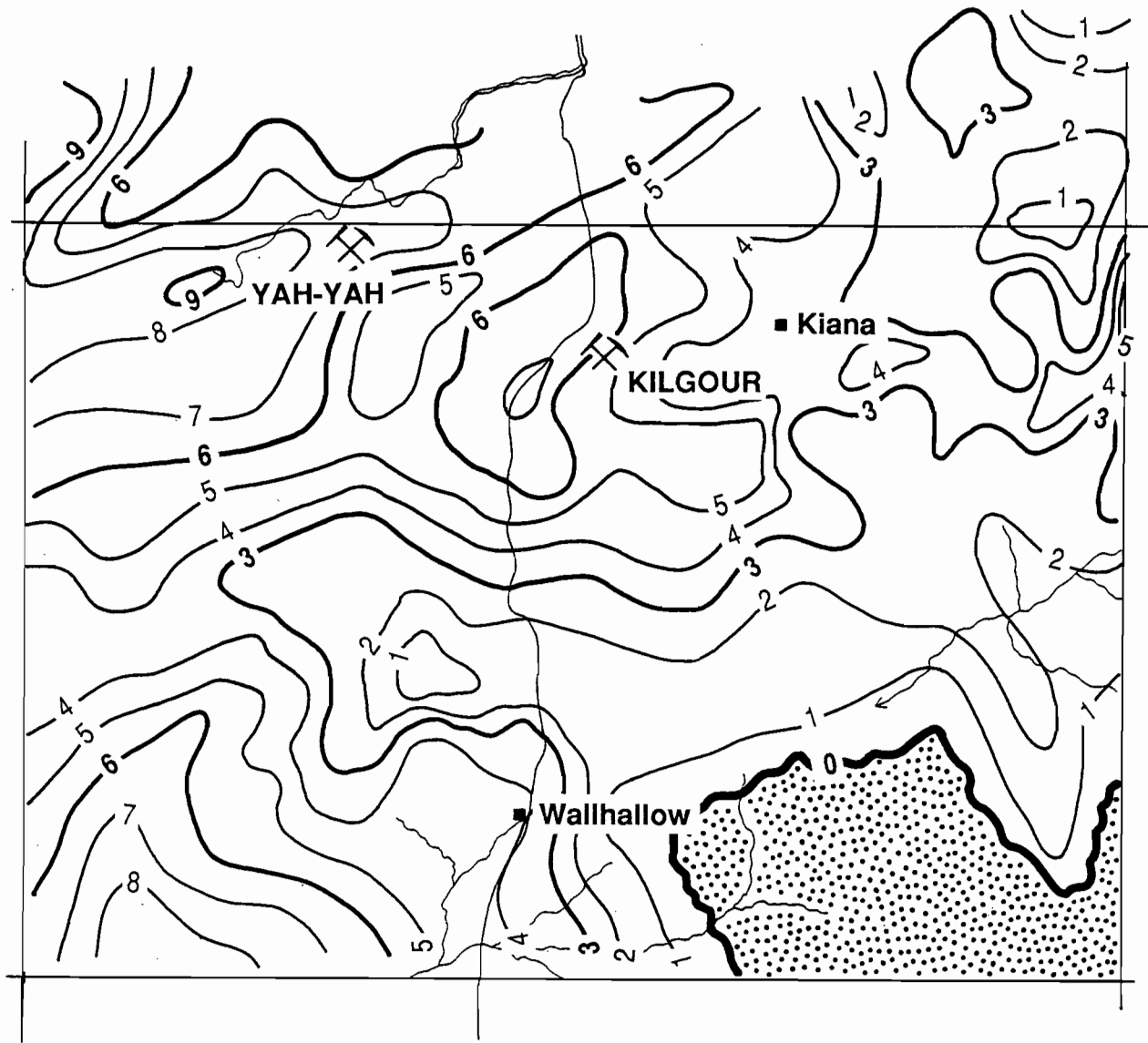


Figure 15 — Thickness of mafic volcanic members which underlie the Tawallah Group of the Wallhallow region. Contours in km.

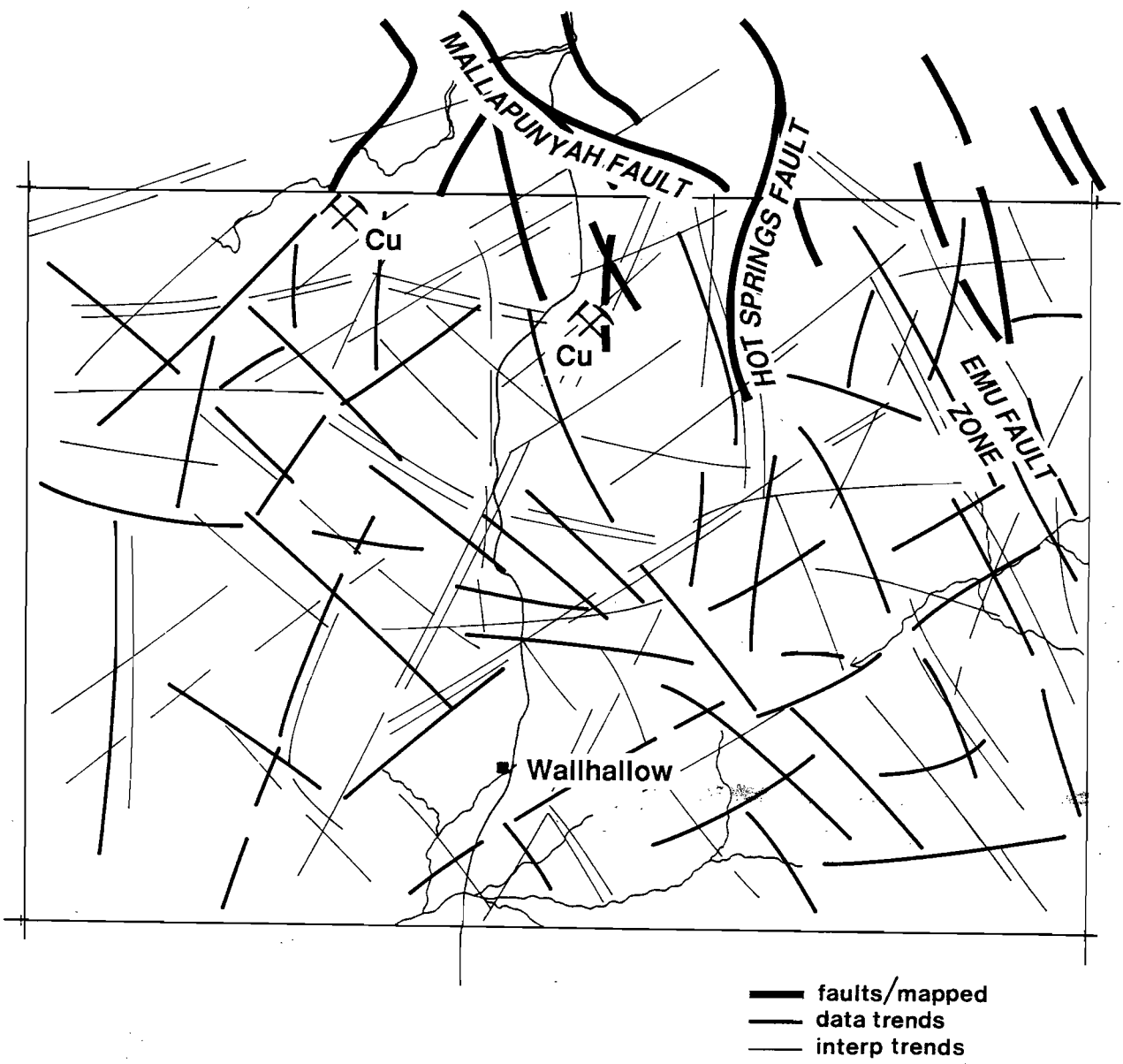


Figure 16 — Trend patterns evident in mapped structures, raw data and interpreted forms for all units older than the Tawallah Group within the Wallhallow region.





## ISSUES IN INTERPRETATION — McARTHUR BASIN

### Do Thick Volcanic Piles Really Exist?

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Following presentation of a comprehensive regional gravity and magnetics interpretation for the Batten Trough Region in Progress Report 1 some have expressed concern that:

1. alternatives may exist in respect of many elements,
2. thick volcanic piles may not exist,
3. pile and granite assumptions may lead to mass cancellation,
4. generally poor fits were presented for the models,
5. the use of potential field methods for sub-horizontal structures may not be valid or lack resolving power,
6. the criteria used to evaluate the results are not adequately explained,
7. shallow volcanic units known to be present may explain all effects.

It is important that these issues, queries and doubts be resolved.

This note aims to show that such concerns are unfounded from two perspectives.

From a geophysicist's point of view it is desirable to have a perfect profile fit. But is it feasible, realistic or even relevant in terms of this project or the data available to it?

From a geologist's viewpoint the real issue is whether the solution gives a true indication of unit relationships while remaining fuzzy on details. It is important that the reader feel comfortable that a wide

range of geological options has been tested and that this relationship is established regardless of perceived imperfections in fit, property or other assumptions.

The example chosen for discussion has been taken at random from the Wearyan Shelf investigation currently in progress. All the intermediate files saved have been accumulated and presented to indicate some of the options tested and the quite strict limitations imposed by them. Each stage displayed reflects an evolution of at least ten variations within a chain of ideas and checks.

The suite of diagrams illustrates the power of the interpretation criteria as well as the focus generated on what is really feasible geologically. They provide a clear and proper perspective about what really counts during the interpretation process.

#### LINE 34

Line 34 (see fig. 0, p. 28) bears 25° east of north from the SW corner of the Calvert Hills 1:250 000 geological map sheet and extends for 250 km into the Gulf of Carpentaria to the SE of the Pellew Islands.

Section point B, as marked on the Robinson River sheet, lies at 145 km from the origin of the profile.

This line provides a cross section of the Wearyan Shelf but may not provide true two dimensional conditions with respect to all structures since many are unknown.







## THE INTERPRETATION SEQUENCE

## MODEL A (fig. 1)

Inspection of the available geological and magnetic maps suggests that the mafic members of the Tawallah Group are variably magnetised and few clear estimates of their properties can be established using actual responses and surface distribution. This is partly due to the sub horizontal presentation of the units and partly to the regional line and data sampling of the magnetic survey used.

However, if one accepts the implications of the described lithologies and considers that an effective resultant susceptibility is about 0.003 cgs units — which may include both the true susceptibility and the possible contribution due to any permanent magnetisation — then a model may be prepared.

Model A simply accepts the nominal thickness, separation and stratigraphy of the exposed Tawallah Group volcanic units. The thickness of Peters Creek Volcanics is as shown in the regional map sections. This model does not explain any part of the observed field and its result is of very low relief.

We may conclude that the Tawallah Group volcanics either are not as they seem, either in thickness, thickness variation or contrast, or there are other explanations for the magnetic field.

## MODEL B (fig. 1)

This model allows some minor variations in thickness, dips and an increase in contrast to 0.005 cgs. This is the maximum likely contrast for these rocks and lithologies and it is clear that the Tawallah Group units, in any simple tabular form, will never explain the observed field.

## COMMENT

The form of the observed profile should now be noted. It displays a broad increase to the north and is generally low near the projected position of the inlier complex. This would seem to be due to the likely nearness of granite at 50 km.

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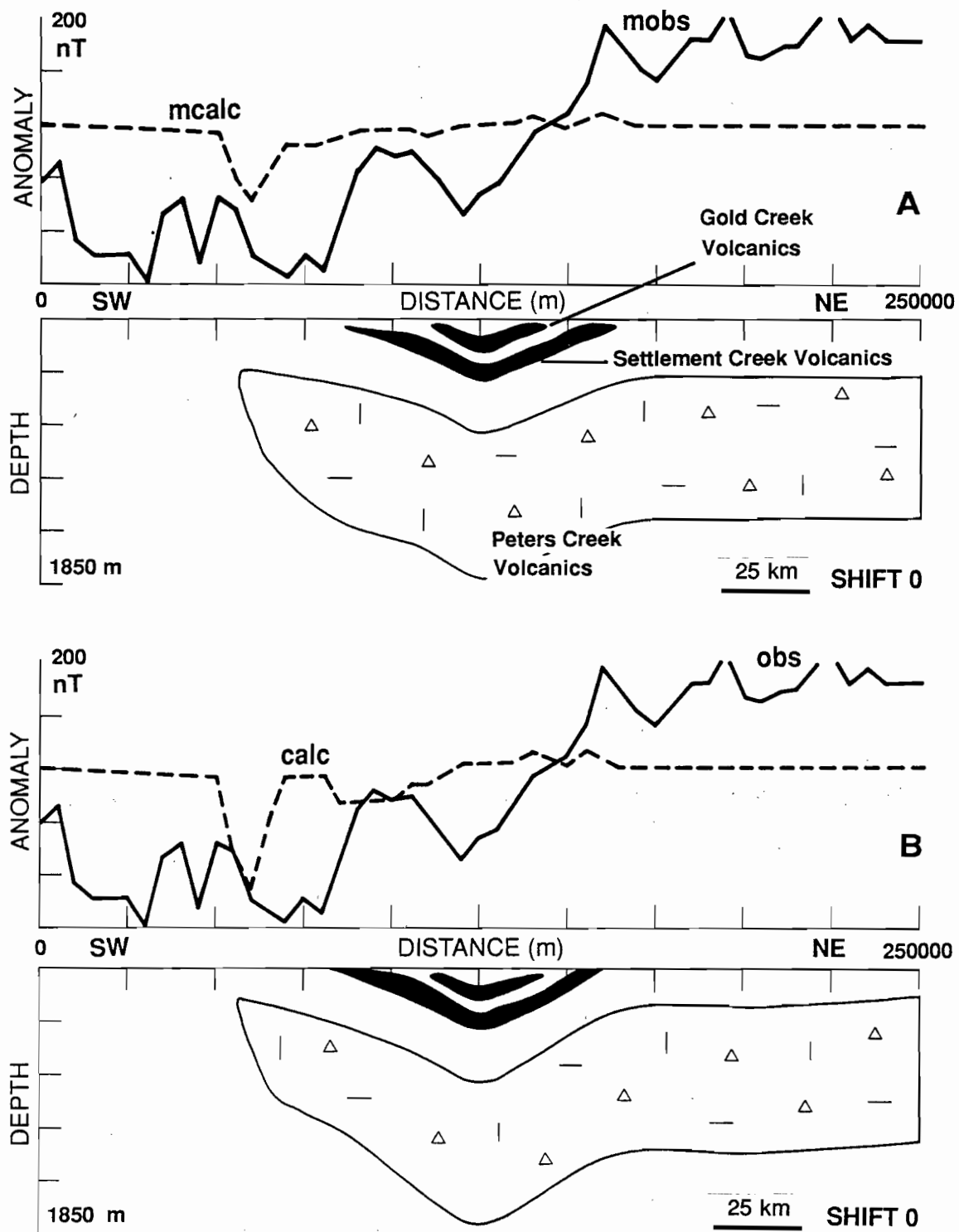


Figure 1 — Models A and B.



**MODEL C (fig. 2)**

If we hold these maximum possible contrasts fixed and change thickness (the only other obvious variable) then the result does achieve some similarities in form.

But there are clearly problems at the origin of the line near the inlier and the issue of base levels must now be considered.

Do the low values represent base level, or should the calculated profile be lifted onto the observed line? Doing the latter will only worsen the situation from 0 to 75 km. Just what is the base level? Or, where is the zero in the observed field?

The large anomaly near 100 km is ghosted in this model and perhaps related to some variation in base

form and thickness of the Peters Creek Volcanics. The large negative spike nearby shows that the field is very sensitive to dip of the base of the volcanics and any thickness changes. This is not easily compensated or resolved.

**MODEL D (fig. 2)**

Model D presents a variation in base form which minimises the spike response and which, with various arrangements might fit 80% of the profile in gross terms. A shift of about 50 nT would certainly help for 60% of the profile. If the model were correct we might also expect some 3D effects so any attempt to create a perfect fit might be more misleading than useful.

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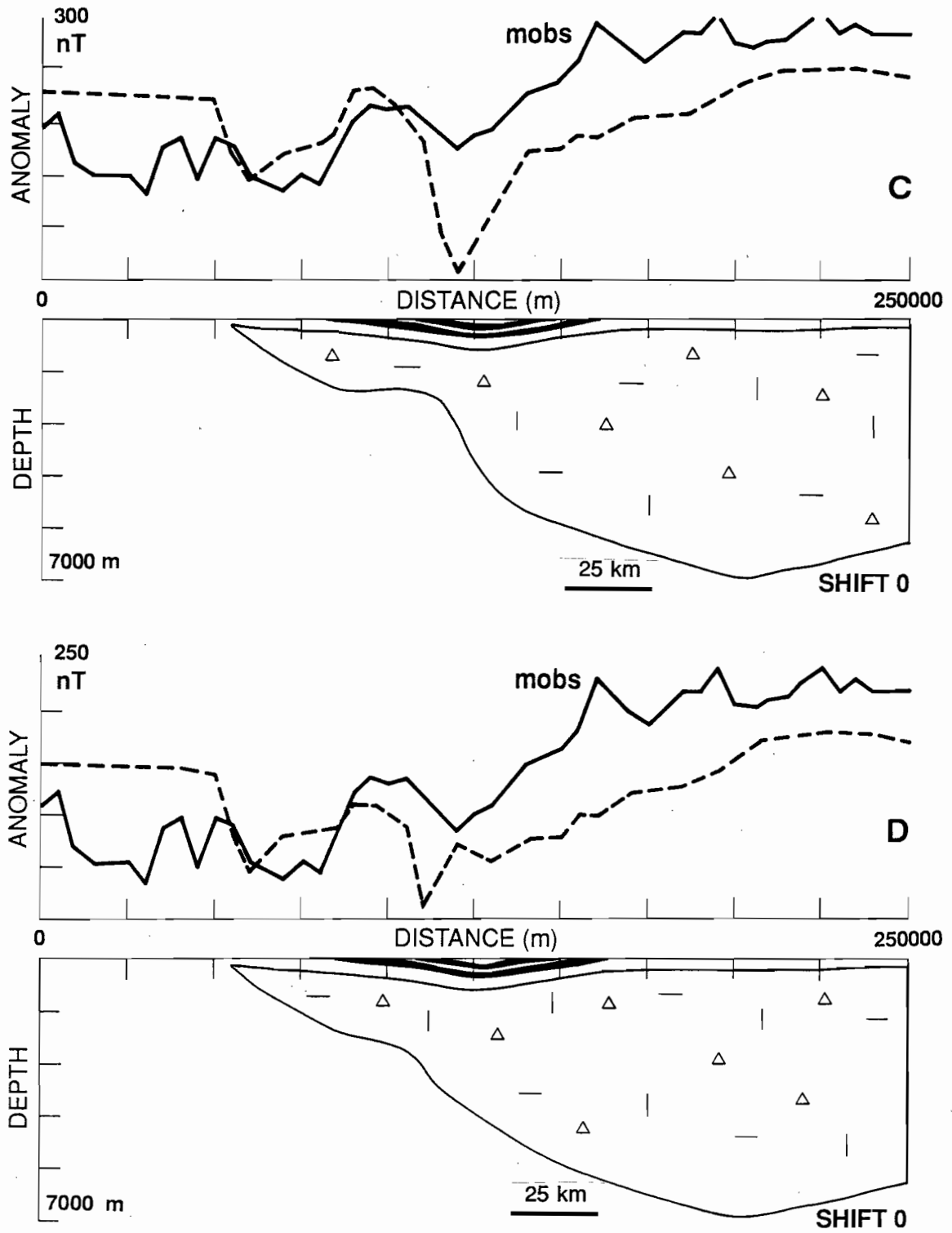


Figure 2 — Models C and D.



## MODEL E (fig. 3)

This model shows what might happen with a 50 nT base shift and slight modifications of the base of the mafic unit.

## ANOTHER COMMENT

We now begin to see several things:

1. It is difficult to fit details at the scale of these sections.
2. It is of dubious value to fit to perfection given the sampling of the data set, its line spacing and filtering, and the possibility that 2D assumptions may be imperfect. Note that it is not established that the implied volcanic thickness occurs in the sense of the profile.
3. It is clear that the Peters Creek Volcanics (or something deeper) thickens to the north. THERE IS ABSOLUTELY NO DOUBT THAT VERY MAJOR CHANGES OCCUR EITHER IN THIS UNIT OR ANOTHER NOT FAR BELOW IT. Nothing shallower can explain the observed field.
4. It is also clear, regardless of how the curves are matched, that a major problem exists to the SW across the concealed inlier.

However #4 is resolved there is now no doubt about #3.

Some further questions may now be posed:

- What is the base level and does it matter?
- Should/could the volcanics be thicker?
- Where are the Cliffdale Volcanics which may underlie the conglomerate?

And, any model produced thus far uses the maximum possible bulk contrasts and hence presents the minimum possible thicknesses.

It is also evident that some relatively minor changes affecting some part of the upper sequences must be considered from 160 km.

But the crucial point at this stage is that we have learnt something, regardless of gross misfits.

Modelling to this point has satisfied the first and third criteria which may test an interpretation. Geometric issues are clearly important but an interlocking of the second, fourth and fifth may become critical. Let us assume for the moment that there are no problems with the second, since resolution of the fourth and fifth may be integrated. The interpretation across the Batten Trough indicated that the base levels for Bauhinia Downs were near neutral (within 10 nT) and adjacent data sets have been adjusted to match. This means that any sound fits should be near neutral on line 34.

This can only mean that model E is invalid — if the curves are fitted by a 50 nT shift (criterion 5).

## MODEL F (fig. 3)

This model shows that a substantial deepening of the volcanics does not achieve a fit, or a neutral shift for the profiles. And, the deepening causes other problems near 100 km and near the line origin.

Even if the low on the "granitic" area is not at base level but simply a negative interference response where is the source of this interference? It cannot lie to the south since this would erase the low intensity field due to positive response displacement to the north. Further, any such source *cannot* be younger than the conglomerate or it would be exposed near 50 km.

Can the Cliffdale Volcanics help?

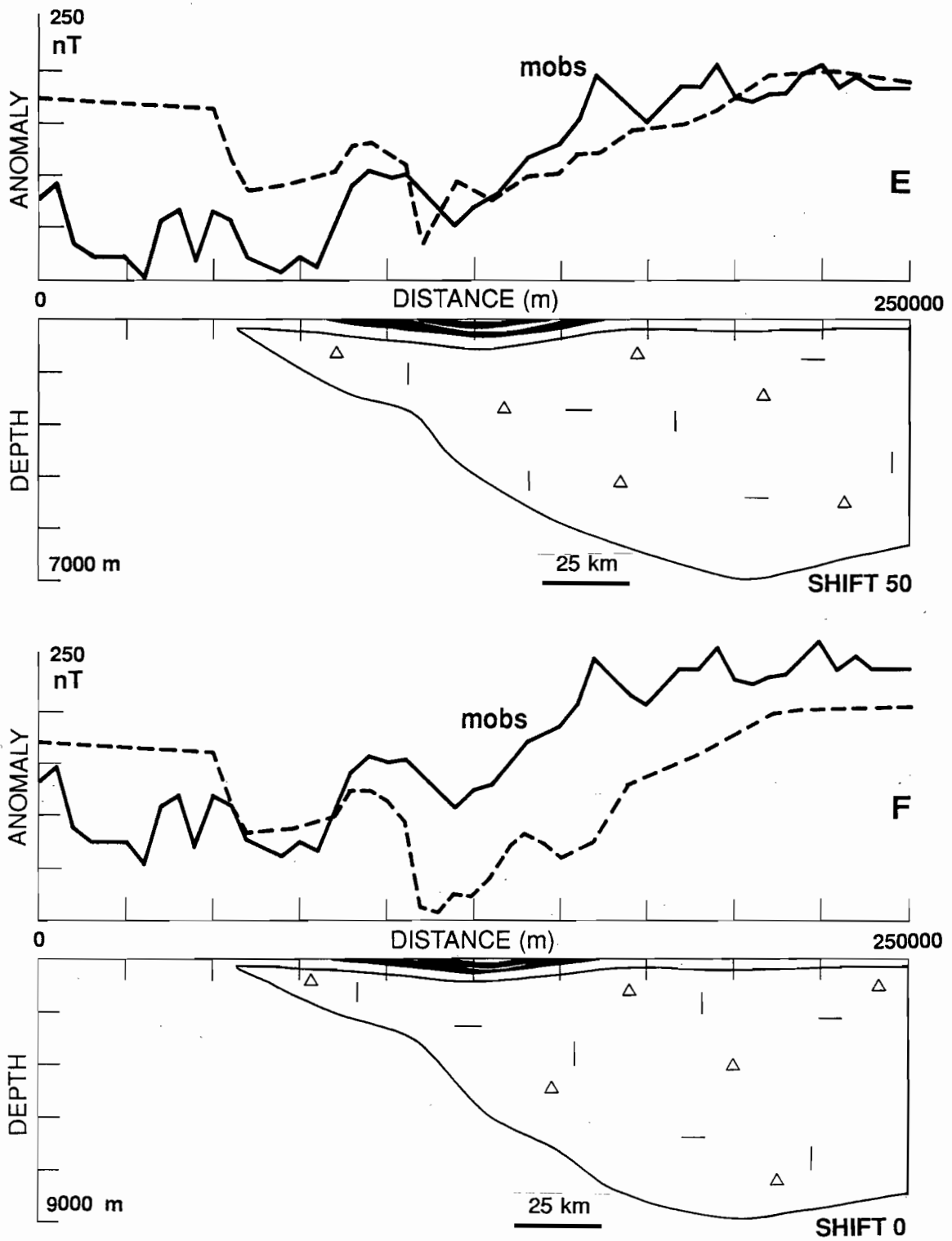


Figure 3 — Models E and F.



**MODEL G (fig. 4)**

Model G presents a crude early version of a model containing a substantial volume of Cliffdale Volcanics but it is already apparent that the enigma of the origin has been resolved in gross terms and that the overall form has been retained. The only problem is the gross misfit in the zone presumed to include thick Peters Creek Volcanics (120 to 250 km). The contrast employed for Cliffdales was 0.002 cgs which is only about 70% of the possible maximum. And a further question is raised. Could the Cliffdales also thicken to the north?

**MODEL H (fig. 4)**

This model allows for some variation in the volume of Cliffdale Volcanics and the entire profile match shows improvement. There are clearly some gross interference effects present which are generated by both the volumes of the materials and the dips of the interfaces. Note that all the models have vertical exaggerations of about 6 to 15:1 and that all dips are very shallow. The responses generated, however, are not insignificant.

This model shows that a neutral shift may be possible since both ends of the profile already approach similar values.

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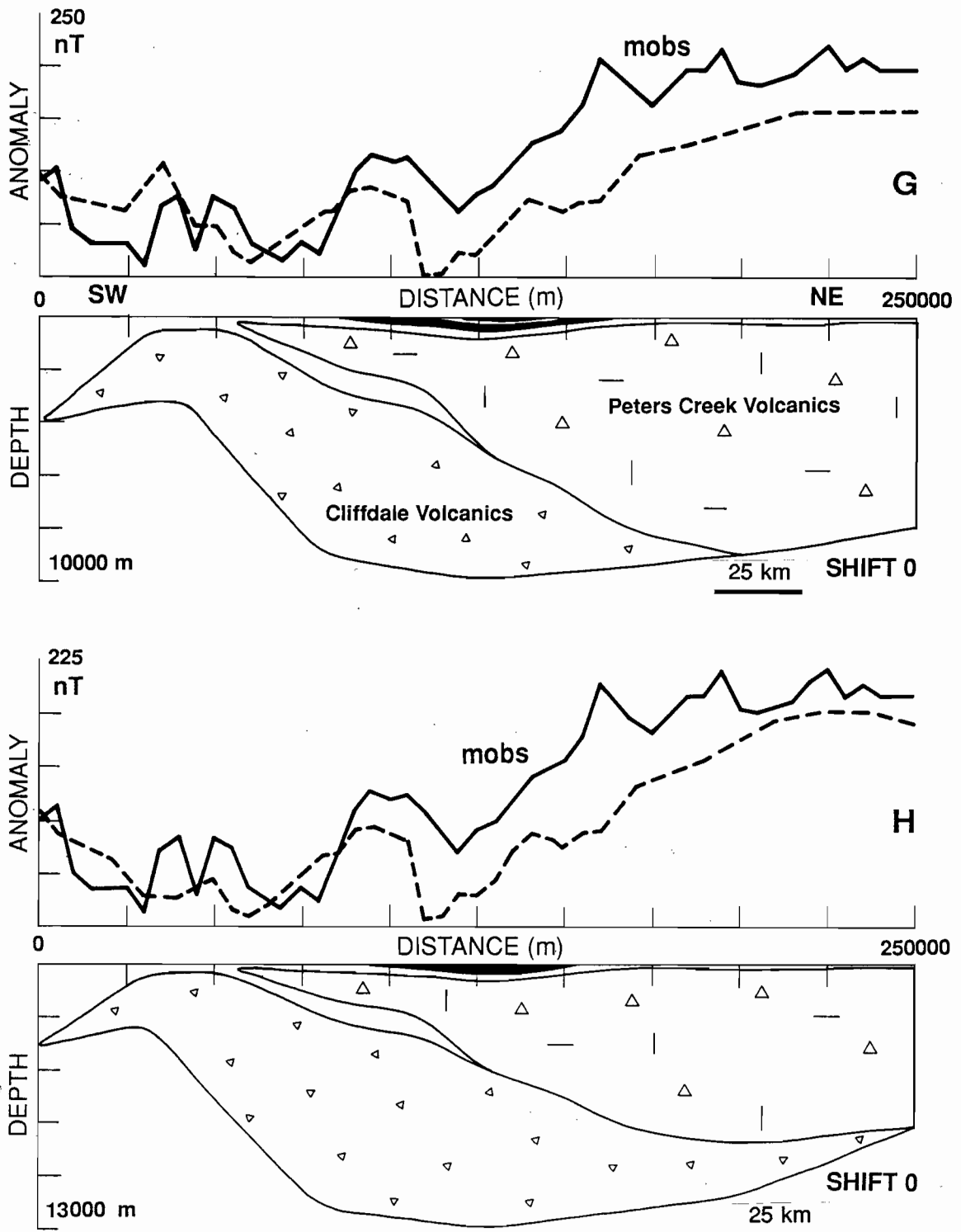


Figure 4 — Models G and H.



**MODEL I (fig. 5)**

This version converted previous models to a maximum contrast solution for the Cliffdale Volcanics (0.003 cgs). This has resolved the general amplitudes for a large part of the profile while retaining the minimum possible volumes.

The solution is very sensitive to geometry near 45 km but only a precise balance is now required.

While we may argue about details, such as the northern spikes or misfits, interference and the origin of deviations two things have been determined.

The Cliffdale Volcanics are present, and the associated volcanic pile is at least 15 km thick and thickens away from the Murphy Inlier Zone.

**MODEL J (fig. 5)**

This version shows how modest variations to the form of the Cliffdales near the conglomerate, including depth to upper surface, can remove large spikes and even insert the twin anomaly observed near 45 km. These responses isolate any solutions from the Peters Creek Volcanics in this zone, if there was ever any doubt, and fine tuning is clearly possible.

Fifteen variations were tried between I and J in an effort to assess just what creates which effect and many more are needed. There must be simultaneous adjustment of both upper and lower surfaces.

But, is the effort productive? The consideration of a perfect curve fit and an explanatory geometry must be placed in perspective with the time taken to achieve it and the limitations of the observed data and the subsampled version that is the observed profile. Not to mention poverty of control. It can be argued that such detailed work is neither justified nor warranted.

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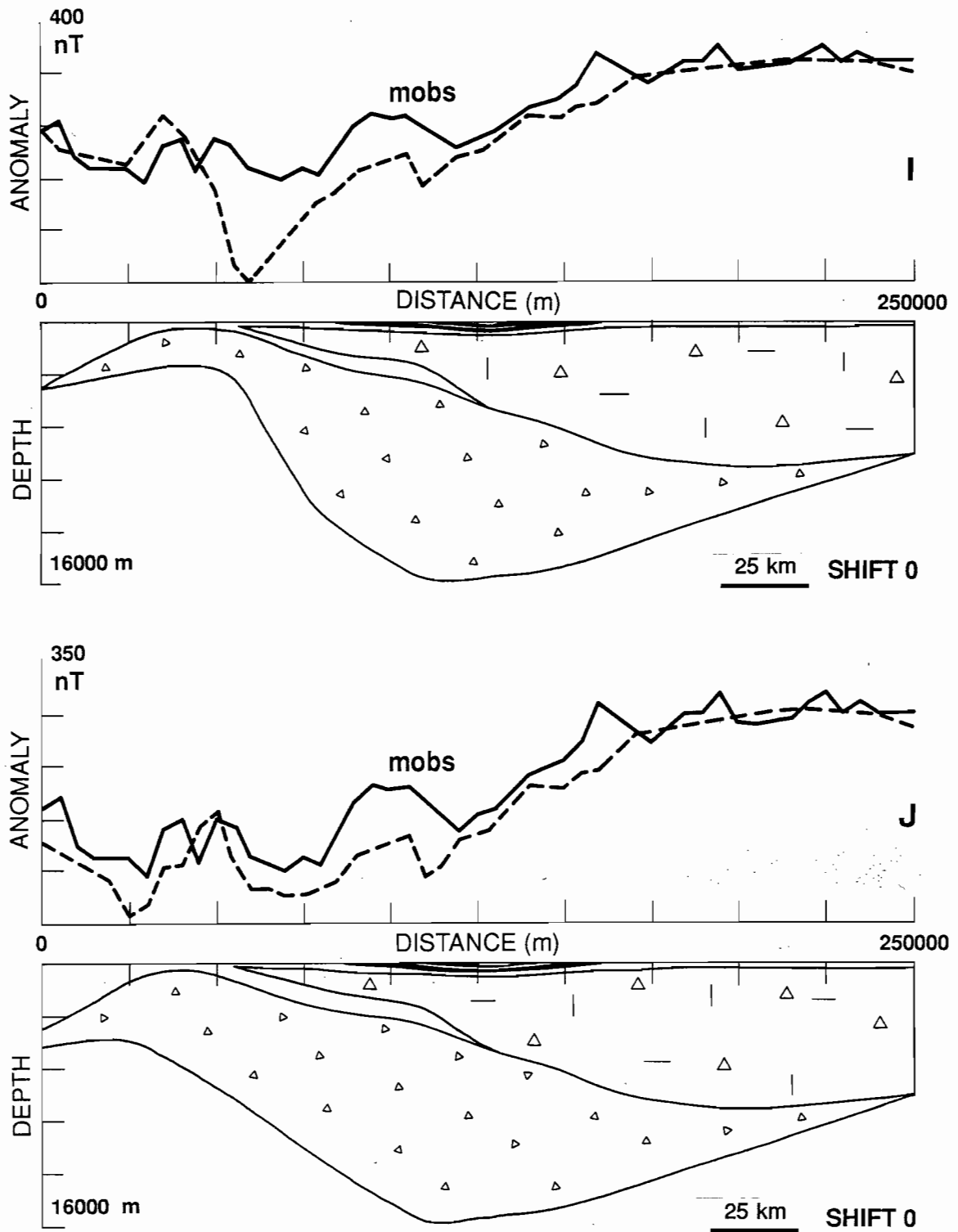


Figure 5 — Models I and J.



**MODEL K (fig. 6)**

This model attempts to refine the profile and account for the peak near 100 km. This can be related to thickness changes (or property changes) in the Peters Creek Volcanics. But any change in thickness of these volcanics also requires changes in the Cliffdale component but the key effect occurs further west near 60 km. This is essential if negative instability is to be avoided in the model and the feature at 75 km is to be controlled and smoothed as observed.

It might also be possible to argue that a better fit might be obtained with a shift of about 10 nT but this is really a trivial item when contrasted with the gross match.

AT THIS POINT THE SOLUTION SHOWN AS MODEL K COULD BE REFINED. BUT ARE THERE VIABLE ALTERNATIVES?

**MODEL L (fig. 6)**

This model seeks to test the proposition that the entire response is due to the Cliffdales. The Peters Creek Volcanics have been restored to their original thickness as based on local mapping near the inlier.

The model shows that the profile can be fitted without any abnormal mafic volcanics but a thickened

pod of Cliffdale Volcanics is required. The curve shift has remained neutral using the maximum realistic contrast option.

The critical variables in the geometry now occur deep in the volume and not near the top.

**FURTHER COMMENT**

Model L poses the question as to whether some mixture of mafics and felsics is involved or whether the mafics are indeed absent. This can only be resolved by consideration of a number of intersecting profiles (criterion 4) and the conclusion based on other profiles will not be introduced here in order to ensure clarity of the evolutionary arguments being outlined.

Precisely what happens SW of 25 km can only be resolved by extension of the profiles across the Nicholson River and this issue will not be considered further here other than to comment that any effects will not spill seriously across the inlier.

Model L does show that the double spike near 45 km can be explained by near surface variations in the Cliffdale Volcanics (see model N for confirmation)

The matter of the low amplitude spikiness of the profile north of 150 km may also be considered. Is this due to local exposure of the various Tawallah volcanic members or disruption of them?

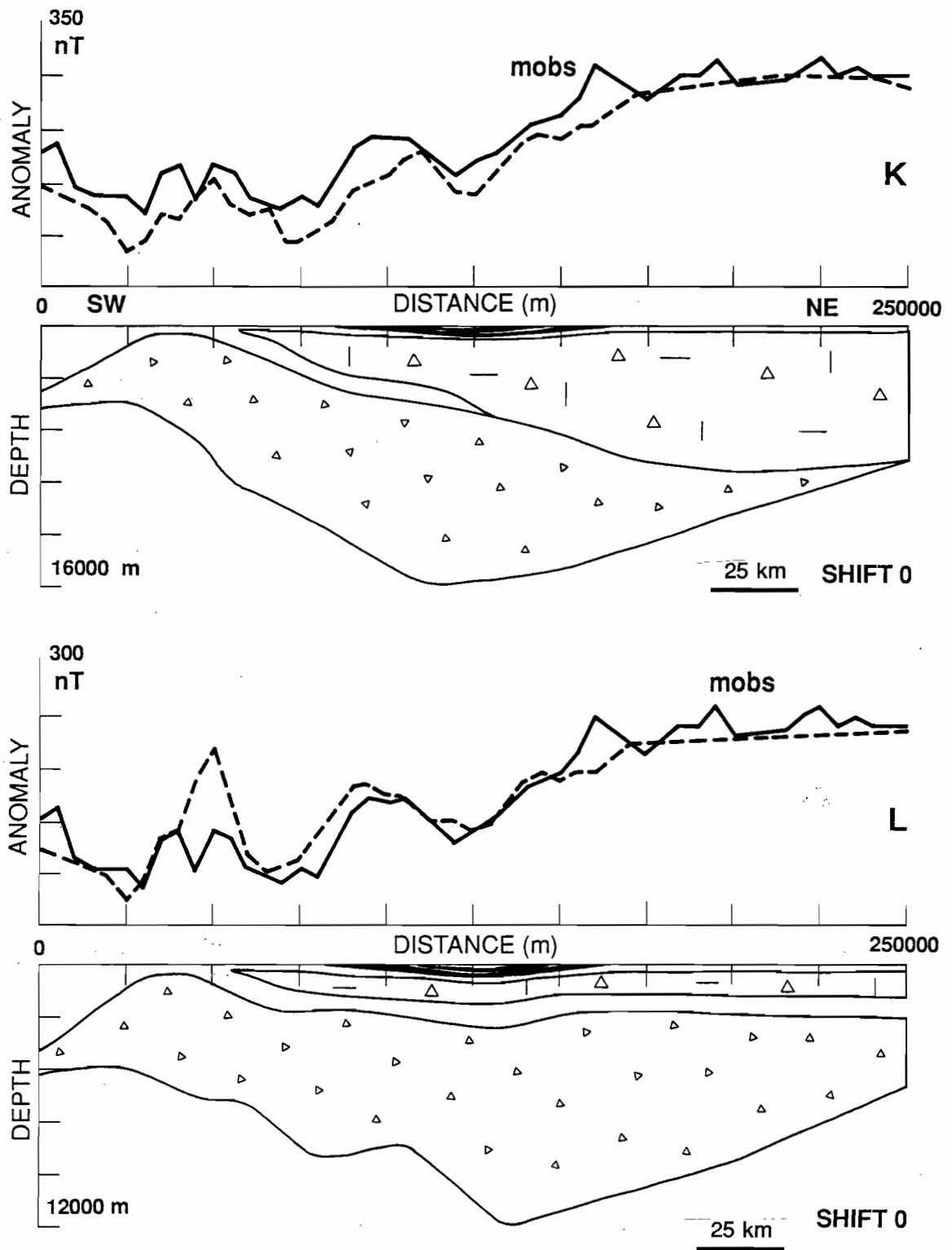


Figure 6 — Models K and L.



**MODEL M (fig. 7)**

Model M examines the effect of near surface disruption of the Peters Creek Volcanics north of 150 km. It is presumed that the mappers are correct in concluding that the upper volcanics are indeed absent.

The model shows the effect of 200 m vertical displacements affecting the upper surface of the mafic sheet. The response is clearly an exaggeration of that observed. This suggests that the spikiness is due to subtler displacements or bends in the unit. This variant did not disturb the lower surface of the mafic volcanics but clearly this should be done.

Precise fitting of such features, sourced at less than 300 m depth, within a controlling data set based on 1500 m line separations and up to 5000 m subsampling for modelling is almost certainly improper and meaningless.

**MODEL N (fig. 7)**

This model illustrates the effect of some allowance for reduced displacements — of the order of 50 m. It will be noted that the amplitudes are about right but there are some minor offsets or inversions in the responses. These simply reflect a need to properly link the geometry. But again, with positions only likely to be approximate, is it really justified? The features have been explained.

The model SUGGESTS THE ORIGIN of the features present but no model of this profile need put the source in the correct location since the anomalies themselves are not precisely located or fully defined.

GEOLOGICALLY, HOWEVER, WE HAVE WHAT WE WANT. The STYLE of the structure and the NATURE of the solution.

Interpretation could cease at this point depending on the implications of cross lines (criterion 4) or proceed to a refinement process controlled by other data (more geology, closer sampling of field, consideration of the original data and resampling, etc).

If we may argue that geophysical purity of fit is not relevant, and may be positively misleading since it implies a precision which is not justified, then this is a satisfactory conclusion. Perfect fits are aesthetically pleasing but they are not necessarily justified by the additional time and effort or any minor improvement in conclusions. At basin scale there is little point.

Minor shaping of the anomalies along strike from the inlier, near 45 km, shows that it is possible to break up the anomalies calculated into the two parts observed. But, again, do we want to know exactly where (not possible with this data anyway) or by how much vertical change (when it will be relatively minor)? If we do then we need much better data.

A review of the magnetic map which was sampled for the observed profile showed that the field near 35–50 km is irregular with local deviations up to 30 nT above and below values shown in the observed profile. Its character is very similar to that observed near exposed Cliffdale Volcanics 150 km to the east and perfect fitting is not meaningful in these circumstances with ill defined data.

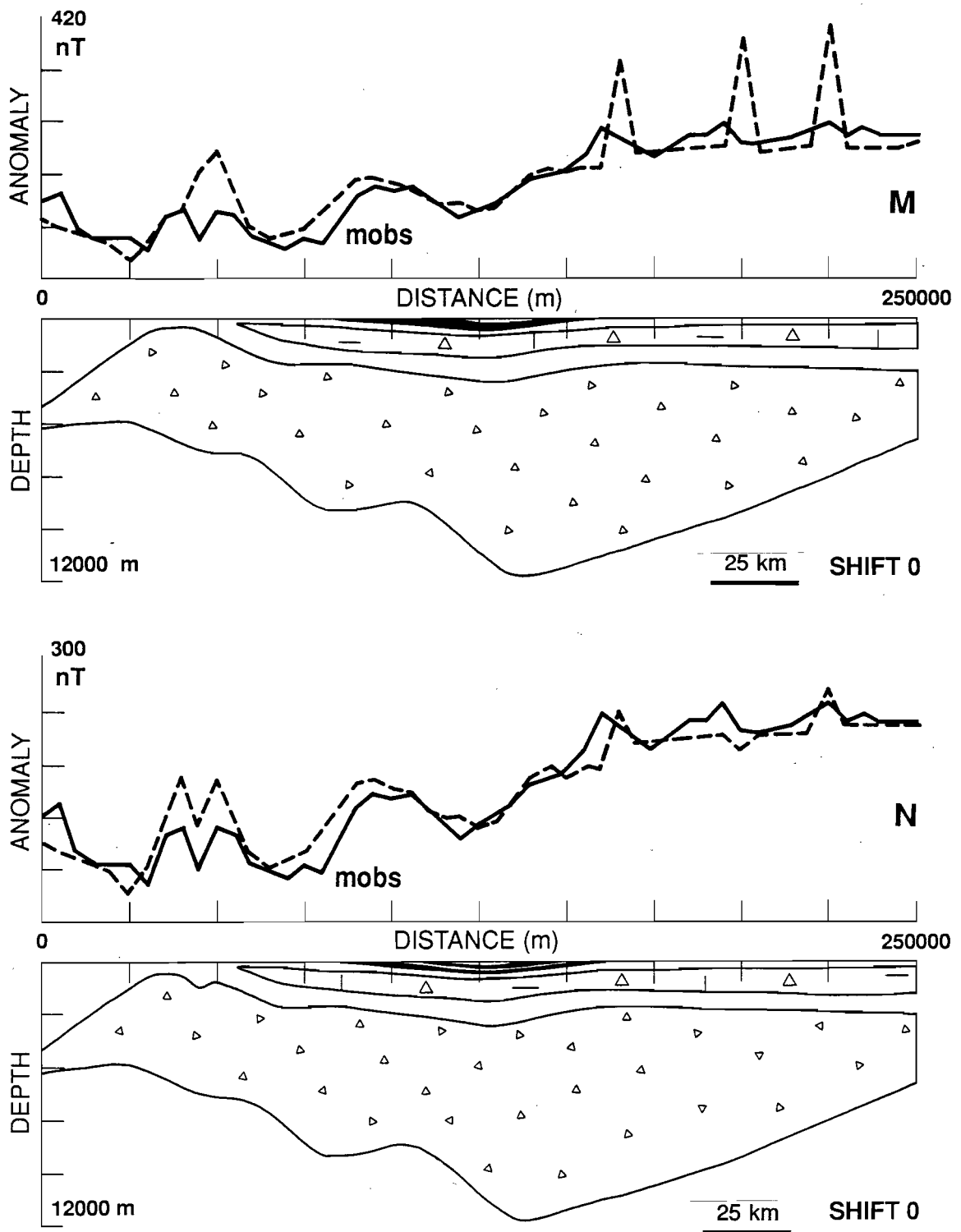


Figure 7 — Models M and N.



## WHAT THE MAGNETICS DATA SUGGEST

The magnetic analysis leaves little doubt that a volcanic pile does exist and that it is gigantic. This pile extends beneath much of the Wearyan Shelf.

On the basis of a single line it is not possible to establish beyond any reasonable doubt that the pile consists only of felsic volcanics. There may be some combination of felsic and mafic materials.

In spite of this important limitation the treatment and the data do provide some unambiguous conclusions and results.

This topic is resolved and concluded in the forthcoming report on the Wearyan Shelf. Proper resolution requires an interpretation array.

Interpretation criteria are essential if even the limited solution given above is to be achieved. The application of potential field methods to large basin studies and sub horizontal units is viable. Considerable detail may also be extracted. Assumptions about contrasts or the data are not critical to recovery of the general basin wide architecture and relationships. And it is not necessary to perfectly fit the data. Of all topics this is the most redundant since it is possible to generate two perfect fits; one with no mafics, one with mafics mixed. This issue can only be resolved by consideration of more of the data set (other profiles and test of base levels) or correlation with another method — not with inspection of aesthetically pleasing tight fits of curves.

## GRAVITY DATA

The final model presented here (model O, fig. 8) considers a basic gravity solution to the problem of the nature of the volcanic pile and its precise location and thickness.

The model is based on magnetic model N (fig. 7) with no modification of the magnetic components. A partial granitic basement has been included with a density (2.64 gm/cc) consistent with the lithologies exposed less than 20 km off the section on the inlier. Other densities are felsic pile (2.79), mafics (2.84+), Tawallah Group and sedimentary basement (2.74). All values are regionally credible.

Given a granite relief of a typical nine or ten kilometres the model easily satisfies the observed gravity field.

It should be noted that while the solution does mean that it is unlikely that mafics do not form a sizeable component of the pile SW of about 130 km this may not be true to the north. This is readily explained. The granite density cannot be reduced by more than about 0.02 gm/cc whereas the density of the pile may be increased by up to 0.1 gm/cc with a thick mafic component. This means that the mafics

can swamp the effect of a deep granite and they will be resolved. This balance might be possible near the north end of the profile but cross profiles are required to test such alternatives.

The deviation at 125–150 km could be a 3D effect — as judged by cross field interference patterns west and east of this profile. The need to insert some Cambrian and Cainozoic cover could mitigate the effect for at least part of this interval.

Alternatively it may be possible, with magnetics checking, to trim about 1000 m off the base of the pile at this distance along the profile. A large mafic solution would not be so easily fitted due to the magnetic response patterns.

The deviation at 225–250 km may mark onset of gulf sedimentary cover. Or, the peak near 215 km may be regarded as a 3D effect induced by the large positive anomalies observed to the NW around the Pellew Group. These may be due to thick mafic piles which do not persist to the easting of this line. As noted above the granite must then extend further NE in order to compensate.

Apparent ambiguities of this type are soluble by array modelling and assessment of interference. Yet the basic solution remains broadly unaffected and supportable by the two methods.

It may also be noted that the gravity data restrict the distribution of granitic rocks about the inlier and show that the contact from the Fish River Fault zone must dip north. This may mean that the granitic mass is not simply an elevated pluton with onlapping sedimentation.

This comment does not exclude the possibility that the SW side of the inlier is composed of more dense monzonitic and granodioritic bodies and there is some evidence of such compositions in the exposures only a few kilometres to the east.

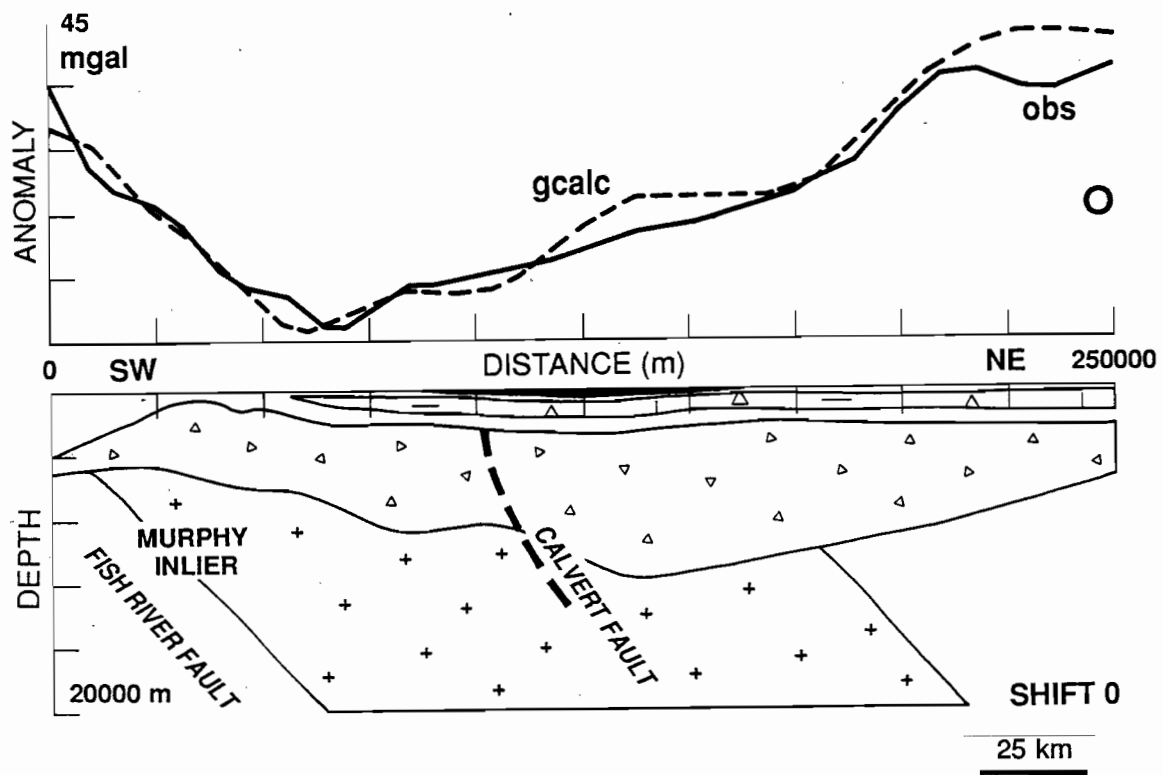


Figure 8 — Model O.



## CONCLUSION

Although only regional data have been used, and those rather coarsely subsampled, in order to derive a basin view across a region with limited outcrop, little property contrast guidance and only partial display of the stratigraphic section it has been shown that it is possible to derive an impressive and limited solution of structural and lithological relationships.

The result, fuzzy in detail, is not ambiguous in style or content even on the basis of a single line coherently modelled. Much of the residual ambiguity, if there is any, can be resolved by consistent treatment of transverse profiles as part of an array. Rigour in modelling of this type can force a definitive solution.

In terms of the objectives stated in introduction it may be concluded that:

1. Perfect profile fits are neither necessary nor relevant for this type of analysis. However desirable or aesthetic or geophysically sought, they are basically a waste of effort.
2. Maximum contrast modelling places consistent minimum limits on possible source volumes. If something is evident with maximum contrasts it can only be more significant if later data forces a downward revision in property assumptions.
3. Solutions reported for Amira P384 are the result of rigorous evaluation of geological options, many variations (>250 were tested on line 34), and application of interpretation criteria relevant to the entire data set and analysis. These solutions should not be dismissed simply because the evolution is not provided, or the fits appear poor.
4. Refinements are always possible — if justified. But better data sets or finer sampling to the limit possible with the given data set must be supplied and used. Where large volumes are involved 3D methods should also be used after a general view has been obtained with 2D methods.  
It is always possible to conceive more detail. For example, does the base of the volcanic pile steepen in the vicinity of the Calvert Fault projected at depth? Consider the step in the models near 105 km.
5. Examination of line 34, even taken in isolation, shows that a thick volcanic pile does occur beneath the Wearyan Shelf. On the basis of this line alone it is inferred to be predominantly or totally felsic and composed of Cliffdale Volcanics.  
But a caution must be recorded here. It was noted above that more than one path to solution was possible from about model J. At this point there was no doubt that the upper volcanics (parts of the Tawallah Group) were not responsible for the magnetic responses and a large deep pile was unambiguously present. What was not clear were any proportions or variation of properties within it and thus the consequent total thickness. Conclusion #5 above simply records the conclusion for one path. What the interpretation trail does prove, however, is that at least some of the pile along the section is felsic. It cannot all be mafic if such a trade-off is made on the basis of further analysis and transverse profile implications. But, until those transverse profiles have been reviewed it is not possible to suggest compositional variations within the pile. This final ambiguity, and an improved estimate of depth range, can be removed by the modelling of many more profiles. The interpretation of a single profile should never be assumed to be valid.

## INTERPRETATION CRITERIA

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The interpretation of the Batten Trough described in Progress Report 1 for AMIRA Project P384 included a brief discussion of the criteria used to apply rigour to, and assessment of, the analysis described.

Reference was made in that report to the original presentation of the arguments concerning the criteria at a meeting of the European Association of Exploration Geophysicists in Paris in June 1992. A short paper was published at that time.

A complete text has since been submitted to *First Break* (published by the EAEG) for review and publication and a copy of that paper is appended here. I believe that this paper makes some crucial

points about data analysis by modelling which are apparently self evident but are far from as transparent as they seem and which are almost never heeded in practice.

They provide a means whereby interfering aspects of the geology can be included in a model and assessed reliably since the base level factor forces consideration of both subtler intervening sources or interference effects between strongly magnetised or volumetrically large sources.

These criteria are also referred to in the accompanying discussion about the evaluation of the existence of thick volcanic piles.





## CRITERIA FOR EVALUATION OF POTENTIAL FIELD INTERPRETATIONS

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Five criteria are described which can enforce a degree of rigour in potential field interpretation and allow the methods to be used to the limit of their resolution. These criteria relate geological input, geometric and contrast validity, multi-facet treatment of the data and observation base levels. The criteria are relevant to all model-based interpretations. Their use by interpreters and reviewers alike can remove much potential ambiguity, discriminate faulty solutions and provide more detailed results or appraisal.

Recognition of true base levels and possible inherent interference effects, and their effect on modelling, is shown to be a crucial element in sound interpretation which can lead to unique interpretation styles with detailed internal resolution limited only by the data set.

### Introduction

Although the potential field methods have well established theory, acquisition technology and interpretation procedures they have a poor reputation in many quarters. Many companies and workers refuse to use the methods or accept any results; often due to previous bad experiences or a belief that ambiguity is inevitable and resolution poor. Even sympathetic users have encountered problems with interpretations. The lack, or apparent lack, of rigour in interpretation methods and the possible multiplicity of solutions deters many users even though the methods are relatively cheap to use and capable of cost effective coverage of survey areas. The combination of low cost surveys but indeterminate results can be very frustrating.

Now, with a proliferation of modern, fast and easy-to-use modelling and processing software the pitfalls will be faced by many more workers, most of whom will lack a solid background in the methods or the assumptions at the heart of their applications. There is a risk that more users will be disillusioned and the methods discredited.

This paper outlines some criteria evolved over more than twenty five years by which interpretations

can be tested or created and which force the original interpreter to consider multiple options. Their application adds considerable rigour and effort with consequent improvement in reliability.

The criteria apply only to quantitative modelling procedures and not to profile processing or rule-of-thumb estimates since these do not consider all of the interactions or information available.

Some issues related to potential field data are introduced before considering each criterion. Two of the case examples are then considered in terms of all the criteria. All examples are of real data in typical applications.

### Data Issues

#### Base values

Magnetic data are normally corrected for base and diurnal variations and then adjusted for the International Geomagnetic Reference Field (IGRF) to yield residual anomalies. Values range about zero. Some contractors confuse this situation by adding some constant to ensure all values are positive. We may then accept these residual values and model

them. It is usually found that the anomaly shapes can be reproduced but amplitudes, overall, may require some scalar shift (see Fig. 7-1). If the model is geologically correct and the field is a true residual then the shift should be zero.

This situation reflects one fact and one assumption. The zero in any model calculation is absolute while that in the observed data may not be. The zero in our data after IGRF removal depends on the reference value chosen for the survey. This is usually made arbitrarily since the magnetic field is time variant. Careful choice may mean a true zero but commercial experience suggests this is rarely the case and the base chosen may deviate by hundreds of nanoTeslas. The resultant residual "zero" may thus be far from true. None of this affects the relativity of responses, simply their absolute values. But model curve fits may have to be scalar shifted by the appropriate amount — if known. This is essential for reliable interpretation (below).

Gravity data presented in Bouguer form are normalised and absolute within the assumptions framework of the reduction but the actual values depend on regional influences and the geology to considerable depths. When we attempt to extract residuals from such data we either assume something about background effects — if recognisable — or we ignore parts of the earth and mass producing the field, usually the deeper parts. It is clear that the zero produced in residuals may be suspect. It does not matter how the residuals were produced although it may be commented that filter method results are more suspect than simple smooth gradient separations where these can be justified since anomaly frequencies and filter imperfections commonly lead to distortions. This problem is illustrated for the Sydney Basin (criterion 1 below).

#### Interference

The potential fields, as observed, integrate the effects of all sources in a region. Maps thus represent an interference pattern. Gravity field plots, in particular, must be seen in this way since the common, smoothly varying result represents a balance from all parts of the geology present. The magnetic field is less obviously affected since relative contrasts and

responses are of greater amplitude and fewer materials contribute to the field observed. Interference is, however, still a serious and neglected problem which can destroy an interpretation.

Figure 2 provides an illustration of the problem. If the effects of many sources interfere then the background or zero level may be lost. If there are few sources or they are widely spaced with respect to depth or width then, regardless of contrast, magnetisation or line orientation a suggestion of background may be evident. Many situations may arise in which apparent anomalies may be formed which, to gradient analysis or rules-of-thumb, may appear real and yield depth or source estimates and yet have no source. These may be termed counterfeit anomalies or ghost sources (\* in Figs 2, 3). Depending on the scale, depth of bodies or contrasts the resultant effect may appear subtle or comparable to real effects. The problem occurs in all potential field data sets to some extent. Figure 3 presents a fragment of magnetic survey in which the central subtle feature is an artifact of all the sources about it. The residual zero in this map is also false. Modelling using the five criteria to be described suggested that the base was some 70 to 80 nT too low and search of the survey records has confirmed this (75 nT). The constraint of the true zero can remove many of the ambiguities from interpretation as shown in the following discussion.

### Criterion One

Does the model honour geological or other control?

All interpreters claim to observe this test but control may be depth restricted or absent in many cases, as at sea or in "virgin" basins.

Consider the gravity field across the Sydney Basin in eastern Australia (Fig. 1). The detailed profile was observed and interpreted by Qureshi (1984, 1989) and offers a classic example for regional separation. All textbooks would suggest drawing a trend line through the minima and straight portions of the curve. Indeed Qureshi did this after first checking with crustal seismic data and making a calculation of the effect of the change in Moho shape at 30 km. He assumed credible densities for crust and mantle and found that the calculated response of the continental margin fell close to the Bouguer minima along the

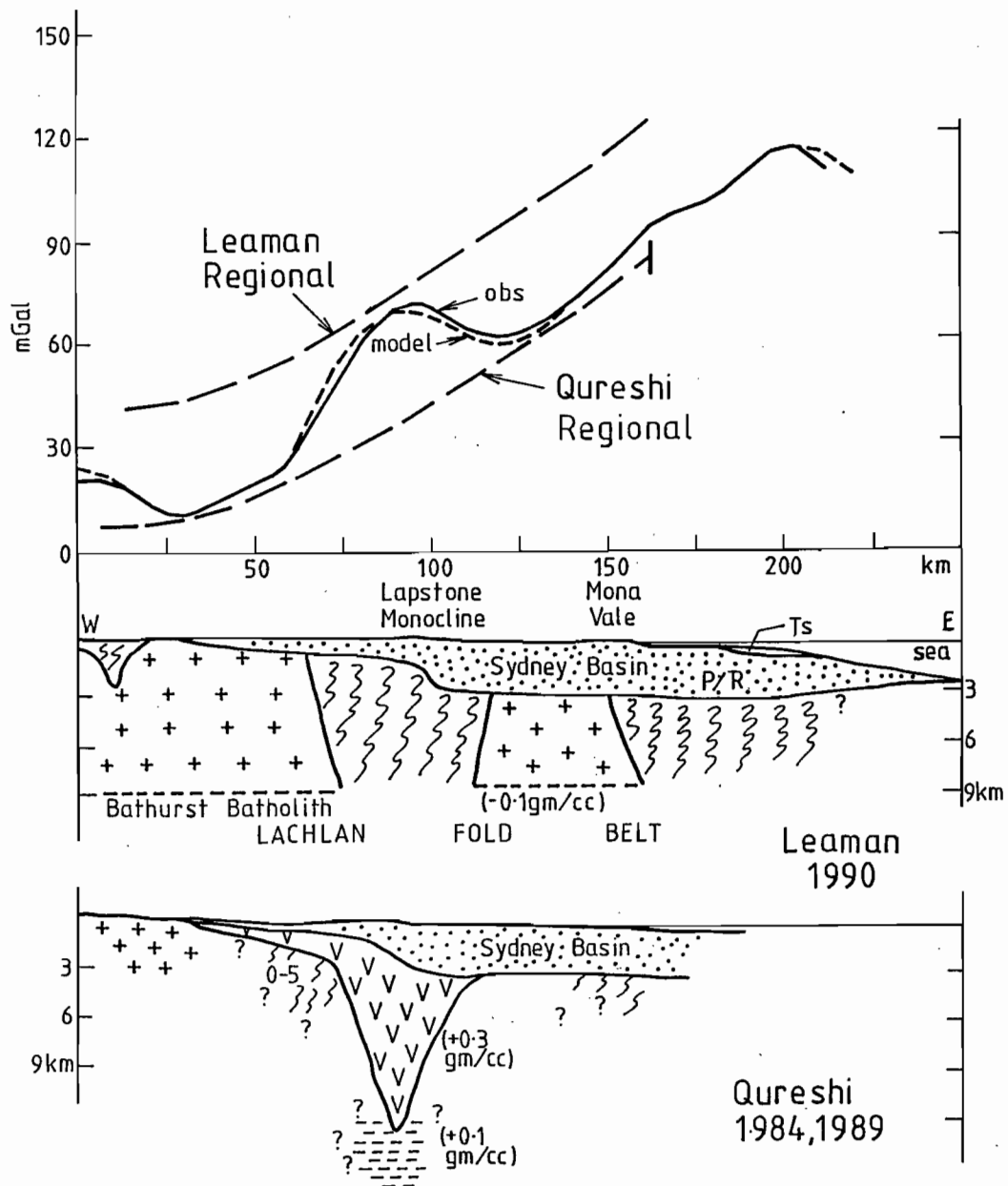


FIGURE 1. Bouguer anomaly profile across the Sydney Basin, Australia. Regional effect due to continental margin. Two possible interpretations are shown dependent on how the regional-residual separation is undertaken. Two placements for the regional are shown, one yielding all negative residuals, the other all positives, with very different results. Geological considerations (criterion 1) can limit this ambiguity.

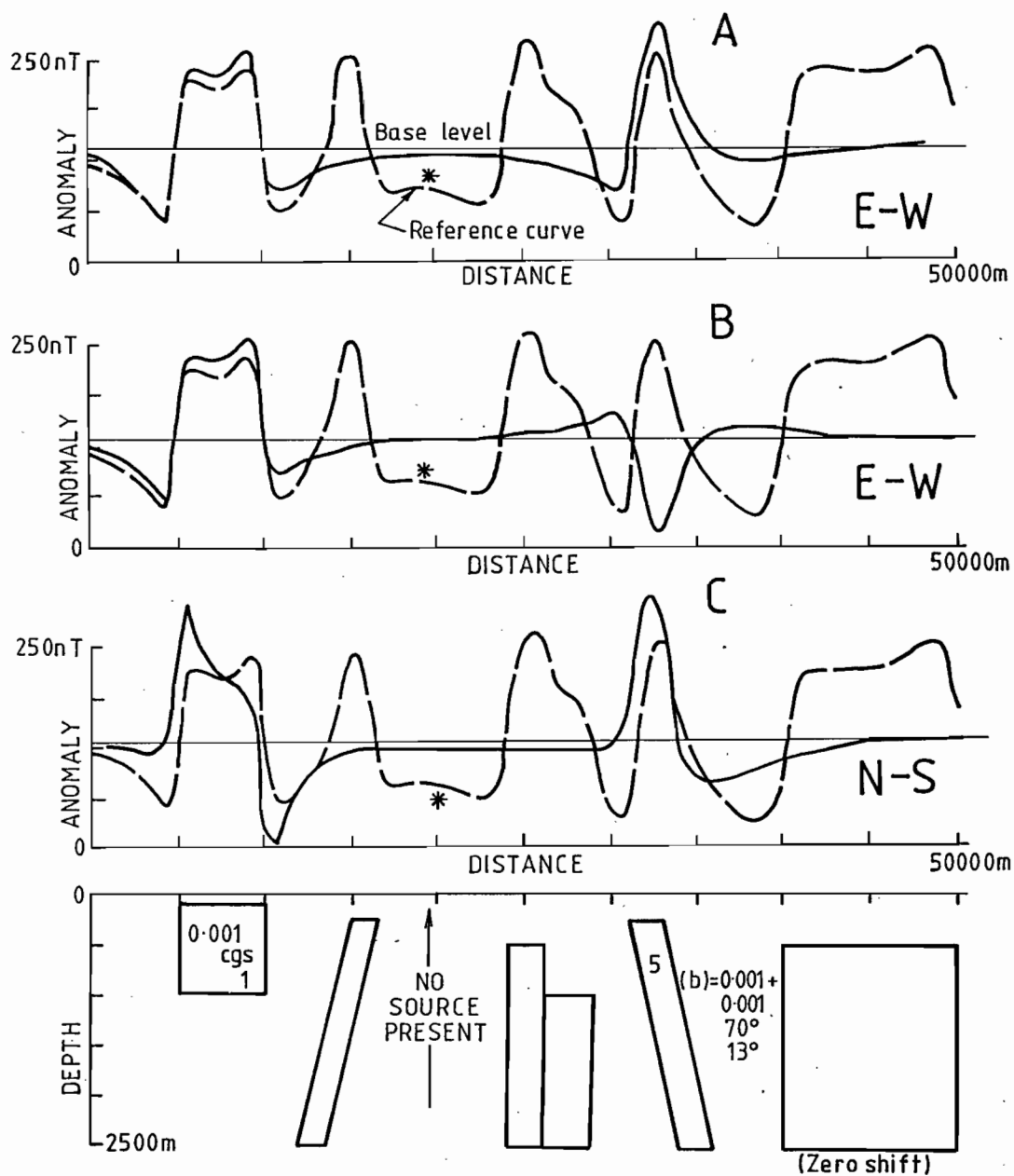


FIGURE 2. Profiles illustrating the effect of anomaly interference. The natural base level in the data may not be apparent as a result. Separated sources allow suggestions of base level but deep sources may produce low amplitude effects across large distances. Failure to recognise these may offset the interpretation base level (criterion 5). The problems are more common in the gravity case. Interference effects may generate apparent anomalies for which there is no source (\*) or which may mislead upon modelling (Figure 8). Such effects are ghost anomalies with no substance. It is more important to match the subtler elements of the observed field than the obvious spikes if a geologically coherent solution is required rather than mere indication of source or geometry changes typical of rule of thumb methods.

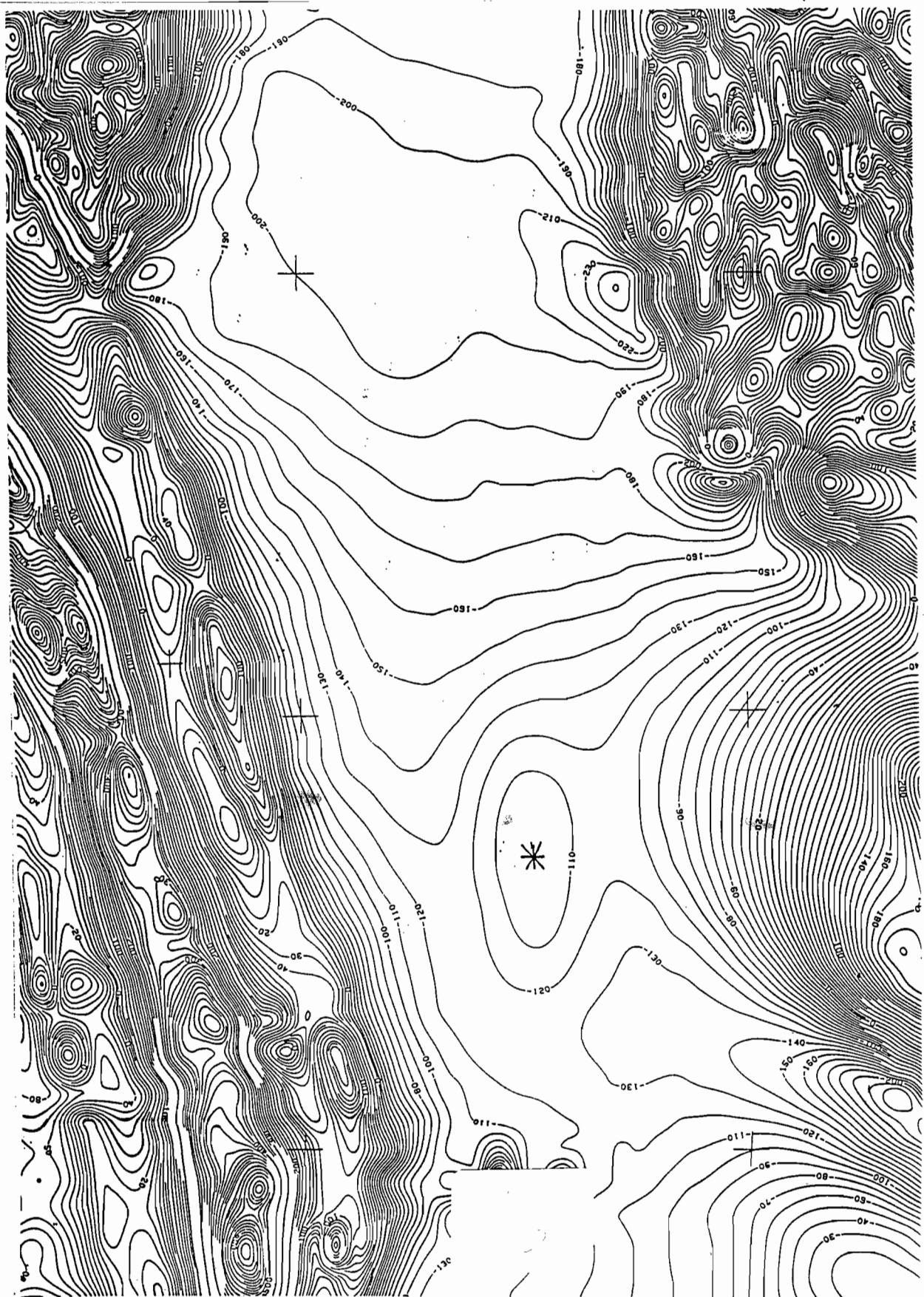


FIGURE 3. Aeromagnetic data from northern Queensland, Australia showing clear near surface effects from volcanics and a central subtler anomaly (\*) which is due entirely to the interactions of the long wavelength tails of other responses. Such features can yield false sources using all types of interpretation procedures unless all responses are assessed and compared with the field base level (criterion 5).

profile. The minimum position, thus reinforced was accepted. The result: all residuals become positive and the anomaly at about 90 km can only be interpreted by inserting a thick (> 9 km), dense (> 2.9 gm/cc), localised source in the basement. He inferred this to be a mafic pile in a precursor rift.

Now there are several problems with this solution which perfectly fits the observed (residual) curve. First, there is no two dimensional magnetic anomaly corresponding to the thick pile. All magnetic anomalies in the basin can be explained by young volcanics, vents or localised pods of quite thin Early Permian mafic units at the bottom of the basin cover. Secondly, the regional calculation based on crustal thickness and contrast assumptions can be modified by small changes in parameters and is not absolute in itself. Using reasonable ranges it is possible to place the regional function up to 30 mgal either above the maxima or 30 mgal below the minima of the profile. This is clearly a source of ambiguity. How to choose from an infinity of possibilities? Thirdly, Qureshi (1984) ignored the effect of the Bathurst Batholith exposed at the western end of the profile. Consideration of anomaly patterns about this and similar bodies beyond the basin cover suggests that such sources may generate relative effects of up to -45 mgal. This is the magnitude of the change in profile between 60 and 90 km and is consistent with established granite/metasediment contrasts noted near surface extending to about 9 km minimum depth.

If we accept that the regional effect can be placed almost anywhere then the batholith response shows that it must be at least 45 mgal higher than the observed minimum at 25 km. This position is also shown in figure 1. When this placement is used any residuals are wholly negative. An interpretation on this basis has little problem with the basin sedimentary cover and infers an additional granite in the basement. The relatively positive anomaly becomes simply a block of basement rocks of the type exposed about the basin. Further, it also accounts for the offshore responses (including water, Tertiary sediment) of Leaman's (1990) extended profile.

This example, appraised further below, shows that even sketchy geological or logical constraints may reduce an infinity of options to a small range. In this case to regional-residual separations at or above Leaman's position. Other criteria determine whether the solution itself is viable.

## Criterion Two

Does the model contain discontinuities in either properties or geometry which are not sustainable?

Application of this criterion cannot be assessed independently of criteria 3 and especially 4 and 5. Many examples exist of interpretations where profiles are drawn for widely separated parts of a region in order to illustrate different geological relationships. Quite often the modelling is forced to employ different properties for the same unit or is affected by different aspects (3D effects) which shift the zero by interference, or regional effects. Without the rigour of criterion 5 (below) inadequacies cannot be recognised. Changes in contrast for the convenience of a solution are unacceptable unless sufficient geological information exists (criterion 1) to justify massive facies or structural change and those changes must be tested by modelling a profile across the proposed change (criterion 4) which also then satisfies criterion 5. Model properties must be clearly stated so that this criterion can be reviewed.

Figures 4 and 5 indicate some of the issues. Figure 4 (based on Leaman, 1991b) presents two magnetic profiles of total field data. The volcanic sequence is more than 5 km thick and near Mt Isa Mine (12000mE) is altered. The models include normal magnetisations to the east and altered values beneath the mine. The extent of the latter were determined using criteria 4 and 5. Note that the models recover a base level which, dependent on the survey reference value, must mimic or equal the IGRF across the survey area (50 km north-south). Thus the zero shows a shift of 25 nT between the profiles shown. This recovery of the regional field is a test of the model (criterion 5).

If the various elements of the structure (magnetic sources) or model are calculated independently it is possible to evaluate variations in contrast and/or geometry. This is shown in figure 5 where inspection of the observed and resultant profiles for the model do not reveal any important internal geometric relationships or possible errors due to cancellation. Review of the components forming the resultant are more interesting. Source elements 3, 4 and 7 are off line while most of 2, 5, 6 and 8 are either deep or off line. Only aspect 1 is exposed on line in this complex 3D model.

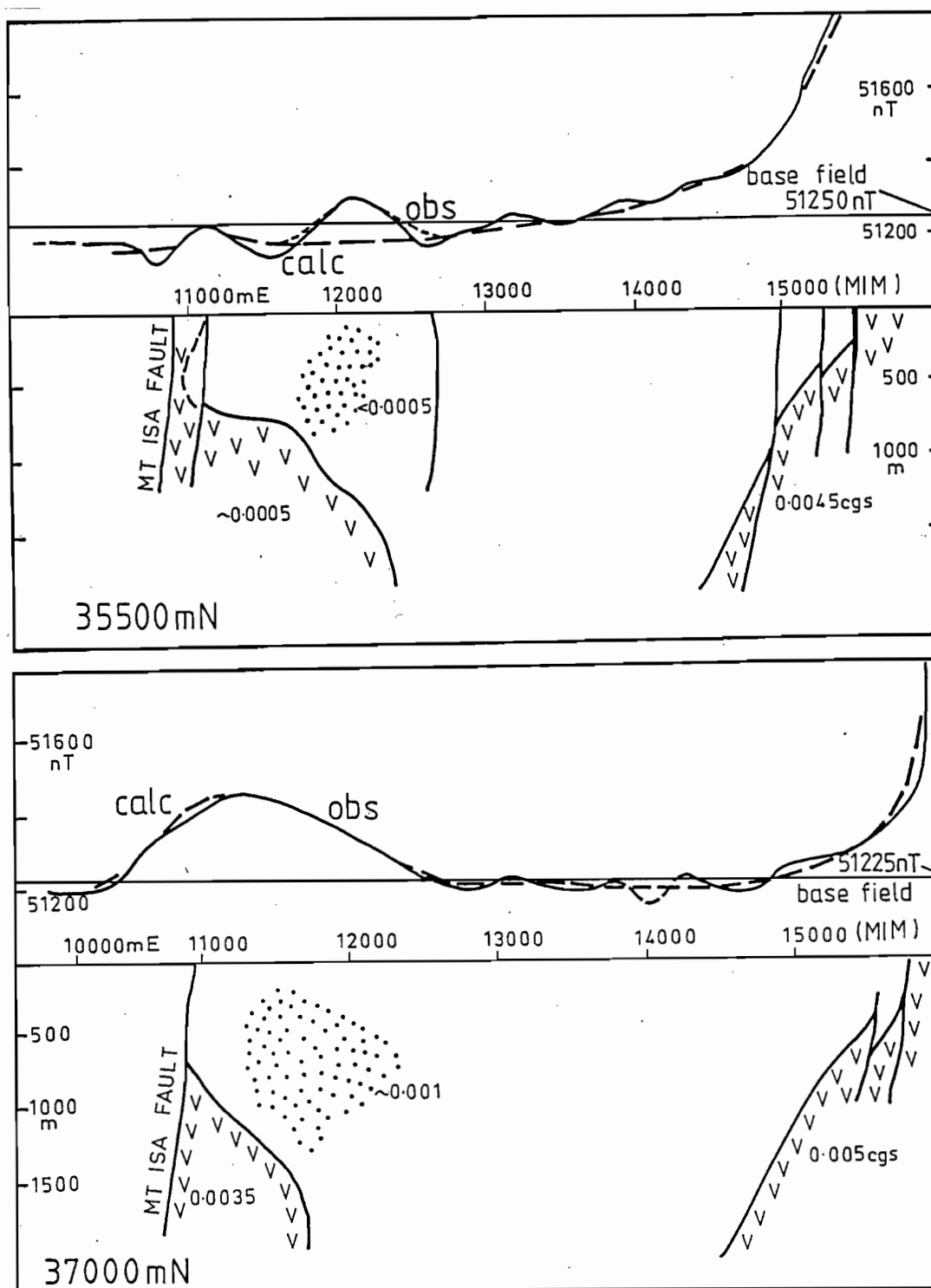


FIGURE 4. Profiles from interpretation at Mt Isa, Queensland (Leaman, 1991b). Different contrasts within a unit as well as changes in geometry can only be assessed by considering many facets of the geology and data set (criteria 2, 3, 4, 5). This application using 3D methods to sculpt a structure tested by many randomly oriented profiles was able to show that the basement rocks beneath the mine site (12000 mE) were massively, but locally, altered. Other, rare, concealed sites with similar characteristics have become targets for exploration. The variation is not evident in the observed field by inspection and can only be determined by calculation of the interference and geometric aspects.

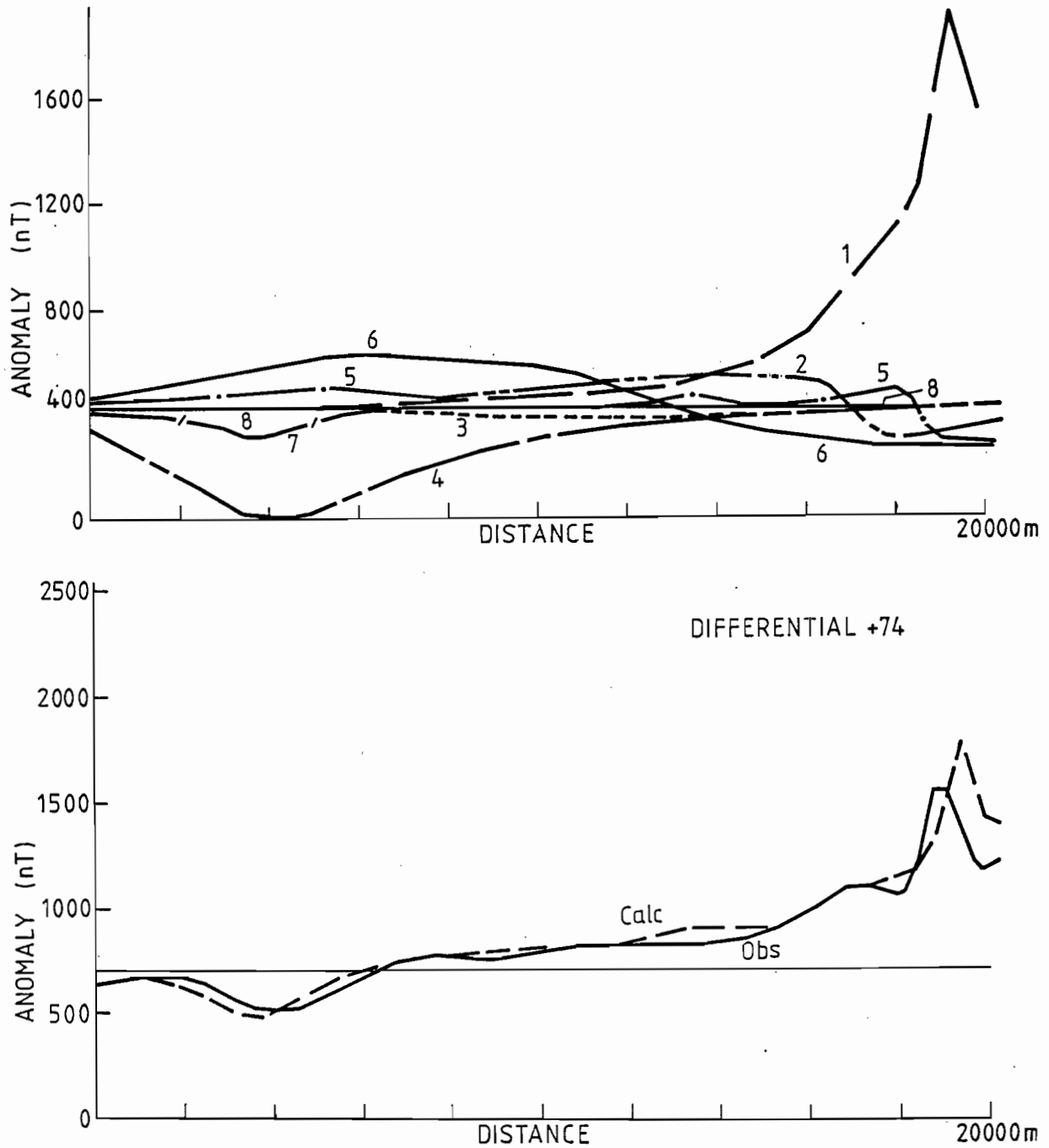


FIGURE 5. Example of three dimensional component modelling to expose variations in geometry and contrast if present (criteria 2, 3). Each source or facet of the geology or structure is calculated separately to reveal its contribution to the resultant. The contrast weighting may be modified to review various possible resultant results for the same geometry. The form of the profiles may also reveal geometric inadequacies independent of the contrast applied. The resultant must fit the observed data, but at the required base level shift for the data (criterion 5). These constraints force consistency and care.

If all sources are computed with the same contrast then the resultant is not only the wrong shape but its best fit requires a zero shift of about 200 nT. This is due to swamping by component 4. Only the spike due to near exposure is represented properly. Constant contrast assumptions cannot be justified in folded rocks which are locally altered and which possess significant remanent magnetisations. Changes in orientation of induced and remanent vectors due to folding aspect alone may introduce variations of  $\pm 30\%$ . If such variations are allowed, as in figure 5, the resultant fits well at a base shift of  $74 \text{ nT} \pm 5 \text{ nT}$  which is close to the  $75 \text{ nT}$  the data set is known to be offset. This value was determined independently of survey records using criterion 4.

Discontinuities can be defined and checked for credibility. Geometric errors in this preliminary model result are also evident but are largely linked to elements 2 and 5 which offset the peak due to 1. This process may define concealed contacts accurately. Similar balancing may be undertaken between elements 4, 5, 6 and 7 near 4 km. Geometric adjustments can be isolated from amplitude effects related to contrast changes but many profiles should be reviewed. Leaman (1991b) provides a detailed example of the power of this approach and its ability to distinguish real from false changes.

### Criterion Three

Are the properties used within ranges measured or which can be inferred from the data?

Figure 6 illustrates this factor. An observed ground magnetic profile from Lake Moondarra near Mount Isa in Queensland can be explained by different models dependent on the assumed contrast. Thick mafic sequences have typical magnetisations of 0.005 cgs yet the initial contractor interpretation used a value of 0.0018 cgs based on the basement properties at the nearby Mt Isa Mine (also Fig. 4). Leaman (1983, 1991a, b) has shown that these properties are not typical. Direct measurements and inferences from local anomalies indicates a range of 0.004–0.006 cgs. If a contrast of 0.005 cgs is used then a high relief solution can be found which also satisfies criterion 1.

Two exposed faults which affect the volcanics are marked on the figure. All rocks are folded and

dip steeply south of the faults. The high contrast solution readily involves all these elements and drilling has disproven the original view which cannot.

Figure 6 also compares 2D and 3D models beneath the profile. There is no essential difference in solution style although deviations in dip and depth may exceed 10% in some zones for the same contrast (see also Leaman, 1983).

### Criterion Four

Is the solution based on several, preferably interlocking, profiles across the data set? A direct map match for the entire survey area is an alternative.

The effect of this criterion has been alluded to in previous examples. Profiles must test many aspects of the geology or the field and thus allow review of all property assumptions, variations and geometric interactions. Only in this way can a consistent and proper base level be derived if not stated (criterion 5). The Sydney Basin example (fig. 1) shows how critical a proper base choice may be. Experience suggests that a minimum of 3 to 5 randomly oriented intersecting profiles is required. These may locally strain 2D assumptions but should be attempted wherever possible. Even parallel profiles should extract consistent property, geometry and shift factors (as in fig. 4 and Leaman, 1991b).

Leaman & Richardson (1989) found that if this is done with 3D procedures that a very high resolution and sensitivity can be obtained. For example, it was found that a zonal variation of 150 m in Moho relief at 27 km produced recognisable effects which exceeded the noise envelope in the regional gravity data for the island of Tasmania when referred against the demands of criterion 5. This is a resolution to rival the seismic reflection method.

### Criterion Five

Has a consistent (or correct) base level been derived for the entire data set from the modelling? Uniform acquisition and processing, as well as interpretation, assumptions are required.

Thus models should be based on the same data set, or tied data sets, possess unit-consistent properties and have comparable depth ranges.

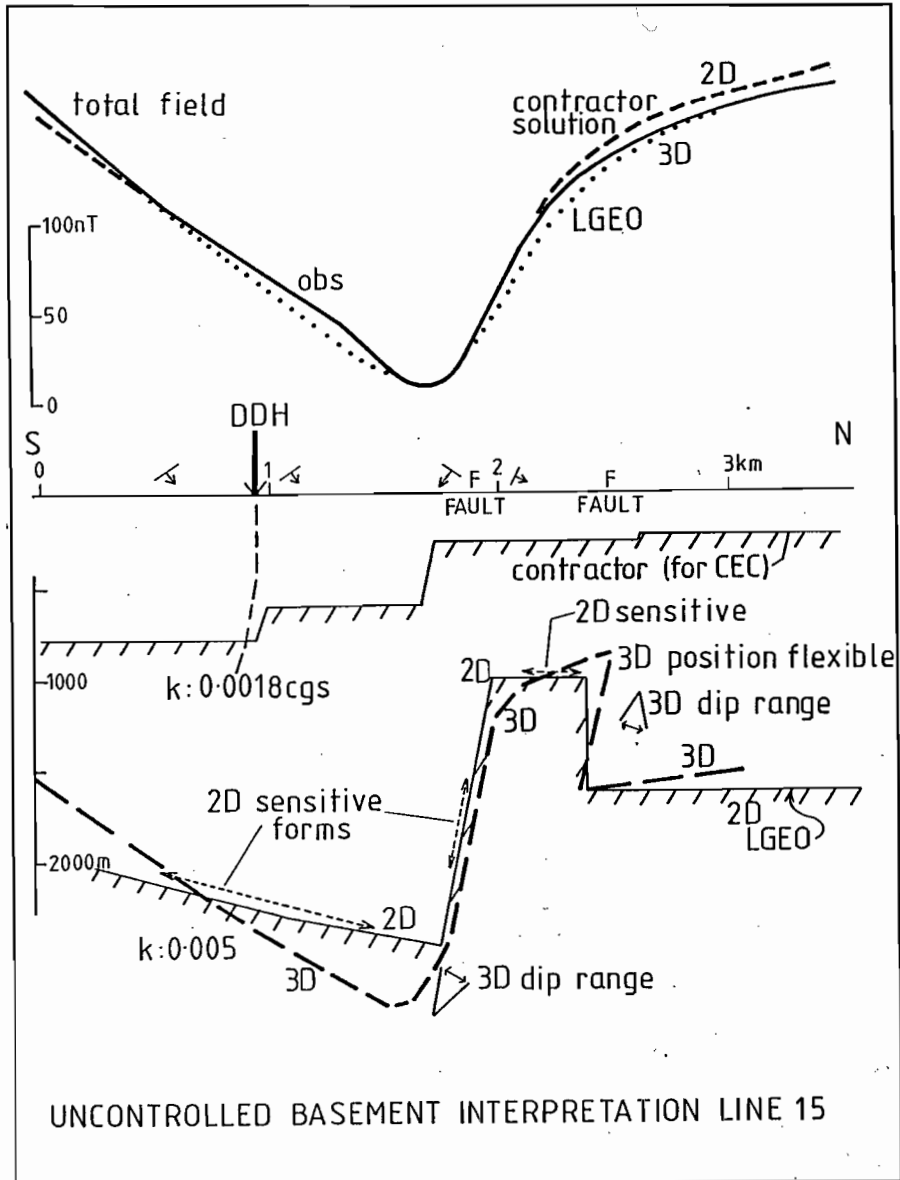


FIGURE 6. Ground magnetic profile from near Mt Isa (Leaman, 1983, 1991b). An early interpretation based on rock properties from a nearby mine led to a false basement interpretation. Use of realistic properties (criterion 3) for the region led to a view which is consistent with surface geological constraints (F = fault positions). Use of 2D or 3D methods does not make a significant difference in conclusions. Drilling disproved the original concept.

The importance of a correct determination of base level was described for the Sydney Basin (Fig. 1, criterion 1) and NW Queensland structures (Figs 4, 6). Unless a realistic residual is available no subsequent interpretation can be valid. The amount of zero or curve shifting required to fit profiles must be stated. The consistency of the shift is a measure of model concept, contents and

assumptions. This information is input or retained by all software but is rarely output, displayed, requested or recorded. It must be.

Note that the shift for the calculated profile may vary according to depth range and model content. Proper use of this criterion implies, especially in the gravity or regional magnetics cases, that sources be of comparable depth ranges. Consider a gravity assessment of a granite. If some profiles indicate that the contrasts should be applied for 9 km then this must also be done for all other profiles. No comparison can be made with a section where the same pluton is given only a 7 km range. The same comment applies to granites off line but which affect the profile. In many situations only 3D methods can achieve satisfactory results.

### The Sydney Basin

This basin was discussed in terms of criterion 1. The models shown in figure 1 were generated using available control on the basin rocks. The nature of the basement rocks and maximum basin depths were the basis for each interpretation. Few wells penetrate to basement. Criterion 1 showed how geological constraints can restrict physical options. Use of realistic properties (criterion 3) further limits them. Many profiles (criterion 4) sampling all aspects of the basin, and the basement, confirm the interpretation and a consistent shift status assuming a maximum mantle depth of 33 km .

While Qureshi (1984) modelled a residual profile after assessing and removing a regional assessed separately, Leaman (1990) included the crust as part of the model. Criterion 5 remains the critical element however modelled. One solution requires some special conditions beneath the basin, the other simply a continuation of the Lachlan Fold Belt exposed around the basin. A well south of the section has confirmed another granite in the position predicted

but application of all five criteria would suggest that Qureshi's model cannot be correct. Note that this does not mean that the other is automatically correct, merely feasible and sustainable. But there is only one real solution and no others can be conceived which satisfy the conditions. The criteria absolutely define possible error and suggest what is most likely stylistically.

### West Tasmania

The final example from a poorly explored and little understood region about the Henty River in western Tasmania shows all criteria contributing to an improved understanding. The region contains Cambrian volcanics, sedimentary sequences and mafic intrusives. All are folded, faulted, possibly overthrust, poorly exposed and with no defined stratigraphy. Figure 7 shows how green fields exploration can be aided in such circumstances. There is no drilling control.

Interpretation A was based on published regional geological mapping. Each data set (aeromagnetics, gravity) was differentially continued from nominal drape state to 900 m above sea level in order to allow simpler modelling, inclusion of terrain and comparison of both methods. Properties used were based on responses from believed correlates nearby and the model was depth limited to 2000 m below reference plane. The curves fit well with a zero shift of 60 nT. This happens to be close to the required differential of 55 nT with respect to IGRF established from comprehensive analysis of other better known parts of the survey area. It might be assumed that this is a valid solution since it appears to satisfy criteria 1, 2, 3, and 5. It does in fact break 2, 3 and 4 (when cross profiles are considered). Actual field checks of properties in the area showed that the original contrast assumptions were invalid.

A revised solution was produced (B). The curve fit now depends on a depth range of 5000 m and a 30 nT differential. Criterion 5 shows this to be invalid. It may be commented that the limited gravity data available can support solutions B, C and D (the latter preferred).

If complex low angle faulting is included in the model together with an increased depth range and similar properties an equivalent fit can be obtained with a shift of 53 nT. This would appear to offer a

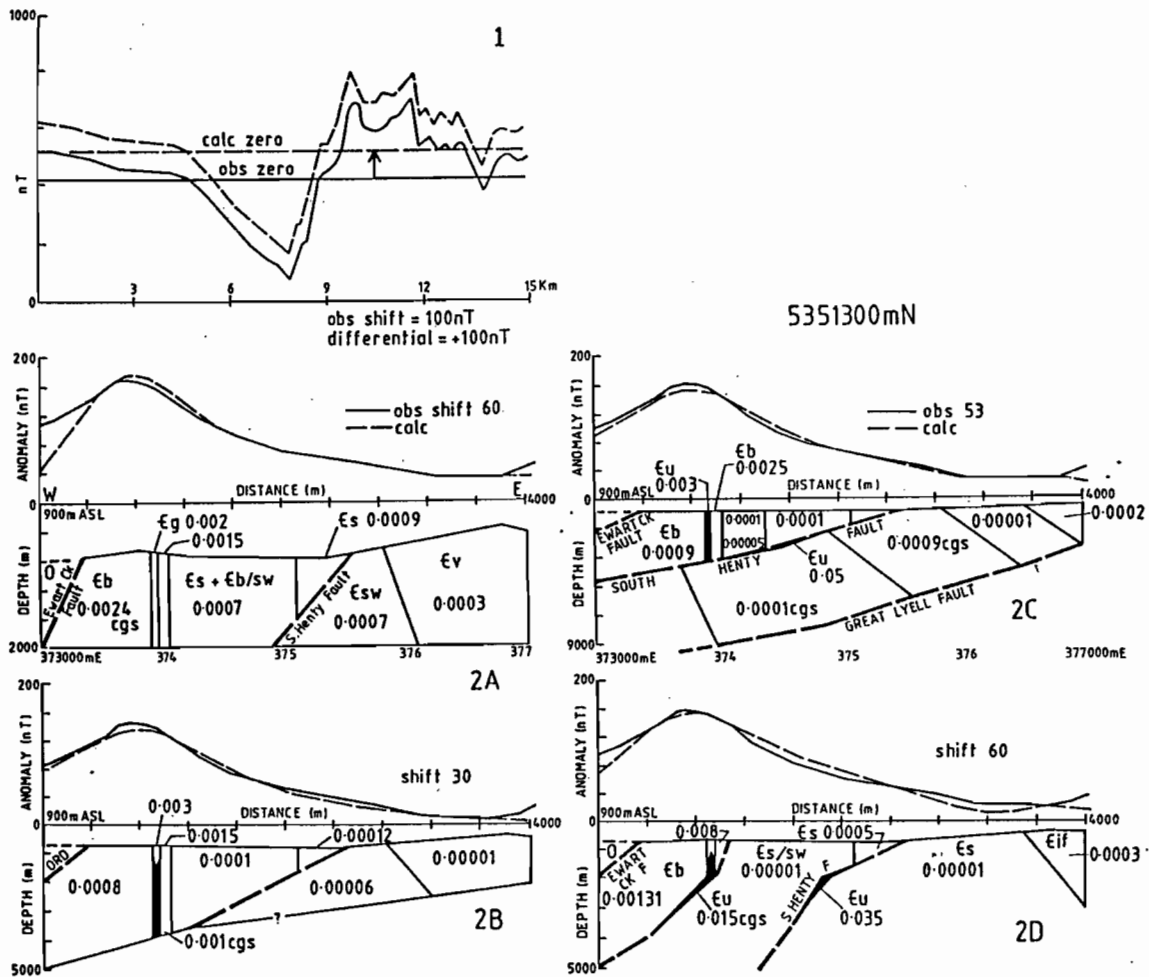


FIGURE 7. Contrasting interpretations from the Henty River area of western Tasmania. 1 shows the definition of base shift and the need to note how much scalar shift is required to fit observed and calculated curves. 2A, B, C, D show different models based on various depth ranges, assumed or real properties and various concepts. Only model D satisfies all criteria even though others satisfy 3 or 4 criteria and some extract the required base shift of about 55 nT. All solutions fit well and are inseparable on a fit basis.

satisfactory answer but it fails criteria 2 and 4. Transverse profiles cannot support it with these properties or depths and demand unacceptable discontinuities in geology or properties.

Solution D presents a different concept in which the magnetic field is generated by pods and sheets of ultramafic rocks along the major fault surfaces. Other units are assigned conservative bulk properties. The depth range remains about 5000 m and the shift is acceptable at 60 nT. This very radical view of the geology was not initially accepted even though it satisfied all criteria including 2 and 4. It was the only solution style found to do so and was unique. The exploration company involved remapped the area, traced the implied faults and found four previously unmapped pods of magnetised ultramafics. Many more are now believed to be present in this densely vegetated inaccessible area. This model and its acceptance has important ramifications for the geology of western Tasmania but this is beyond the scope of this paper.

## 2D versus 3D

The principles described in this paper apply regardless of algorithm or assumptions (2D, 2.5D, 3D). Use of randomly oriented profiles and 3D techniques can force the interpreter to the noise envelope of the data set and a unique solution style at whatever resolution the data can sustain. 2.5D methods can give a false sense of security by catering for some 3D aspects but not others; such as where the source is wholly off line. 2D preliminary interpretations controlled by the criteria are often more than adequate for most analyses while also providing a concept basis for any subsequent 3D modelling. 3D methods coupled with the criteria provide maximum reliability, resolution and sensitivity but the modelled volume must be large enough to ensure that no unaccounted interference effects are present. In the case of the deep Mt Isa interpretation of Leaman (1991b) this meant that the model, if in reducing detail, extended at least 25 km beyond the end of any profile calculated.

Figure 8, however, illustrates an extreme condition where 2D and 3D solutions yield very different models (opposing dips) due to complex closed geological structures and massive interference. Leaman (1983) discussed other problems of this type.

## Conclusion

The five criteria defined appear simple and obvious but they are rarely applied as a group. The rigour forced on an interpreter causes more alternatives to be considered and calculated than would otherwise be the case. This means a better chance of a good or true solution.

Application of the criteria commonly establish a unique model style with negligible ambiguity. Only precise interface depths within it may be subject to the constraints imposed by knowledge of properties or the resolution possible with the data set. This is a great advance on current conditions and user suspicions.

Several related issues may also be reviewed:

1. Goodness of curve fit is not critical and may be quite irrelevant unless the criteria are also satisfied. A first found solution is not necessarily correct simply because it fits.
2. Failure to meet all criteria confirms a solution as positively incorrect. If two models from the same data set yield solutions which vary in criteria demands then at least one or both is invalid. Criteria support does not guarantee correctness simply that the solution is feasible and probably valid.
3. The exact status of residual data and the claimed zero in it must be reviewed prior to, or during, interpretation.
4. Base values for magnetic surveys must be set at the IGRF value for the location if a shift is to be avoided later.
5. Rock property ranges should be determined from core, outcrop sampling and direct responses in the field measured.
6. Modelling display and output software should declare how the data was fitted. Shift parameters must be recorded.
7. Models must employ depth ranges which allow proper evaluation of relatively low amplitude, long wavelength interference of anomaly tails. These subtler elements of anomaly responses are more critical to valid model analysis than the dominant spike parts since they may distort conclusions about base levels and complex geometries at depth. These elements must be fitted well; a more difficult process.
8. Papers and reports should clearly state shifts and

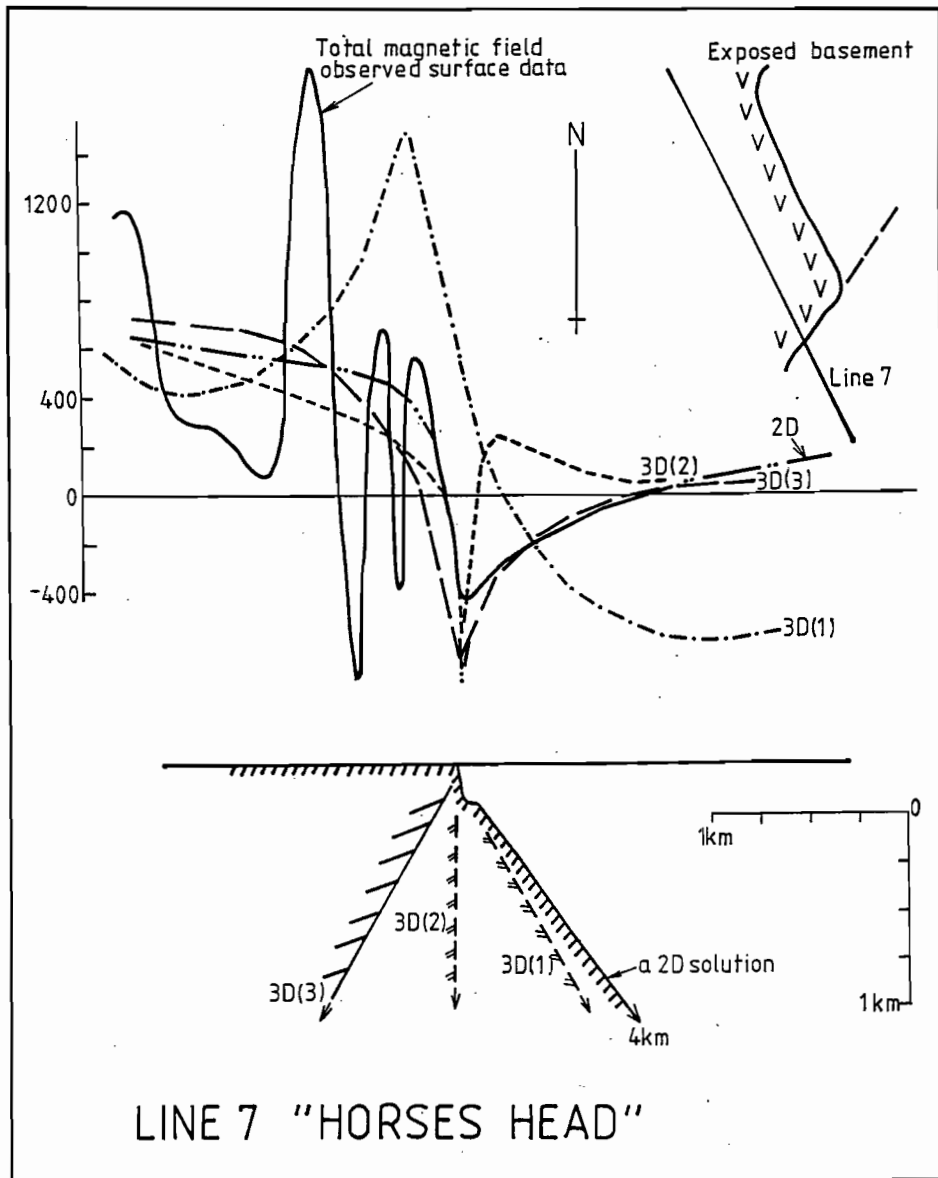


FIGURE 8. Complex structure modelled using 2D and 3D methods at "Horses Head" prospect north of Mt Isa in Queensland. Only one side of the structure is shown. The name of the prospect indicates the complex shape of the magnetic units. Interference from all facets has completely misled the 2D approach within the "head" such that the interpreted dip of the contact is quite incorrect. The field can only be explained when all contributions are included. This is an extreme case of interference.

properties so that the reader can assess consistency and geological faithfulness in isolated sections.

9. Use of the criteria is analogous to many routine seismic procedures which control acquisition or interpretation precision. Note, for example, that few seismic interpretations are based on a single profile. An array always shot. The time base is also defined. Equivalents exist for other criteria.

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## REGIONAL GEOPHYSICS — BASIN ARCHITECTURE

### 3. The Wearyan Shelf and Murphy Inlier

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#### SUMMARY

Examination of potential field data across the Wearyan Shelf within the McArthur Basin of northern Australia has shown that the stable platform style which has dominated the region since the onset of the Tawallah Group deposition is the result of limited disruption of the basement granitic complexes and massive blanketing by thick mafic volcanic suites which preceded normal basin deposition.

The region has remained rigid and moved only as a large block. Negligible tensile, and consequent uplift, forces have been applied since the onset of rifting in the region which controlled the disposition of felsic volcanics which unconformably overlie the basement complex directly. This uplift effect was re-inforced by the rifting and extension of the Batten Region resulting in reduced sedimentation in the Wearyan Region. No major structural heterogeneities exist north of the Murphy Inlier until about 50 km east of the Emu Fault Zone. At this easting the proportions and continuity of the volcanic pile changes rapidly and this zone must mark the limit of the mobile Batten Zone. The active margin trends N-S within a gross framework which is NW-SE. These orientations are fundamental and reflected in basement granite patterns. Other fracture systems, such as those which trend ENE or NE are superimposed and related to early basin developments.

All units up to upper members of the Tawallah Group onlap the basement rocks of the Murphy Inlier. The deep volcanic piles also thin or disappear along the inlier but are locally very thick near it. Long-lived activity is indicated. The present disposition of the inlier, however, is quite different. It forms part of a major low angle detachment which has transferred the northern plate southward. The possible displace-

ment may exceed 30 km. The Fish River Fault Zone marks the site of the detachment. The entire block of the Wearyan Shelf has been carried as an entity. The increased dips near the inlier reflect the local stresses approaching the detachment which steepens toward the Fish River Fault.

The detachment must predate the deposition of the McArthur or Fickling Groups since these unconformably onlap all older units and the fault zone along the inlier.

Faulting across the shelf appears to be very minor and displacements greater than 250 m are difficult to demonstrate. This contrasts with the Batten Trough region and also with the nature of faults which preceded onset of the two deep volcanic piles.

Known mineralisation can be linked with the general distribution and thickness of the volcanic piles but the region would not appear to possess the same active history or potential for fluid circulation offered by the region west of the Foelsche River. Dolomitic units are also generally absent. Any connate or confined circulation would have been largely restricted to the rocks west of the shelf margin since these are thicker, could pressurise more fluid and were almost certainly more permeable overall.

#### INTRODUCTION

This report outlines analysis of gravity and magnetic data within the Pellew, Robinson River and Calvert Hills 1: 250 000 map sheets in the eastern McArthur Basin. This area is known as the Wearyan Shelf (Plumb & Wellman, 1987).

Previous work reported for adjacent parts of the basin include:



1. The Batten Trough region (Leaman, 1992)
2. The Wallhallow region (Leaman, 1993a).

The basic methodology for this analysis has been outlined by Leaman (1992) and clarified in Leaman (1993b, c).

The principal objectives of the interpretation have been to extract general and gross basin architectural forms and relationships which may provide information on fluid paths (depth range, circulation) or volume (unit scale or storage), implied thermal and tectonic history and correlations between known mineralisation and basin elements. Achievement of these goals requires a coherent assessment of the entire basin. The present work completes the second stage of this process.

## GEOLOGY

The Wearyan Shelf lies south of the Gulf of Carpentaria, north of the Nicholson River and east of the Emu Fault Zone (figs 1, 2). The exposed geology is straightforward and consists primarily of members of the Tawallah Group with some thin McArthur Group and more recent cover. There is little evidence of any significant disturbance. Dips are shallow and fault displacements are small. Most of the region displays a few members of the central Tawallah Group and basal members are only exposed where onlapped formations are uplifted near the Murphy Inlier. The basal members include a thick (> 1 km) volcanic unit (Seigal or Peters Creek Volcanics depending on author; e.g., Firman et al, 1963; Ahmad & Wygralak, 1989) and the Westmoreland Conglomerate. The latter may be very thick locally.

Basement rocks, including various granitoids and metamorphics, are exposed along the inlier. Several members of the Tawallah Group unconformably onlap the inlier suggesting that a primary marginal structure existed in the region. Members of the Tawallah Group, the rocks of the inlier and the faults along its south face are all overlain by younger rocks equivalent to the McArthur Group. The major fault zone along the south face is known as the Fish River Fault and this has been rejuvenated. All published sections (Firman et al, 1963; Ahmad & Wygralak, 1989 for example) present a confused view of the inlier, and these faults, and suggest direct correlations of all units across the inlier which was simply an elevated zone during deposition. A difficulty with the published view of the inlier is the asymmetry of units or lithologies across it if there has been little temporal or geometric displacement and simple onlapping. The north face is very different from the south face, especially in terms of the older members of the Tawallah Group and the felsic suites which are piled between the

basement complex, granites and the Westmoreland Conglomerate.

The felsic suites have been considered to include two members and all are known as the Cliffdale Volcanics. These are best exposed, and thickest, in the eastern half of the inlier and are almost unrepresented within the Calvert Hills sheet.

Some changes in Tawallah Group and other onlapped units may be noted along the inlier. The conglomerate appears thickest in the west while the mafic and felsic volcanics appear to thicken eastward. The only mafic volcanics mapped are parts of the Tawallah Group whereas the felsic rocks predate the group. This pattern of volcanism was inferred by Leaman (1992) to be widespread within the Batten Trough even though only thinned members of the Tawallah Group are exposed.

Some correlations may be suggested across the six 250 000 sheets now examined for this project and some consolidation of nomenclature will become essential. There are at least two relatively thin bimodal volcanic units within the Tawallah Group which may be known as the Gold Creek and Settlement Creek Volcanics. A lower member variously known as the Seigal or Peters Creek Volcanics may be predominantly mafic and is more variable and certainly may be thicker. The thickest, mapped occurrences are near the Murphy Inlier where uplift folding has provided improved sections. The volcanic sequence is in two parts.

Leaman (1992) implied that the thick mafic suite inferred to underlie the Tawallah Group of the Batten-Tawallah region was the Seigal-Peters Creek unit. This required considerable variation in thickness of the unit; a property which could not be denied on the basis of exposures and other control in the Bauhinia Downs or Mt Young sheets.

Tectonic relationships within the Batten region did, however, indicate major changes in relationships and patterns prior to deposition of upper volcanic units and other units of the Tawallah Group and on this basis it may be argued that the thickened mafic piles are both eroded, and older than, the Tawallah Group. As argued below, this view can be sustained across the Wearyan Shelf to the Murphy Inlier itself — and beyond. The implied stratigraphy now suggested is that of the Haslingden Group of the Isa Inlier as the direct correlate of the deep mafic piles deduced in Leaman (1992, 1993a, b).

Leaman (1992) inferred that the Scrutton and Cliffdale Volcanics may also be direct temporal correlates. Given their position in the basin sequence these may also be correlates of the Leichhardt Volcanics (and perhaps also the Argylla Formation) of the Isa Inlier. Such propositions may have very wide ramifications within northern Australia since they would suggest that we are dealing with a single



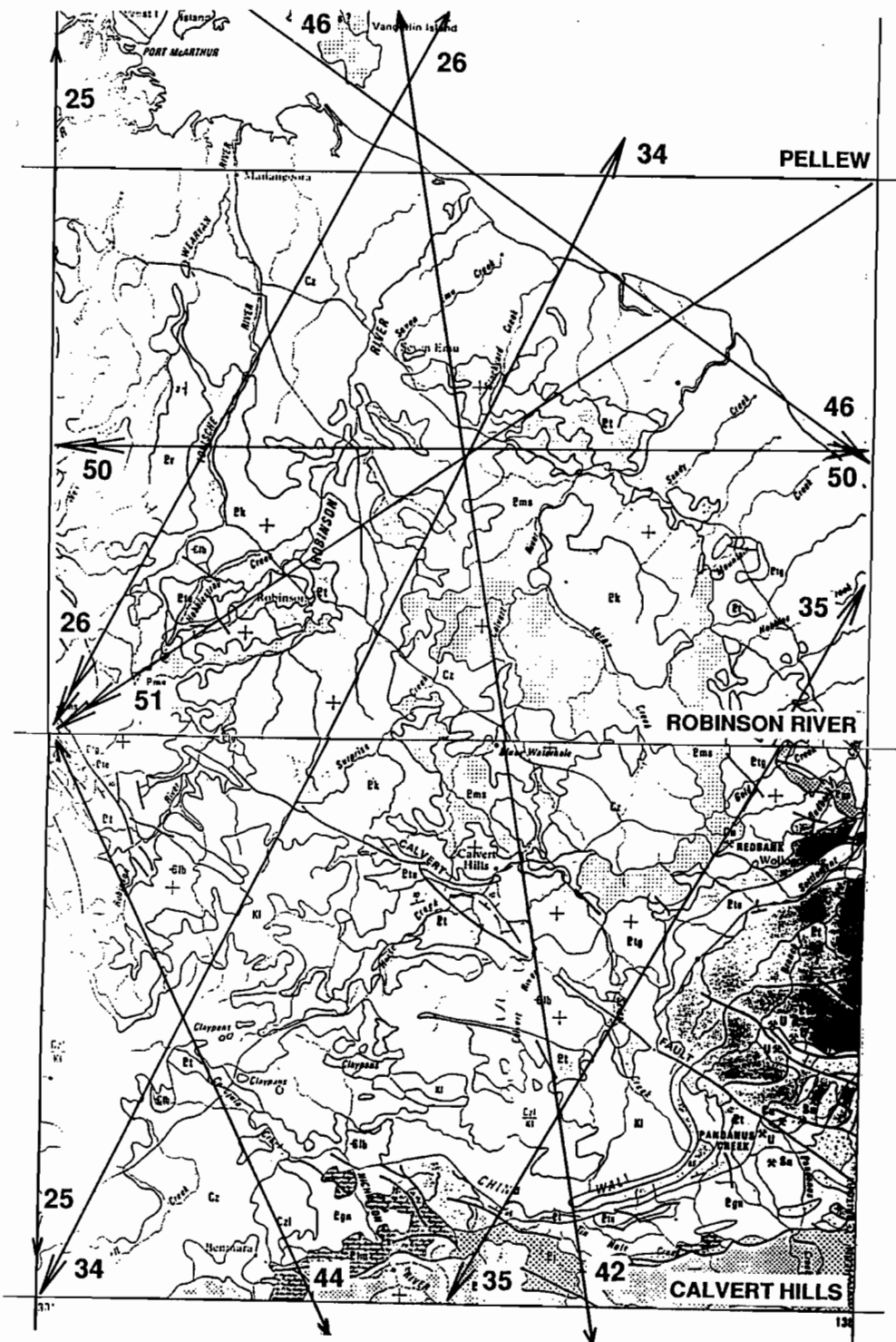


Figure 2 — Location of displayed profiles — Wearyan Shelf and Murphy Inlier.



giant basin, with consistent evolutionary stages, sedimentation patterns and only a variable uplift and metamorphic history depending on particular local developments.

Some ages have been linked to parts of these correlations. But how valid and assured are these? Given the distribution of the units, the difficulties of true correlations and the actual unit groupings and associations (which I would count more highly than some datings which are disputed or which may be disputed) the possibility remains and should be tested. Contrast approach and legend of Blake (1987).

The real issue for this particular element of the basin study is why, or if, the Wearyan Shelf exists. How does it differ from the nearby Batten Region? Where do the N-S structures which dominated the modern view of the Batten Region begin? Where are they? Is the basement different? And what are the implications for fluid circulation and mineralisation?

## GEOPHYSICAL DATA

In order to assess the primary elements of the basin only regional data have been reviewed. For much of the region this is the only data available.

Regional magnetic data is shown in figures 3 and 4. The compilation was provided by AGSO and is based on data with line separations of about 1500 m, sampling of 30 to 60 m, and terrain clearances of about 150 m. While some relatively high frequency data has survived these specifications, and the subsequent plotting, most of the data is relevant only to major and semi-crustal sources. Differing specifications and detail can be recognised on some sheets.

Figure 3 presents typical character for the Pellew-Robinson River areas. Some large anomalies are evident, such as east of the Pellew Islands and across the southern part of the Robinson River region. Near N-S, sub E-W, NNW and NW trends are evident but few are regionally continuous. Anomaly character varies across the Robinson River sheet and reflects the shallowness, and even exposure, of upper volcanic members of the Tawallah Group in the east. This typically noisy field is normal for shallow, flat lying volcanics.

The pattern in Calvert Hills (fig. 4) is similar. String anomalies mark exposure of particular volcanic horizons or limits, some of which are within the Seigal Volcanics and their correlations. Gross trends within this region are WNW and parallel the Calvert Fault system. Some other trends, E-W and NE, are less obvious. The quiet zone in the south of the sheet is associated with the Murphy Inlier. The granites and metamorphics exposed along it are virtually non magnetic and may be contrasted with portions of the

Tawallah Group or the felsic suites exposed near the centre of the inlier (eastern edge of the maps).

Comparable patterns might be present within the Mt Drummond sheet. Resolution is poorer but the character is comparable to that recorded in the Wallhallow and Bauhinia Downs sheets. The same basic trends can be recognised.

The gravity field (figs 5, 6) is much simpler but possesses few obvious correlations with exposed units or features. The Murphy Inlier is, however, readily distinguished as a strongly positive ridge (fig. 6). This is curious since it is composed of granitoids, all of which are less dense than the rock suites to north or south, or the intruded basement. The marked gradient along the northern face of the inlier is associated with the cover and not the inlier. There is no evidence to suggest that the metamorphics of the inlier influence this situation in any way. The large negative anomalies to north and south of the inlier are consistent with large granitic masses within the basement and, if portions of these are exposed in the inlier, then there should be no relative positive effect. This suggests that the rocks of the inlier are compositionally or physically unusual in some way.

The other apparent anomaly occurs near the Pellew Islands (fig. 5).

The rocks exposed are believed to be basal McArthur Group and thus the units presumably responsible for the effect are no different from those exposed across the Wearyan Shelf itself. It should be noted that the two relatively positive anomalies are very large in terms of relief with surrounding features — about 50 mgal. Neither can be explained by any sedimentary section known in the basin.

Some trend differences are evident across the shelf. The northern part of the shelf (fig. 5) displays some gross N-S, NW and NE trends while the southern part of the shelf (fig. 6) is dominated by E-W, ENE and some NW-trending features.

The gravity compilations shown in figures 5 and 6 are by courtesy of AGSO and represent Bouguer anomalies using a reduction density of 2.67 gm/cc.

## INTERPRETATION

About 40 regional profiles across the inlier and surrounding shelf have been examined. The profiles have been randomly oriented and have sampled all aspects of the observed fields and known geology. While various 2D and 3D interactions and source interference effects are inevitable on some facets the resultant integrated pattern derived is coherent and can be sustained in respect of lateral effects. Some ambiguity or uncertainty may relate to specification of depth or total thickness but the relationships are

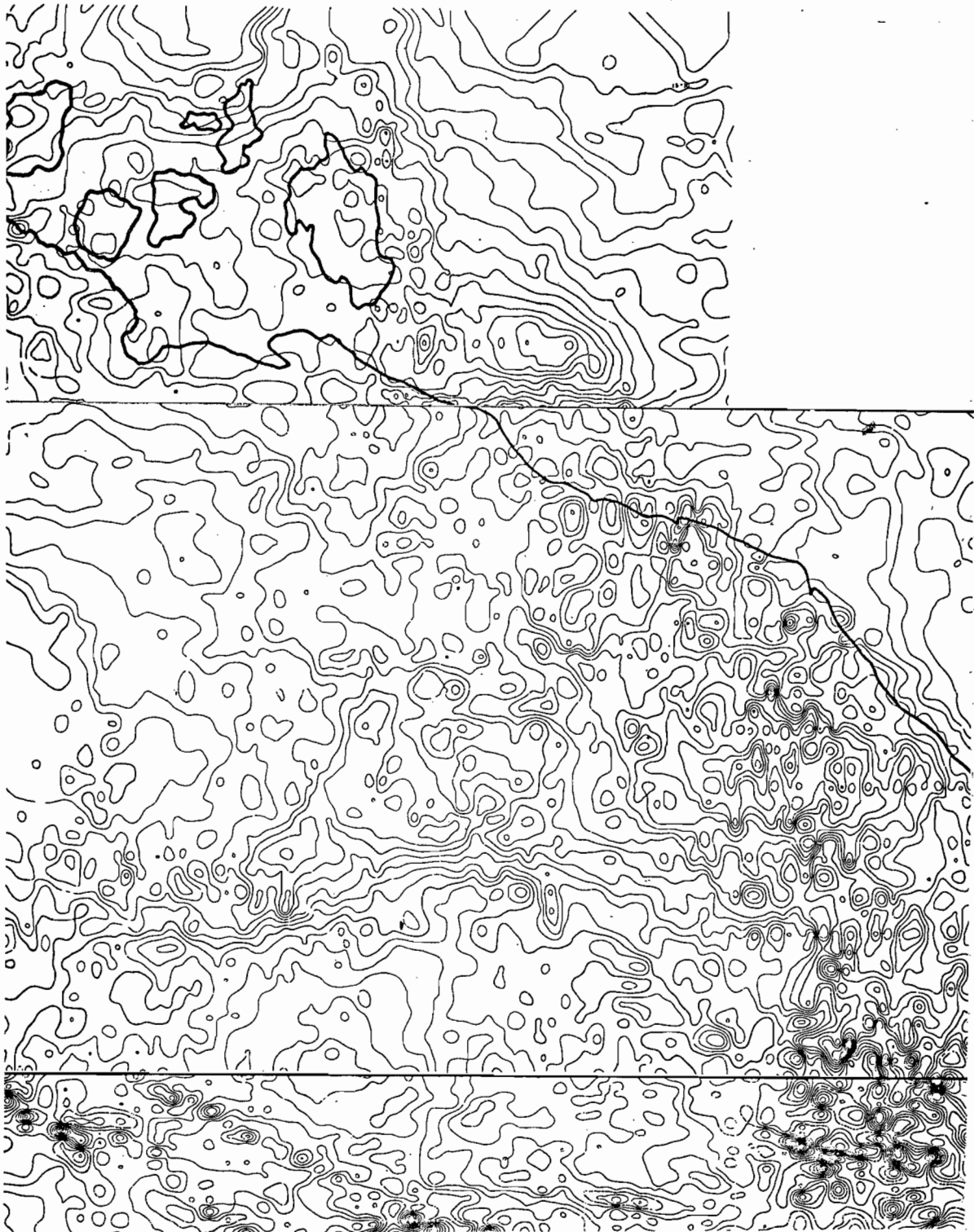


Figure 3 — BMR regional compilation of magnetic field in region of Wearyan Shelf.



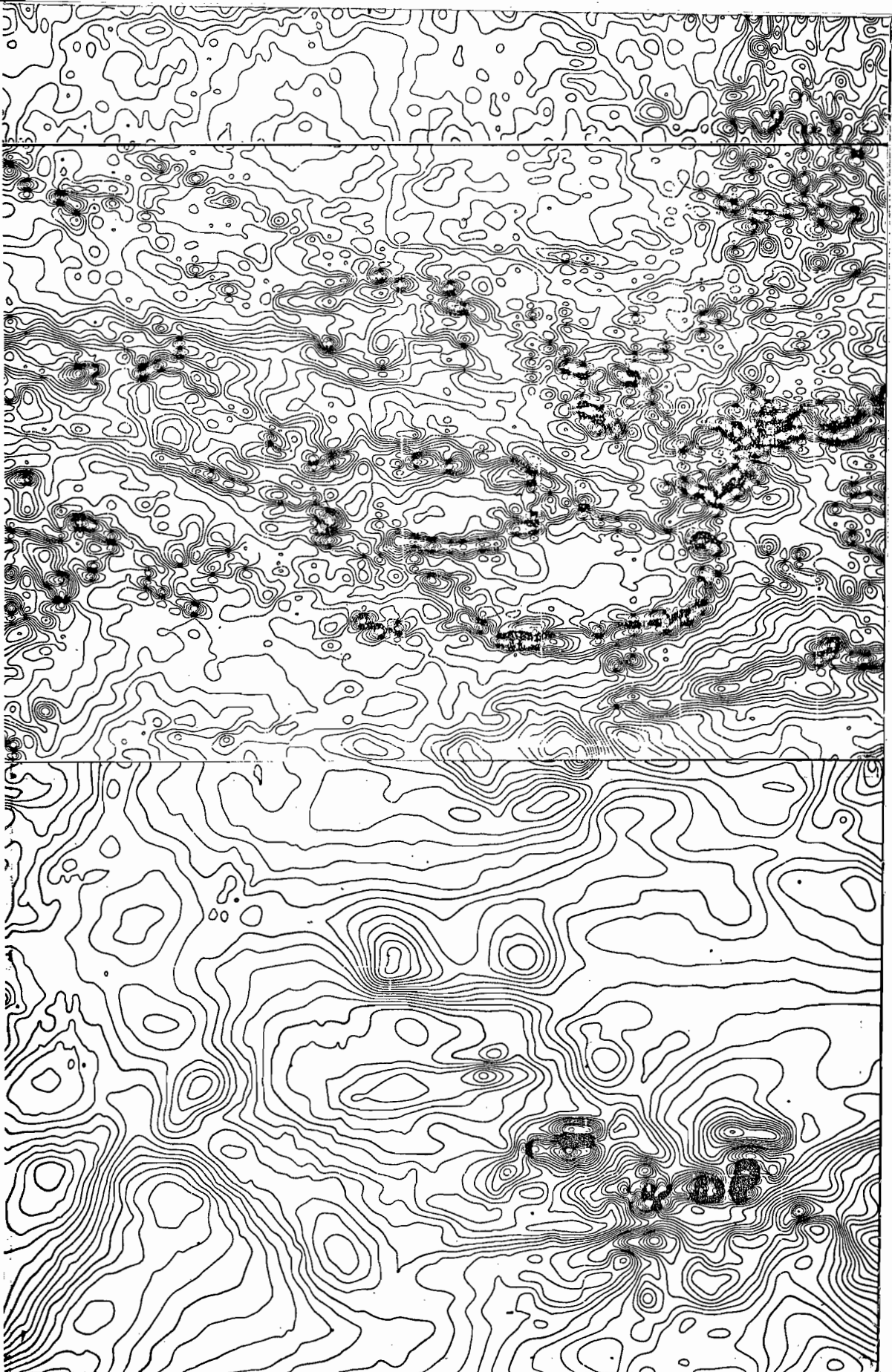


Figure 4 — BMR regional compilation of magnetic field in region of Murphy Inlier.

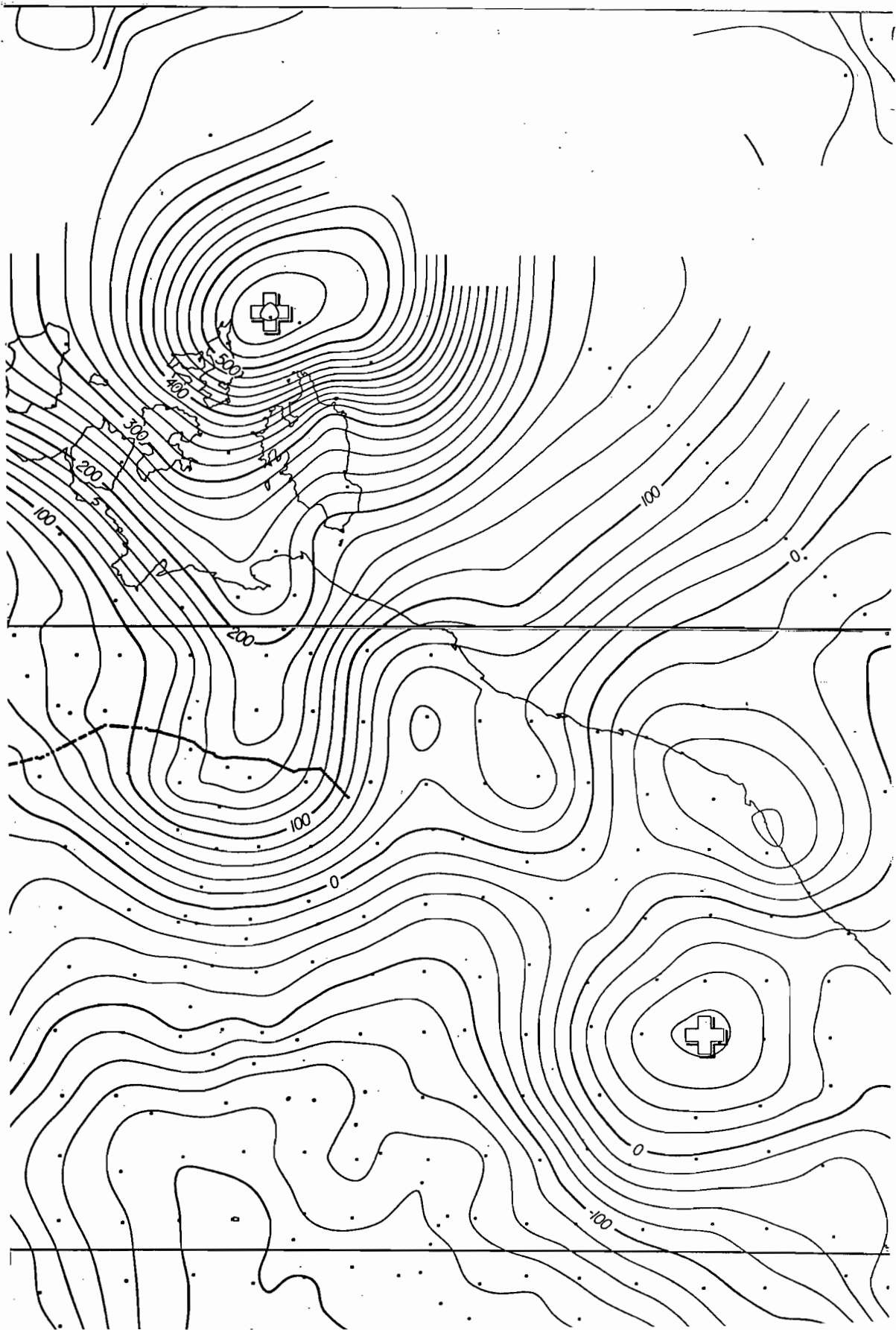


Figure 5 — BMR regional Bouguer anomaly compilation in region of Wearyan Shelf.



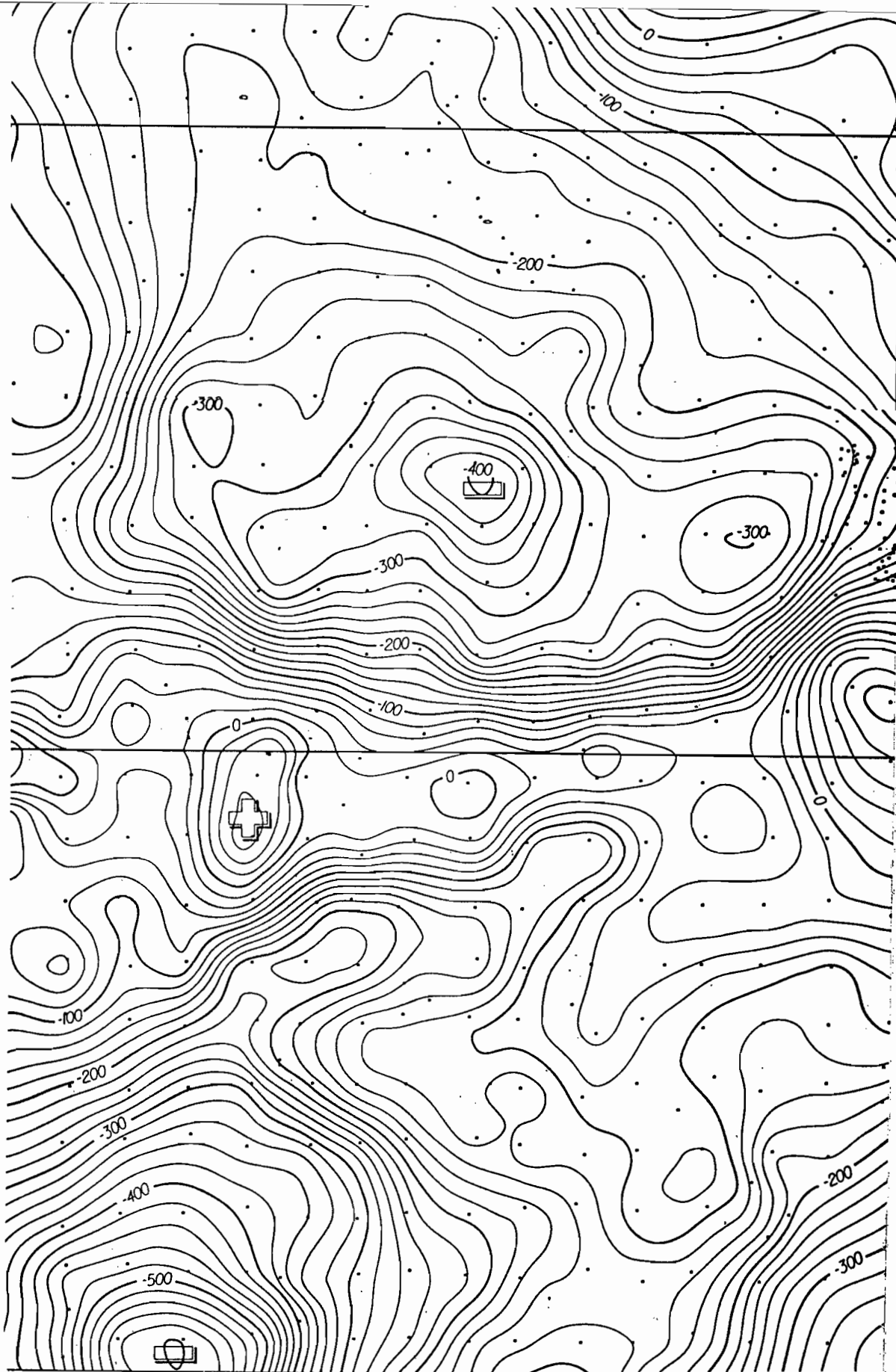


Figure 6 — BMR regional Bouguer anomaly compilation in region of Murphy Inlier.

considered reliable due to consistent application of reasonable properties and the criteria outlined by Leaman (1993c).

Three issues must be mentioned prior to discussion of modelled sections and presentation of integrated conclusions.

1. What is the contribution of the volcanics of the Tawallah Group?
2. What is the evidence for deep volcanic piles?
3. What is the sensitivity of the data, and methods, in an area where all units are virtually horizontal?

The first two to these issues have been considered by Leaman (1993b) where the outline review for line 34 has shown that the thin and shallow volcanic members of the Tawallah Group, including the up to 1.5 km thick Seigal/Peters Creek Volcanics, cannot account for the long wavelength effects; dip of the units is neither relevant nor contributory although changes in dip can explain some of the local high frequency effects observed.

The relatively high frequency anomalies, axes or trends can be shown to be due to:

- (a) local folds, often of low relief ( $\leq 100$  m),
- (b) small faults, often of limited throw (50–250 m).
- (c) some abrupt thickness changes (50–150 m), within the upper members of the Tawallah Group. No deeper units can generate the frequencies noted. These discriminatory aspects prove that other deep sources are involved and that such sources may be locally very thick (km). These patterns have now been confirmed across the entire region reviewed to date for this project.

Potential field data are not noted for high sensitivity or resolution where sources are horizontal or sub horizontal. But this is a function of scale. High frequency effects due to a fault step are very apparent provided the field was observed with adequate sampling at appropriate elevation. Even in regional data, observed at a clearance of at least 150 m with coarse sampling and line spacings, some of this information may be preserved and also survive the filtering process into the final map or image.

While the gravity compilations display the long wavelength and interference effects clearly the magnetic data do not — yet all are present and, in fact, dominant.

Assessment of long wavelength effects shows that very large source volumes are required in explanation — even using relatively high contrasts — and in such situations quite minor geometric changes in the upper surface of the source (due to faults, minor folds etc) or subtle dip changes in either upper or lower surface may induce very large changes in amplitude. It is these responses which allow definition at basin scale,

even though dip changes of less than  $2^\circ$  may be involved, of thickness variations and basin form. These conditions are consistently satisfied throughout the eastern part of the McArthur Basin. There is a negative aspect to the large responses generated; they extend across large areas and interfere with similar responses generated elsewhere. 3D effects also become critical. For these reasons the modelled profiles are always about three times as long as the portion displayed here, and considered in detail, and only modest fits are considered acceptable. Minor changes in dip or thickness, compared with an ill sampled field (due to observation or profile selection), and large effects mean that it is difficult to obtain good 2D fits easily and in general no attempt has been made to achieve them once the style of solution and approximate thicknesses involved have been determined.

As in all previous analyses maximum contrasts inferred from bulk exposure responses have been applied. This means that all solutions offered use the maximum likely/feasible contrasts and deduce the minimum feasible rock volume. Larger rock volumes may be required. Consideration of all solutions determined for the Batten, Wallhallow and Wearyan regions (69 profiles to date) and the link between gravity and magnetic demands suggests that the contrasts employed are credible. The general assumptions involved in these maximum contrast, minimum volume models mean that while estimates of thickness or depth to sources may be suspect pending independent control (drilling, stratigraphy, other methods) the proportions of various sources are virtually immutable. Thus true basin relationships can be derived irrespective of precision problems in any part of the treatment.

Those relationships, expressed as regional isopach or fault patterns, can define aspects of basin evolution and perhaps depositional or mineralisation control. The sought structural variability is always associated with dip or thickness changes at some surfaces. Magnetic methods, in particular, are responsive to these critical situations.

Examples of solutions generated in the region of the Wearyan Shelf and Murphy Inlier are provided in figures 7–10. Fits are generally excellent but could be improved in some cases. The conclusions would not be altered, however. It should be noted that perfect fits may look impressive, but they do not guarantee a more correct or relevant solution (also Leaman, 1993c).



**PROFILE 25** (figure 7) extends along the western side of the Pellew, Robinson River, Calvert Hills and Mt Drummond Sheets

Much of the region is blanketed by post Palaeozoic material but the line does cross the Emu and Calvert Fault zones.

The Emu Fault is clearly important and has influenced deposition of both volcanic suites (felsic and mafic) — but in opposing senses. In the vicinity of the fault the sequence is slightly domed and members of the Tawallah Group thin across it suggesting active but slight uplift during deposition. The magnetic model confirms the required separation of sources and allows discrimination of exposed mafic sources and the buried major source.

Major podding of the felsic suites occurs in the south as the buried western extension of the Murphy Inlier is approached and also north east of the HYC region. The piling near the inlier is similar to that actually observed near the centre of the inlier some 160 km to the east.

The other evident inverted growth fault occurs at about 220 km along the profile and this structure can be traced back to the HYC region (see Leaman, 1992, 1993a).

The gravity field is consistent with this solution overall but does reveal two anomalous regions. The first corresponds to the Pellew Islands. No magnetic units are involved but a dense deep formation is required. Dolomitic rocks could explain the contrast. Note that these materials most likely lie beneath the piles, not in or above the Tawallah Group.

The second anomaly occurs on the extension of the inlier at about 25 km. The magnetic field is truncated immediately north of this feature which suggests that some magnetic units are terminated; only members of the Tawallah Group can be involved. This indicates, along with the gradients of the feature, that the source extends from near surface to the likely depths occupied by the three volcanic members of the Tawallah Group. Dolomite densities are also implied and a fault trough containing upper McArthur Group rocks, as occurs north of HYC could account for this feature.

**PROFILE 26** (figure 7) extends NNE from the Wallhallow region to the eastern parts of the Pellew Islands along the Wearyan and Foelsche Rivers

The magnetic field is not marked by strong character and its resolution requires a delicate balance of sources and information from other orientations. It indicates a reasonably uniform felsic cover and a gently increasing mafic accumulation onto the Wearyan Shelf.

The granite relief and depth range reviewed gravimetrically is wholly consistent with the total thickness of the volcanic package derived magnetically. An additional aspect of the deep, dense Pellew mass is also shown. The source is not more than about 3 km thick but may be fault-bounded and have a contrast against the surrounding rocks indicating a density of about 2.85 gm/cc.

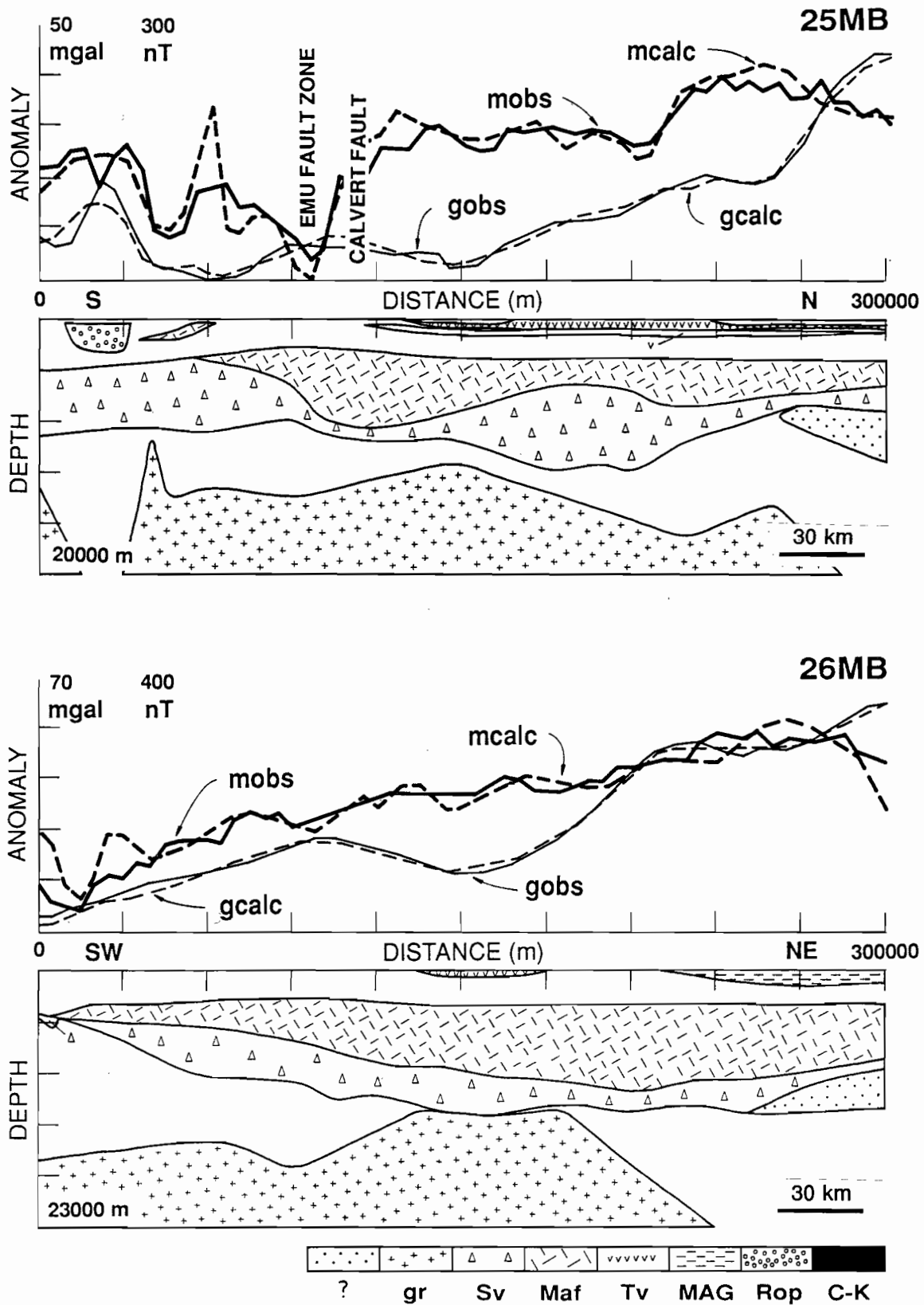


Figure 7 — 2D gravity and magnetic models for profiles 25 and 26.

? = unknown, gr = granite, Sv = Scrutton Volcanics, Maf = mafic volcanic component, Tv = Tawallah Volcanics, MAG = McArthur Group, Rop = Roper Group, C-K = Cambrian-Cretaceous



**PROFILE 34** (figure 8) extends NNE across the heart of the Wearyan Shelf from the buried extension of the Murphy Inlier to the Gulf.

This section has been discussed at length by Leaman (1993b) up to a preliminary solution. Many elements of that solution will be recognised in this currently accepted solution which is supported by the profile array. It should be noted that this solution is supported by 19 other profiles and profile intersections in order to satisfy the fourth criterion of Leaman (1993c). The additional information provided by these profiles proves that the solution cannot embody any concept which is dependent on thickening of the Seigal/Peters Creek Member of the Tawallah Group or any concept that excludes a thick mafic accumulation extending northward.

The solution suggests that a very thick pile of felsic volcanics underlies the exposures of the Westmoreland Conglomerate along the western end of the inlier; no mafics are present. Other sections are consistent with such thickening but also imply that the pile could be at least partly duplicated by thrusting. This cannot be appraised in this part of the area since the granite is consistently involved. The thrust may be steeper and be defined by the north dipping lower face of the granite. This coherence within the plutons has not been observed on other lines, see 35 and 44 for example.

Fault relationships are not clear along this section due to cover. The projection of the Emu Fault Zone and the position of the Calvert Fault can, however, be linked to major changes in the section. In the first instance the mafic pile is terminated or markedly thinned and in the second the felsics are thinned. Primary versions of these structures must have been active during formation of both suites and to have inverted between phases.

**PROFILE 35** (figure 8) extends across the central part of the inlier onto the shelf east of Redbank

The curve fits of this line appear poor but the general curve form recovered is quite sensitive to deep sources. All spikes observed (see fig. 4) can be linked to minor faults, exposure edges and slight dip changes in the Tawallah Group volcanics as discussed in Leaman (1993b).

The forms and relationships noted along line 34 are evident. The felsic rocks are thickest near the inlier, while the mafic units thicken into a large slab across the shelf.

The Calvert Fault position can be associated with some local variation in the felsics at this easting and a thickening of the mafics. This is consistent with line 34.

The most important aspects of this section relate to the anomalies in the region of the inlier. The gravity data are critical and have been fully fitted using the magnetic framework.

The inlier is shown not to be a large piece of granitic basement and it must overlie rocks with the magnetic properties and thickness of those which onlap it.

The magnetic profile is very sensitive to variations in material beneath the slab of granite and the extent of concealed volcanics is well defined. This restriction does not, of course, fully define the extent of the detached inlier slab or the position of the fault even though the gravity model is well restrained. This comment simply reflects the fact that the granite has been treated as a coherent, single composition and the simplest case is presented.

Similarities between profiles 34 and 35 will be noted even though the sections are about 100 km apart. Each presents a systematic solution to the subtle balances required across the Murphy Inlier and both are consistent. It is possible to imagine a translation in form between these limits within a detached structure. In each case volcanics extend SW of the inlier, and beneath the detachment although the relationship is not as clear in line 34.

The solution style offered is the only one which has been found which can satisfy the location of the gravity response and gradient, the surface distribution, the magnetic responses across the inlier and to the south and the interpretation criteria. The solution style is based on the evaluation of twelve profiles across the inlier including one along it. Complete evaluation will require 3D analysis and refinement of these profiles.

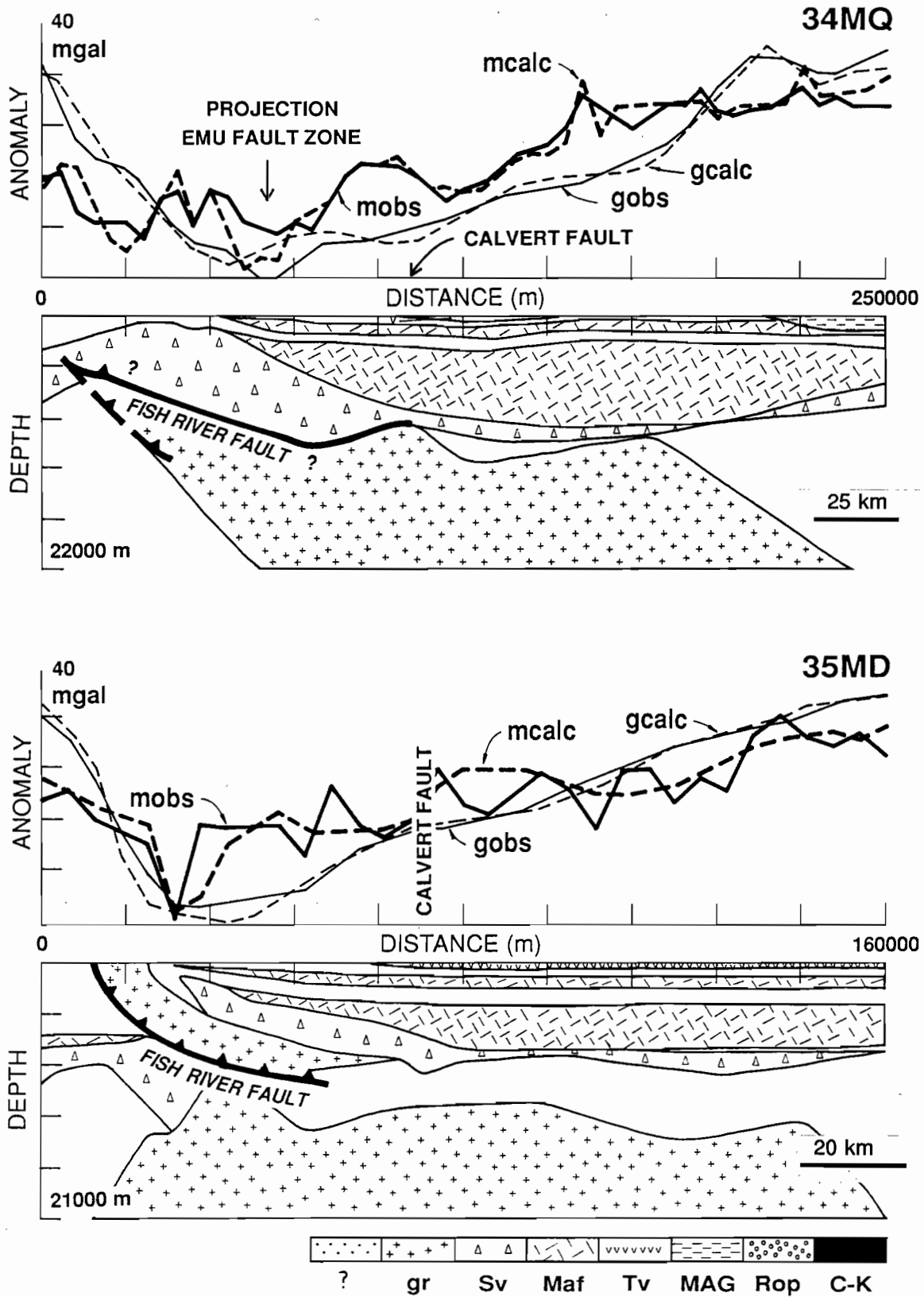


Figure 8 — 2D gravity and magnetic models for profiles 34 and 35.



**PROFILE 42** (figure 9) is a major regional profile extending from the South Nicholson Basin and Lawn Hill Platform across the inlier, the Wearyan Shelf and the Pellew Islands

The extent of this profile allows the dense Pellew section and the relationships beneath the South Nicholson Basin south of the inlier to be placed in perspective.

The combined gravity and magnetic model shows that the felsic piles were locally deposited on the granite in this zone although the gravity field suggests that the model may contain about one kilometre too much volcanics. Alternatively, the deviation may be a 3D effect. The models stress how little granite forms the inlier in this zone and leave no doubt about the presence of substantial volcanic and magnetic successions south of the Fish River Fault — which extend north of the Fish River Fault exposure. These are not overlapped sequences.

The magnetic profiles seem ragged and this is partly due to the compression of the data in the plot. Several of the spikes have been tightly fitted to evaluate the origin of the spikes, as distinct from the lumpy regional effects. In each case the spikes reflect extent of units, truncation by cover, small faults near surface or low relief on the main mafic pile.

The thickest felsics in the detached slab occur near the position of the Calvert Fault while the thickest mafics occur as a major accumulation beneath the Wearyan Shelf. The sequence beneath the detachment is comparable with that near the Calvert Fault and the crude correlation would suggest a displacement of about 60 km in this section. The implied displacement on lines 34 or 35 might be no more than 25 km. The present work shows convincingly that a major detachment exists; detailed 3D analysis would be required to refine the details and the actual displacement which is clearly of the order of 25 to 40 km at least.

The Wearyan Shelf region is marked by thin (absent?) felsics, thick mafics and a granitic basement.

The large positive gravity anomaly near the Pellew Islands can now be explained. It is due to a combination of effects; absence of granite in basement, moderate volcanic pile thickness and a possible older rift fill.

**PROFILE 44** (figure 9) extends NNW across the inlier from the South Nicholson Basin to HYC

This orientation and position presents an intermediate assessment of the inlier (contrast 34 and 35/42). Total detachment of the granite is indicated with a displacement of about 40–50 km. The gravity field provides the sensitive test to this hypothesis in this case. It imposes severe limits on the extent and depth range of the inlier granitoids. It should be noted that mixing granite compositions and bodies does not readily lead to any alternative in structural style since all will have been detached and incorporated in the shifted slab. As such none have any substantial contribution toward the gravity field at the inlier.

The profile is sub parallel to the Emu and Calvert Fault systems SE of HYC and cannot provide a clear representation of them. These limitations notwithstanding these faults occupy a zone in which basement granite crests, presumably reflecting old fractures, and the subsequent felsic and mafic volcanics are thinned and thickened. Both units also thin onto the inlier basement.

These relationships may be detected beneath the inlier and the Nicholson Basin with regional thinning of the volcanics to the north.

Future analysis will detail the anomaly patterns in the region of the South Nicholson Basin but preliminary evaluation at 225 km indicates some repetition of the detachment pattern affecting the Tawallah Volcanics at depth. These units have been covered or removed by the rocks of the basin.

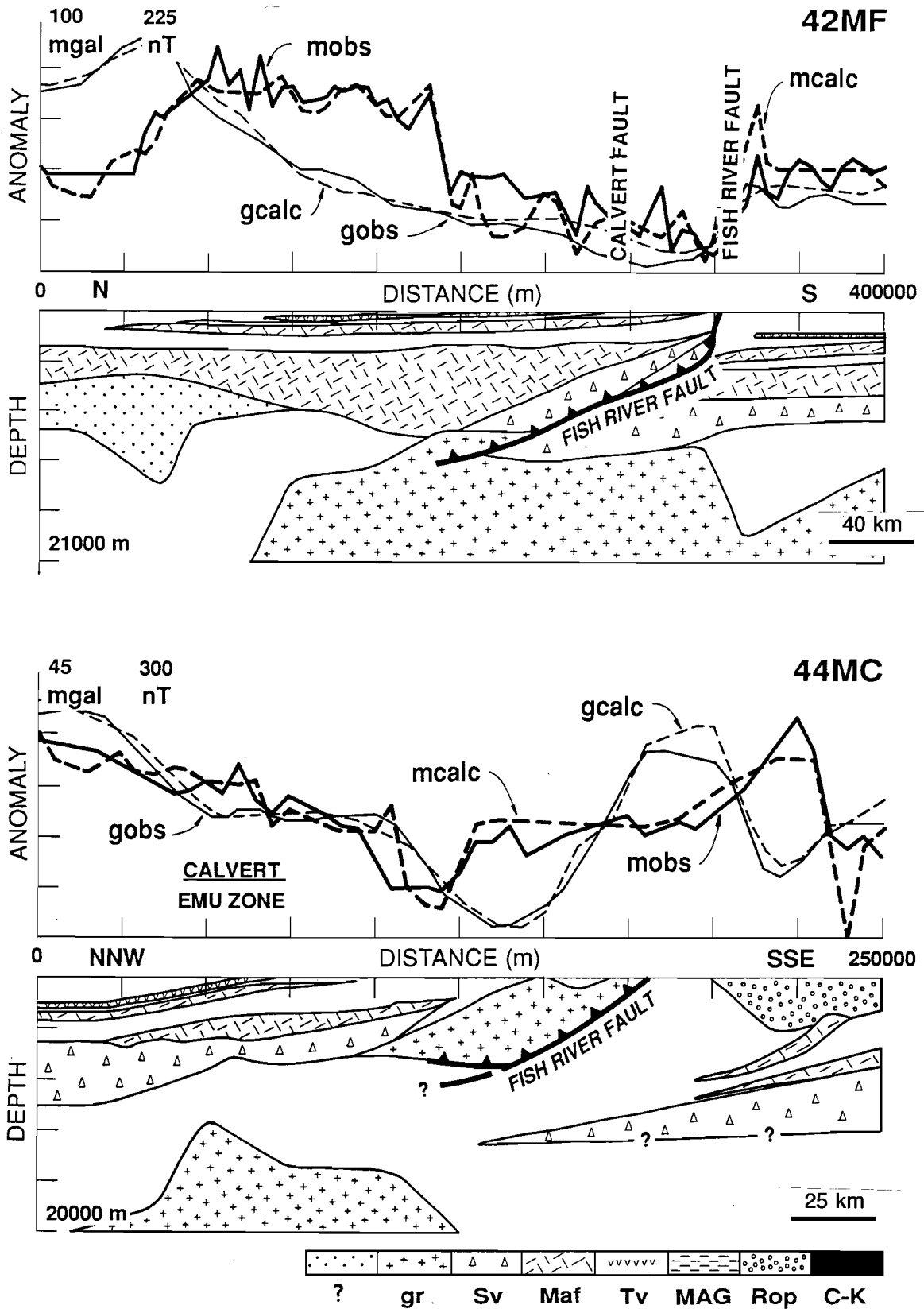


Figure 9 — 2D gravity and magnetic models for profiles 42 and 44.



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**PROFILE 46** (figure 10) extends along the Gulf Coast near the northern edge of the Wearyan Shelf

The models are good fits and suggest a thick mafic cover on a wedge of felsics which increases in thickness toward the inlier. The balance of the base of the basin is composed of a dense non magnetic unit near the Pellew Islands.

Neither model for profile 46 and 50 include the effect of the thin Tawallah volcanic units. They are essentially irrelevant, certainly thin and may not always be present. No high relief information is available to resolve them and most of the apparent spiky effects can be explained by local warp and step features in the top of the mafic pile. Granite underlies the Wearyan Shelf in this region but may be locally absent beneath the Pellew Islands.

This view is consistent with the ten profiles which intersect line 46.

**PROFILE 50** (figure 10) is an east–west line across the heart of the shelf

This demonstrates the ubiquity of both thick mafics on the shelf and a granitic base. Major changes occur in all components at 30 and 100 km and controlling structures are implied which have influenced all developments including basement granitoids.

The models show that neither the felsic nor mafic cover is universal but that the felsic piles are greatest near a zone a little east of the Emu Fault Zone or abutting the Murphy Inlier. The mafic volcanics are more broadcast, at least across the Wearyan Shelf.

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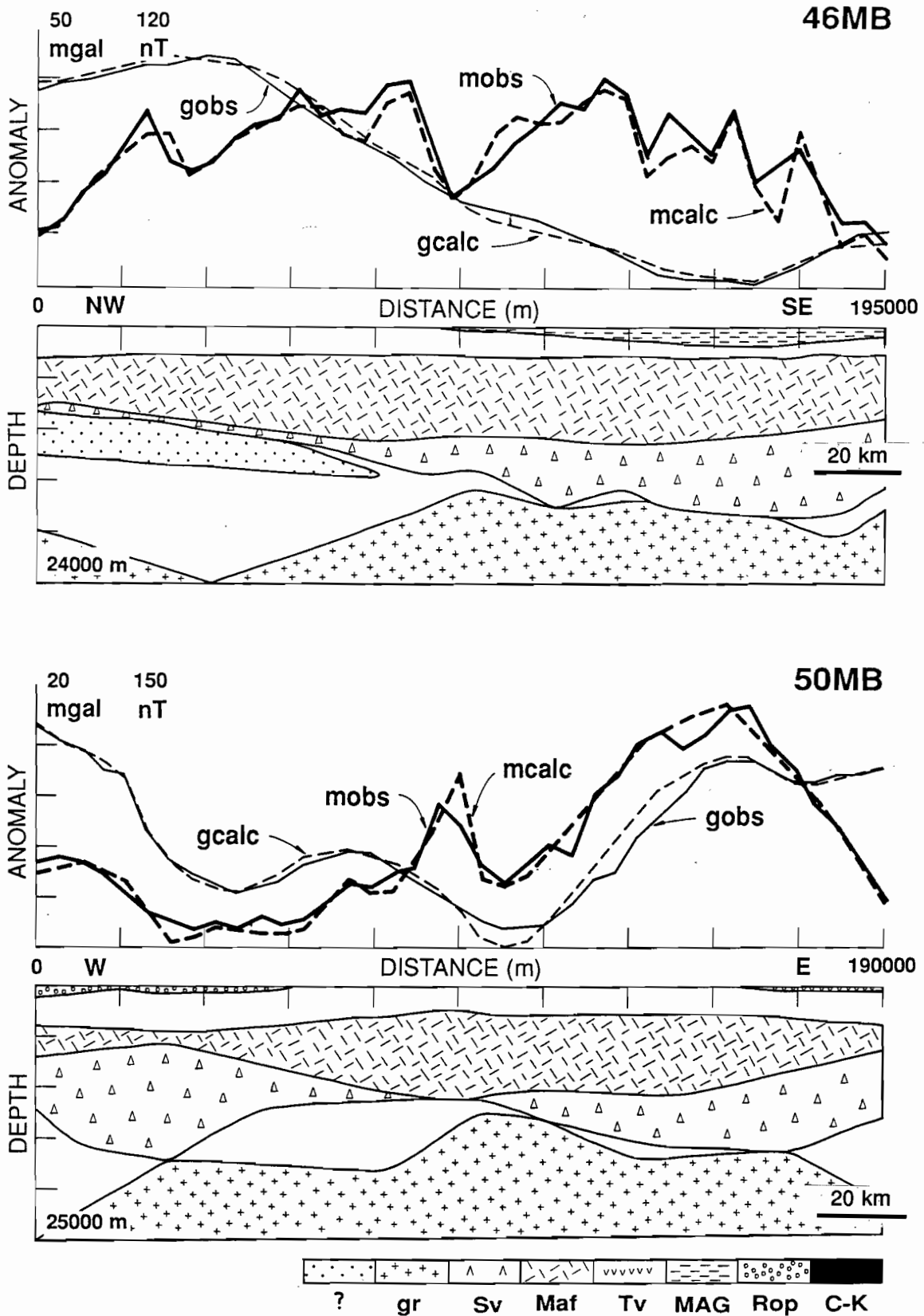


Figure 10 — 2D gravity and magnetic models for profiles 46 and 50.



## DISCUSSION

The results of all profiles, including the overlapping data provided by the Batten and Wallhallow analyses, have been summarised in figures 13 to 19.

Figures 11 and 12 present the implied form and distribution of the basement granitoids. The interpretation indicates that the granites of the basement are continuous and only locally sundered or absent in the northern part of the shelf. The granite complex is however terminated by a NW or WNW trend near the gulf coast.

The nature of the roof of the complex is dominated by sub N-S axes which extend to the disturbed, difficult to interpret and complex region of the inlier. Some subsidiary NW elements may be recognised but NE trends are rare; the most obvious being in the zone south of the Pellew Islands where the granite is locally absent. This type of character would be consistent with crustal extension and rending of the entire crust. It should be noted that comparable extension patterns are occupied by thick wedges of both volcanic sets in the adjacent Batten region where the granite basement is totally disrupted or separated. The effect is consistent with complete separation and extension of a once contiguous granitic crust. Leaman (1993a) has shown that this effect has strongly developed N-S and NE elements.

Figures 13, 14 and 15 indicate the thickness of the interpreted felsic sequence which is either basal, or virtually basal, within the basin. The thickness of the felsic volcanics is very variable and the thickest pods occur to both east and west of the Wearyan Shelf zone which may be defined (see below) as the core region in the Robinson River and Calvert Hills sheets. Axes of deposition may be virtually N-S — as near the limits of the shelf — or NE or NW within it. There is local podding along the Calvert Fault system but in general the felsic cover is patchy to non-existent within the shelf zone. The profiles show that this core zone consists of thin felsics on elevated granitic basement crust.

The interpretation is least certain at the western extension of the inlier where it is impossible to separate the blocks of felsics which lie above or below the detachment due to the absence of any mafics.

Figure 15 presents an indication of the thickness of felsic volcanics beneath the inlier and Fish River Fault detachment and extending beneath the South Nicholson Basin.

Figures 16 and 17 present isopachs for the principal mafic accumulation. Figure 16 essentially explains the nature and origin of the stabilised Wearyan Shelf; there is a thick unbroken blanket of these materials.

The limits of the mafic deposits are well defined; a NW-SE structure near the gulf coast, a N-S structure to east and west and an E-W structure parallel to the

inlier, and the inlier itself. The origin of the inlier and its detachment may also reflect the disposition of the shelf cover and the elevated granitic basement with thin felsic cover. This coherent block has not buckled under compression, simply snapped and overthrust from a root weakness which was part of the control system for the mafic pile.

The most important structures were probably those which define the gulf coast and the western shelf edge. Relief within the mafic pile is greatest near the western edge. It is interesting to note that no significant post Tawallah sedimentation occurs east of this position and that it trends N-S, as does all the younger Batten Region deposition.

It is possible that the entire region was erratically covered by felsic sequences (cover 1) and then, much more completely by cover 2 which included flood basalts. The mafic component of this cover may have averaged 5 to 8 km in thickness. Parts of this cover have survived but, where further active structuring or uplift has been focussed, some has been eroded and perhaps completely removed. Uplift and erosional processes may well have led to the complex patterns and relationships inferred in this report and, more especially, that of Leaman (1992) for the Batten Region. The Batten zone, with considerable post cover 2 activity, has left the Wearyan Block intact and simultaneously caused its gently uplift through Tawallah and later times resulting in generally thinned sequences after the formation of the basal cover sequences.

Figure 17 indicates the onlap limits of the mafic pile in the region of the inlier. These positions generally lie north of the limits of the younger Tawallah formations and the edge effects of all units accounts for the general ridge character in the magnetic field as well as the general WNW orientation. Figure 17 also suggests the distribution and thickness of the mafic sequence beneath the inlier and the South Nicholson Basin. A major N-S offset is implied near the centre of the inlier within the area studied. Assuming that all pre McArthur-Fickling Group sedimentation onlapped the proto inlier and that there was a zone in which no deposition occurred then the offset of the detached block must be at least 30 km. This is a crude estimate based on the limited information in this diagram and further work will be needed within the South Nicholson Basin in order to improve definition.

Figure 18 presents an attempt to define the attitude and location of the detachment. If the reach and amplitude are indeed of the scale inferred then all structural assemblies east of the Batten and Tawallah Ranges must allow for this post Tawallah compression. The surface may be ramped or compound in order to account for the central offset. The structure cannot be described at its western end due to the

general absence of mafic rocks (see also Leaman, 1993a).

Figures 19 and 20 summarise observed and inferred trends within the region based on the present analysis.



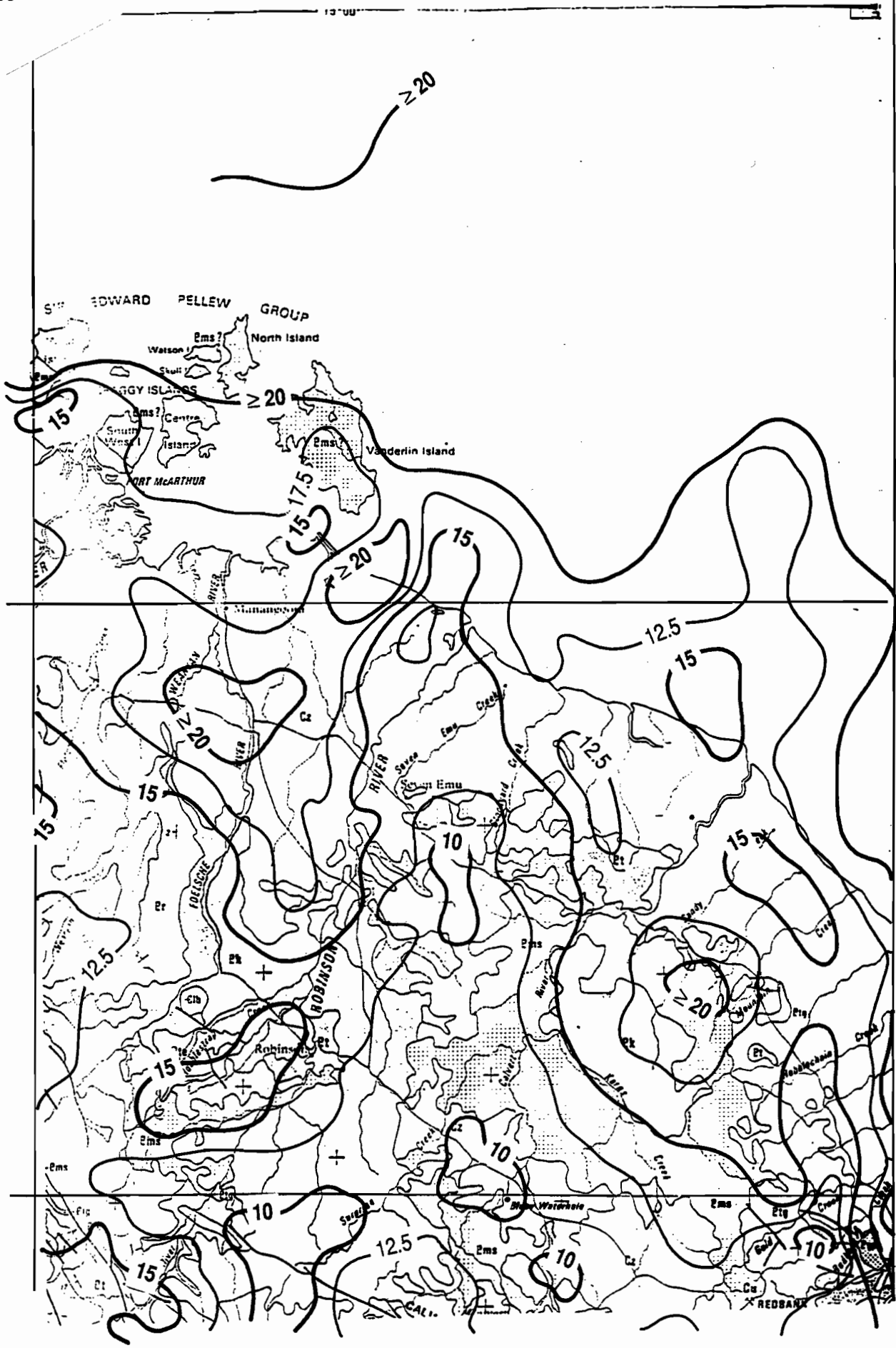


Figure 11 — Distribution and form of the upper surface of the basement granitoids in the Wearyan Shelf region.



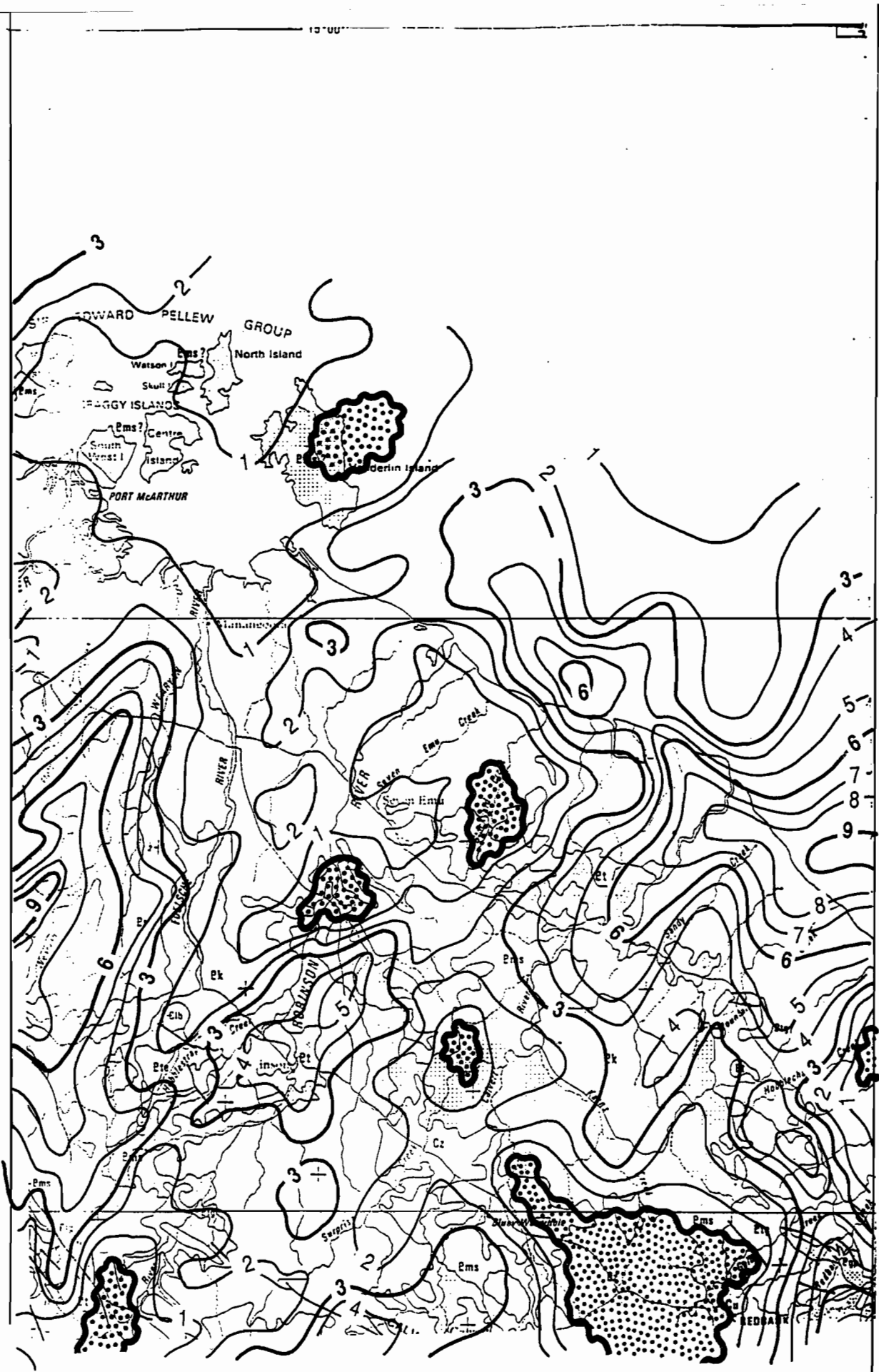


Figure 13 — Thickness interpreted of lower felsic sequence, Wearyan region.

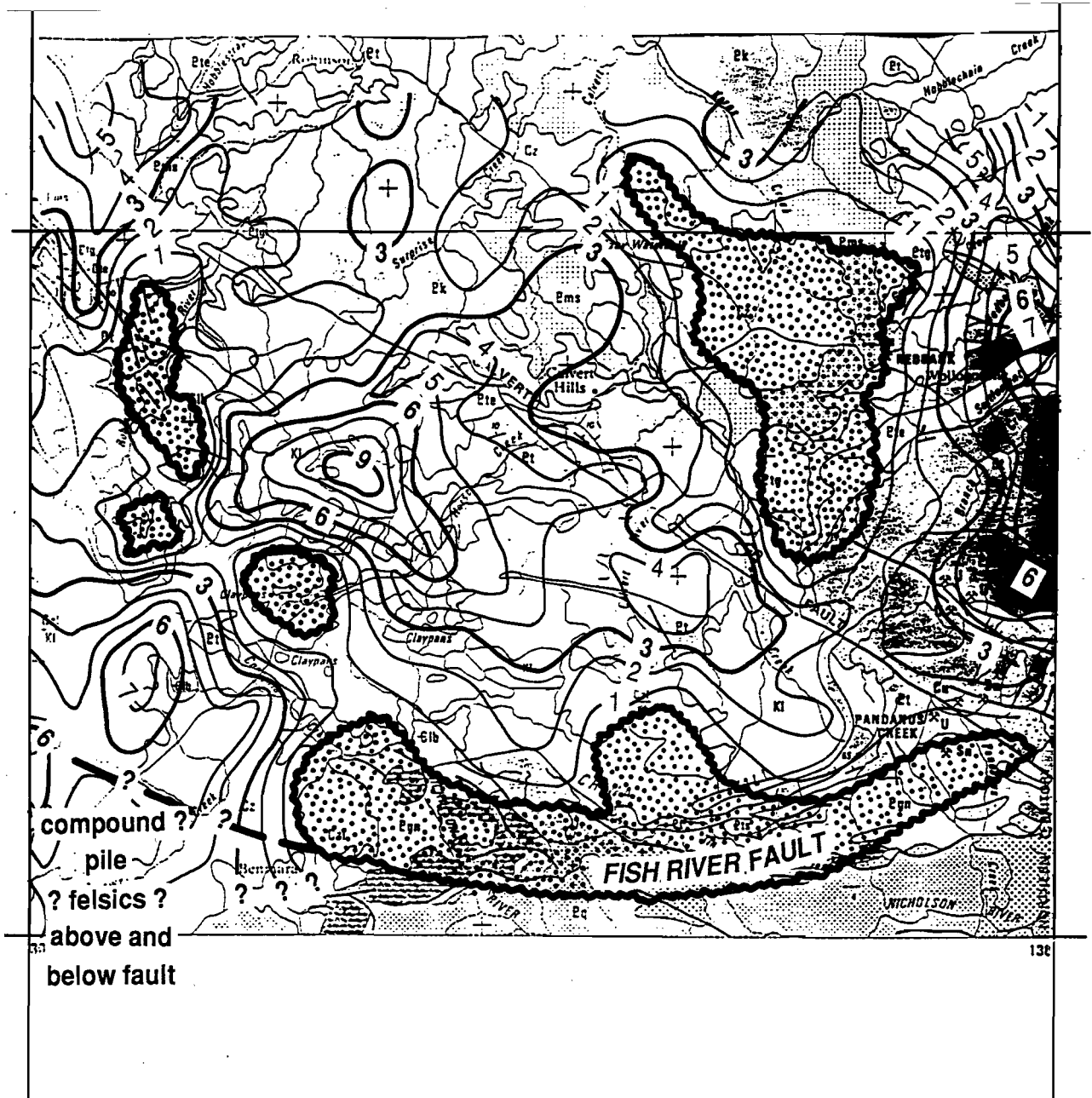


Figure 14 — Thickness interpreted of lower felsic sequence, Murphy Inlier region.



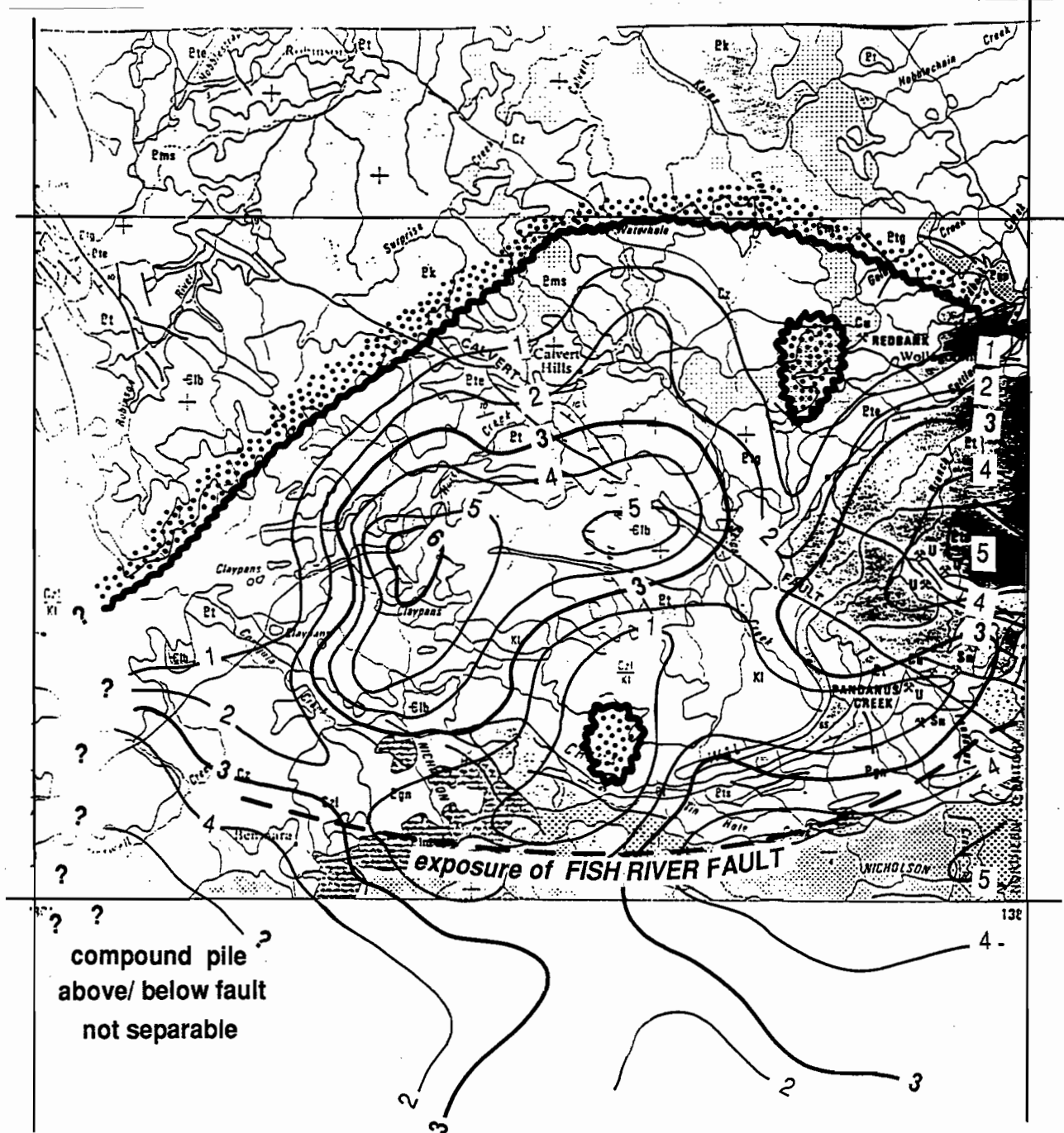


Figure 15 — Thickness interpreted of lower felsic sequence beneath and south of the Murphy Inlier.





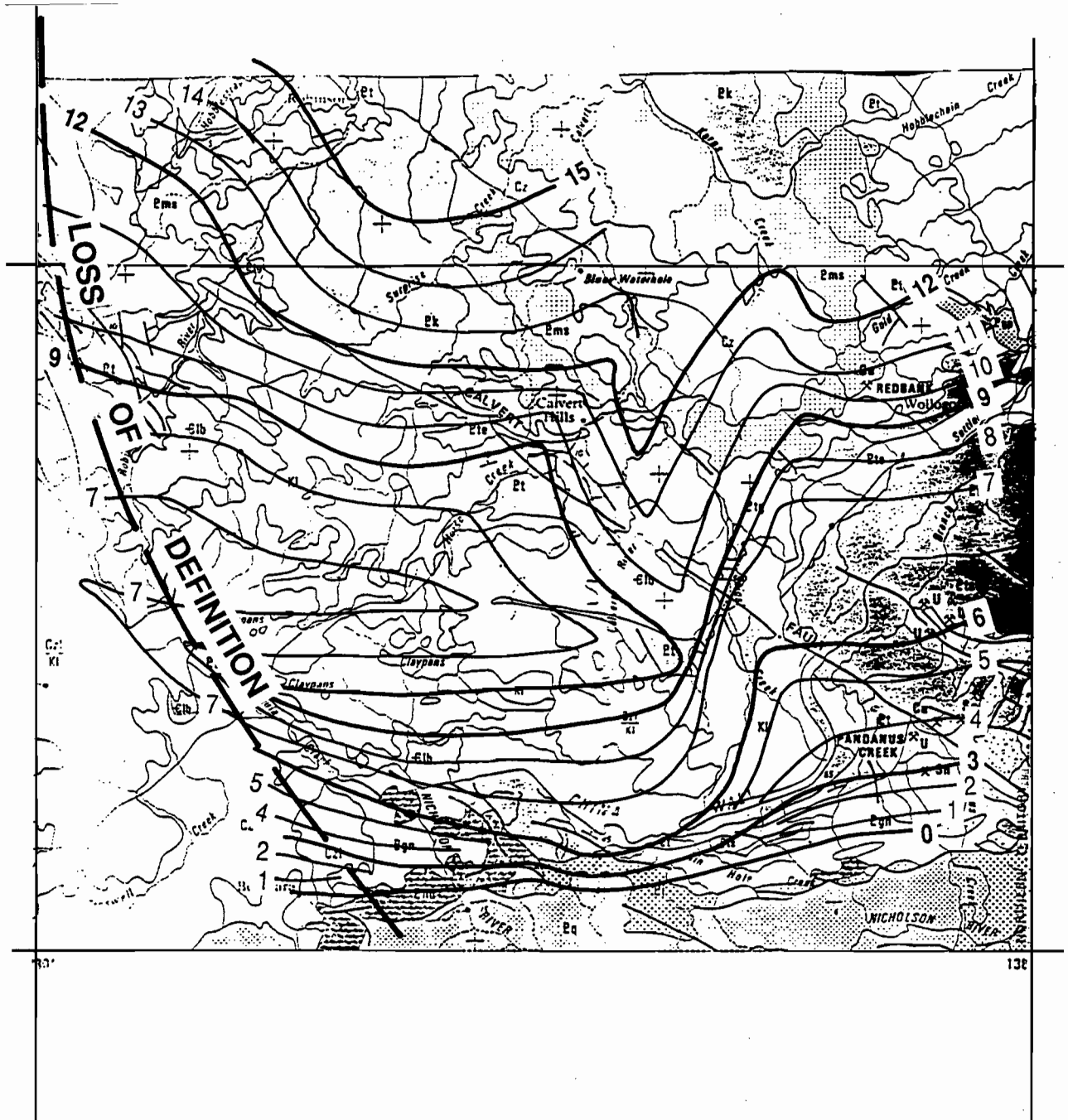


Figure 18 — Structure contours for interpreted surface of Fish River Fault detachment of the Murphy Inlier.



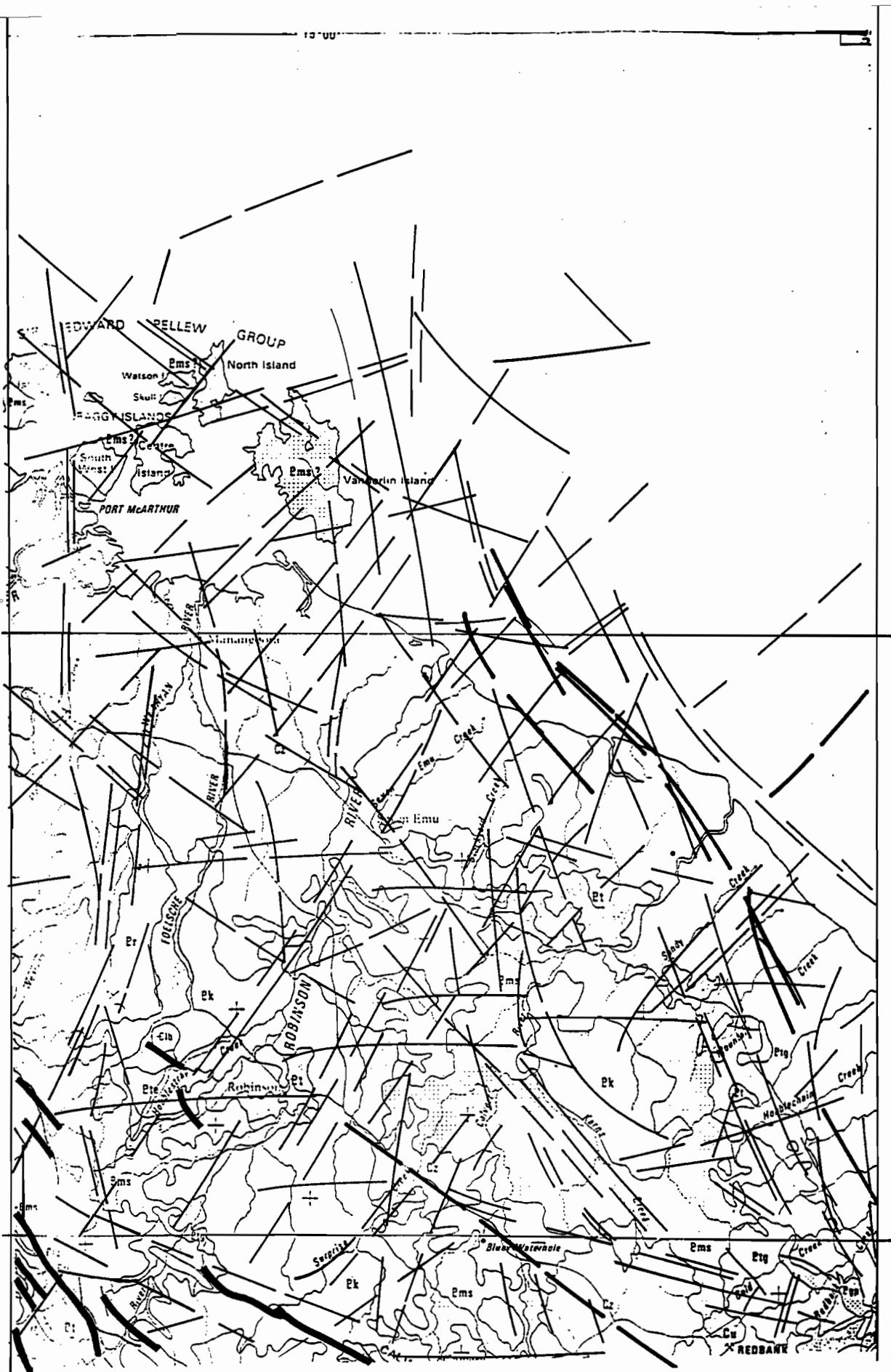


Figure 19 — Trends inferred from observed fields and interpreted structures, Wearyan Shelf region.



## MINERALIZATION AND EXPLORATION SIGNIFICANCE

Although varied mineralisation styles occur within the southern part of the shelf — largely associated with the granitoids of the Murphy Inlier — there is little established base metal mineralisation apart from the Redbank area (Cu). This is hardly surprising given the shallow, largely undisturbed and thick blanket of mafic rocks within the region. There is little reason to anticipate significant fluid transfers through this pile, from it, or from the units deposited on it, and there are no major fracture systems to transfer fluid in any event. The only major structures occur peripheral to the Wearyan Shelf slab, which is where Redbank is, and potential host rocks are not significant east of the western margin of the shelf. West of it, however, lie the Emu and Batten Troughs.

The Redbank area is located on a basement granite high with negligible felsic cover. It lies at a corner edge for the mafic accumulation and large fracture systems can be inferred.

Similar comments apply to the felsic piles and any mineralisation which may be related to them. The greatest potential must lie between the western edge of the shelf and the Emu Fault zone but much of this area is covered by relatively recent materials. A possible Pb–Zn target exists in the central west of the Calvert Hills sheet under cover. The felsics are thickened and adjacent to both Calvert and Emu Faults. The issue is whether any McArthur Group rocks are also present. There is a possibility of this.

Another possible target zone lies near the north edge of the shelf adjacent to the Emu zone but the interesting materials seem very deep with the possibility of leakage to the inlier and limited host potential.

Perhaps the most important issue arising from this stage of work relates to the Murphy Inlier and its time of emplacement. Review of existing geological maps and legends does not unambiguously allow dating of movements on the Fish River Fault zone — and its history is undoubtedly complex. It is overlain by some members of the McArthur and Fickling Groups and this places some limits on high level emplacement of the inlier. Indicated relationships could well place a major event within the basin near the time of deposition of the youngest McArthur Group rocks, i.e., those which host HYC. Such an event could well transform thermal and fluid flow conditions with important consequences. All the relationships along the south side of the inlier need to be carefully reviewed and any possible correlations between the South Nicholson and Wearyan basins should be tested. The analysis reported here also suggests that the Tin Hole Hinge Line — which marks the northern face of the inlier — is simply a

consequence of the uplift and slab bending; the fundamental structure lies within the Fish River Fault Zone on the southern face.

The contrast between this Wearyan region and the Batten region could not be more marked and the basin evolution has been much more limited and stable. Yet, there may be important temporal clues to critical activity as noted above in terms of the Murphy Inlier. If the Batten zone does represent a more complete evolution then the examination of the Bauhinia Shelf should reveal an image comparable to the Wearyan Shelf.

## ROBINSON RIVER SEISMIC DATA

Figure 21 presents a reflection panel observed by the BMR at Robinson River (16° 31.1' S, 137° 3.6' E).

The interpretation reported here suggests a 3 km thickness of Tawallah and younger formations. These directly overlie about 9 km of largely mafic units and negligible felsic units unconformably. Basement may thus be inferred at 12 to 13 km with granitoids at about 15 to 16 km.

The reflection record suggests some coherent noise and broken events at approximately 2, 2.5 and 3.1 seconds with a major ringing event at 3.5 s, another broken event at 4 s, a multiple response at 4.4 s, and other broken events at 5–5.1 s with a major ringing event at 5.6–5.7 s. Other strong or broken events occur at 6.5, 7, 9, 9.3 and 10 seconds.

If we assume that the velocity through the Tawallah cover is of the order of 4000 m/s then allowing for near surface reductions the events then all events less than 2.5 to 3 seconds are likely to be within this cover.

The major ringing event at 3.5 seconds is consistent with the top of thick high velocity mafics at around 4 km. If the velocity within this mafic sequence is of the order of 5000–5500 m/s (reasonable and possibly conservative) then the base event should be expected about 2.5 seconds later — at about 6 seconds. A major ringing event has been observed at 5.7 seconds suggesting that the interpretation is feasible.

A strong single event at 6.5s may mark the base of the felsic and basin cover and onset of basement.

It is hazardous to infer more than the above given the angularities implied in the interpretation and the limited extension of the seismic coverage which may be influenced by sideswipe and diffraction events. It would appear that the interpretation is consistent with the seismic control at least to a first approximation although neither data type is ultimately controlled.

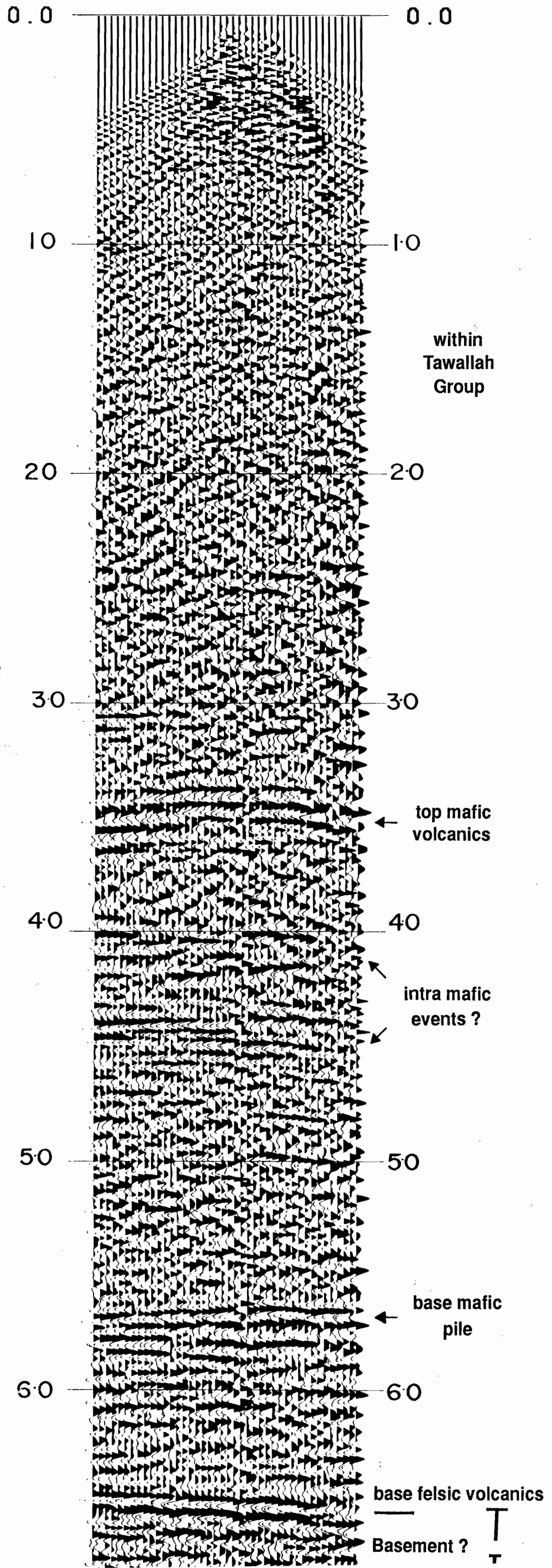
Figure 21 — BMR seismic reflection sounding, Robinson River. Location at 90 km, line 50, figure 10.

**BMR TRAVERSE 5  
ROBINSON RIVER**

16°31.1'S

137° 3.6' E

H = 60m



## COMMENTS ON INTERPRETATION STATUS

Although the combined Batten and Wearyan interpretations have involved up to 70 profiles and developed an encouraging level of consistency and cross verification relative to differing anomaly patterns and geological controls it must be recognised that many large gaps exist between the profiles modelled and that the number of profiles examined is perhaps the minimum required for reasonable interpretation results and conclusions. Some of the basic assumptions, especially those concerning properties, are retained throughout.

Regardless of these possible deficiencies and scope for revision and detailing an important structural view is emergent from the completed phases of analysis. The structural setting is essentially that of Plumb et al. (1980) for the Isa Inlier in that the Isa-Mary Kathleen with a sequence of piled, predominantly felsic, volcanics followed by a cover sequence dominated by mafics, and finally broader cover with limited extrusions (their figure 8, pts 0, 1, 2). This work would suggest an *identical* pattern in the eastern McArthur Basin.

There is some patchy exposure of parts of the felsic piles but no (negligible) exposure of the primary cover in the McArthur Basin. But this work shows that it is present generally, is disrupted in the Batten Region and also forms a key element in the Wearyan Platform.

The implications of the interpretation are such that the general basin evolution proposed by Plumb (1989) and Plumb et al. (1990) is supported. It suggests a long term extensional regime with evolution of short wavelength grabens to half grabens followed by long wavelength half grabens and sag sequences (also Plumb, 1987). By Roper Group times some reversion to short wavelength elements is evident and this indicates a possible new cycle. The above authors develop their basin evolution model from a generally consistent Tawallah Group without considering the basin precursors — which I regard as crucial to appraisal, appreciation of evolution, exploration and some aspects of fluid control and certainly volcanism. They are unable to include these elements since the limited deformation and uplift of the basin limits exposure of the key units. But this geophysical analysis has determined their presence and suggested their scale.

I propose to generate an updated conceptual section of the basin (based on figure 7 of Plumb et al, 1990) incorporating both the newly inferred Tawallah Group variations *and* the primary cover elements with the underlying volcanic piles when the analysis of the Bauhinia Shelf region has been completed (phase 3 of the project).

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## ISSUES: BASIN CORRELATIONS AND OVERALL ARCHITECTURE

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The structure- architecture element of the project is now well advanced. This report volume includes a review of the Wearyan Shelf and Murphy Inlier to the South Nicholson Basin. Previous reports have considered the Batten Trough region (Report 1) and its extension to Wallhallow (Report 2). The next progress report will contain results of analysis across the Bauhinia Shelf.

The completed studies, or those underway, have substantiated some ideas concerning the relationships and evolution of the post Tawallah Group sequences - and denied some others. All work has shown that a much deeper perspective is essential and has revealed the presence of very thick volcanics-dominated sequences early in the basin's history. The implied associations seem comparable to those of the Isa inlier. Few of these patterns can be directly verified by surface mapping in the McArthur Basin due to exposure limitations and shallow dips.

Current research, subject to refinement, has demonstrated the following:

1. A magnetically neutral basement sequence has been intruded by granitoids of mixed composition. Many appear, from their gravimetric responses, to be true granites or adamellites. The granitoids are extensive and may have been nearly contiguous at mid crustal levels (Mid Proterozoic). Some were unroofed prior to basin development.
2. Two thick volcanics-dominated sequences mark the basal cover sequences. These are separated by major unconformities or uplifts. Differences in properties show that the lower sequence is less dense and less magnetic. This can be taken to mean a less mafic content (or more felsic) or a greater dilution by sediments.

The lower sequence can be linked to real materials — the Scrutton and Cliffdale Volcanics. The upper sequence cannot be traced to outcrop. It appears to onlap and thin toward all those sites displaying the lower sequence. But it can be separated from the much thinner volcanic members of the Tawallah Group above either the Yiyintyi Sandstone or the Westmoreland Conglomerate. The upper sequence has a maximum thickness of about 9 km and its scale, and stratigraphic setting, is analogous with the Eastern Creek Volcanics within the Haslingden Group of the western Isa Inlier.

Both sequences now present varied thicknesses and relationships. These could be primary, implying basin/trough-controlled deposition, or secondary as a result of variable uplift and erosion of once more uniform and regular deposition. Systematic review indicates some of each alternative but in either case some critical zones have been defined.

Both sequences have clearly undergone partial uplift and truncation and both onlapped basement.

The lower sequence also has a maximum development of 9 km but is very erratic and rarely exceeds 3 to 4 km today. This may be contrasted with large areas of the more mafic cover where thicknesses exceed 7 km. Such thicknesses apply for about one half of the area of the basin (as studied thus far). This would imply that there was an original regular cover over wide areas.

3. Further cover and sag sequences include the Tawallah, McArthur, Nathan and Roper Groups. Parts of the Tawallah and McArthur Groups can be resolved with the gravity and magnetic



methods employed, as can the entire Roper Group package. Many irregular developments of these materials can be demonstrated.

Further, the active eastern limit of the Batten Trough is located much further east than the Emu Fault. This concealed structure and the materials which overlie it should be reviewed.

4. There is much evidence for sub E–W structuring within the basin. Two well known elements include the Murphy Inlier (and the sympathetic features such as the Carrarra Range) and the Urapunga Belt. Several other disguised features are present beneath the Batten Trough and shelf margins, as revealed during the early stages of this interpretation.

These features have been repeatedly or continuously uplifted since there is considerable evidence for thinned sequences and onlaps onto and across them prior to the McArthur Group. In the case of the Murphy Inlier major detachments are indicated.

All of these elements, although deduced geophysically and perhaps considered less than definitive in pure stratigraphic terms, nevertheless have far reaching ramifications.

In terms of the particular objectives of this project these include:

- the existence of large volumes of volcanics of varied composition with considerable potential for connate storage and supply of base metals in solution,
- possible thermal, compaction and stress control of fluid flow with specific restrictions on flow imposed by lateral and vertical changes (including facies, faults, unconformities, onlaps),
- particular control of base metal bias in any deposit related to any fluid flow through the basin sequence, whether juvenile or connate.

An accessory but no less significant aspect relates to the wider implications of the implied stratigraphy or evolution pattern across northern Australia.

Indeed, how should the gross cover elements and sequences be correlated? Can they be?

Consider three stratigraphic and evolutionary outlines of the past decade.

Figure 1 suggests an evolution for the Isa inlier. Note that a pile of largely felsic rocks is considered part of the basement. Is this really likely? The first cover sequences include a sizeable mafic component and a major unconformity/disconformity is implied above and below each sequence (Plumb et al., 1980).

Figure 2 (a, b, c) (Blake, 1987) attempts a dated sequence which distinguishes basement from felsic cover sequences. Note that the complication of two

felsic and variably deformed units within the Cliffdale Volcanics is not included.

Does part (a) of the Cliffdales tie with the Leichhardt Volcanics and part (b) with the Argylla Formation? Is it possible that the Oroopo and Magna Lynn metabasalts are also correlates and that the Argylla and Bottletree Formations are equivalent?

The Toole Creek Volcanics and Eastern Creek Volcanics may be younger than all the above. This would also imply that the Soldiers Cap Group and the Haslingden Group are equivalent or correlates.

The implied distinctions and linkages are consistent from the McArthur Basin to the Isa Inlier and they are separate from those of the Tawallah Group and younger volcanics. This is the view implied by my primary interpretation inclusive of major erosional breaks.

Younger sequences are not in dispute within the present context. It is the deep and concealed units which must be considered in the context of the McArthur Basin. And that context may not be fully appreciated until similar analyses have been completed across the region from the Arnhem Shelf to Cloncurry.

Figure 3 (Plumb et al., 1980) offers a wider stratigraphic context. A direct link is made here between Mary Kathleen, Soldiers Cap and Haslingden Groups (and perhaps the Peters Creek Volcanics) as well as to the Tawallah Group. This cannot be sustained on the dating base of Blake (1987) or my interpretation. The links between felsic units is also confusing. Should most be linked to the base of the Tewinga Group rather than to the top? Should the Katherine River Group and Tawallah Group be associated with post Quilalar and Corella Formations? All these options are possible if one apparent break in succession is really a compound break due to distal onlap or omission. This could mean that the true correlation is between Fiery Creek and Peters Creek Formations to Tawallah and top (at least) Katherine River Groups.

Figure 4 (Plumb et al., 1990) presents an alternative view of the Katherine River Group — which is why this basin architecture study should extend to the west — and provides no space for the second cover sequence and correlates. The single unconformity is clearly compound on the basis of the Isa Inlier materials and this geophysical interpretation.

Figure 5 (Plumb et al., 1990) makes the regional linkages inferred in discussion above - but omits the Haslingden equivalent now demonstrated within the McArthur Basin.

Figure 6 (Plumb et al., 1990) emphasizes the NW, N–S and rarer NE trends of the surface geology. The greater continuity of NE features and the existence of E–W elements is not indicated. It cannot be. Post Tawallah sedimentation does not obviously reflect

these earlier structures due to cover and absence of exposure of the relevant units.

Figure 7 (Plumb et al., 1990) presents an incomplete view of the basin and its development. It is largely supported by my interpretation post Tawallah Group with one exception; the Roper Group cover is not as systematic. It is much more variable in thickness. So is the Tawallah Group — but this could not be known on the basis of surface mapping alone.

The diagram also implies a fundamental control at the Emu Fault. This structure is, however, not marginal in post Tawallah terms. The ultimate position of the Batten Trough margin is 50 km further east, a position now covered by thin onlap members, and the fault was virtually central during trough development! In order to appreciate the how and why, and significance, of such structures it is necessary to define both Tawallah variations AND fundamental controls beneath the Batten zone which is clearly quite old.

A vital exploration question can be summarised. Is the stratigraphic and structural pattern which is now being developed for the entire basin sequence within the mineralised Batten Trough typical of, or possess any common factors with, other mineralised sites in northern Australia? This simply is not known at present since the kind of analysis required has not been undertaken. Such understanding may well open up many blind plays for exploration as well as allowing focus within known zones.

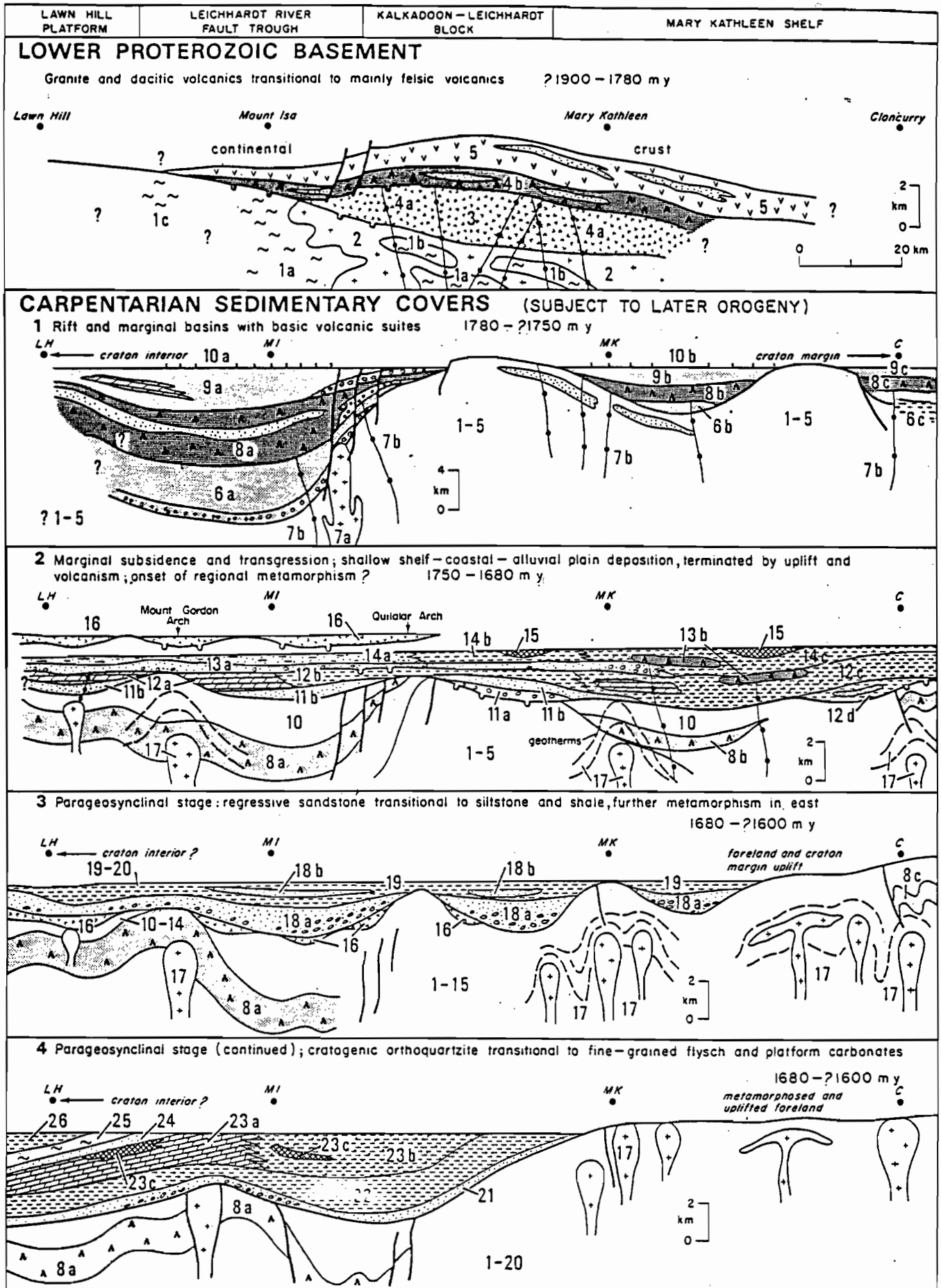
After completion of the Bauhinia Shelf study (currently in progress) the basinwide elements of the interpretation will be assembled, revised if necessary, and applied to the concepts indicated or implied in Figure 7 in order to generate a complete basin section. This should allow appraisal of all key elements in the McArthur Basin.

A similar view style must also be developed across the Isa inlier in order to assess any common denominators in deposit setting and to confirm any regional implications or correlations. For example, can the mafic cover sequence 2 be traced directly to the Haslingden Group? This work will follow the Bauhinia Shelf study.

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**LOWER PROTEROZOIC BASEMENT**

- 1a. grey gneiss, migmatite, recrystallized ?dacitic volcanics.
- 1b. recrystallized dacite, lower grade than 1a. (1a. and 1b. are pendants of the Tewinga Group or an older, pre-Tewinga volcanic sequence).
- 1c. schist, phyllite, gneiss, rhyolite — age unknown (Yaringa Metamorphics).
2. Kalkadoon Granite ( $1865 \pm_{21}^{27}$  m.y.; Zr).
3. Leichhardt Metamorphics (1865 m.y.; Zr); porphyritic rhyodacite and tuff.
- 4a. dolerite dyke swarms.
- 4b. Magna Lynn Metabasalt; basalt, sandstone.
5. Argylla Formation (1780 m.y.; Zr); rhyolite, tuff, sandstone.

(3, 4, 5 — Tewinga Group).

**CARPENTARIAN SEDIMENTARY COVERS**

Stage 1 6a–10a = *Hastingden Group*; 6b–10b = *Malbon Group*; 6c–9c = *Soldiers Cap Group*.

- 6a. arkose, conglomerate, basalt, micaceous sandstone, orthoquartzite.
- 6b. pebbly white sandstone.
- 6c. silty turbidite, sandstone, basalt.
- 7a. Ewen Granite and correlatives (1780 m.y.; Rb/Sr).
- 8a. tholeiitic flood basalt, subaerial; tuff, sandstone, orthoquartzite.
- 8b. basalt, subaerial to shallow submarine.
- 8c. basalt, submarine, with chert, jaspilite, siltstone, sandstone.
- 9a. pink to red, feldspathic shallow shelf sandstone, dolomitic to west.
- 9b. white, shallow shoreline sands, siltstone, minor basalt.
- 9c. sandstone, siltstone, chert, iron formation.
- 10a. dolomitic siltstone, sandstone; with ?halite casts.
- 10b. siltstone, limestone, jaspilite.

Stage 2 11–15 = *Mary Kathleen Group, Quilalar Formation*; 16 = *Fiery Creek Volcanics*.

- 11a. arkosic regolith, conglomerate, over basement.
- 11b. shoreline sandstone; some volcanics and stromatolites to northwest.
- 12a. stromatolitic dolomite, dolomitic and quartz sandstone; halite casts in west.
- 12b. dolomite, sandstone, siltstone, shale-clast breccia, tuff, orthoquartzite.
- 12c. limestone, calcareous and dolomitic siltstone, breccia.
- 12d. siltstone, shale, limestone, sandstone lenses.
- 13a. pebbly feldspathic sandstone, conglomerate, siltstone, orthoquartzite.
- 13b. pillow basalt, tuff, rhyolite, agglomerate.
- 14a. purple siltstone, dolomite, sandstone, conglomerate, shale-clast breccia.
- 14b. siltstone, calcareous siltstone, limestone.
- 14c. limestone, calcareous siltstone, sandstone.
15. black shale, grey limestone; Zn anomalous.
16. hematitic trachybasalt, rhyolite, basalt, tuff, agglomerate.
17. Rising geotherms in crust, felsic plutons, gabbro. (Burstall, Wonga Granites etc.; Lunch Creek Gabbro)

Stage 3 18–20 *Surprise Creek, Mammoth Formations*

18. sandstone, conglomerate.
19. siltstone, carbonaceous siltstone, shale, dolomite, sandstone.
20. sandstone.

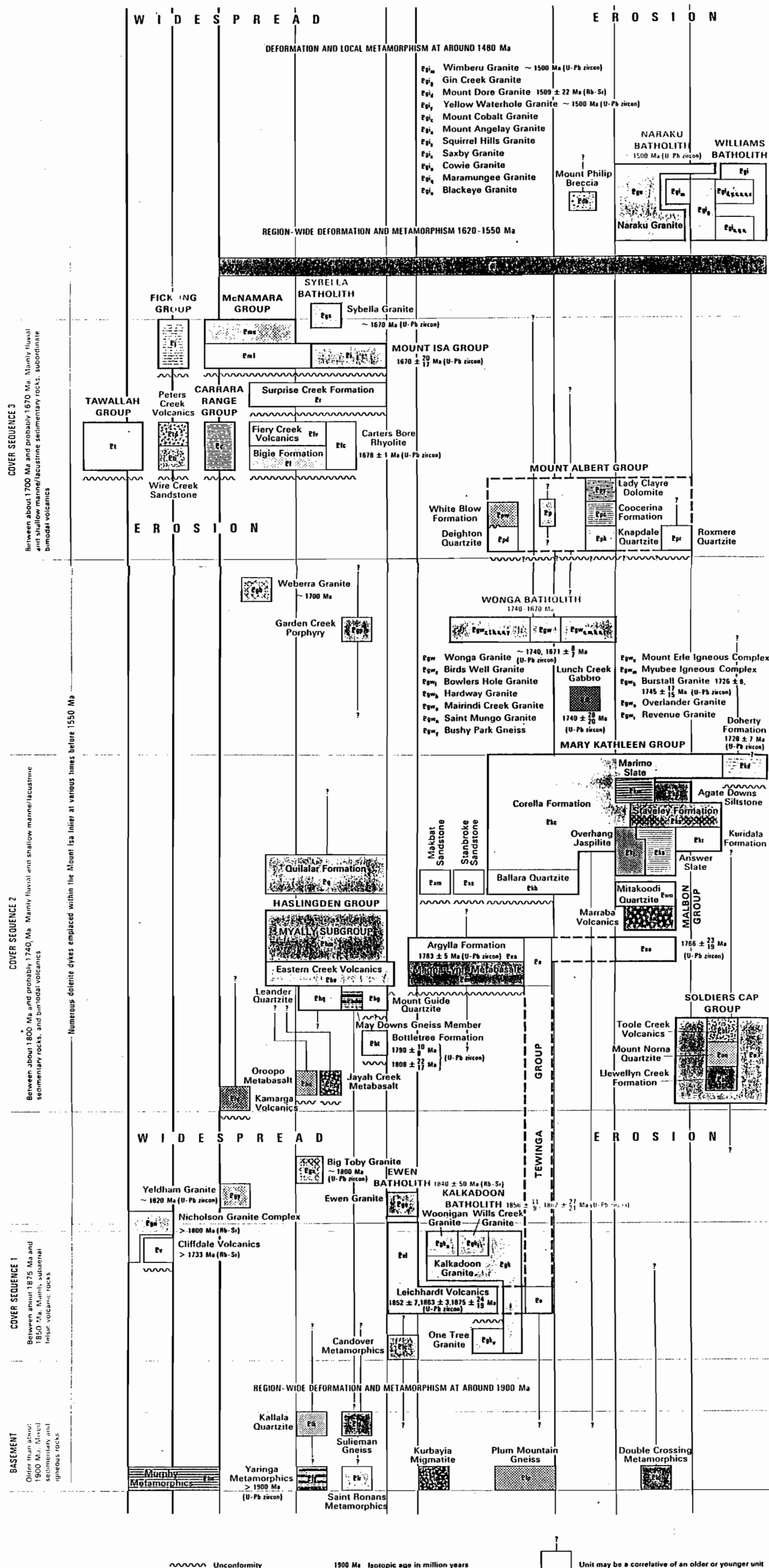
Stage 4 *Mount Isa, McNamara Groups*

21. orthoquartzite, feldspathic sandstone, conglomerate; shallow water blanket.
22. siltstone, carbonaceous and dolomitic siltstone, dolomite, fine sandstone.
- 23a. stromatolitic dolomite, chert, potassic tuff, dolomitic siltstone.
- 23c. Pb-Zn mineralization.
24. shallow water sandstone.
25. lithic sandstone, quartzwacke, siltstone, shale.
26. shale, siltstone.

Figure 8. Volcanic, sedimentary and plutonic evolution of the Mount Isa Orogen-Lawn Hill Platform. (from Plumb et al. 1990)







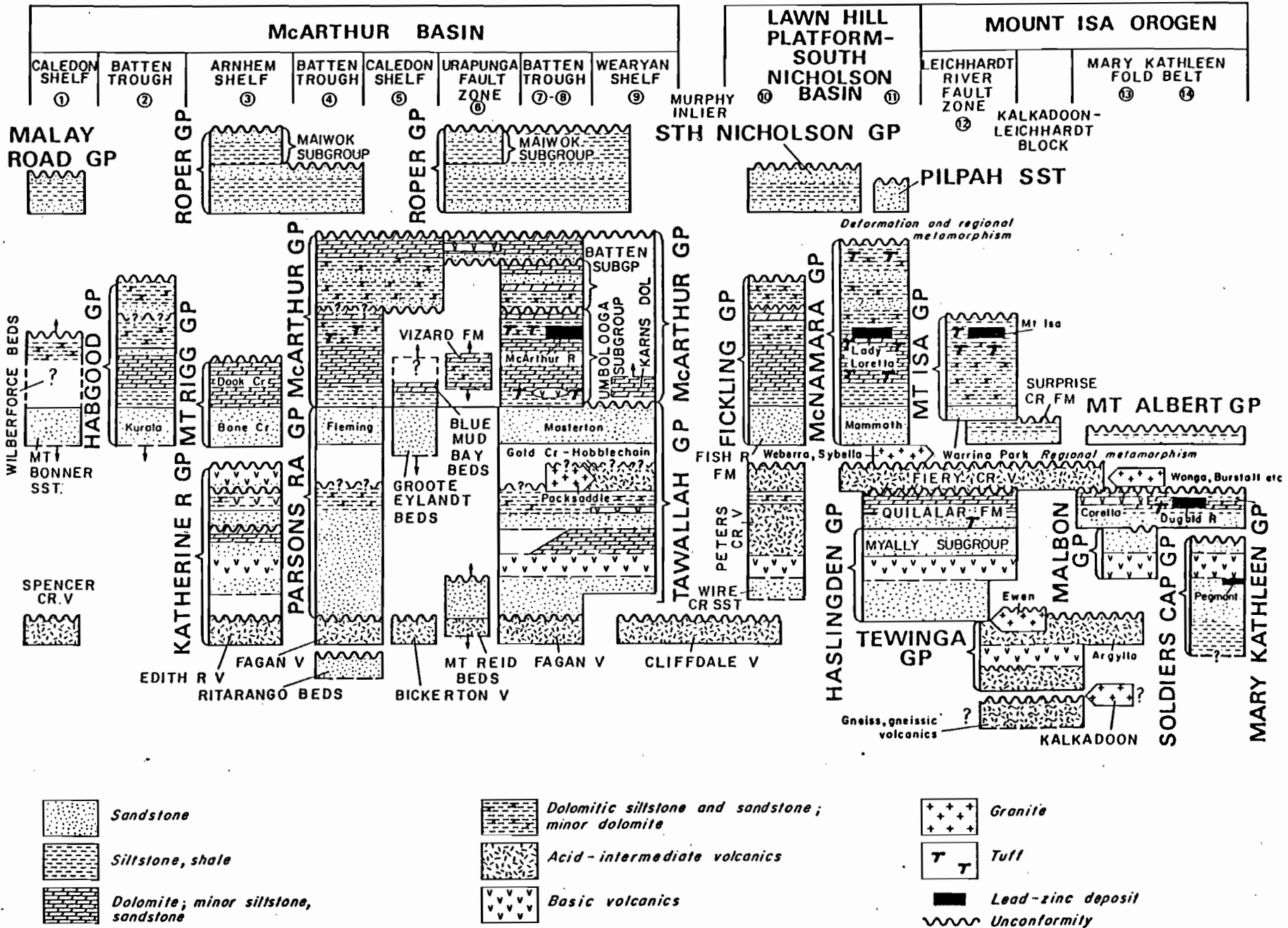


Figure 3 Inferred time relationships of principal Carpentarian rock units, McArthur Basin to Mount Isa Orogen. Locality index refers to Fig. 3.

(Plumb et al 1990)

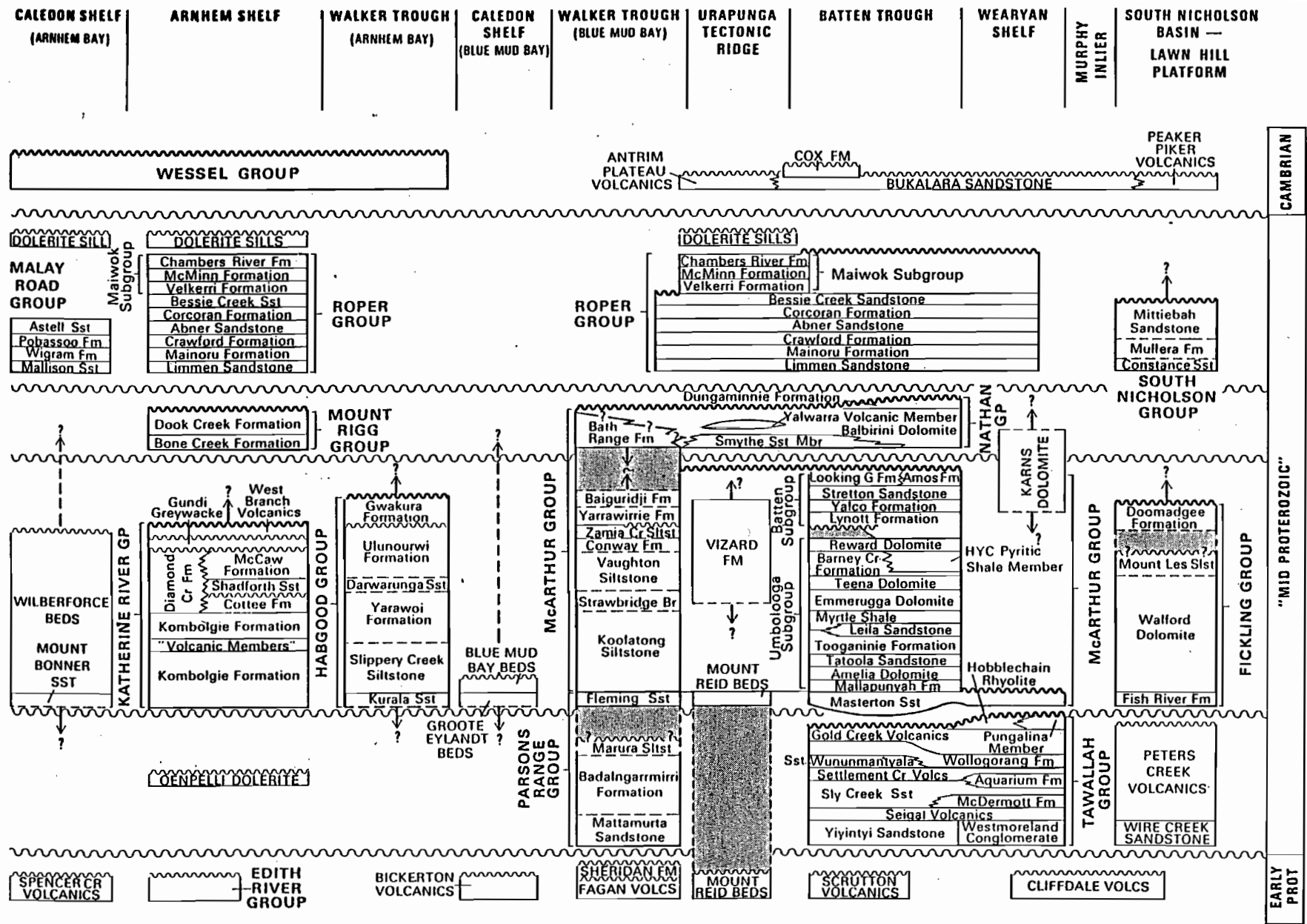


Fig. 4 Stratigraphic correlation chart of the McArthur Basin-South Nicholson Region. Patterned areas refer to time gaps postulated herein within units previously defined as continuous. (Plumb et al. 1990)

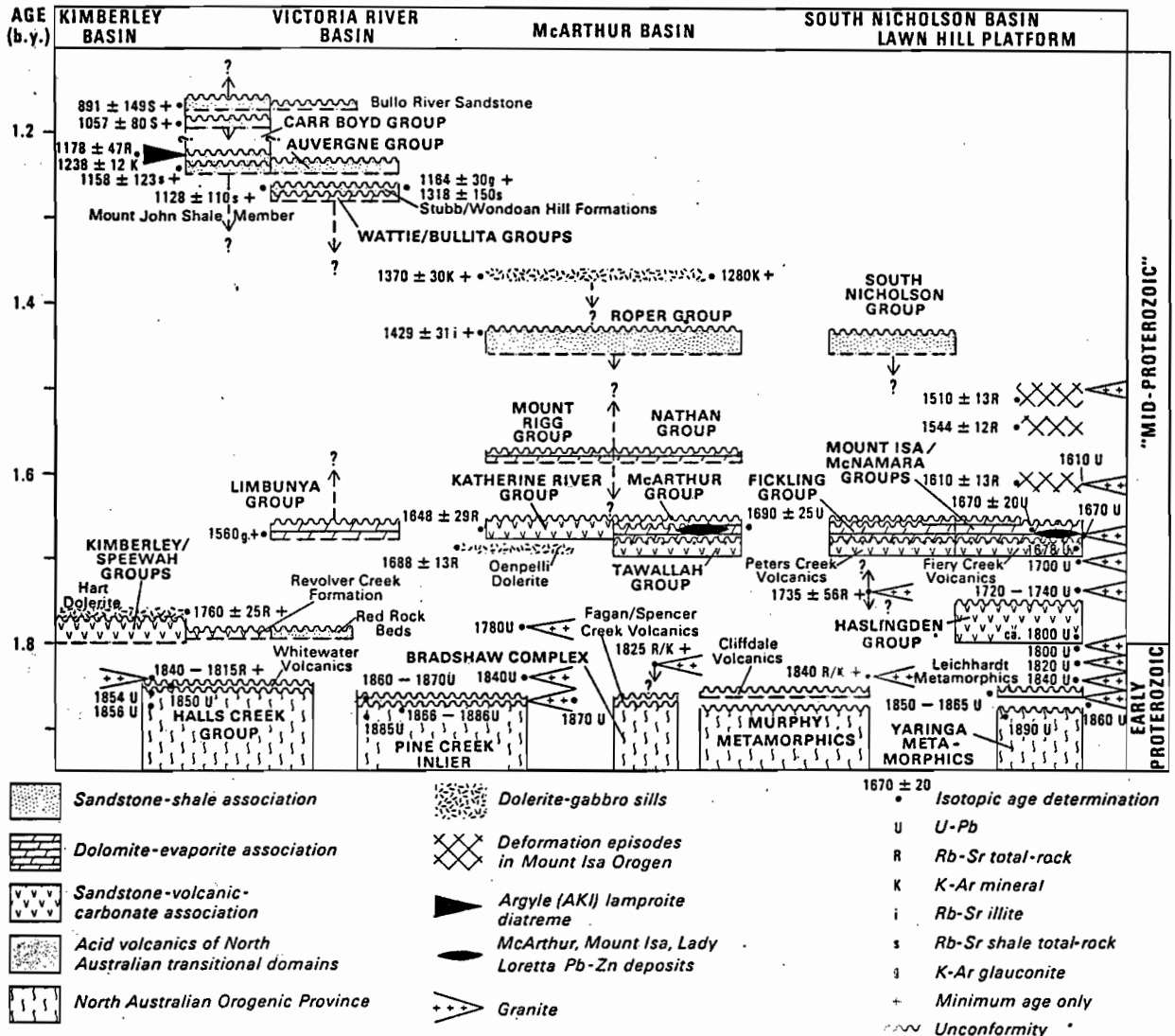


Fig. 5 Time relations for the Mid-Proterozoic covers of northern Australia. (Plumb et al. 1990)



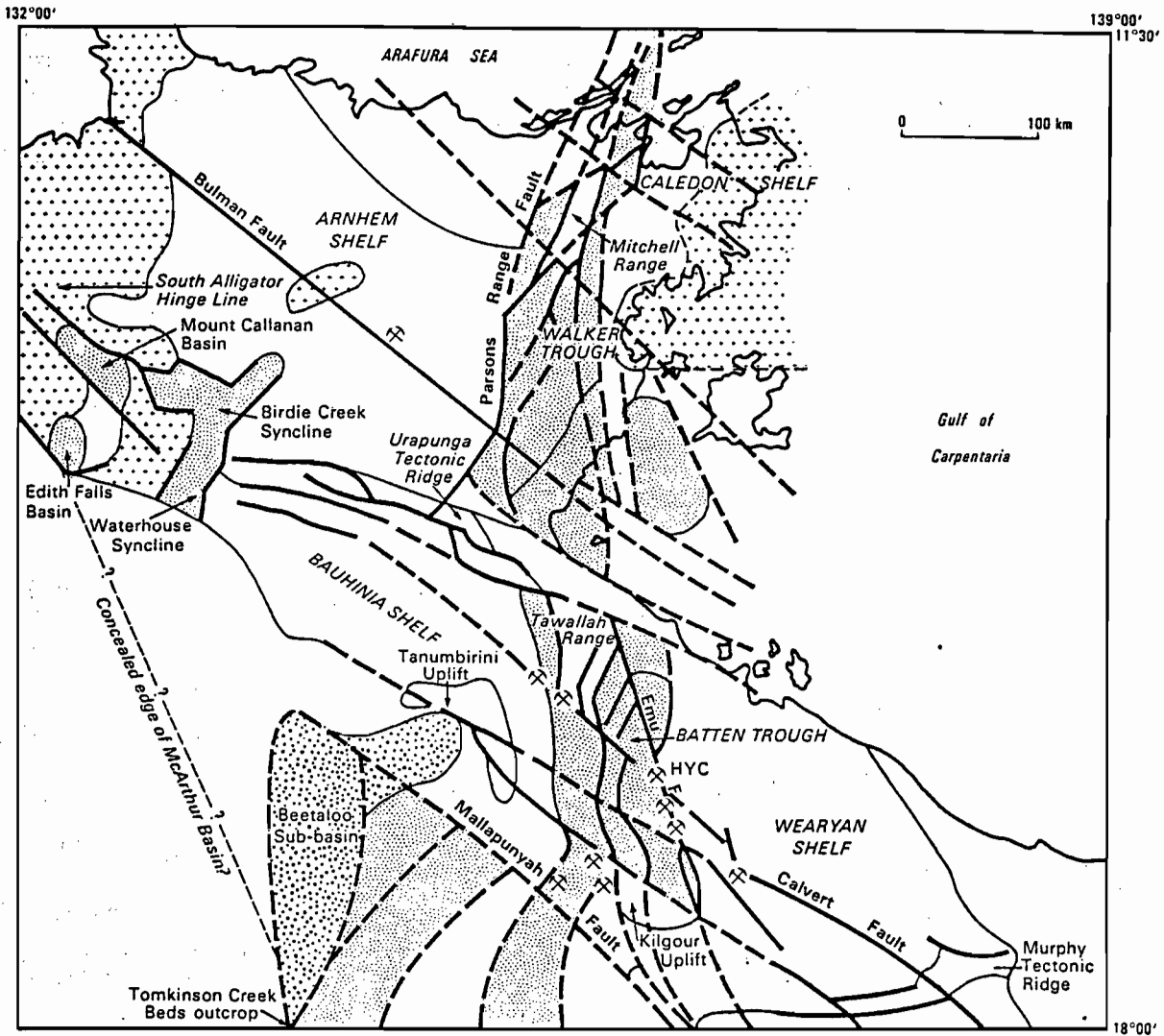


Fig. 6 Principal tectonic elements of the McArthur Basin (from Plumb, 1987). Patterned areas outline major rifts (stipples), tectonic highs (diagonal lines) and basement inliers (crosses). (from Plumb et al. 1990)

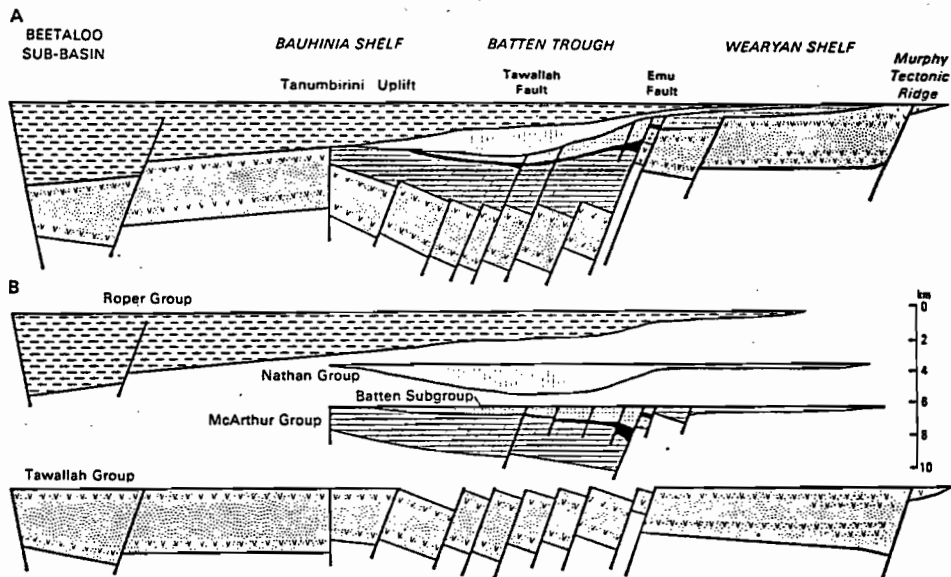


Fig. 7 Schematic development of the southern McArthur Basin, from the Beetaloo Sub-basin to the Wearyan Shelf, through the Batten Trough (from Plumb, 1987).  
 A. Schematic cross section at the close of Roper Group sedimentation.  
 B. Schematic development of the principal depositional units.  
 Horizontal length of schematic section about 500 km. Unlabelled black unit is prospective Barney Creek Formation.

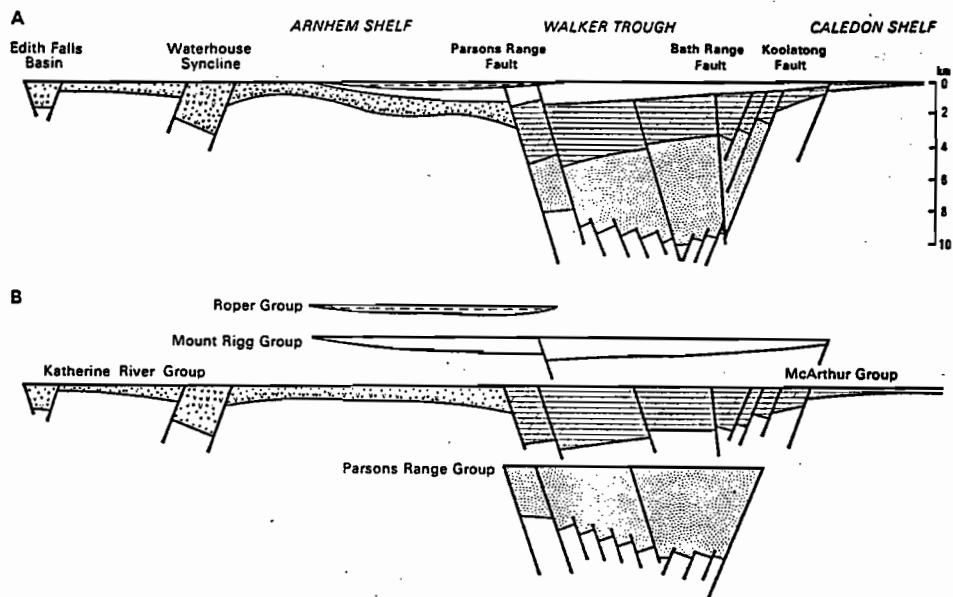


Fig. 7 Schematic development of the northern McArthur Basin, from the Arnhem to Caledon shelves, through the Walker Trough (from Plumb, 1987).  
 A. Schematic cross section at the close of Roper Group sedimentation.  
 B. Schematic development of the principal depositional units.  
 Horizontal length of schematic section about 450 km. (from Plumb et al. 1990)





## Gold metallogeny and the copper–gold association of the Australian Proterozoic

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**Abstract.** Australian Proterozoic copper–gold deposits, emplaced mainly at 1.6 to 2.0 Ga, are divided into the following categories: (1) breccia-hosted iron oxide-dominated Cu–U–Au–REE deposits spatially associated with fractionated felsic intrusions (273t Au); (2) Au ± Cu-bearing iron formations (128t Au); (3) unconformity-style U ± Cu/PGM/Au deposits (53t Au); (4) iron-oxide-dominated pipes hosted within shears and folds (147t Au); (5) Broken Hill and volcanic-hosted massive sulphides (150t Au); (6) iron-sulphide-dominated veins and replacement zones spatially related to felsic intrusions (148.7t Au), and (7) iron-sulphide-dominated veins and replacement zones spatially related to elements of regional deformation (147t Au). Categories (1) to (4) are mainly confined to Proterozoic rocks, constituting an association in which Au and Cu are commonly present together, with variable amounts of U, Bi, Co, W, Se, Te and REE. Most examples in categories 1 to 4 fall into either of two groups: Cu–Au–magnetite±hematite types formed at relatively high temperature (300 to 450° C), and Cu–U ± Au–hematite types formed at 150 to 300° C. We postulate that these ores formed from a common high salinity (15–35 wt. % NaCl equiv.), low total sulphur ( $a_{SS} = 10^{-3}$  to  $10^{-2}$ ), high  $fO_2$  fluid-type, in which metal transport was dominated by chloride-complexing. The most effective method of metal deposition was fluid mixing, achieving a synchronous decrease in  $fO_2$  and temperature. This unusual oxidised fluid association was favoured in high heat-flow extensional settings containing oxidised and/or oxidised-evaporitic sedimentary sequences. The intrusion of oxidised fractionated granites, which are commonly temporally associated with metal emplacement, acted in some places to heat and focus basinal fluids, and in others was the ultimate source of metals.

(Woodall 1988), bringing total Archean production to 51,000 t, compared to approximately 3000 t for the Proterozoic. Woodall (1979) noted that Australian production has faithfully followed this pattern (Fig. 1), although the Early Palaeozoic was also a major contributing period. Up until 1978, Australian Proterozoic rocks had only contributed 160 t of gold production, mainly from the Tennant Creek and Pine Creek Inlier fields.

In the last fifteen years, exploration in Australian Proterozoic terrains (Fig. 1) has produced a dramatic change in these figures, particularly with the discovery of the Olympic Dam deposit, aged ~1.61 Ga (Lambert et al. 1987). The total *inferred* resource at Olympic Dam is 2000 Mt of 1.6% Cu and 0.6ppm Au, although the reserves plus indicated reserves provide only 270 t of Au (Woodall 1990). Other new deposits which have contributed or will soon contribute to increased Proterozoic production include Telfer, Starra (Selwyn), Pine Creek–Enterprise, The Granites, White Devil and Mount Todd. An estimate for total “endowed” Proterozoic gold (production + reserves + resources up to 1987) is 1047 t, whereas the Archean 1987 estimate is 3089 t (Woodall 1990), and the 1987 Phanerozoic estimate is 1938 t (Woodall 1990). These new deposits have given Proterozoic gold a respectable stature compared to the other eras.

The statistics of Australian gold deposits have been comprehensively compiled by Tyrwhitt (1990), Woodall (1990), and Barley and Groves (1992). For comparison, the tonnages quoted here are based on the 1987 reserves plus indicated resources as quoted by Woodall (1990), and only deposits or deposit clusters with extractable gold reserves greater than 3 tonnes are included. However, gold-only and gold by-product deposits are considered together. Some Proterozoic gold-bearing deposits were not dealt with in the above sources, and for these, tonnage figures may be younger than 1987; individual sources are quoted in appendix 1.

The increased abundance and accuracy of age dating has enhanced knowledge of the timing of ore deposition in the Proterozoic. An important result is the episodic nature of ore deposit formation, although this is clearly biased by the inclusion of very large, single deposits such as Roxby Downs, the Golden Mile, and the Ballarat deep leads and alluvials (Fig. 2). As pointed out by Woodall (1990), this is a special feature of gold metallogeny. The distinct periods of Australian gold ore deposition are 0.25 to 0.45 Ga, 1.6 to 2.0 Ga, and 2.6

### Introduction

Past studies on the global metallogeny of gold have highlighted the late Archean and Mesozoic as the important periods of gold deposit formation (Boyle 1979; Woodall 1979, 1988; Meyer 1988), although an association between gold deposits, orogeny and volcanism is apparent throughout earth history. Global gold production has been dominated by the South African Witwatersrand deposits (2.9 Ga), at 37,000 tonnes

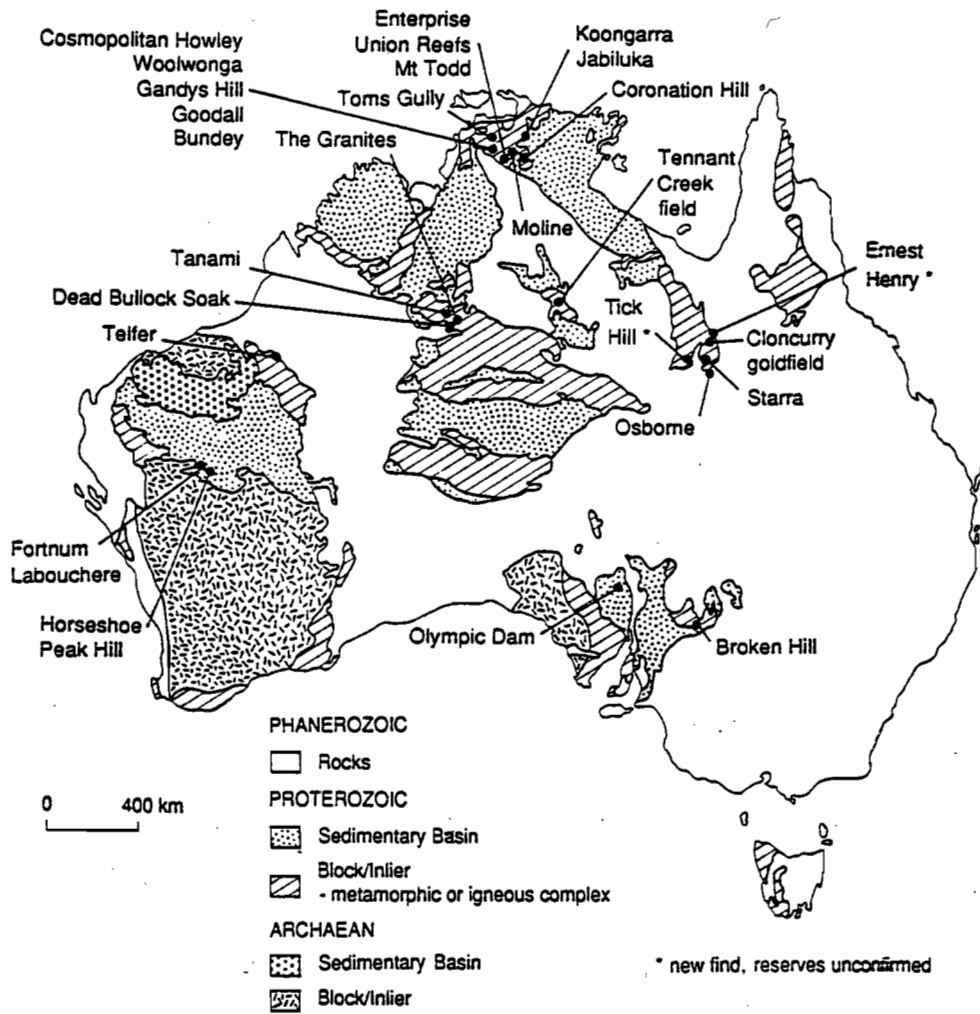


Fig. 1. Location diagram for Australian Proterozoic terrains locating the Au deposits.

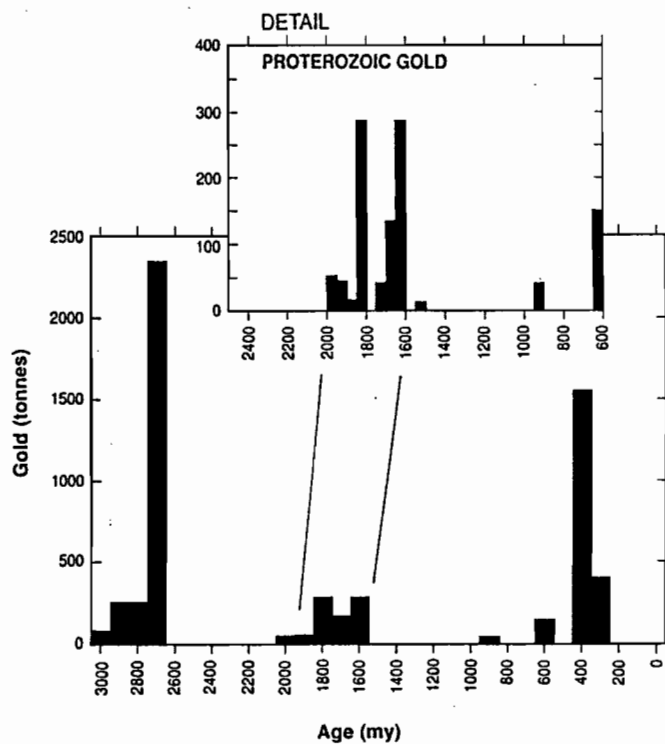


Fig. 2. Australian gold-bearing deposits: age versus tonnage.

to 2.8 Ga. It is a point of argument whether the Tertiary should also be included, because it is the accumulation period of 1730 t of placer gold derived from the eastern Australian Phanerozoic fold-belts (Woodall, 1979); this gold has been added to the Ordovician–Devonian total in this review.

#### A brief comparison between Archean, Proterozoic and Phanerozoic gold styles

Each of the three gold deposition 'episodes' (Fig. 2) has its own suite of deposit styles. Australian Archean deposits are dominated by vein, shear and fault-hosted types, and by structurally-controlled replacement deposits adjacent to faults and fold hinges (BIF and mafic-igneous hosted) (Groves et al. 1989). Most of these styles occur in greenschist facies greenstone belts, with a small number in amphibolite and granulite grade rocks. Base-metal to gold ratios are usually low, of the order of 100:1 (Groves et al. 1987). Phanerozoic deposits are mainly veins in greenschist facies turbidites (Phillips 1991), with some significant epithermal, skarn, diatreme and breccia pipe mineralisation in and around granitoids, and within felsic volcanic piles (Morrison 1988). Many of the turbidite-hosted gold-bearing reefs were formed during deformation and metamorphism, resulting in saddle, neck and leg vein-geometries within anticlines. By-product gold produced from Cambrian to Permian volcanic-hosted massive sulphide deposits is also very significant (Large et al. 1989).

Most mineralisation styles in both the Archean and Phanerozoic were deposited from reduced  $H_2O-CO_2-CH_4$  fluids which contained abundant sulphur (Ho et al. 1992), depositing gold in equilibrium with pyrite or pyrrhotite, very commonly with associated arsenopyrite. A notable feature in these styles is the lack of iron oxide minerals, and the general lack of Cu, Co and Bi as ore-forming constituents, with some notable exceptions (e.g., Cobar field, Parkes, Lancefield, and portions of some seafloor massive sulphide ores). In contrast, the Proterozoic gold deposits are commonly associated with significant Cu, and other elements such as U, Bi, Co, Mo; many of the deposits are hosted by magnetite or hematite rather than pyrite-rich lodes.

It is emerging that the nature of Australian Proterozoic gold-bearing systems differs markedly from the those of the other eras. Rutland et al. (1990) aptly describe the Proterozoic precious-metal-bearing ores as a "loosely knit group of commonly polymetallic, high level, hydrothermal deposits that are structurally-controlled and up to 300 My younger than their hostrocks". Barley and Groves (1992) view them as ore-types which are globally characteristic of intracontinental basins and large scale anorogenic magmatism. In detail, Myers and Barley (in press) find that most Proterozoic gold mineralisation was developed along the northern compressive margin of the Archean North Australian craton, associated with late deformation or granitoids. They also note a systematic younging of mineralisation eastward, and suggest that several of the large Au  $\pm$  Cu deposits associated with granitoids are

**Table 1.** Classification of significant Australian Proterozoic gold-bearing deposits and deposit clusters (> 3 t Au). See Appendix 1 for the source of tonnage figures. Contained gold is defined as reserves plus indicated reserves.

Number of deposits/gold (t)	Contained	Ore-type	Examples
2	273.0	Fe-oxide-dominated hydrothermal systems forming skarns, breccias and replacement ores. Cu $\pm$ U/Au/REE	Olympic Dam Mount Elliott
8	128.0	Fe-oxide-dominated chemical sediment-hosted mineralisation (stratabound). Au $\pm$ Cu/As	Starra The Granites
3	53.0	Fe-oxide-dominated unconformity-style hydrothermal systems. U $\pm$ PGM/Au/Te	Jabiluka Koongarra
9	146.7	Fe-oxide-dominated hydrothermal systems formed during deformation/metamorphism (epigenetic or cross-cutting) Au–Cu–Bi	Tennant Creek field (9 major deposits)
3	150.0	Seafloor massive-sulphide and Broken Hill-type. Pb–Zn–Ag–Au	Broken Hill Horseshoe
2	148.7	Fe-sulphide-dominated veins and adjacent replacement zones clearly spatially related to intrusions. Au $\pm$ As/Cu/Pb/Zn/Bi	Telfer Kuridala
13	147.2	Fe-sulphide-dominated veins and adjacent replacement zones spatially related to elements of regional deformation. Au $\pm$ As/Cu/Pb/Zn	Mt Todd Enterprise Peak Hill
	<b>1046.7</b>		

Proterozoic analogues of the porphyry copper ores which characterise modern convergent margins and magmatic arcs. This contradicts the implications of previous tectonic syntheses (e.g., Etheridge et al. 1987), which view Australian Proterozoic geology in terms of the growth and inversion of intracontinental rifts.

Significant gold-bearing mineralisation (deposits > 3 t of gold) is present in seven Australian Proterozoic provinces. In twenty two out of forty deposits or deposit clusters, distributed across five provinces, copper is present as either an economic by-product or an important associated trace element (Appendix 1). In seventeen of the examples magnetite or hematite are the dominant Fe-bearing phases in equilibrium with the ore fluids, indicating either relatively oxidised conditions, or sulphur-poor, mildly-reduced conditions.

Gold-bearing ore-styles shared between the Proterozoic and the other eras (Table 1) include massive sulphide deposits, and deformation-related Au–As vein deposits with reduced mineral assemblages. Most of these are located within either the Pine Creek Inlier or the Willyama Block. Deposit-styles confined to the Proterozoic include (1) Fe-oxide-dominated Cu–U–Au–REE-bearing breccias, skarns and replacement mineralisation, spatially associated with fractionated granites; (2) Au ± Cu-bearing iron formations; (3) unconformity-style U ± Cu/Pt/Au, and (4) iron-oxide-bearing pipes containing Cu–Au ± Bi mineralisation, hosted within shears and folds. The critical point is that in the Proterozoic-specific ore-types, iron occurs dominantly as an oxide, indicating a low reduced sulphur content. In comparison to the Archean and Phanerozoic eras, there are far fewer economically-significant examples of each ore-style; the chances of new finds being regarded as unique styles in their own right are high.

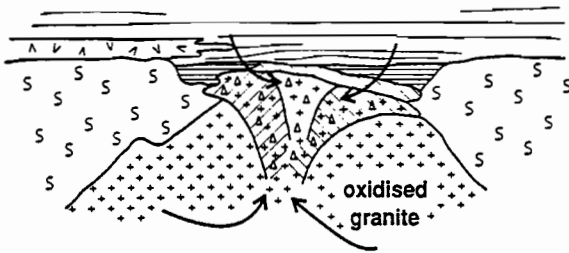
## Characteristics of the unique Proterozoic association

### *Breccia-hosted Fe-oxide-bearing Cu–U–Au–REE style (Olympic Dam-type)*

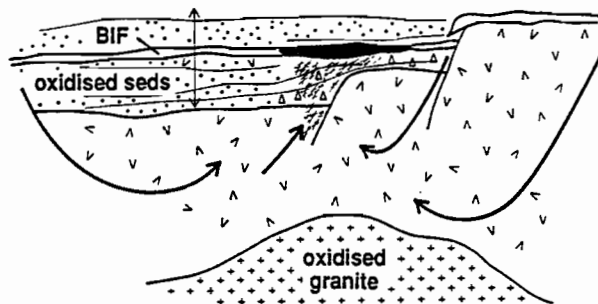
Olympic Dam is the largest single resource of  $U_3O_8$  on the planet (1.2 Mt), and one of the largest and richest resources of Cu and Au ever discovered (inferred reserves of 2000 mt @ 1.6% Cu, 0.06%  $U_3O_8$ , 0.6 g/t Au and 3.5 g/t Ag). It is the only member of the globally-distributed intrusive-related iron-oxide deposits to be mined for its base and precious metals, despite the vast scales of hydrothermal activity which characterise most other examples globally (Pratt and Sims 1990). The only known Australian examples of this style occur on the Stuart Shelf, including giant sub-economic bodies at Acropolis, Wirrda Well and Oak Dam (Parker 1990). Descriptions and interpretations of the Olympic Dam deposit are given by Roberts and Hudson (1983), Reeve et al. (1990) and Oreskes & Einaudi (1990); a summary of their work is provided below.

Olympic Dam (Fig. 3) was emplaced in a shallow extensional setting during the late stages of intrusion of voluminous, relatively anhydrous, felsic melts (Creaser 1989). Mafic and felsic igneous activity occurred before, during, and after ore deposition. The ore host, the upwardly fanning Olympic Dam Breccia Complex (ODBC; Reeve et al. (1990)), was formed in a large diatreme or maar complex, now manifested as numerous dyke-like breccia bodies in fractured, hematite–sericite-altered Roxby Downs Granite, below chaotically redistributed crater-facies sediments and epiclastics. Breccias are more hematitic towards the centre of the complex, and are divided into hematite, hematite–quartz, and heterolithic breccias by Reeve et al. (1990). A fault-bound irregular zone of crater facies

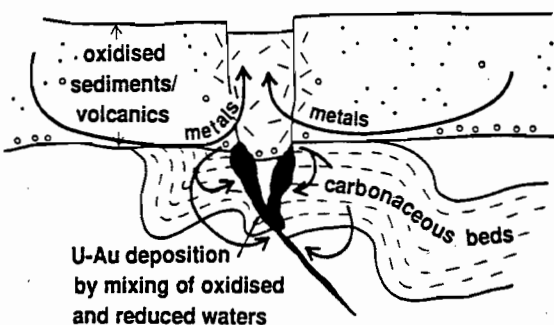
#### A) MAGMATIC BRECCIA COMPLEX (e.g. Olympic Dam)



#### B) EXHALATIVE SYN-VOLCANIC (e.g. Starra, magnetite-rich VMS)



#### C) UNCONFORMITY-STYLE



#### D) EPIGENETIC SYN-DEFORMATION (e.g. Tennant Creek)

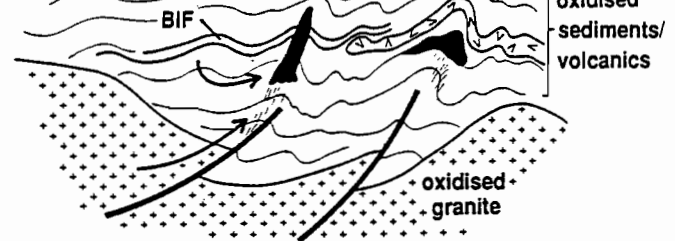


Fig. 3. Styles of Australian proterozoic Cu–Au ores. (A) Breccia-hosted iron-oxide Cu–Au±U-style. (B) Stratabound Au ± Cu in iron-rich chemical sediments. (C) Unconformity-style U ± Au/PGM. (D) Iron-oxide-dominated Uu–Cu-bearing pipes in folds and shears.

volcaniclastics, hematitic sediments, reworked breccias, and banded iron formations, formerly termed the Greenfield Formation, overlies the ODBC but is unmineralised. The entire deposit constitutes a topographic high on a Late Proterozoic unconformity surface ~260 m below the modern land-surface.

Mineralogically hematite greatly exceeds magnetite, although petrographic evidence indicates that the latter was once more widespread. Mineralised breccias (~150 in all) contain their economic grades in a sinuating zone thought to parallel a fossil water-table (Reeve et al. 1990). Pyrite is replaced by chalcopyrite below this layer, and chalcopyrite is replaced by bornite–chalcocite within the layer (4 to 6% Cu grades are common). Uranium as fine-grained pitchblende shows a positive but inconsistent correlation with Cu, concentrating at the upper margin of bornite–chalcocite zones. Gold too is concentrated in these zones (intimately associated with Cu–sulphides), but shows a clear tendency towards higher grades closer to the centre of the ODBC. High-grade Au-bearing pods lie separate but adjacent to U–Cu-enriched zones on the margins of some steeply-dipping quartz-hematite breccias. “The gross zonation from the lower and outer parts of the ODBC, to the upper and inner, is pyrite → cpy → bn → chalcoc → native Cu → gold → silicification” (Reeve et al. 1990).

Geochemical variation in a typical profile includes fluorine and barium at % levels, strongly enriched LREE (Bastnaesite is the common REE phase; Oreskes & Einaudi (1990)), and strongly anomalous Pb, Zn, Co and As. Compared to other deposits of the intrusive-related iron-oxide family (Pratt and Sims 1990), P<sub>2</sub>O<sub>5</sub> is notably deficient, and Ti is low compared to Boss–Bixby, which is the only significantly Cu-mineralised member of the Missouri Granite–Rhyolite Province intrusive-related iron ores (Hagni and Brandom 1990).

Fluid conditions during ore deposition are not well constrained, because few primary fluid inclusions are preserved. Two broad but very variable fluid populations are distinguished. One homogenises to liquid at around 400°C, containing salinities of up to 50 wt. % NaCl equivalent, in equilibrium with magnetite (Oreskes and Einaudi 1992). The other, in equilibrium with hematite, homogenises between 130 and 280°C, with a strong mode at 190°C, and moderately salinities (7.3 to 23.0 wt. % equivalent) (Roberts and Hudson 1983, Reeves et al. 1990, Oreskes and Einaudi 1992). Temperatures obtained from fluid inclusions are lower but overlap those obtained from the stable isotopes of mineral pairs. Fluorine complexing, circumstantially evidenced by abundant fluorine-bearing phases, may have transported uranium in the hotter saline fluid under reduced conditions (Oreskes and Einaudi 1990).

Location of most ores at a particular level in Olympic Dam, coincident with a desulphidation sequence of sulphide minerals, is consistent with the interaction of a lower fluid (probably partly magmatic) with an upper (more oxidised) fluid (Haynes pers. comm. 1991; Oreskes and Einaudi 1992). Reeves et al. (1990) also suggest that desulphidation could have resulted from the boiling of a single fluid. It is possible that “zone-refining”, in a manner analogous to modern supergene ore-upgrading processes, operated to significantly concentrate Cu and Au in the upper levels of the hydrothermal system. Such interfaces are rare in other members of the intrusive-related Fe-oxide family of hydrothermal ores, but where present they are also associated with Cu, Au and U

enrichment (e.g., Davidson and Patterson 1993).

Several features set Olympic Dam apart from Phanerozoic intrusive-related copper–gold systems:

- (1) Emplacement in an intracontinental anorogenic setting;
- (2) Dominance of hematite and magnetite throughout the alteration history, not just early stages of hydrothermal activity as in Phanerozoic porphyry–Cu deposits (Sillitoe 1991), indicating a general low content of reduced sulphur in all fluids, and a high level of oxidation;
- (3) The vast scale of brecciation of wallrocks and early hydrothermal products, underlying and reworking crater-facies sediments and volcanic rocks;
- (4) The alkaline, relatively anhydrous, fractionated character of associated granitoids, enriched in K, F, Zr and other incompatible elements (Creaser 1989).
- (5) The regional oxidised alteration history of the host granites, resulting in widespread alteration of K-feldspar and biotite to hematite, sericite, and chlorite (Guthrie 1991).

The volatile-rich character of the oxidised felsic melts probably permitted them to intrude to abnormally high crustal levels, generating very high heat-flow near to surface. It is also possible that external extensional faulting, related to a regional fault corridor (O’Driscoll 1985), and synchronous with magmatism (Reeves et al. 1990), exacerbated hydrothermal excavation of the crystallising batholith. Another essential element was a thick near-surface water-table or body of surface water, which (1) interacted explosively with intrusions to form extensive open-space breccias, and (2) played a vital chemical role in the deposition of both hematite and ore-bearing phases. Ultimately the deposit owes its vast metal endowment to the nature of deep crustal melting, which was responsible for the initial concentration and delivery of metals close to the site of deposition.

#### *Stratabound Au ± Cu in iron-rich chemical sediments*

Economic deposits in this group include Starra, Osborne, Labouchere, Fortnum (all Au–Cu-bearing), and The Granites, Dead Bullock Soak, Cosmopolitan Howley and Moline (all Au–As ± Pb–Zn–Bi–Cu-bearing). The division is intentionally non-genetic, which is important because of disagreement over the origin of metals: exhalitive, or stratabound skarn/replacement (Fig. 3).

Labouchere and Fortnum, in the Glengarry Basin of Western Australia, typify the problems in interpretation of this ore style. The Glengarry Basin developed in a rift setting on the northern margin of the Archean Yilgarn Craton at ~1800 Ma (Hynes and Gee 1986). It was subsequently deformed and incorporated into the Capricorn Orogen during the development of a major oblique fold-and-thrust belt (Tyler and Thorne 1990).

Like the exhalitive copper–gold-bearing lens which forms the Horseshoe deposit, Labouchere and Fortnum occur “a short distance above the oceanic basalts of the Narracoota Volcanics” (Blockley and Myers 1990). Ore at Labouchere is contained within stratabound pyritic cherts, in which the gold grade is directly proportional to pyrite abundance. Ore within the cherts are broadly related to northwest-striking faults; mineralisation either terminates or increases in grade against them (Hanna and Ivey 1990). An exhalitive origin is cited for Labouchere ore by these authors because it coincides with a vertical sedimentary facies change and is associated with bedded

pyrite. Windh and Barley (1990) argue an epigenetic origin because the mineralisation is associated with silicification and veining.

At Fortnum, ore is stratigraphically close to Labouchere, but a relationship to post-volcanic faulting is more definite. Gold occurs mainly in veins within magnetite-hematite-bearing "jasperoids" in mafic volcanics, surrounded by quartz-chlorite-sericite alteration. Jasperoid probably formed by replacement along a major fault (Hill and Craney 1990), but it has also been regarded as a possible seafloor product (Windh and Barley 1990). Deposition of gold by sulphidation, typical of BIF-hosted gold deposits in the Yilgarn craton, is indicated by pseudomorphing of iron oxides by pyrite and chalcopyrite. No information on fluid conditions are available.

The rift-related Pine Creek Inlier (Needham et al. 1988) contains several stratabound gold deposits in iron-rich chemical sediments (Nicholson and Eupene 1990), of which Cosmopolitan Howley and Moline are the most economically significant. Most occur in the Early Proterozoic South Alligator Group, which developed during post-extension subsidence of the basin. At the Cosmopolitan Howley deposit epigenetic/replacement ore occurs in pyritic Koolpin Formation carbonaceous shale and ferruginous chert (Alexander et al. 1990, Partington 1990), where it is cut by quartz-breccia-filled shear zones within the major Howley Anticline. Fine-grained pyrite (5 to 30%), gold, and arsenopyrite are disseminated along bedding and cleavage, but most ore is contained within cross-cutting veins and shears. However, at Moline, hosted by laminated chert/BIF and shale of the Mount Bonnie Formation Member, there is no clear relationship to deformational structures (Miller 1990). Disseminated pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, and bismuthinite occur in a gangue of quartz and albite. Adularia, albite, sericite, chlorite, tourmaline, and a distinctive nodular quartz fabric comprise associated low-grade alteration. Miller (1990) concludes a syngenetic origin for Moline on the basis of a lack of quartz veining, and the uniform concordance of ore-grade within the host chemical sediments.

The Starra (Greenschist facies) and Osborne (Amphibolite facies) deposits (Kary and Harley 1990; Davidson et al. 1989; Davidson 1992) in the rift-related Eastern Succession of the Mount Isa Inlier, consist mainly of magnetite, quartz and chalcopyrite, with subordinate pyrite and hematite. Both occur in thin (generally < 20 m thick) chemical sediment packages, either overlying or closely associated with felsic volcanics, but the distribution of mineralisation varies from focussed at Starra (four major ore bodies with strike-lengths of no greater than 250 m, connected by discontinuous barren iron formations) to disseminated sulphide within extensive BIF at Osborne. Pervasive footwall albite alteration is overgrown by disseminated fine clots and veinlets of hematite, pyrite, epidote, carbonate, chalcopyrite and magnetite. Starra ore is anomalous (in comparison to sedimentary iron formations) in Fe, Cu, Au, W, Mo, Sn, and strikingly depleted in Ba, Pb and Zn; REE, U and Bi abundances are not anomalous as has been reported elsewhere (Wall and Valenta 1990), although REE mobility is documented in footwall alteration (Davidson, this volume). Osborne metalliferous iron formation is anomalous in Fe, Cu, Au, Co, V and P, and depleted in Pb, Zn and Ba. Proximity to a major shear at Starra has prompted Laing et al. (1988) to suggest an epigenetic ore origin, but Davidson et al. (1989) advance an exhalative genesis because the ore occurs at a

volcanosedimentary contact, has experienced all recognised ductile deformation, and is stratigraphically underlain by alteration.

It is evident that some of the above ores were formed by replacement of favourable chemical horizons, and others by exhalation of fluids on to the seafloor. There is no commonality between genesis and geochemical association. If the genesis claims of the above authors are accepted, diverse fluid-types are capable of forming superficially similar ore both epigenetically and syngenetically. For instance, in the Pine Creek Inlier, epigenetic and apparently syngenetic ores with the Au-As association both formed in equilibrium with pyrrhotite and pyrite; fluid inclusions indicate that fluids forming epigenetic examples contained abundant CH<sub>4</sub> and CO<sub>2</sub>, were moderately saline (two populations average 7.6 and 13.5 wt % NaCl equiv.), with homogenisation temperatures between 200 and 300°C (Wygralak and Ahmad 1990); the fluids for syngenetic ore in the Pine Creek Inlier have not been characterised. At Starra, saline, oxidised, moderately acid fluids between 260 and 380°C are invoked to form the Au-Cu ores (Davidson 1992). A critical feature here is a low-H<sub>2</sub>S condition ( $a_{\text{S}_2} \sim 10^{-3}$ ) inherited by fluids circulating through oxidised wallrocks, to account for the general lack of sulphide, particularly sphalerite and galena.

#### *Unconformity-style U ± Cu/PGMAu*

Two distinct provinces of this ore-style exist, one associated with strike-slip faulting (Valenta 1990) in the South Alligator Valley Mineral Field (Au-PGM-Se-Ag-U), Pine Creek Inlier, and the other in the Alligator Rivers Mineral Field, N.T. (U ± PGM-Au-Te). In both provinces mineralisation is localised at the unconformity between relatively undeformed oxidised sequences and strongly deformed carbonaceous/graphitic units (Fig. 3).

Coronation Hill is the only economically viable South Alligator Valley deposit, although El Sherana, Palette and Rockhole historically produced 0.37 t Au (Wilde et al. 1989). In detail the folded, carbonaceous, ferruginous Koolpin Formation (1884 ± 3 My; Needham and Ross (1990)) is overlain by a chloritic felsic volcanoclastic sequence correlated with the Edith River Volcanics (Valenta 1990), in turn unconformably overlain by polymict sedimentary breccias containing clasts of porphyry, siltstone and tuff. These lithologies are all unconformably overlain by conglomeratic Coronation Sandstone (Carville et al. 1990). Alteration is pervasive. Wyborn (1990a) documents sericite-chlorite ± pyrite ± kaolinite ± biotite ± hematite alteration up to 1 km away from mineralisation, characterised by very high Fe<sup>3+</sup>/Fe<sup>2+</sup> ratios, leaching of Na<sub>2</sub>O, CaO and Th, and variable behaviour of SiO<sub>2</sub>. Hematite alteration is most intense in the Coronation Sandstone, extending into the lower sequence to overprint the main-stage alteration phases; no correlation exists between intensity of alteration and ore grade (Carville et al. 1990). Fault control has produced tabular steeply-dipping ore-bodies in all units within 400 m of the Coronation Sandstone contact. Fluid conditions are not well characterised, but the alteration indicates the involvement of "low temperature, highly oxidised, low-pH, saline fluids" (Wyborn 1990a) which were reduced by basement carbonaceous horizons (Valenta 1990) in a combined structural/chemical trap.

By comparison, U ± Au ± PGM mineralisation in the Alligator Rivers Mineral Field has been comparatively well-studied. In this region structural control is minimal, although mineralised reverse faults are documented, and several deposits are fault-displaced (Hancock et al. 1990). Regionally, massive hematitic Kombolgie Sandstone (1648 ± 219 Ma; Page et al. 1980) and mafic Nungbalgarri Volcanics unconformably overlies polydeformed semipelitic to graphitic schist and amphibolite of the Lower Proterozoic Cahill Formation and the Myra Falls Metamorphics (Wilde et al. 1989). At its deepest, mineralisation is inferred to have formed 500 m below the unconformity. Primary ore occurs as urannite-filled veins, cements and disseminations, in which gold and tellurides are present as inclusions and veins, closely associated with magnesian chlorite (and anhydrite at Jabiluka; Binns et al. (1980)). Chalcopyrite, galena, dolomite and quartz occupy post-uraninite veins. Minor primary overprinting by sericite-kaolinite-hematite veins also occurs (Wilde and Wall 1987), but hematite and anatase are also common in the innermost main phase mineralisation. Hydrothermal alteration extends over 1 km from ore, represented by Fe-chlorite and white mica replacement, and a pre-ore envelope of quartz, pyrite and/or hematite veins (Wilde and Noakes 1990). Desilicification occurs locally, with all assemblages being overprinted by magnesian chlorite and sericite. Kombolgie Sandstone above the Jabiluka deposit is silicified, chloritised and tourmalinised, with veins of chlorite and sericite extending over 300 m above the unconformity (Hancock et al. 1990). The unconformity is most severely altered, testifying to its role as a major fluid conduit. The most widely accepted ore age determination is 1625 ± 25 Ma (Sm-Nd; Mass (1989)).

Fluid inclusions, chlorite/white mica chemistry and preservation of metamorphic ages in residual muscovite indicates average ore conditions of ~200°C, pH ~ 4.5, and  $fO_2$  up to 6 log units above hematite-magnetite stability (Wilde et al. 1989). No  $SO_4^{2-}$ ,  $HS^-$ , or  $H_2S$  was detected in Laser Raman microprobe analyses of fluid inclusions (Wilde et al. 1989). Inclusion salinities break into two groups at Jabiluka, a mean 23 wt. % equiv.  $CaCl_2$  group, with only  $H_2O$  in the vapour phase, and an over-35 wt %  $CH_4$ -bearing group (Hancock et al. 1990). Detailed chemical simulations by Wilde et al. (1989) indicate that ore deposition could have been achieved by interaction between an oxidised Kombolgie Sandstone-derived fluid and (1) graphitic schist (2) graphite-absent schist, and (3) methane evolved during Interaction (1).

#### *Iron-oxide-bearing Au-Cu pipes in folds and shears (Tennant Creek-style)*

Iron-oxide-bearing copper-gold pipes are a distinct and very rich Proterozoic metal contributor, but occur in only one Australian Proterozoic province, the Tennant Creek Inlier. Approximately 130 pipes, lenses and pods of mineralised massive magnetite-hematite—zoned with respect to oxides, sulphides, gold and silicates—occur within the large folded turbidite basin. The lodes contain anomalous Au, Cu, Bi, Se ± U. Most of the metals have been recovered from nine high-grade deposits (Appendix 1), including Juno, Warrego, White Devil, and Peko. The age of Warramunga Group sedimentation, minor volcanism and major deformation in the Tennant Creek Inlier is estimated at 1870 ± 15 Ma, which is within the error

attached to ages of crystallisation of some granites in the region (e.g., Tennant Creek Granite Complex, 1870 ± 20 Ma (Black 1984)). Rb-Sr ages of hydrothermal muscovite from Warrego, Juno, TC8 and Nobles Nob mines yield consistent ages around 1810 Ma for the mineralisation (Black 1987).

Some of the ore deposits occur in structural locations, such as the crests of anticlines (e.g., Juno, Gecko), in shear zones along fold axes (e.g., White Devil and Orlando), or in minor fold flexures (e.g., TC8). However, other deposits such as Nobles Nob are confined to weak cleavage zones in otherwise planar dipping sediments (Rattenbury 1992). Based on the asymmetric chevron style of folding and nature of the east-west shear zones, Rattenbury (this volume) has developed a fold-thrust model for the goldfield, with ironstone genesis related to fluid migration into structural sites above the tips of blind thrusts.

Textural, geochemical and zonation studies of the ironstones (Large 1975; Wedekind et al. 1989; Huston et al. in press) indicate that the deposits formed by replacement of the greywacke-shale turbidites in structurally prepared sites, commonly at particular stratigraphic zones which represent oxidation/reduction boundaries. Such boundaries are marked by the presence of hematite-rich argillites, (e.g., Juno, Nobles Nob), rhyolitic porphyries (e.g., Warrego) or syn-sedimentary conglomerates (e.g., Gecko). Textural evidence indicates that ironstone formation predated the gold-copper mineralization (Nguyen et al. 1989; Wedekind et al. 1989; Huston et al. in press) however, rather than a significant time gap between the two events, Wedekind et al. (1989) consider that the deposits formed in an evolving hydrothermal system that commenced with magnetite-hematite (ironstone) deposition and finished with gold, bismuth and copper emplacement. This contrasts with the view of Wall and Valenta (1990), who favour initial growth of magnetite-chlorite during the main deformation, and gold precipitation ~60 My later, when basement structures were reactivated during partially decoupled deformation of the Davenport Inlier cover sequence. Fluid inclusion studies by Khin Zaw et al. (this volume) demonstrate that the ironstone stage formed from saline fluids (averaging 20 equiv. wt % NaCl) at a temperature of about 225°C, whereas the later Cu-Au mineralising fluids ranged to both higher salinity (averaging 35 equiv. wt. % NaCl) and higher temperatures, of about 350°C.

Multidisciplinary studies on oxygen/hydrogen isotopes, fluid inclusions, leaching models, granite chemistry, regional structure and gravity modelling of the basement-granite topography (Wedekind this volume, Khin Zaw this volume, Stolz and Morrison this volume, Rattenbury this volume, Leaman 1989, Huston et al. in press) indicate that the source of the ironstone-forming fluids were high-salinity connate brines, which evolved toward a mixture of connate brine and magmatic brine during the later Cu-Au-Bi mineralising stage, accompanied by granite intrusion into the basin. There is currently disagreement as to whether the I-type (magnetite series) Tennant Creek granites, and related porphyries, are the source of the metals (favoured by Wedekind et al. (1989) and Large (1991)) or the S-type, (ilmenite series) Warrego granitoid (favoured by Stolz and Morrison (this volume) on chemical grounds), although the latter is currently dated between 1660 and 1690 My (Page 1988), and hornfelsed the Warrego ironstone alteration. A schematic model depicting the progressive formation of the Tennant Creek-style Cu-Au deposits is shown in Figure 4.

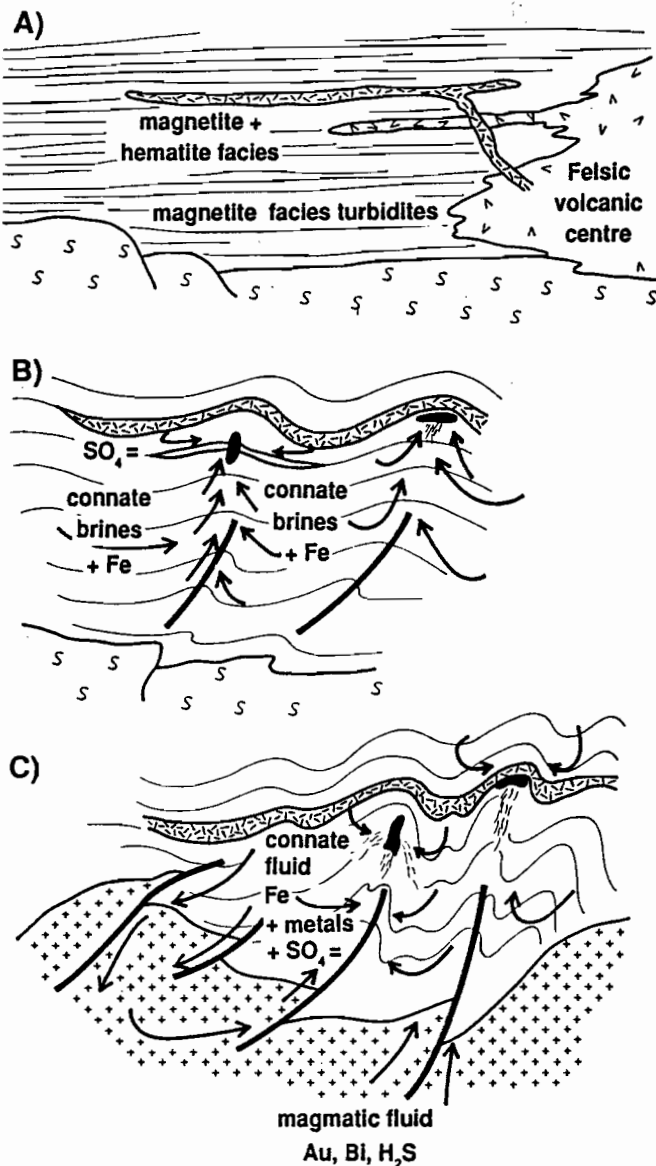


Fig. 4. Schematic model to depict development of the Tennant Creek iron stones. (A) Deposition of iron-bearing turbidites in a marine basin distal from felsic volcanic centres. Pepperitic intrusion of quartz-feldspar porphyry dykes and sills (McPhie, in press). (B) East-west folding and minor thrusting with release of connate-metamorphic brines and deposition of hematite-rich ironstone in structural and stratigraphic trap-sites. (C) Intrusion of Tennant Creek granite complex, mixing of gold-copper-bearing magmatic fluids with iron-rich connate brines, followed by deposition of metals within the partially deformed ironstone lodes.

## Factors controlling Australian Proterozoic metallogeny

### Tectonics

The unique character of some Australian Proterozoic ore-styles is likely to have developed in response to unusual conditions within the evolving Proterozoic crust and/or palaeo-hydrosphere/atmosphere. Most provinces containing significant Au ± Cu mineralisation were dominated by cycles of ensialic

rifting and basin-inversion-related orogeny (Wyborn et al. 1987, Rutland et al. 1990). Three successive periods of rift-basin formation occurred at 2.0 to 1.87 Ga, 1.8 to 1.6 Ga and 1.1 to 0.6 Ga, with deformations at 1.9 to 1.8 Ga and 1.6 to 1.4 Ga around the continent (Wyborn et al. 1988, Rutland et al. 1990). Lower Proterozoic provinces in southwest Australia, such as the Glengarry Basin (host to small Au-Cu deposits such as Horseshoe) and Paterson Orogen (host to the giant Telfer deposit), experienced collisional orogeny at 1.8 Ga, 1.2 to 1.1 Ga, and 0.7 Ga (Myers 1990).

Rift formation generated thick piles of sediment in arid (often evaporitic) settings during the sag phase following rifting (Etheridge et al. 1987). These sediments varied substantially in their oxidation state and alkalinity, (e.g., hematite-stable arenites, carbonaceous pyritic shales, shelf carbonates, feldspar-rich volcanoclastic rocks). Igneous activity decreased volumetrically in Proterozoic sedimentary sequences with time, but many felsic suites contained unusual volatile-rich fractionated granite members which ascended high into the crust (Wyborn et al. 1987, Creaser and White 1991), and played a key role in ore formation. This role may have only been the driving of fluid circulation in the upper crust, but it likely also extended to the supply of ore components, given the high abundances of incompatible elements in some ores (e.g., REE at Olympic Dam).

The role of granites is supported by the close correlation between granite emplacement and Au-deposit formation in some basins (Fig. 5). On the basis of temporal association, this factor is more important than stratigraphic position or the presence/absence of deformation. For instance, in the Pine Creek Inlier the main phase of stratabound-replacement and vein Au-deposition was synchronous with the intrusion of syn- to post-orogenic granites, and most deposits occur within or close to granite aureoles (Needham and De Ross 1990). High salinities detected in Tennant Creek ironstone fluid inclusions are likely to be magmatically derived given a lack of evaporites in the Tennant Creek Inlier, although as indicated previously, the source of metals for these deposits is not well-constrained. On the Stuart Shelf, magmatic and Cu-U±Au-forming hydrothermal activity continuously overprinted one another at sites of ore deposition. Although syn- to post-orogenic magmatism was also a vital factor in Cu ± Au deposition in the Mount Isa Inlier, crustal development of this province through several rift, sag and deformation cycles ("crustal preconditioning" of Laing (1991)) increasingly favoured a non-magmatic metal supply. The extensive development of evaporitic environments during Mt Isa Cover Sequence 2 supplied saline metal-bearing fluids to (1) the basin-water interface during Cover Sequence 2 (Starra/Osborne deposits; Davidson (1992)); (2) zones of middle crustal extension during Cover Sequence 3 (Holcombe et al. 1992), and most extensively to (3) dilatant and/or chemically reactive sites during the compressional Isan Orogeny. However, the intrusion of the volatile-rich Williams Batholith into a metamorphic regime dominated by saline fluids, late in the Isan Orogeny, closely corresponded to the emplacement timing of numerous Cu, Au and Cu-Au deposits in the Mt Isa Eastern Succession, some of which are currently emerging as the largest Au deposits in the inlier.

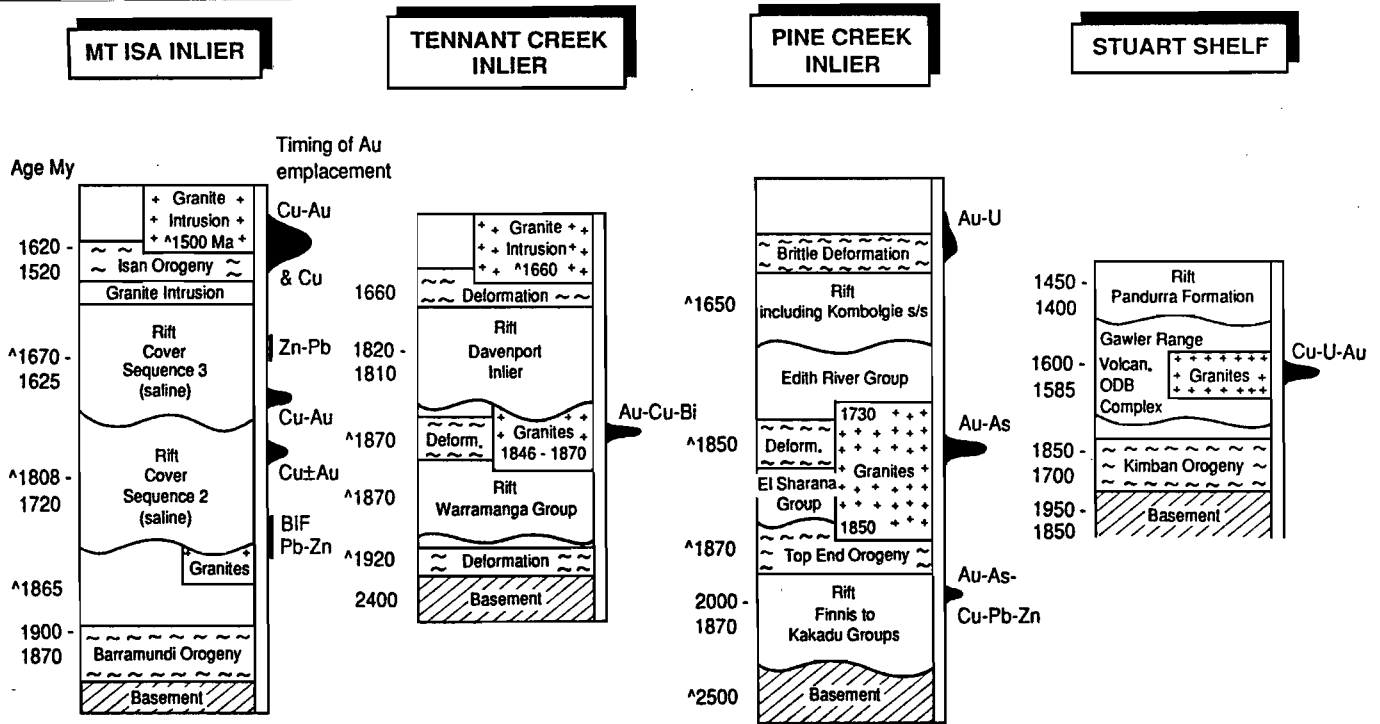


Fig. 5. Au deposit location versus stratigraphic position, magmatism, and deformation in four Australian Proterozoic basins. Tennant Creek deposits are located according to the geological evidence linking them to the major deformation (~1870), although current radiometric dating places them at ~1810 My.

### Fluid Chemistry

Fluid inclusion research on the Proterozoic gold-copper ± uranium systems at Olympic Dam, Tennant Creek, Alligator Rivers and Starra (Davidson 1989; Nguyen et al. 1989; Wilde et al. 1989; Khin Zaw et al. this volume; Hancock et al. 1990; Oreskes and Einaudi 1992; Huston et al. in press) indicate that the ore fluids are at a consistently high salinity with mean values around 15 to 35 equiv. wt % NaCl. Temperature data, although far from complete for all deposits, suggests that the Cu-Au-magnetite types are relatively high temperature (300 to 450°C), while the copper-uranium ± gold-hematite types are generally lower temperature ranging from 150 to 300°C.

Previous research on the solubility of gold and base-metals in hydrothermal systems (e.g., Huston and Large 1989; Large et al. 1989) suggests that the gold-copper association is typically developed in relatively high temperature, saline and low pH fluid environments where both copper and gold are transported as chloride complexes and deposition occurs due to a decrease in temperature, decrease in oxidation or increase in pH. This contrasts with the more common transport mechanism for gold as the  $\text{Au}(\text{HS})_2$  complex, which occurs in moderate temperature, neutral pH, low salinity and more reduced fluids, such as those associated with epithermal gold deposits and Archean lode systems. Such fluids cannot carry significant copper due to their lower salinity, temperature and  $f\text{O}_2$  characteristics; and commonly develop ores with a gold-pyrite association with minimal base metals. The fields in  $f\text{O}_2$ -T space for these alternate gold related hydrothermal systems are depicted in Figure 6. It is apparent from this diagram that the gold-copper association is restricted to conditions of high fluid  $f\text{O}_2$  (above  $10^{-35}$  atm) and high temperature (above 300°C).

There is a general progression with increasing  $f\text{O}_2$  and decreasing temperature through the sequence of assemblages; (gold-chalcopyrite-pyrrhotite) → (gold-chalcopyrite-magnetite) → (gold-chalcopyrite-pyrite ± hematite) → (gold-chalcopyrite (bornite)-hematite). It is important to realise that this figure is calculated for a low total sulphur content of  $a_{\text{S}_2} = 10^{-3}$ . At higher sulphur values, say around  $10^{-2}$ , the magnetite-chalcopyrite field shrinks considerably while the pyrite-chalcopyrite and pyrrhotite-chalcopyrite fields expand. Low total sulphur is thus an important requirement for the development of significant magnetite-chalcopyrite-gold ores. In the gold-copper-hematite field, uranium deposition is more likely due to the restriction of uranium transport to very high levels of oxidation (Wilde et al. 1989).

A comparison of the temperature-salinity ore-fluid characteristics of Proterozoic gold-copper-magnetite deposits, such as Tennant Creek and Starra, with other typical gold-bearing styles including epithermal deposits, volcanogenic massive sulphides and porphyry copper deposits is given in Figure 7 after Large (1992). In this diagram, the theoretical transport/deposition zones for gold and the base metals, calculated from currently accepted thermodynamic data, are compared to the boxes of fluid temperature-salinity characteristics available from published fluid inclusion data. The magnetite-copper-gold box which is based on Tennant Creek fluid inclusion data, is shown to overlap with the porphyry copper box on the high temperature-salinity side and the VMS box on the low temperature-salinity side. The conditions for epithermal systems (based on the adularia-sericite type) are at considerably lower temperatures and salinities.

From a study of Figs. 6 and 7 it is apparent that the critical chemical conditions that have led to the unique nature of the Australian Proterozoic gold-copper-iron oxide deposits are;

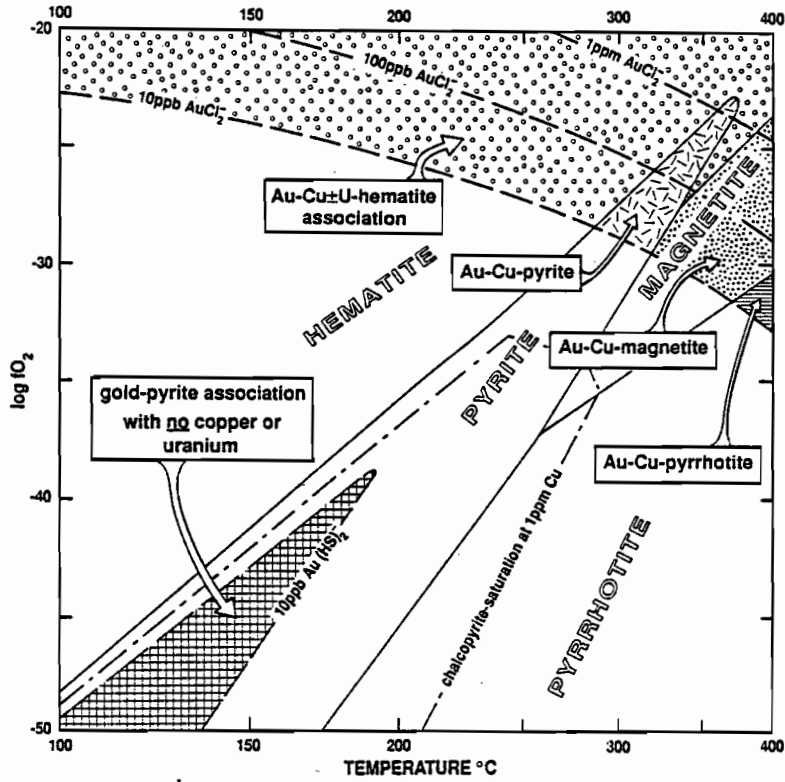


Fig. 6. Fields of gold transport and deposition in  $fO_2$ -temperature space showing the gold-copper association related to  $AuCl_2^-$  stability at high temperature and  $fO_2$  conditions compared with the gold-pyrite-copper absent association related to  $Au(HS)_2^-$  transport conditions at lower temperatures only in the pyrite field. (Calculated from data provided in Huston and Large (1989) and Large et al. (1989); conditions— $a_{\Sigma S} = 10^{-3}$ ,  $a_{Cl^-} = 10^{0.5}$ ,  $pH = 4$ ).

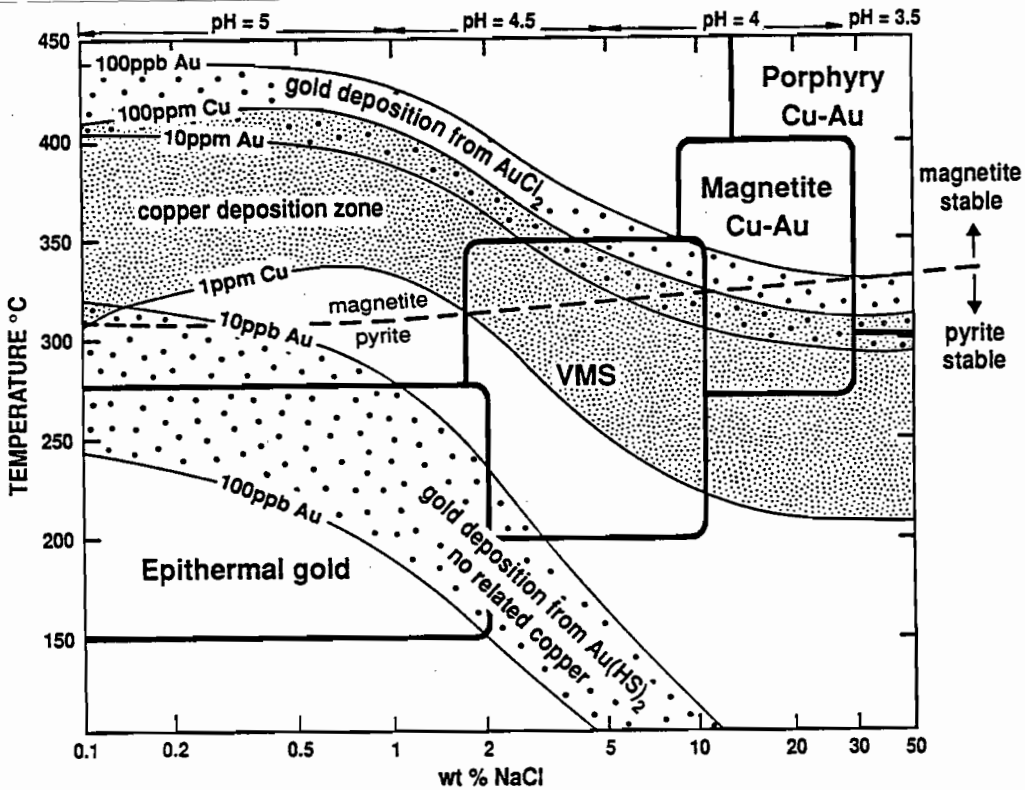


Fig. 7. A temperature-salinity diagram, which models the relationship between fluid chemistry for various ore deposit types based on fluid inclusion data (the boxes) with the zones of gold and copper deposition (dots) based on chloride complex and this complex solubility data. Note the overlap zone for copper and gold deposition from chloride complexes passes through the magnetite Cu-Au field, the porphyry field, and the high temperature end of the VMS field. In contrast, the gold deposition zone for thio complex transport passes through the epithermal box and the low temperature end of the VMS box. The zones of gold and copper deposition are based on thermodynamic modelling of a solution with  $\Sigma S = 0.001M$ ,  $\Sigma H_2S/\Sigma SO_4 = 10$ , and  $pH = 3.5$  to  $5$ . The magnetite-pyrite boundary is based on the above conditions but will move upwards for increasing  $\Sigma S$  content.

1. High fluid  $fO_2$  ( $>10^{-30}$ ).
2. Moderate to high temperature (300 to 400°C).
3. Moderate to high salinity (10–50 wt. % NaCl).
4. Low activity of aqueous sulphur ( $<10^{-3}$ ).

The common development of fluids with these characteristics in the Australian Proterozoic can be related back to the prevailing tectonic regimes where the following features were common;

1. Rifting producing high heat flow.
2. Shallow water saline sedimentary environments providing a source of hypersaline connate fluids.
3. Periods of extensive surface oxidation producing substantial thicknesses of oxidised rock packages.
4. Distinct episodes of intrusion of oxidised and fractionated granites, which represent an additional source of copper, gold and uranium.

#### *Nature of the trap-sites*

Research at Tennant Creek by Wedekind et al. (1989), Wall and Valenta (1990), and Huston et al. (in press) has emphasised the importance of redox boundaries as trap sites for ironstone development and subsequent copper–gold deposition. Similarly Wilde et al. (1989) consider that redox boundaries are critical for uranium–gold deposition in the unconformity style deposits. Whether redox boundaries developed more commonly in the Australian Proterozoic than in other periods is difficult to ascertain, however, three factors may have contributed to variable oxidation state: (1) fluctuating atmospheric oxygen content during the transition from Archean conditions to the comparatively stable Phanerozoic environment; (2) highly variable sedimentological environments in tectonically and volcanically active basins; (3) variable oxidation state of erupted lavas and pyroclastics, which were sourced from strongly fractionated magmas, or from magmas derived from the melting of variably oxidised source rocks at the base of rift sequences.

Due to the fact that decreasing both  $fO_2$  and temperature are the two most effective ways of depositing gold and

chalcopyrite together, then mixing of a hot, highly oxidised, ore fluid with a cooler more reduced fluid is probably the most effective method of forming a copper–gold–iron oxide deposit. Such mixing models have been proposed for Olympic Dam (Haynes pers. comm. 1991; Oreskes and Einaudi 1992) and Tennant Creek (Huston et al. in press).

#### **Relationship of Cu/Au ores to Pb/Zn/Ag ores in the Proterozoic**

The Australian Proterozoic Sedimentary basins are best known for their giant stratiform lead–zinc–silver deposits such as McArthur River, Mt Isa, Dugald River, Lady Loretta (Gustafson and Williams 1981). The obvious question arises as to whether there is any genetic relationship between these deposits and the copper–gold styles discussed in this paper.

Both styles are considered to have developed within large rift controlled sedimentary basins, precipitating from moderate to high salinity fluids. In some areas, such as the Eastern Succession of the Mt Isa Inlier, copper–gold–magnetite style ores (e.g., Starra, Osborne, Eloise, Fort Constantine) occur within the same sedimentary–volcanic province as stratiform Pb–Zn–Ag ores (e.g., Dugald River), and Broken Hill-type ores (e.g., Pegmont, Cannington) providing the basis for a suggestion that the two styles represent different stages in the evolution of a complex Proterozoic sedimentary basin, involving an interplay between sedimentation, magmatism, deformation and metamorphism.

A summary of the major differences between these two associations is given in Table 2. Many of the mineralogical and chemical differences stem from the fact that ores of the Cu–Au association are the result of precipitation from high temperature relatively oxidised fluids, whereas ores of the Pb–Zn–Ag association result from precipitation from lower temperature relatively reduced fluids (Large and Davidson 1991). Broken Hill-type ores (Pb–Zn–Fe-rich, Cu–Au–W deficient), develop from moderately reduced, relatively low

**Table 2.** Comparison of features of Proterozoic Cu–Au deposits and Proterozoic Pb–Zn–Ag deposits. Modified from Large (1990).

	Cu–Au Association	Pb–Zn–Ag Association
1. Form.	Commonly discordant, some stratiform examples.	Typically stratiform and commonly finely laminated.
2. Major Fe–S–O mineralogy.	Magnetite and hematite common. Some pyrite–pyrrhotite examples.	Pyrite dominant, some pyrrhotite examples Magnetite, hematite rare or a distal facies.
3. Host rocks.	Oxidised arenaceous sedimentary ± volcanic ± granite package, may include BIF.	Dolomites ± black shales, typically reduced, may include stratiform pyrite beds.
4. Trace elements.	± Bi, W, U, REE, Se, Sn, Mo, Co, F.	± Ba, As, Sb, Tl, Cd, Hg
5. Interpreted fluid temperature.	300°–450°C	150°–250°C.
6. Fluid salinity.	High (15–50 wt. % NaCl)	High (15–50 wt. % NaCl)
7. Redox conditions.	Oxidised fluid (stable in the magnetite or hematite fields).	Reduced fluid (stable in the pyrite field).

temperature fluids (<260° C), incapable of dissolving Au and Cu as chloride complexes.

It may be argued that the Pb–Zn–Ag-forming ore fluids evolved directly from connate brines developed in reduced argillite–carbonate-dominated sedimentary packages, whereas the more oxidised, high temperature, Cu–Au-related ore fluids represent a mixture of connate brines evolved from an oxidised arenaceous sedimentary package with magmatic fluids discharged from oxidised granitoids. Further research on individual deposits and districts will be required to address these problems.

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Appendix 1 Summary of Proterozoic gold and gold-base metal deposits. Key to cited origins: (A) Fe-oxide dominated hydrothermal systems forming skarns, breccia and replacement bodies; (B) Fe-oxide dominated chemical sediment-hosted mineralisation; (C) Fe-oxide dominated unconformity-style; (D) Fe-oxide dominated mineralisation hosted within elements of ductile deformation; (E) Broken Hill type or Kuroko-type seafloor massive sulphides; (F) Fe-sulphide-dominated veins and adjacent replacement zones clearly spatially related to felsic granites; (G) Fe-sulphide-dominated veins and adjacent replacement zones spatially related to elements of ductile deformation.

	Age My	Au (kg)	Million tonnes	g/t Au	Other Economic metals	Trace metal association	Source of figures	Oxidation state	Cited origin
<b>TENNANT CREEK INLIER</b>									
Warrego, T.C.	1810	46020	6.95	6.6	2% Cu	0.32% Bi	Wedekind et al. (1989)	pyrh/mag	D
Nobles Nob	1810	39000	2	19.5	-	Cu	Wedekind et al. (1989)	mag/hem	D
Juno	1810	25344	0.45	56.1	0.5% Bi	0.33% Cu, 0.57% Bi	Wedekind et al. (1989)	pyrh/mag	D
Peko	1810	12870	3.7	3.5	4.01% Cu	0.2% Bi	Wedekind et al. (1989)	pyrh/mag	D
White Devil	1810	6160	0.28	22	-	-	Wedekind et al. (1989)	pyrh/mag	D
Orlando	1810	5997	0.68	8.8	4.01% Cu	0.1% Bi	Wedekind et al. (1989)	pyrh/mag	D
Argo	1810	4080	0.3	13.6	-	0.8% Cu, 0.6% Bi	Wedekind et al. (1989)	pyrh/mag	D
Gecko	1810	3920	4.9	0.8	3.8% Cu	-	Wedekind et al. (1989)	mag/hem	D
Eldorado	1810	3314	0.15	22.7	-	-	Wedekind et al. (1989)	pyrh/mag	D
<b>MOUNT ISA INLIER</b>									
Cloncurry gold field	1510	3174	-	-	Cu commonly dominated	± Co	Woodall (1990)	py± hem	G
Mount Elliott	1509	3001	1,564	1.92	3.65% Cu	Se	Garrett (1992)	py/pyrh/mag	A
Starra	1720	26500	5.3	5	1.98% Cu	W	Kary and Harley (1990)	py/mag/hem	B
Osborne	1720	13600	13.6	1	1.9% Cu	Co, P	Laing (1991)	mag/py	B
Kuridala	1510	4600	2	2.3	5% Cu	?	Laing (1991)	py	F
<b>GRANITES-TANAMI INLIER</b>									
The Granites	1960	39327	7.39	5.32	-	As, Cu	Mayer (1990)	pyrh/mag/asp	B
Dead Bullock Soak	1960	10530	2.9	3.67	-	-	Louthean (1992)	-	B
Tanami	1960	2400	0.8	3	-	-	Nicholson (1990)	py	G
<b>PINE CREEK GEOSYNCLINE</b>									
Cosmopolitan Howley	1800	7515	2.83	2.66	-	As, Pb, Zn, Cu	Woodall (1990)	asp/py/pyrh	B
Pine Ck region, excluding mines noted here	1800	5362	-	-	-	As, Bi	Needham and de Ross (1990)	py/asp/pyrh	G
Coronation Hill	900	38039	8.34	4.56	0.19g/t Pt, 0.65g/t Pd	Ag, Se, Cu, Zn, Pb	Woodall (1990)	hem/py	C
Enterprise	1800	24684	8.78	2.81	-	As, Zn, Pb, Cu	Woodall (1990)	py/pyrh/asp	G
Iron Blow & Mt Bonnie	1884	3714	-	-	Ag, Zn, Pb, Cu	As, Sn	Eupene and Nicholson (1990)	pyrh/py	E
Yam Creek	1800	3000	0.75	4	?	?	Woodall (1990)	?	G
Mt Todd	1800	53540	32.9	1.63	-	As, Bi, Pb, Zn, Cu	Louthean (1992)	asp/py/pyrh	G
Union Reefs	1800	3173	1.9	1.67	-	As, Pb, Zn, Cu	Woodall (1990)	py/pyrh/asp	G
Toms Gully	1800	3192	0.38	8.4	Ag	As, Pb, Cu, Zn	Woodall (1990)	py/pyrh/asp	G
Woolwonga	1800	5838	2.1	2.78	-	As, Pb, Zn, Cu	Kavanagh and Voors (1990)	py/asp	G
Jabiluka	1600	11770	1.1	10.7	0.25-0.39% U3O8	Pd, Te, Cu, Ni, Pb	Woodall (1990)	py/graphite	C
Moline	1884	11950	6.674	1.79	-	As, Cu, Bi, Pb, Zn, B	Miller (1990)	py/pyrh/asp	B
Koongarra	1600	3152	-	-	0.44-0.80 U3O8	Cu, Pb, As, V, Ni, Co	Woodall (1990)	py/hem	C
Gandy's Hill	1800	8750	2.5	3.5	?	?	Woodall (1990)	?	G
Bundey	1800	13464	6.12	2.2	?	U, Pb, Zn	Woodall (1990)	?	G
Goodall	1800	10300	4.3	2.4	?	?	Woodall (1990)	?	G
<b>WILLYAMA INLIER</b>									
Broken Hill	1690	132293	?	~0.12	Dominantly Pb, Zn, Ag	P, Hg, Cu, Mn	Woodall (1990)	py/mag/pyrh	E
<b>STUART SHELF</b>									
Olympic Dam	1603	270000	450	0.6	2.5% Cu, 0.8kg/t U3O8	REE, Ba, Co, F	Reeve et al. (1990)	py/bohn/cc/hem	A
<b>GLENGARRY BASIN</b>									
Labouchere and Deep Soul	1900	5780	1.7	3.4	-	As, Pb, Ba	Hanna and Ivey (1990)	py	B
Fornum	1900	12838	4.01	3.2	-	Cu, Ba, La, Ce	Woodall (1990)	py altering mag	B
Peak Hill	1900	10355	?	3.1	?	?	Woodall (1990)	?	G
Horseshoe	1900	13908	2.7	2.8	3.4% Cu, 27 g/t Ag	Pb, Zn, Hg, Se, Te	Parker and Brown (1990)	py	E
<b>PATERSON PROVINCE</b>									
Telfer	630	144136	49.9	2.89	-	Cu, As, Co, Pb, Zn, Bi	Woodall (1990)	py/cpy/cc/ore	F
						Ag, B, Ce, La, Mo, Y	Dimo (1990)	ore=supergene	
							Goellnicht (1989)		
<b>TOTAL (N=40)</b>		<b>1046590</b>							



