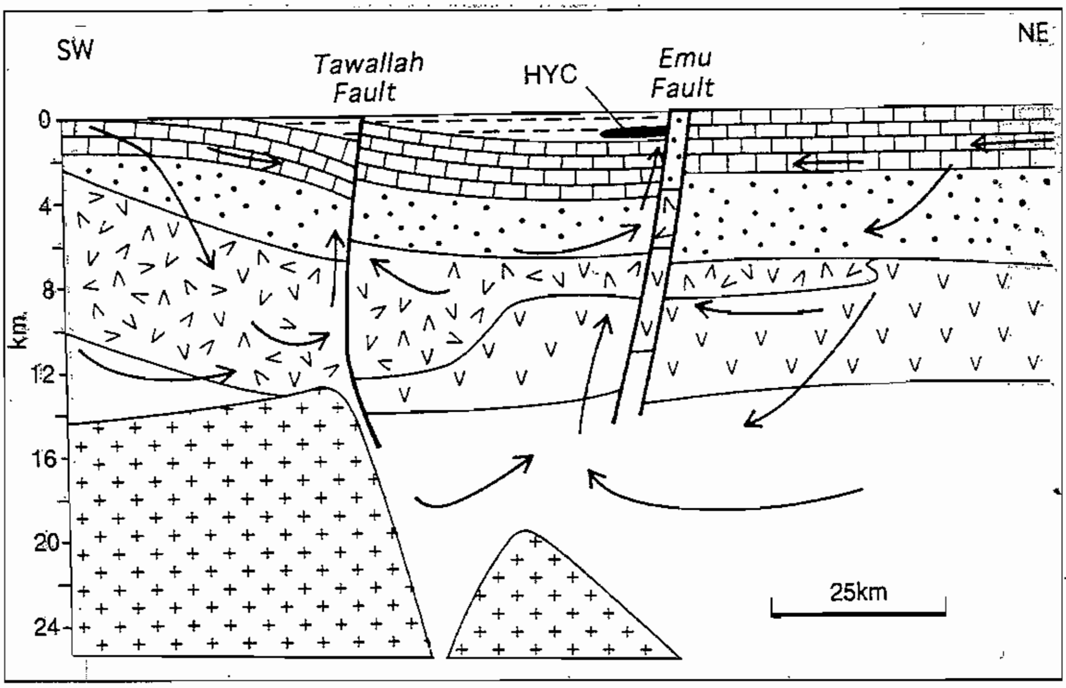
Sediment-hosted base metal deposits



AMIRA/ARC project P384A

Report 5
May 1998

CODES SRC
Centre for Ore Deposit Research
University of Tasmania

Sediment-hosted base metal deposits

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Contents

Introduction

Project Objectives

- To determine the primary geological, geochemical and structural controls on the location and timing of base metal mineral deposits in sedimentary basins, and to develop and refine ore deposit models applicable to exploration.

- To investigate the chemical processes controlling brine compositions and metal sulfide accumulation during fluid movements in sedimentary basins, including the relationships between copper and lead-zinc deposition

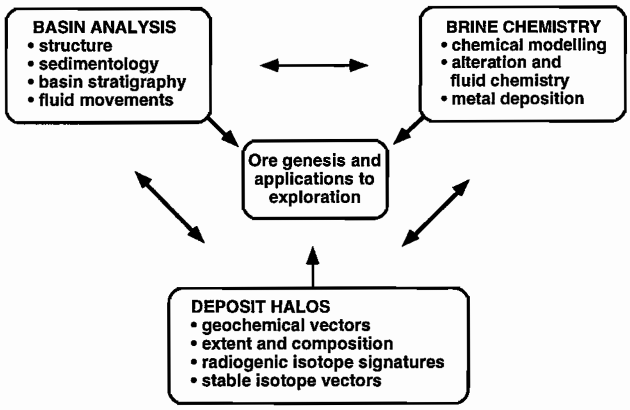
- To investigate the physical and hydrological processes involved in the evolution and movement of metalliferous fluids in sedimentary basins

- To develop geological and geochemical vectors to a variety of styles of sedimentary base metal mineralisation that may be used in the exploration for large tonnage deposits.

For convenience, the programme for these projects has been run as three separate, but related modules (see figure). Several studies overlap more than one module, and several integrated reports were presented in P384 and are planned for P384A (see below). The final report in P384A will present a new integrated exploration model for Australian Proterozoic stratiform sediment-hosted Zn-Pb-Ag deposits.

This introduction includes a coloured synoptic diagram illustrating an idealised Australian Proterozoic basin cross-section showing the location of research reported in this progress report, and a generalised geologic locality map of the Mount Isa and McArthur Basins with areas covered in this report highlighted in red.

Research Modules for P384/P384A



Basin Analysis

Aims

- to develop sedimentologic and basin stratigraphic criteria to enable the identification of favourable horizons for Zn-Pb deposits
- to better understand the basement architecture of the McArthur and Mt Isa Basins
- to document the detailed structural evolution, and the interplay between structure and sedimentation, in key areas of the McArthur and Mt Isa Basins
- to integrate sediment facies studies with sediment chemistry and alteration indices from the other two modules

Methods

- geophysical modelling of public domain gravity and magnetic data sets
- sedimentary facies mapping & core logging
- diagenetic studies
- detailed structural mapping of key areas

Deposit Halos

Aims

- to document primary geochemical, mineralogical and isotopic dispersion halos associated with sedimentary base metal deposits
- to use indices defined for known deposits to define 'favourable horizons' for mineralisation

Methods

- major and trace element geochemical studies and C/O/S isotopic analysis of (barren) host sediments to known mineralisation
- regional studies to help define 'background' variations. and detailed geochemistry and isotopic analysis in conjunction with diagenetic studies
- radiogenic isotope studies to discriminate source rocks for base metals

Brine Chemistry

Aims

- to model base metal and ore associated elements solubility in a variety of possible ore fluids
- to test metal sulphide preciptation processes
- to account for the geochemical halos documented in the Deposit Halos module
- to test novel potential ore-forming ('trap') scenarios in sedimentary basins

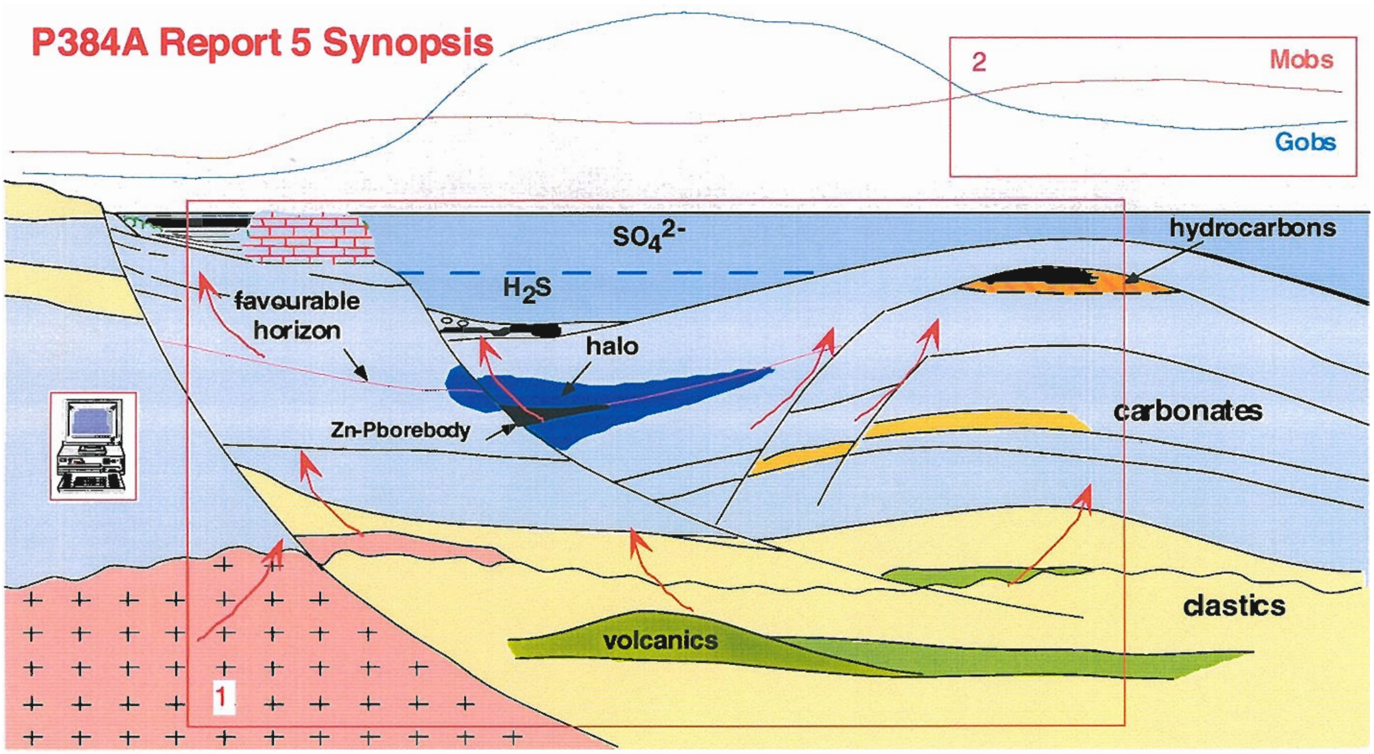
Methods

- the thermodynamic modelling packages developed by Mark Read (CHILLER and SOLVEQ) will be used for computer modelling studies
- (where possible) fluid inclusion and stable isotope studies will be used to constrain fluid character for this modelling.

This Report

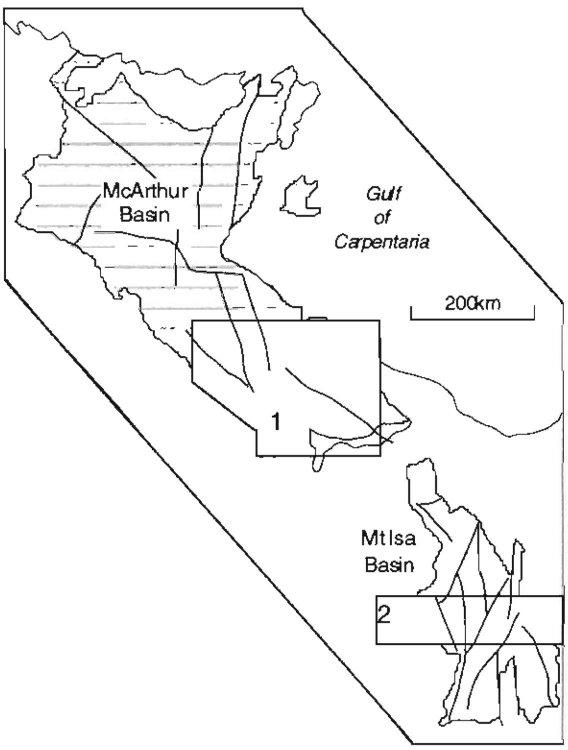
This is the fifth progress report for AMIRA Project P384A and comprises two reports prepared by David Leaman in the latter half of 1997. The first is called 'Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit' is an attempt to address the fourth objective of the project. It has been the subject of considerable discussion within the CODES P384A research team and does not represent a consensus view on where the HYC ore-forming fluids originate. The second report, 'Some regional geophysical models for the Mount Isa - Cloncurry region', was previously circulated to sponsors in loose format in November 1997. An Appendix to the report reproduces a paper by Leaman from issue 1 of this years Australian Journal of Earth Science. It is essentially the same report prepared by David Leaman for the final report in AMIRA P384, circulated to sponsors in June 1995; it is included here because it provides important background to the first report in this volume.

Peter McGoldrick
Project Manager



1 Basin Analysis Module: Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit, p. 1-42 .

2 Basin Analysis Module: Some regional geophysical models for the Mount Isa-Cloncurry region, p.43-58.



Summaries

Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit

David Leaman

An indicative study using relatively simple assumptions designed to evaluate possibilities and constraints on fluid requirements needed to generate the HYC ore system in the McArthur Basin has been completed. The ideas and conclusions are intended as feedstock for further observation, mathematical modelling and identification of additional observations.

The ore body is finely layered and was formed in an interval of perhaps only one million years. These observations imply some site specific tectonic influences in association with host or precipitation requirements.

The metal required might well have been supplied by volcanic elements of the section (especially the thicker, older sequence) at depth which have been interpreted in regional studies but which are rarely exposed in the McArthur Basin. The brines needed to carry the metals are, however, more special. These are considered to be neutral and oxidised, with temperature a non-critical factor, and may not need an evaporite as source; silicate exchanges long term are argued here. This imposes other limitations; the fluid and metal solution must be in place for a considerable period and may not be rapidly flushed in order to preserve and develop a homogenised character for supply during the critical period.

Although some background processes may well be applicable for flow control (gravity, perhaps convection) these cannot guarantee large volume homogeneity upon sampling due to directed flow patterns (intake to discharge points). Seismic processes superimposed on such a system can provide pulsing of local, large volumes; volumes comfortable in excess of those required and which can be isolated — long term — such that homogenisation is almost certain. Seismic withdrawal also focusses flow, radially, to the active structure — a characteristic which makes the entire local volume part of the flow system, a factor which reduces the flushing risks associated with background processes unless these can operate over hundreds of kilometres. Such a range of application is not possible for HYC due to applied head from the Tawallah Ranges nearby.

Estimates suggest, however, that brines of the type required may well only be feasible at depth within the thick volcanic sequences believed to be present . The conjunction of regional thermal basin cells over long periods, continuing subsidence (host formation), active faulting and stress fields at the time are crucial elements. It is also likely that metals can be provided by the same volcanic units.

Thermal constraints are loose. Flow disturbance due to depth of circulation, convection, local young granitoids may all combine to vary flow patterns, convection, rate of release and even metal content but thermal conditions are essentially background components. A heat flow maximum near Barney

Creek times might well be associated with particular tectonics in the area. It is likely, though, that the coupling of unusual, pulsed compressions (tectonic factor) with a heat flow maximum may fully account for the deposit — given the existence of an appropriate precipitating host. The absence of any of these factors would mean metal dispersion and no orebody.

Some additional information will be required before a complete geological, or mathematical, appraisal is possible. All formations known to be, or likely to be, within the section should be sampled for trace metal content and evaluated for their brine generation potential (not easy). Brine evaluation must not be limited to apparent evaporites. There also needs to be some evaluation of cross stratification flow and its potential contributions and whether convective cells are tightly constrained either by formation hydraulics, temperature or fluid density.

Some regional geophysical models for the Mount Isa–Cloncurry region

David Leaman

Five sections across the Mount Isa and Cloncurry region have been reviewed regionally. The preliminary results show that the data sets, especially the magnetic data base, contain some base level problems and that many features are not readily explained without consideration of a large number of local elements. This condition applies particularly to the Cloncurry region with its array of intensely and variably magnetised units. Gravity models are much simpler and dominated by granitoids.

Some gross structural conclusions may be drawn. The structure east of the Coolullah–Fountain Range Faults (Eastern Fold Belt) may include a repeated thrust stack but the deformation is more limited. The region immediately west of the Coolullah Fault (Kalkadoon–Leichhardt Belt) is much more altered and deformed and folding is essentially isoclinal and large pieces of the structure are wholly detached. Further west (Western Fold Belt) structures, initially detached, pass into more gently folded, long wavelength features. West of Mt Isa structures are covered by late Proterozoic to Recent materials but the gentler pattern implied throughout much of the McArthur Basin study is indicated.

The interpretation completed has not been comprehensive enough to define all stratigraphic variations in sequence but it is clear that substantial variations in thickness, some presumably primary, affect many units within the Western Fold Belt as inferred further north. It may be concluded from the present study that the principal correlation made in all previous interpretation; namely that a thick mafic sequence almost universally present within the McArthur and Isa Basins is a direct correlate of the Eastern Creek Volcanics of the Haslingden Group. Concealed extensions of this suite can be traced to outcrop.

Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit

David Leaman

CODES Special Research Centre, School of Earth Sciences, University of Tasmania

SUMMARY

An indicative study using relatively simple assumptions designed to evaluate possibilities and constraints on fluid requirements needed to generate the HYC ore system in the McArthur Basin has been completed. The ideas and conclusions are intended as feedstock for further observation, mathematical modelling and identification of additional observations.

The ore body is finely layered and was formed in an interval of perhaps only one million years. These observations imply some site specific tectonic influences in association with host or precipitation requirements.

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Although some background processes may well be applicable for flow control (gravity, perhaps convection) these cannot guarantee large volume homogeneity upon sampling due to directed flow patterns (intake to discharge points). Seismic processes superimposed on such a system can provide pulsing of local, large volumes; volumes comfortable in excess of those required and which can be isolated — long term — such that homogenisation is almost certain. Seismic withdrawal also focusses flow, radially, to the active structure — a characteristic which makes the entire local volume part of the flow system, a factor which reduces the flushing risks associated with background processes unless these can operate over hundreds of kilometres. Such a range of application is not possible for HYC due to applied head from the Tawallah Ranges nearby.

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Thermal constraints are loose. Flow disturbance due to depth of circulation, convection, local young granitoids may all combine to vary flow patterns, convection, rate of release and even metal content but thermal conditions are essentially background components. A heat flow maximum near Barney Creek times might well be associated with particular tectonics in the area. It is likely, though, that the coupling of unusual, pulsed compressions (tectonic factor) with a heat flow maximum may fully account

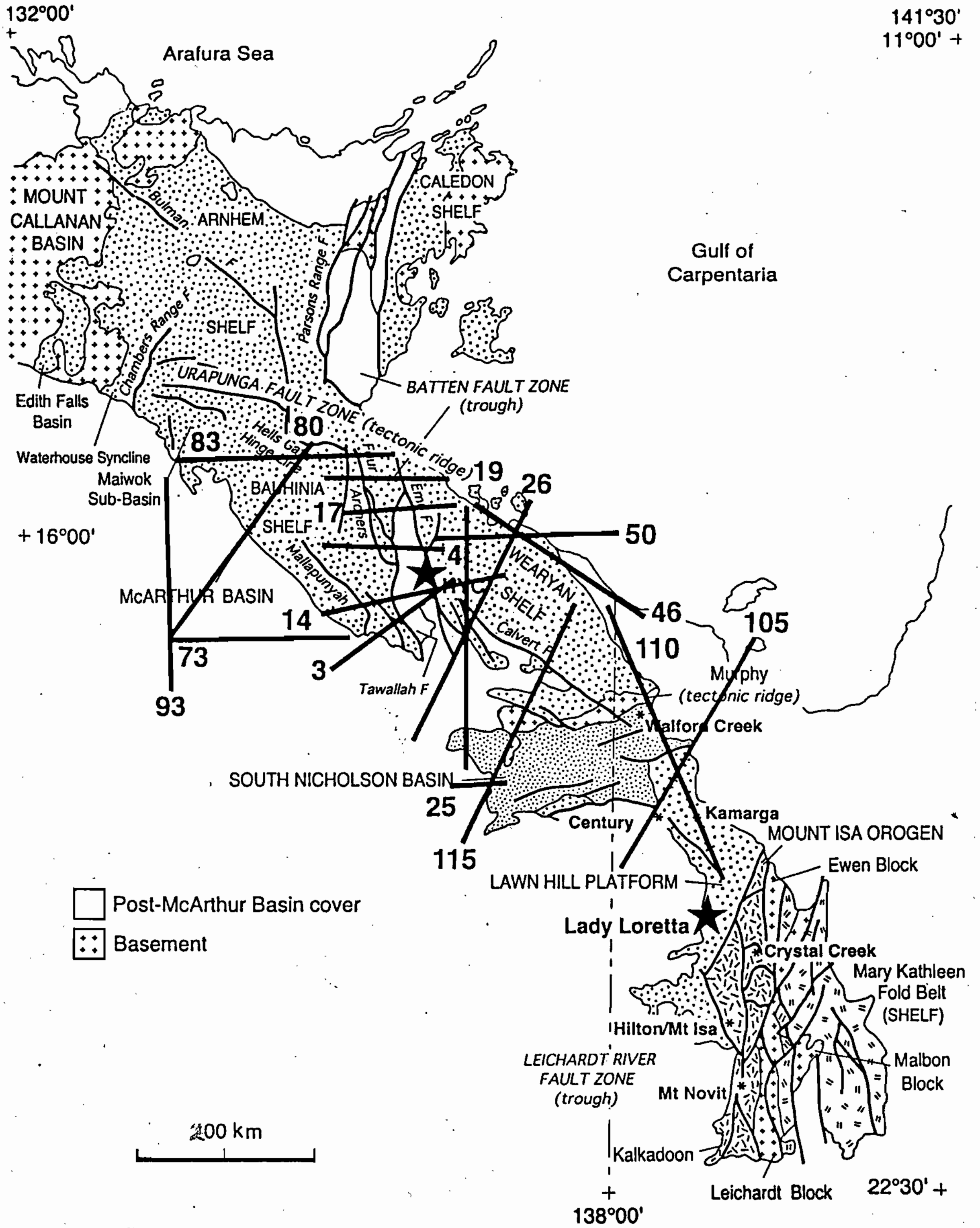

Figure 1: The McArthur Basin and features referred to in previous literature. Heavy labelled lines indicate locations of modelled profiles.

for the deposit — given the existence of an appropriate precipitating host. The absence of any of these factors would mean metal dispersion and no orebody.

Some additional information will be required before a complete geological, or mathematical, appraisal is possible. All formations known to be, or likely to be, within the section should be sampled for trace metal content and evaluated for their brine generation potential (not easy). Brine evaluation must not be limited to apparent evaporites. There also needs to be some evaluation of cross stratification flow and its potential contributions and whether convective cells are tightly constrained either by formation hydraulics, temperature or fluid density.

INTRODUCTION

This report presents a review of the characteristics of a large sedex deposit with particular emphasis on the nature of the originating fluids and their movement within the basin containing that deposit. In these terms, much of what follows is generic and universal but, without definition of the real constraints presented by an actual ore body, such treatments are indicative and possibly misleading.

The HYC deposit was selected as the exemplary case for this review of basin fluid systems related to large stratiform sedimentary-hosted Pb-Zn deposits. Project AMIRA P384A has collected much information about the setting and geological characteristics of this deposit and the surrounding region. An equivalent *range* of background information is not yet available for other deposits (e.g., Century or Mount Isa) although some classes of information are better represented for these deposits. Peripheral, background informaton has been considered crucial to the understanding and appraisal of the fluids which might have created the deposit. The complete basin-setting data are, for example, not available for Mount Isa and their absence means that no comprehensive evaluation of fluid circulation is possible.

The discussion may be applied to a range of other deposits even though the present evaluation is framed in terms of HYC. The particular factors which can be defined from this deposit must have equivalents in other deposits and the special character of those elements for those deposits must be used to vary the actual balance of inter-relationships.

The direct objective of the review has been the appraisal of fluid needs and transfer arrangements or capacity in order to provide an indication of what is known or feasible, and thence to suggest the essential properties of the fluid and its movement.

All estimates are based on simple conditions and limiting cases only. No complex finite element or multiple variable analysis has been undertaken at this stage. Unless stated otherwise all assumptions are conservative in order to develop some indication of limiting supply rates, storage volumes, circulation periods and metal availability.

The first section of the review considers what is known of the deposit and possible fluids and the particular requirements of the deposit and any fluid or flow pattern. Estimates defined in this section are then used to appraise possible scenarios for the origin of the deposit in order to clarify what is feasible in an integrated system and what other information may be needed in order to distinguish between various options.

BASIC ISSUES AND CONSTRAINTS

The HYC deposit

Regional setting

The HYC deposit is located in a region known as the Batten Trough which is centrally located within the McArthur Basin (Fig. 1). Previous reports have discussed the precise character of the "trough" but there is no doubt that the site is located within a small sub-basin which was active at the time of ore formation. The detailed setting of the deposit cannot be understood without some appreciation of the entire basin and the structures which have formed it and controlled its evolution.

The style of the McArthur Basin has been defined by regional geophysics (Leaman, 1992, 1995) and sections

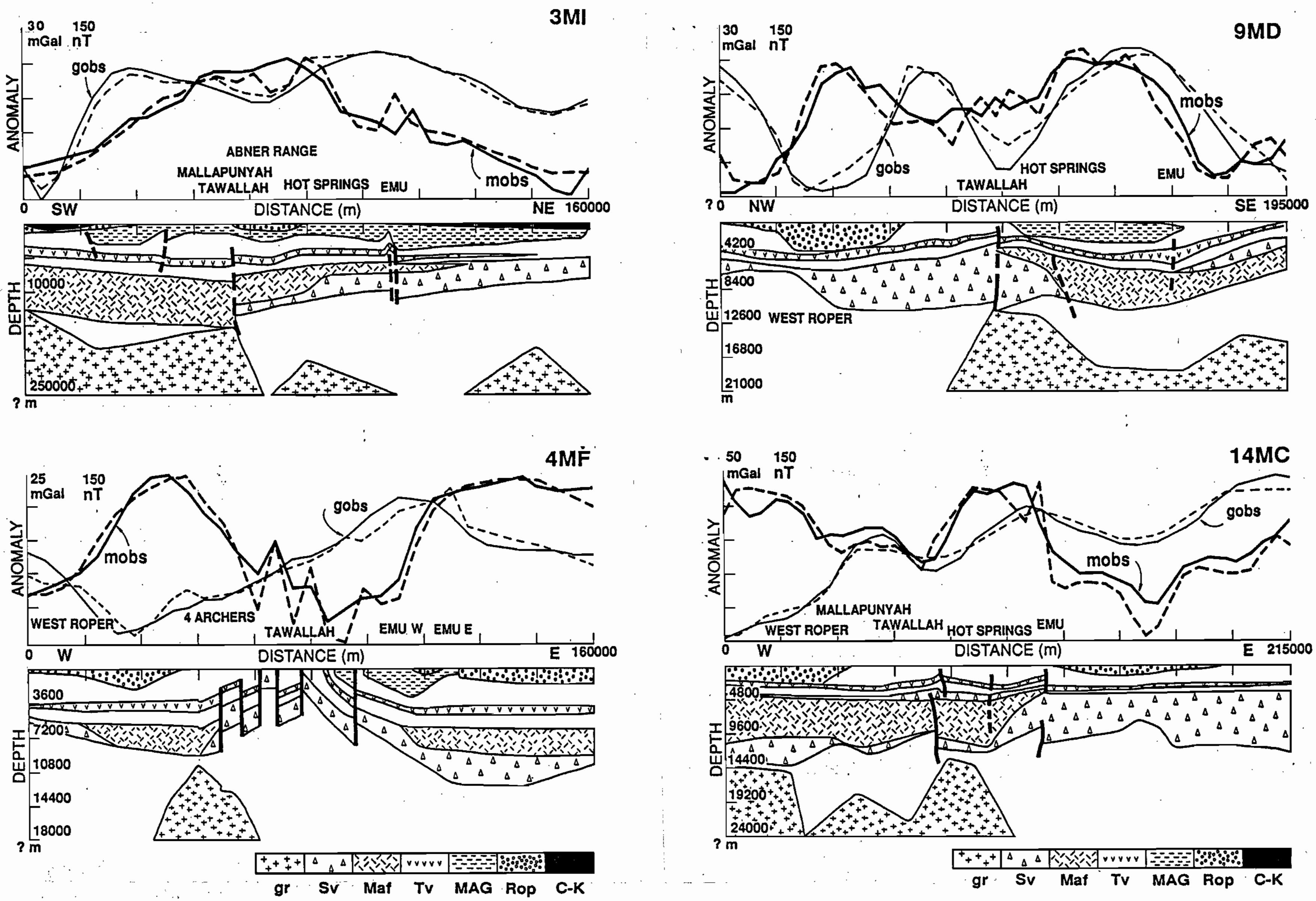

Figure 2: Sections suggesting relationships and scale of the McArthur Basin near HYC, based on geophysical analysis.

3 and 14 typify the form of the basin in the region of HYC. Much of the content, and implication, of these sections is not evident, nor can be derived, from surface exposure. The low structural relief of this part of the McArthur Basin means that units of the Lower Tawallah Group are rarely exposed and anything older is virtually never exposed. Yet, these lower units are indeed present and have thicknesses and associations comparable to formations in the Mount Isa Basin.

Such correlations have been discussed at length during the project and the regional inferences suggested have now been tested by extension of the interpretation to exposures within the Mount Isa region (Leaman, 1997, 1998a, b).

Several factors have been defined from the basin structure, evolution and architecture sub project and all may have influenced the formation of the deposit or the nature and volumes of fluid flow. These are:

(a) The basin is substantial in scale (Fig. 4). It has an ultimate width of several hundred kilometres and a strike length which may exceed this by a factor of at least four. The basin displays multi-phase evolutionary character with early rifts and at least three, and possibly five, sag phases (also O'Dea et al., 1997a, b).

(b) The rift phase of the basin includes massive deposits of flood and other volcanics. The architecture study has always described these in terms of mafic and felsic, a pattern which matches what may be observed in various minor exposures around the region as well as within the Mount Isa Basin. Tracing units and structures to exposure suggests that the mafic, flood basalt complex is a correlate of the Eastern Creek Volcanics of the Haslingden Group. It might be expected that such massive flood volcanism would not be confined to only one basin within a craton or terrane, and it clearly was not. Indicated correlations of the felsic suite are less certain but the properties inferred suggest correlations with materials comparable to the Argylla Formation — at least in part.

    There has always been a property definition problem with the deduction of the felsic suite. The density and magnetic contrast is too high to represent a suite of either pure felsic rocks or felsic rocks interleaved with sediments but is too low to represent a basaltic pile although the lower parts of the Eastern Creek Volcanics do possess similar magnetic properties. It has always been possible, therefore, to imply that the felsic suite is either a mixed volcanic association, a mafic association with at least half the volume composed of sediments, or a mafic association which has undertaken some bulk alteration. All three options are possible although the general inferences about the property, as defined in many parts of the basin, would indicate that such universal alteration is unlikely. The first option, of course, does not exclude an Argylla correlation.

(c) There are some relatively young, shallow and penetrative granitoids within the basin. These are generally quite small but may intrude rocks of at least the early Tawallah Group. If so, this would indicate intrusive and active thermal processes into the sag cycle immediately preceding the formation of the ore, at least. One of these is about 25 km west of HYC (Leaman, 1998b) and there may be some association between such, relatively, young intrusives and deposits (Fig. 5).

(d) The entire basin sequence may exceed 15 km in thickness today and probably exceeded 20 km at the time of ore formation. This estimate is comparable with the scale of the rift basins adjacent to Mount Isa and implies a very thick crust at the time (at least 80 km) since there is only evidence of rifting and no suggestion of rupture.

(e) Several large faults have been mapped or implied within the region and the regional analysis has shown that several of these have complex and extended histories. The present fractures are not always located in the projected positions of the deeper features but are clearly related to the long term position. There is also no need for a continuous and connected fracture system between the underlying crustal or deep basin breakage and the modern fault although we may assume that such connections did exist earlier in the basin history. Stresses can be, and almost certainly have been, transferred within the cover sequences. The Emu Fault is such a feature.

(f) Some areas have been consistently uplifted or deformed and others were generally uplifted after mid Tawallah time during the second (?) sag phase. The Tawallah Ranges and the Murphy Inlier zones are examples of such progressive and continuing uplifts. The former is located about 50 km to the west of HYC while the latter is some 200 km to the southeast. Most of the uplift now inferred or evident must be post McArthur Group but onlapping of units and general thinning of the basin toward the margins implies gentle uplifts, at least, prior to ore formation (e.g., Bull, 1995). The relationships demonstrated in seismic data east of the Murphy Inlier (see McConachie et al., 1993; Leaman, 1994) show that these involve all units of the first and second sag sequences and that the volcanic associations do thicken toward axes some distance from the inlier. Essentially the same conclusions are drawn by Scott et al., 1997.

Local setting

Many details of the local setting of the HYC deposit are unavailable and retained in confidential reports for MIM. Some elements have been defined or released into the public domain (e.g., Logan et al., 1990, Hinman, 1996).

The deposit was formed adjacent to the Emu Fault and about 1.5 km from it. This offset, and the brecciate zone between the main ore body and the fault is consistent with the regional inferences of underlying fracture control and local stress transfer within newly formed deposits. The Emu Fault, as viewed at basin scale, had already had a long and compound movement history prior to formation of the deposit (Leaman, 1992, 1995). During formation of the McArthur Group the fault was growing and in the vicinity of the HYC deposit motion was mainly down to the east (Fig. 3). A little further north this sense was reversed and the site is located near the hinge point. The site is, therefore, anomalous in terms of local fault and stress character. The interplay of possible major structures near HYC was suggested by Leaman & Keele (1995). Concealed structures in the HYC region have trends to the NNE and NW while the Emu Fault is oriented slightly west of north (Leaman, 1995, 1998b).

The distribution of the active sub-basins within the region was suggested by Leaman (1992) based on the gravity response of the denser upper dolomitic units. The diagram (reproduced here as Fig. 4) may be used to indicate the general form of the basins which contain most parts of the McArthur Group.

Evidence of internal compressions has recently been described within this framework involving general, if punctuated, subsidence and extension (Selley & Bull, 1997). It has been suggested that thrusts oriented E–W and derived from a N–S directed compression have generated N–S rifts. This character would be consistent with the more regional elements defined. The observations also do not imply that any major fracture set retains any direct continuity through the section, simply that the stresses have been applied and have generated detached deformations and minor intra-unit inversions. This form of structuring has been reported in younger basins, is multiple, and widespread (Davidson, 1995, 1997). Davidson has also argued that the regional stress field has been persistent through time and this means that definitive separation of events depends upon detailed stratigraphic and structural observations particular to the time of formation of the units and structures, all of which may be overprinted subsequently or confused with effects of more major events elsewhere. Evidence for pulsed compressions and related structures within the Barney Creek Formation, however, does show that something abnormal occurred at the time of deposition of the pyritic shales and formation of the ore deposit.

It is also thought that there may have been up to 100–200 m of water cover within the sub basins at time of ore formation (Bull, 1998; Large et al., in press). This is based on sedimentological studies and the absence of evidence of boiling of any fluids, and hence some confinement upon release at sea floor, but estimates may not be definitive judgments since critical evidence could well have been removed and the materials recycled if the depths were less. Pouring dense fluids onto a basin floor is not necessarily a quiet process and some disturbance of fine settlements — into suspension — could be expected, especially at shallow depths.

Heat flow and thermal conditions

Heat flow and temperature conditions have been mentioned during various parts of the project analysis but it now seems that any absolute determinations of these may not be relevant. It has been argued that the temperature of the fluids forming the HYC deposit is not critical to their chemistry or the amount of metal carried (Cooke & Large et al., in press) and temperatures of 125°–250° may be the indicated range.

Clearly the actual temperature of any fluid within the basin, whether in motion or trapped, may be higher than the maximum indicated near the deposit provided that it be mixed with cooler fluids before mineral deposition. In reality, however, if the movement is relatively rapid, significant adjustments may not occur.

If the basinal rocks have a typical depth range of 12 km then the maximum background temperatures would range from 120° to 360° at gradients of 10° or 30° per kilometre. There is no evidence for any more elevated temperatures within any part of the basin sequence or its fluids and the lack of significant amounts of copper would suggest temperatures less than 250°.

Where, however, there are confined conditions which are periodically disrupted then it is possible that flow may occur between gross aquifer units either by pressure difference or thermally-derived buoyancy differences. This matter is discussed in the second part of this review.

Residual regional heat flow variations may persist due to the original crustal controls on the basin (Fig. 4). Leaman (1995) has suggested a cellular character for the early rift phases and it might be expected that some minor flow differences could be related to cell boundaries. Some of these intersect in the vicinity of HYC and the newly forming local sub basin involving thickening of the McArthur Group.

An additional regional variation may be imposed by cyclical heat flow variations associated with basin formation. Heat flows clearly peak early in the active rifting phase of basin development and this is confirmed by the existence of massive volcanic piles. It has also been noted, however, that while a basin may subside for some considerable time after active volcanism there is usually at least one return period in which volcanism is again important. This occurs during the second or third sag sequence period. For example, in the North Sea Basin, and in Bass Basin (Williamson et al., 1987). Many post-Cambrian basins display this character and the causes are not easily determined. The fact is not in dispute, however. Volcanism at this stage is usually relatively minor, takes the form of flood basalts, and is sub-aerial. Many of the products are eroded or weathered and the deposits, when covered, are irregular, patchy and variable. Continuity is rare although fragmental deposits and an unconformity often marks the horizon (see Blake et al., 1990; Davidson, 1997). The argued existence of tuffs and their increased occurrence or observation near Barney Creek times for HYC (and Urquhart Shale times at Mount Isa) may reflect this sag period volcanism — or its residual traces.

It may be that the volcanics, so called, of the Upper Tawallah Group are younger than their implied stratigraphic position would suggest. If significant parts of these materials are intrusive then dating of both the intrusions and the intruded rocks must be completed before any conclusions may be drawn.

Localised heat flow differences related to younger, or radioactive, granites may modify local temperature regimes and may vary fluid flow conditions but since temperature is not considered a necessary factor in ore transfer or formation this may not be a relevant element in deposit formation.

Metal sources

Formations within the basin sequence contain significant trace amounts of copper, lead and zinc which may be removed in solution given time and their character.

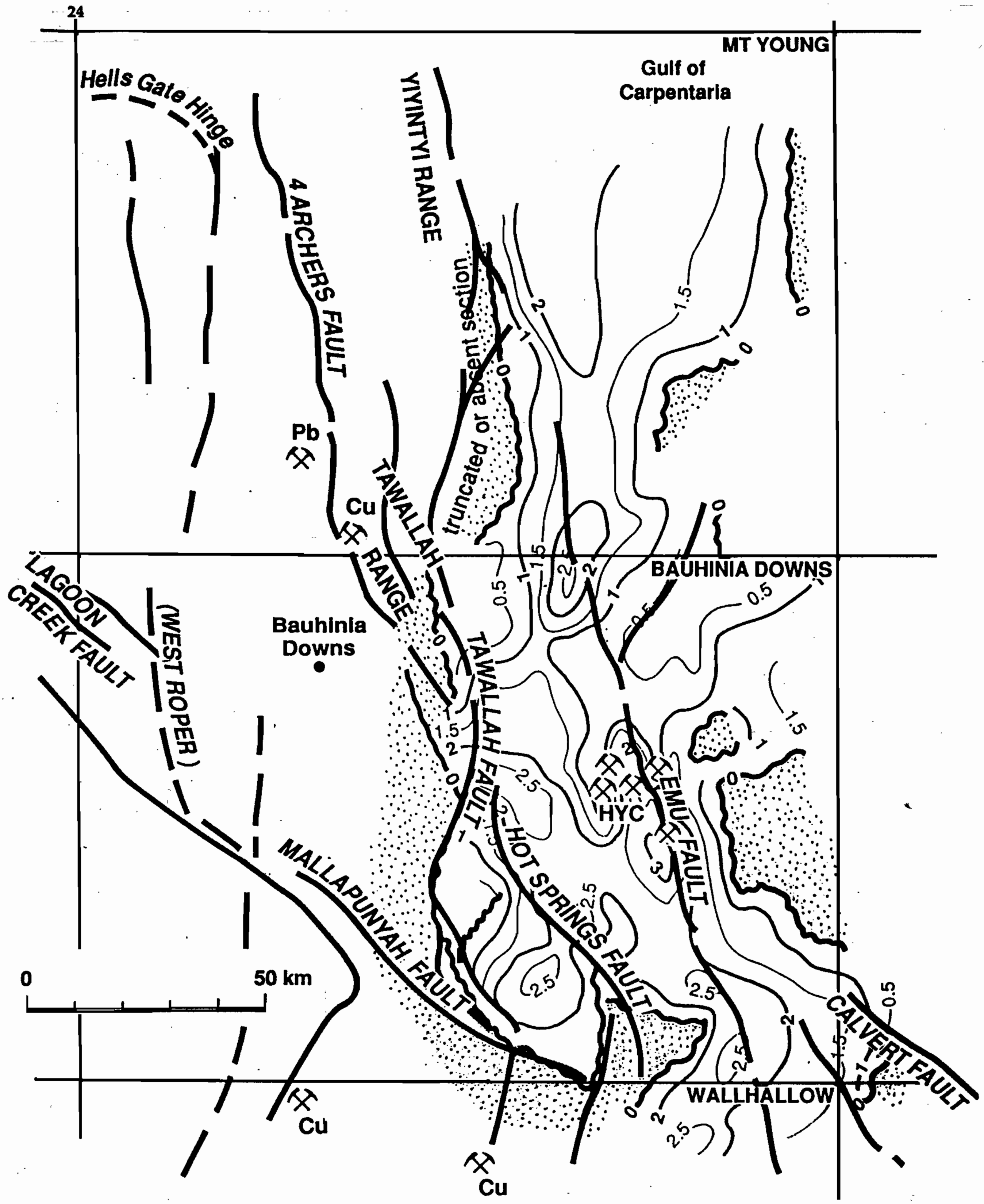

Figure 3: Interpreted distribution of more massive sequences in the eastern McArthur Group. Structural and depositional truncations indicate the present distributions and suggest it was once more widespread, especially to the east. There are only localised indications of control by the Emu Fault System. Contours in kilometres show residual present-day thicknesses.

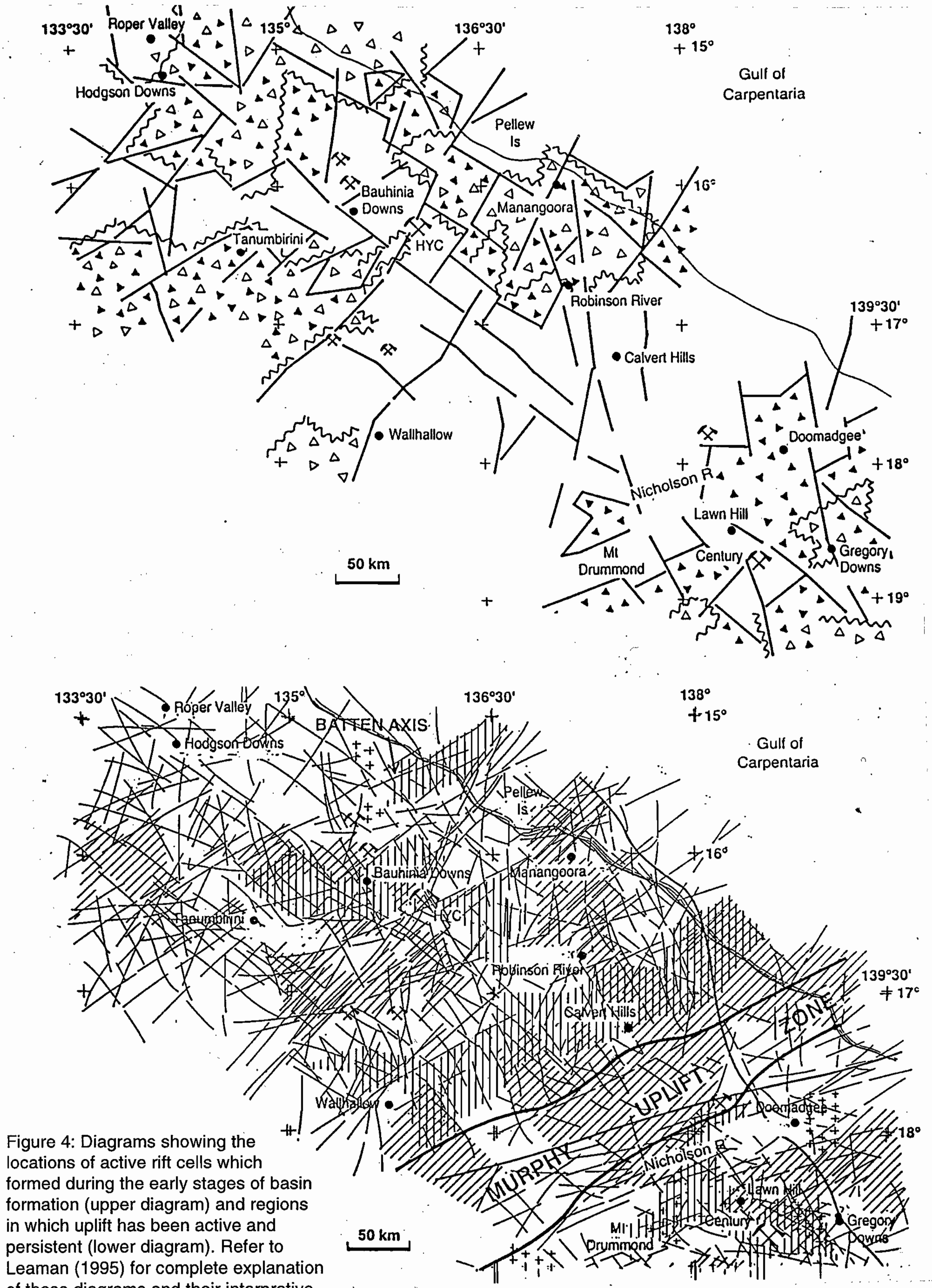

Figure 4: Diagrams showing the locations of active rift cells which formed during the early stages of basin formation (upper diagram) and regions in which uplift has been active and persistent (lower diagram). Refer to Leaman (1995) for complete explanation of these diagrams and their interpretive basis. Note that the HYC deposit is located in the zone where two regions (rift cells) which have been affected by active subsidence over a long period are in contact. The linking zone was active (uplift and subsidence) at time of ore formation.

It is known that the Settlement Creek Volcanics and the Eastern Creek Volcanics can provide much copper and locally may have had this metal wholly removed. The Seigal Volcanics may be a source for zinc. Felsic suites may provide both lead and zinc. It is not known what metals may be sourced from basement rocks but if the metals were released from the mantle only in the period leading up to the formation of this basin and the initial deposits within it, then they may not be significant sources of base metals. The basement does appear, however, to contain uranium and perhaps gold.

Zinc is the least problematic of the metals and much more conservative values must be considered for lead and copper, especially lead. There is little information available about the background levels likely in the formations of the basin; a situation which should be remedied.

Care must be taken, however, when appraising rock sources. A unit may now be partly or wholly depleted locally in some component; but was this component removed at the time of ore formation, or subsequently — or even before? Any rock which has been able to transmit fluids could well have been chemically transformed many times. The depletion of the Settlement Creek Volcanics and their silicification only tells us that it has been an aquifer, probably a good one, and may still be. Metals might have been removed at any time.

Limiting conditions can be posed if the possible units are assessed in terms of the metals available presuming that each, individually or in combination, might have been able to supply those metals to HYC.

For the purposes of this discussion we need consider only two basic sources; mafic lavas, or volcaniclastics derived from them. Felsic lavas can be considered an alternative subset until sufficient chemical data suggesting otherwise becomes available.

Consider a lava source. If the issue of solubility, or rates of dissolution is ignored and only the amount of metal available is considered, then suppose the lava sequence is 500 m thick, is widespread and contains 20 ppm of either, or both, Pb or Zn. This grade is predicated in terms of lead, zinc may be much more abundant and is suggested only as a conservative estimate. Note also that the fluids must carry both zinc and lead and if one metal is a constraining element then its concentration in both source and fluid becomes the crucial factor regardless of the abundance of any others.

If the unit underlies an area of 100 x 100 km then the rock volume is

$$100 \times 100 \times 10^3 \times 10^3 \times 500 \text{ m}^3$$

equivalent to 1.5×10^{13} t if a density of 3 t/m^3 is assumed. The amount of metal available in this material (at stated grade) is then 3×10^8 t (Pb or Zn). This result may be scaled for thickness or cross section. If only 20 x 20 km is affected (or acts as source) then the tonnage available is only about 1×10^7 t. **[1]**

It may be noted that copper often occurs at higher levels in mafic rocks and sources for this metal are less problematic if such materials are available in large quantities.

Consider a volcaniclastic source. Sedimentary sources cannot be considered as rich as igneous sources. This reflects the weathering, sorting and fragmental processes and the reality that minerals with high metal contents may have been lost from the system. If, however, it is supposed that 10% of the original volcanic source is preserved as fragments within a sediment and that these fragments then provide metals to a passing fluid then it is clear that the maximum yield can only be 10% of the solid igneous rock as calculated above. This proportion should also be examined in typical source rocks.

In this case a 20 x 20 km area of a unit 500 m thick could provide 1×10^6 t of metal at the nominal base concentration of 20 ppm. **[2]**

Sulphur is considered to be largely maintained or supplied at surface by bacterial action and the existence of a sulphur rich shale at time of formation may also be significant. Sulphur is also likely in the fluid as sulphates, although it may only form a small part of the brine (Hanor, 1994). Iron presents an additional problem but could be derived in many ways. Much of it may also be present in the host sediment or added subsequently since there is little textural evidence of significant iron precipitation with the base metals (Large, pers. comm.).

The deposit

No attempt is made here to detail the ore bodies. The object is merely to define those elements which may assist hydraulic appraisal and analysis.

The ore bodies have an average thickness of about 55 m and a surface area projection of about 1500 x 2000 m. The ore body consists of eight major lenses, each about 5 m in thickness, within the HYC Pyritic Shale Member of the Barney Creek Formation. This formation overlies the Cooley Dolomite Member. The bulk of the mineralisation occurs at least 1500 m west of the Emu Fault (Logan et al., 1990).

The defined resource is some 230 million tonnes at 9.2% Zn, 4.1% Pb and 0.2% Cu.

Other disseminated pockets and veins of ore are widely distributed in the area.

The ore is considered to be syngenetic/diagenetic within the shale deposit within which it is layered. Each lens contains thin ore rich bands about 0.3–0.5 mm thick interspersed with thin layers of turbidite or mud. Each lens thus contains about 8000 cycles of deposition (see also Large et al., 1995). A total of about 65 000 cycles is indicated for the entire deposit. **[3]**

The total metal content may be grossly estimated for the region. The amount of metal in the defined resource can be estimated as 25, 10 and 0.5 million tonnes of Zn, Pb and Cu respectively. The total amount of metal present in the region of the ore body, and not simply the economic resource, is likely to be at least four times this mass. This is considered to be a conservative mass estimate and may certainly serve as a guide to the total amount of metal in the area.

It is also possible to estimate the amount of metal in each layer based on a thickness of 0.5 mm and a cross sectional area of 3 $x10^6$ m^2 given a maximum total of 50 000 layers. This indicates 25 $x10^{6}/5$ x 10^4 t = 500 t Zn, 200 t Pb, 10 t Cu per layer. Given that the layers are generally thinner and more numerous than assumed here these values provide maximum estimates of metal content per indicated layer and fluid pulse. The amount of metal per pulse could be about 60% of these values. **[4]**

If we further assume that the fluid forming the layer carried 100 ppm of each metal and can therefore yield 0.1 kg/m^3 then 500 t metal implies 5 x 10^6 m^3 of fluid.

Note that this uses a modest but reasonable metal concentration (see brine discussions below).

Since each fluid pulse must have extended beyond the limited confines of the resource then the total volume clearly was of the order of 10^6–10^7 m^3 allowing for some range in metal content or increased fluid volume. If the concentration of metal within the fluid was only 10 ppm then the maximum volume would have been about 2 x 10^8 m^3. **[5]**

Clearly, if the concentration is increased then the volume of fluid is commensurately decreased. The release of such a volume implies a blanketing of sea floor or a water depth increase, if into sea floor or basin, of 0.3–3 m across the entire site if confined only to the area of the deposit and if it occurred as an instantaneous release. Modern processes release such volumes over many months, or a few years. This depth change is thus a maximum depth or height change if the rate were very fast and ignores the effects of outward dispersion, absorption, evaporation (perhaps) or displacement.

Anomalous conditions

The ore body must be seen as an anomaly within a very large structure. The processes which have formed it, or which have modified or controlled active processes, must be seen as localised or distinctive within that gross framework. Any element which is, or has been, applied over a wide area and a long time is not anomalous in terms of the mineralisation even though it may form part of the transfer mechanism. A distinction must be made between background, and perhaps contributory processes and mechanisms, and active, localised systems which may be marginal in the longer term but which are crucial in the short term. A "spike" process superimposed upon a "long wavelenth" process is of this type. Any element or process, however, which lends focus or drive, at a particular time — the right time, is the truly anomalous element regardless of all other factors.

Thus the presence of a small basin which was actively subsiding about an active fault zone may be important factors but many such elements exist. Indeed, it could be argued that a least two such basin cells and structures exist in the general vicinity (Fig. 4).

Sundry source conditions, both for fluid and metal, also exist generally. These are thus not unique to this site or region. This comment provides for the fact that the provenance of the mineralisation, say felsics, is possible in many places.

Local or specific heat sources of plutonic type may be involved such that, at the time of formation, local heat flows or convective circulation may have been abnormal. Again, however, the key issue is whether these thermally-generated changes were specific to Barney Creek times. Clearly they are not and there is no simple reason to suggest any increased effect at that time.

This comment, notwithstanding, there are two lines of argument which suggest that thermal conditions may have been focussed. It is known that elevated heat flows do occur at a specific point in the sag cycle — usually well into the diminished sag phases. This usually results in flood volcanism, often aerial and usually eroded. It can be argued further that the "tuffs" described for Barney Creek times may reflect this. This is not regarded as confirmed fact or proven observation but their arguable presence may support the regional implication.

Such thermal factors would be anomalous if proven.

Structure and structural history near the site is anomalous. Fault reversals and offsets are anomalous at McArthur Group times. The local breccias may indicate action adjacent to the Emu Fault during Barney Creek times although a preferred hydraulic alternative is given below. The recent discovery of compressive pulses (AMIRA P384A Report 4, Sept 1997) and local related structuring of this period is decidedly anomalous at the time of ore formation. Such compressions are secondary to overall subsidence and regional extension. This style of tectonic activity is time specific and focussed within the sub basins, and is able to activate old structures and generate new local structures and stresses. Both compressive and extensional elements can be enhanced in the affected area.

This local tectonic element which is time anomalous and essentially superimposed on second stage heat flow peaks probably accounts for both the timing and location of the deposit.

Nothing, however, could be deposited unless the fluid were chemically ready and transferred — with a means to also precipitate metals within the host material; the organic, sulphur rich sediments.

Summary of key indicators

The deposit is layered and this indicates numerous pulses of fluid transfer and deposition.

There are local structures implying anomalous stress conditions at the time of deposition. Extension is a part of this stress field.

Axes of subsidence are focussed on intersecting deep-seated structures, several of which were active, hinging or capable or reaction under an applied sub N–S compression.

FLUID AND AQUIFER CONSIDERATIONS

Aquifer characteristics

We may now consider the materials thought to be present within the basin. Since few of these are exposed in typical or significant sections, correlations with rocks of adjacent basins have been used to infer likely or feasible ranges for their properties as aquifers.

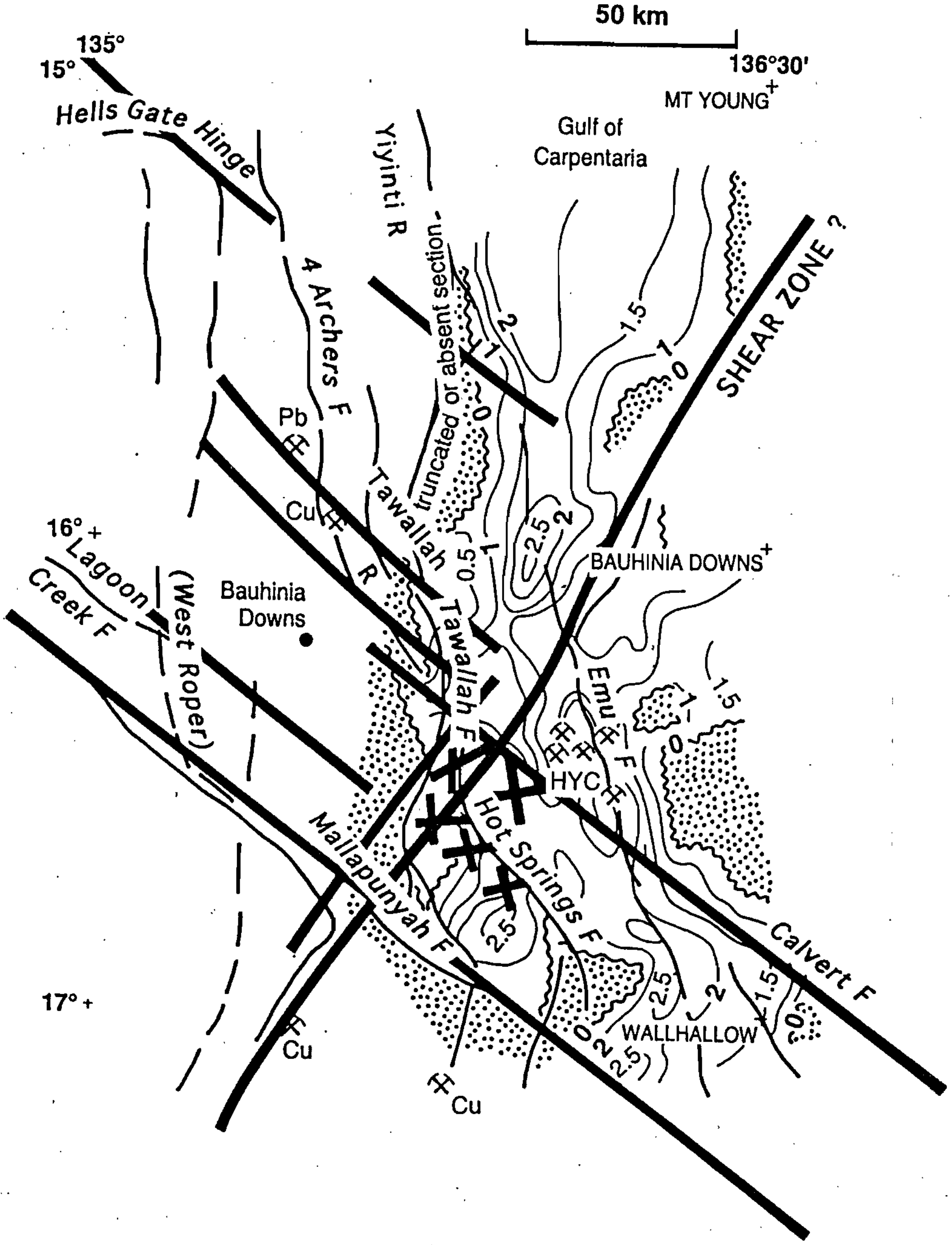

Figure 5: Structures within the HYC region. Large underlying shears and faults inferred from geophysical analysis. Crosses indicate location of relatively young granitoid intrusive into early basin phases at moderate depth.

The basin contains a substantial thickness of volcanic rocks and these amount for at least half of the total section in all areas, including the vicinity of HYC (Fig. 2). The remainder of the section within the basin includes various clastics (sandstones, turbidites and conglomerates) but is dominated by, usually dolomitic, carbonates. The total thickness at the time of emplacement of HYC ores was probably of the order of 12 to 15 km but may have been as little as 10 km, locally, near uplifted axes, and perhaps 20 km in major depocentres.

At the time of mineralisation, about 1640 Ma, fully half this section was more than 150 Ma old, and much of the remainder was at least 100 Ma old. All pre McArthur Group rocks were therefore moderately to fully consolidated and those which were capable of compaction had been largely compacted. Further consolidation would only have been likely within the non carbonate members of the Upper Tawallah Group, a quite small proportion of the total section. Further, most Tawallah units and all older units would have depended extensively upon fracture transmission of any contained fluids. It might also be expected that cementation of clastic formations might also have been complete or significant. These conditions impose clear limits on all units as hydraulic media. The carbonates present different problems and issues but, in the absence of corrosion or solution cavities, these have to be considered as coherent, cemented materials which had been in that condition since soon after deposition.

There are, in fact, few classical aquifers if we define these as porous, well-sorted sedimentary media. Such aquifers include the Masterton Sandstone at the base of the McArthur Group and underlying sandstones of the Tawallah Group (Wununmantyala and Sly Creek Sandstones). Unfortunately most of these units appear to be quite thin and rarely exceed 250 m in thickness. Such thickness estimates may ultimately prove to be misleading, however, in the same way that it has been shown that volcanic sections vary away from basin margins. It is possible that we can only see the thinned, onlapped portions of these formations in most cases although there is little geophysical evidence for large increases in thickness in any section. Geophysical interpretations, although biassed toward the volcanic or dolomitic sequences due to property contrasts, do not generally allow large spaces for other units (see Fig. 2). Some have been identified; the Yiyintyi Sandstone has been shown to vary in thickness up to about 3000 m in the Mt Young region. No comparable variations have been indicated for any other units or packages. It seems unlikely, therefore, that the apparently "ideal" aquifers of the Upper Tawallah and basal McArthur Groups can exceed total thicknesses of much more than 1000 m anywhere.

If we wish to appraise the characteristics of such units, at the time of mineralisation, then we may consider some possible analogies. The Permo-Triassic rocks of the Great Artesian and Cooper Basins of Central Australia are the equivalents of the clastic, better sorted members of the lower and central basin fills. These presently offer the equivalent age range, from formation, but may be less compacted or altered since they have not been buried to the same depth. Even so, the characteristics of these rocks may be taken as a guide to the likely properties of some members of the Tawallah Group. Porosities of about 15% and permeabilities of less than 10 mdarcies are likely. Huang & Williamson (1997) have observed typical ranges in aquifer packages according to texture, lithology and grain size. For example a fine sandstone with thin shales may have porosities of 15% and 0.1 md, while medium to coarse sandstones or shales and siltstones with minor sandstone may possess porosities in excess of 20% and have permeabilities up to 2.5 md. These more conservative values, for rocks of about the same likely age and compaction as those discussed in the context of HYC, should be noted.

Carbonates, in contrast, may have high or low porosity but also depend on fractures or cavities for transmission. There is no evidence of the latter. Many of the carbonates in this region may have acted as hydraulic barriers.

The substantial volcanic component is clearly the critical and most significant aquiferous volume. If it is presumed that this is dominated by mafic volcanics then it may be stated, regardless of their age, that these were almost certainly the best aquifers in the basin, at local and basin scales (e.g., Meinzer, 1923; Newcomb, 1961). Comparable rocks in the Mount Isa Basin include thick sequences of lava flows which are well fractured and with both porous flow tops and rubbly bases. Thin sand units are often interleaved. The felsic volcanics, if present — rather than some more significant combination of mafic rocks and sediments, will provide more patchy conditions but may have been important fracture aquifers in their own right. And may still be.

Typical porosities for the mafic and felsic volcanics and clastics may be of the order of 30%, 10% and 15% respectively. Equivalent hydraulic conductivities might be 10, 1 and 5 m/yr respectively for the same materials based on comparable modern provinces such as Hawaii and the Columbia River basalts, Karroo and Deccan traps (Clark & Stearns, 1930; Frommurze, 1937; Mack, 1960; van Wyk, 1963; Garven & Freeze, 1984). **[6]**

Given these rates the total cross sectional area involved in the flow becomes critical if large volumes need to be moved, either in the long term, or by particular events.

Some idea of quantities implicit in these aquifers at these properties can be offered (see Fig. 6a).

Consider a cross section (two dimensional) of 5 km x 20 km. This could yield 3.33, 0.1, 0.75 x 10^8 m^3 /yr from mafics, felsics and Tawallah Group respectively. **[7]**

Assuming maximum properties (after Garven, 1995) these values could be as much as 3330, 10, 1.5 x 10^9 m^3/yr respectively but presume involvement of the ***entire*** lower sag and rift sequence volcanic section in the aquifer system.

These results (7) define the volume of transmission through a cross section; clearly the amount of water which can be delivered in geologically important times depends upon the strike length (i.e., total volume) and mechanism driving transmission, or flushing factors.

Note that the Tawallah Group units of the type indicated do not have this cross section and the yield from them is unlikely to exceed 0.3 x 10^9 m^3/yr.

These values offer the necessary perspective for this basin; **the volcanics are the dominant hydraulic element**. Whether they are the only significant unit in terms of solution and volume transfer must be assessed by other means (below) but it is clear that within the basin, taken as a whole, these rocks and their associates are the dominant aquifers. The mechanisms which may operate to exchange or circulate water depend on exposure of intakes, existence of outflows and the extent, scale and uniformity of confinement.

The values implied or observed in statements 6, 7 and Figure 6a simply illustrate how much fluid might be mobilised in a basin section if its contents are thick and permeable enough. Note that thinning the section, which is being considered aquiferous, directly reduces the transfer capacity. As does transmissibility; the value of 10 m/yr chosen should be regarded as a reasonable value possibly toward the low end of hydraulic conductivities for good basalts (see Garven & Freeze, 1984) which recognises that any thick sequence will contain a range of materials and properties.

How much of the fluid stored in such units could be moved, and at what rates, are separate issues. So is the matter of recharge and aquifer filling. See below.

The matter of transmissivity can be assessed by review of volume transfers. Suppose it is necessary to move 10^{13} m^3 in 5 million years through an aquifer cross section of 5 x 20 km. If the hydraulic conductivity is 10 m/yr then the transfer is 2 x 10^8 m^3 /yr or 10^{15} m^3 in the stated period. Is this quantity consistent with recharge considerations, the movement mechanism implied and does it require steady state conditions? These become the essential questions and are discussed below. **[8]**

The total volumes of fluid available within the central part of the basin are quite enormous. If profile 14 (Fig. 2) is used as an example then the minimum amount of water available is about 10^{12} and 5 x 10^{11} m^3

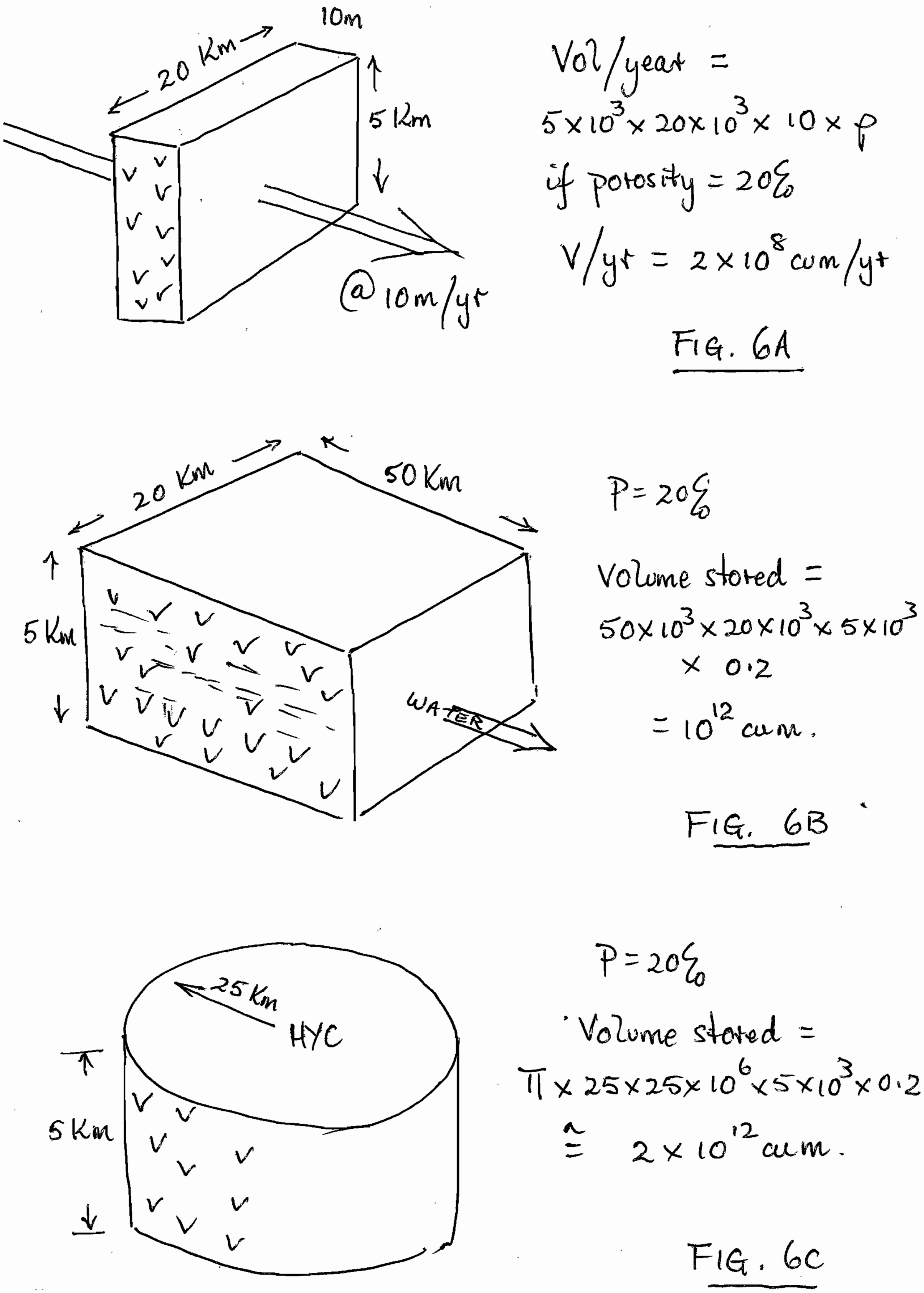

Figure 6: Volumes and possible transfer rates for some representative rock sections.

for mafic and felsic volcanics respectively, assuming 20% porosity. This calculation is based on a two dimensional cross section of the basin with 50 km strike length and is quite conservative (Fig. 6b). It is evident that a basin, of the scale of the McArthur Basin in terms of cross section and depth, can contain very large fluid volumes. Unfortunately, most of the volume cannot be drawn upon for supply to any particular site. **[9]**

The sedimentary section (clastics and carbonates) might supply a volume about half that of the felsic volcanics.

If, however, the volume is considered radially, say with respect to HYC, then the first 25 km of the site could have provided at least 10^{12} m^3 from volcanics and all other units might have supplied about a quarter of this (see Fig. 6c). This is an important calculation since it shows what fluid volumes were available in the immediate locale of the developing sub basin near HYC.

Some calculations may also be made for the Masterton Sandstone. If it had a porosity of 15%, a conductivity of 5 m/yr and a thickness of 1000 m then the maximum yield on a 20 km front would have been about 1.5×10^7 m^3/yr (Fig. 7a). **[10]**

There are, however, some additional constraints upon the volume available for delivery, and its rate of supply.

The calculations and estimates for transmitted volumes per year given above presume a two-dimensional interface for extraction of fluid. This type of surface is clearly not valid for any ore deposit, much less one as obviously focussed as that at HYC. The cross sectional estimates offer maximum fluid flow conditions; the reality must have been more three dimensional.

If the fluid flow is concentrated in one place then calculations should be based on cylindrical volumes. If we consider volcanics with a possible porosity of 33%, a 5000 m section and a 10m/yr flow rate then the volume which could be extracted at any point is

$$\pi \times 10 \times 10 \times 5000 \times 0.33 \sim 5 \times 10^5 \ m^3 . \quad \textbf{[11]}$$

This estimate is not geologically realistic but it does provide the minimum outflow possible at the given rate.

The calculation can be made more realistic if it is assumed that flow is neither to a point nor to a single place on the surface of escape. In the simplest case given above we may consider the situation as that of a single crossover fracture intersecting a large fault surface. The intersection generates a single axis although both surfaces, that of the fault and that of the fracture, may also transmit fluid.

If we consider the escape path to be essentially an axis but one composed of many intersecting fractures which have enhanced the local permeability then the escape cylinder may be considered to possess the radius of the enhanced fracture system, as focussed, plus the hydraulic conductivity. Thus, if the conductivity is 10 m/yr and the radius of the enhanced fracture set is not zero, but 50 m, then the volume which might be transferred per year from 5000 m of volcanic section becomes

$$\pi \times 60 \times 60 \times 5000 \times 0.33 \ m^3 \sim 2 \times 10^7 \ m^3 \quad \textbf{[12]}$$

Note that the effective radius is the fracture zone radius (50 m) plus the distance which can be traversed per year (10 m). See Figure7b.

This result may be compared with (11) above. It shows how important local conditions may be to estimations of volumes transferred and that even small changes in fracture density, or permeability, can make large changes in focus and available volumes.

This point can be re-inforced if a larger part of the fault surface, or focal surface within the aquifer, is used.

Suppose the axis of release is compound and extends for about 1500 m along the transfer surface. This is important in the HYC case since the ore deposit is spread out over a fault length of at least 1500 m. In

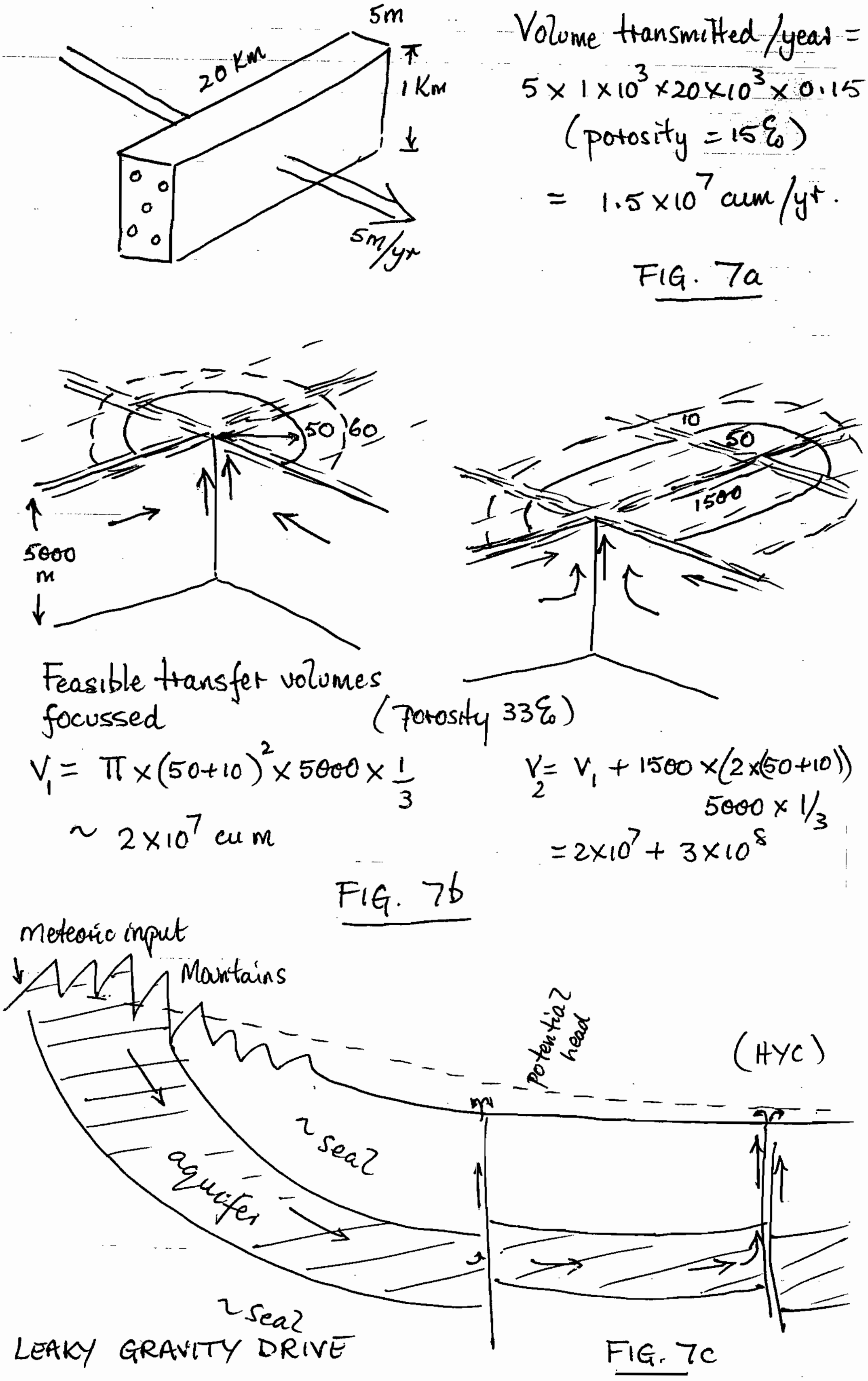

Figure 7: Effect of material and fractures, and nature of basic gravity flow, on stored volumes and discharge.

these conditions the volcanics could release 1500 x 5000 x 20 x 0.33 m^3 or approximately 5 x 10^7 m^3 per year.

This value assumes a single fracture and no local storage. If, however, the surface were considered compound with a fracture net up to 50 m wide then this volume would increase to more than 3 x 10^8 m^3 per year (all at a conductivity of 10 m/yr). This situation is also sketched in Figure 7b.

An important corollary of this calculation is the effect of widening the local fracture net; how extensive is the local fracture system and what is its actual porosity either in dormant/sealed or active state? Inspection of most faults and their hydraulic transfer capacity would suggest that the local storage could be increased by a factor of up to 50% of that assumed here. Doubling the width of the fracture zone clearly makes a significant difference to these calculations and a large fault such as the Emu Fault may well be associated with a zone of local fracturing possibly hundreds of metres wide (not 50 as exemplified here).

The above calculations show why fracture aquifers are so important generally even though the host rock, for the fractures, may itself possess low hydraulic properties and negligible porosity. Anything which enhances the fracture content will make a significant difference to its ability to store and transfer any fluid. **[13]**

These estimates for the volcanic series, or a nominal 5000 m section of very good aquifer may be scaled to suit thinner sections of sandstone such as provided by the Masterton Sandstone. If these are about 1000 m thick and have a porosity half that of the volcanics then the yield under the same hydraulic conditions (probably too high for this unit) would be about 2 x 10^7 m^3/yr

This type of calculation provides some indication of the rates of transfer to a single site if both the transfer permeability and driving mechanism commensurate with it can be supplied.

Water sources for mineralisation

This topic cannot be separated into simple elements since many aspects may be interconnected. For example, the chemistry of the water, especially if a brine, may be dependent on lack of movement for long periods within a unit of the required composition yet release may need to be very rapid, when it occurs. There must also be adequate storage and the unit must be capable of both yielding and replenishing the fluid if the volume required is a significant fraction of available storage, or if it exceeds base storage. There is little evidence for any marked variation in the chemistry of the fluid during formation of the deposit, which may have taken one half to two million years, and perhaps longer, and either a very large storage or an homogenisation process must be demonstrated.

Storage

It must be presumed that all aquifers are filled at all times. This condition may include direct replenishment from meteoric or marine sources, or it may mean gas replacement (mainly methane?) where seals are effective or circulation is restricted. The latter factor may be important at the greater depths of the large volcanic systems which are now mid crust and which always were at a significant fraction of crustal thickness. Mantle degasification cannot be excluded at any stage and it certainly occurs on the modern earth.

No comments are possible for any water source beyond the basin section but it may again be assumed that any aquifer potential within basement materials has been realised. Hydrothermal sources and reserve volumes, or magma releases, can not be estimated and have been ignored. No voids are feasible; spaces are either filled with fluid or the rock is compacted and compaction is not likely for most of the materials in the McArthur Basin and certainly not for those older than the McArthur Group.

Aquifer connection

It must be presumed that each aquifer possesses some standard or consistent properties and that, over long periods, there may be points of connection and circulation. Some subsets may be confined but this character is more likely to be restricted to the upper, carbonate-rich parts of the section.

Interconnection is an important issue at basin scale. If it is a requirement that fluid may circulate or convect across hydraulic units, each defined by different porosities, permeabilities or hydraulic contrasts of whatever origin, then the rates of exchange between, across or along the aquifer, or aquiclude, must be assessed. Boundary conditions will apply. The writer is not aware of any realistic modelling of this situation but any flow-restricting unit between two good aquifers can be treated as a leaky confinement. This means that circulation within the good units is dominant and that linkage is long term and minimal, but noticeable.

A more serious restriction may be imposed by regional fractures which disrupt all units. First order faults and major fracture systems fit this condition. The existence of such structures leads to fracture flow dominance across boundaries and the actual unit properties may be irrelevant. The fracture density may be 1/100 m for major fractures and 1/5 km for large faults. The fracture density estimate is based on regional fracture densities seen in rocks more than one hundred million years old now exposed. More intense, and more common, local fractures cannot be assumed to have sufficient continuity but if they did then the confinement would be very leaky and circulation very probable.

Any linkages, from source reservoir to focal point level, must affect discharge since it cannot be assumed that any surface which allows leakage or circulation in order to recharge an aquifer must also allow tapping of any flow past it. This cannot be a one-way process just to suit any scenario.

Recharge

Aquifer circulation may involve replacement by meteoric, marine or convective circulation or input. Each of these sources may enhance or cause circulation in association with physical attitudes, such as elevation. It may not be assumed that meteoric circulation or input has any direct influence on stored fluids in deep aquifers other than in the longest term. Recharge is directly linked to availability of input points or zones and cross boundary permeability.

Rates of movement

Limitations on the rate of movement of water in an aquifer may be important if that same aquifer is acting as the source for key, dissolved elements. High exchange rates must mean either that the aquifer will be leached quickly of that element or that concentrations of that element in the fluid will be very low. It is also unlikely that concentrated brines could ever be formed in such cases. There is thus a critical threshold affecting rate of circulation and solution, and high TDS brines may require essentially stagnant conditions.

Chemistry of the fluid

Geochemical analysis indicates that the mineralising fluid was a neutral, oxidised, brine with high dissolved solids and a maximum temperature less than 300° (Cooke et al., in press).

An oxidised brine is necessary in order to carry reasonable metal concentrations and neutrality ensures limited reaction with carbonates during transfer and deposition stages. The final reaction is one of precipitation and depends primarily upon the presence of organic matter and sulphur (Large et al., in press). A "cool" fluid (perhaps less than 150°) has also been thought likely (D. Cooke, pers. comm.).

A high TDS brine implies very slow circulation over long periods or very small tapping volumes. These characteristics are not consistent with rapid, shallow circulation involving meteoric or sea water. The origin of such brines is an important issue since possible sources may indicate the extent of circulation or location of metal sources.

It has often been presumed that high TDS brines have been derived from solution of evaporites but recent work on basinal brines shows that this is not the case and that such brines may occur in the complete absence of such materials (Frape & Fritz, 1987). There is also little doubt that the original waters may have been connate accumulations trapped during deposition but that slow solution of silicates, or clay exchanges, can yield the cation balances observed along with the chloride content. This would suggest that some rocks in a sequence, such as igneous rocks or mudstones, may be the significant brine producers — given adequate time. There may also be a cumulative solution effect, where a fluid with slow passage along a unit becomes more saline and as it does so also becomes more reactive. In such conditions we might expect to see a graded alteration of the aquifer toward any outflow point.

It should be noted that concentrated brines (400 000 ppm TDS) can be found in modern basins at depths between 1 and 3 km (Hanor, 1979; Ranganathan & Hanor, 1987) and also in crystalline shield rocks at depths less than 2 km (Frape & Fritz, 1987). Isotopic data show that the water is of clear meteoric origin in most cases (Kharaka, 1986) but that evaporites are not an essential part of brine formation and that rock interactions may be critical (Frape & Fritz, 1987, Nicholson, 1994). There is a general relationship between depth and salinity which indicates a decreasing circulation, regardless of driving mechanism, and hence longer solution times with depth. Many such brines carry modest sulphate and carbonate concentrations and are predominantly chloride waters.

Hanor (1994) also indicates that silicate buffering is an important aspect of brine formation and that not all characteristics of typical brines can be explained by solution of evaporites. Hanor also suggests that the effective limiting concentration of metals in very saline brines is about 600 ppm Zn, 100 ppm Pb and 50 ppm Cu. These concentrations should not be exceeded in any estimates of fluid requirement without good argument.

pH values greater than 6 have been recorded for concentrations up to 300 000 ppm TDS and greater than 7 for TDS less than 100 000 ppm (Hanor 1994).

The metals

An efficient ore fluid clearly requires some abnormal levels of metal in solution.

Those metals cannot be derived from normal sedimentary rocks (much of Tawallah Group, McArthur Group)(see discussion for eq. 2 as special case) but fluids could have been transferred to such rocks early in their history or that of the basin although there is limited evidence that such rocks have ever stored metal rich brines. Indeed, many examined sedimentary aquifers suggest passage of large volumes of fluid and extensive leaching.

The volcanic rocks are implicated as the significant source for metal provided the water is saline and there is negligible circulation. Brines carrying up to 400 000 ppm TDS may easily carry 200, 100 and 60 ppm Zn, Pb and Cu respectively and have the potential to carry at least 600 ppm Zn or Pb. Pb content may vary by up to an order of magnitude within the temperature range 100–250°. Hanor (1994) also shows that these levels are markedly reduced when the TDS for the fluid is less than 100 000 ppm. The organic content of the fluids may also vary their capacity to carry metals and even at 100° C and TDS of 100 000 ppm appropriate complexes may raise Pb, and especially Zn, levels by a factor of sixty for the equivalent TDS brine lacking such complexes. These may return metal concentrations approaching those feasible with more concentrated brines.

It has been argued that we do not know the composition and capacity of ancient brines and that, in order to decrease the amount of fluid transfer involved, concentrations may exceed these values by up to an order of magnitude. Explanations should not presume such results since conservative estimates are most reliable in suggesting constraints and limitations on the hydraulic system; published geochemical results for known brines do not support such amplifications.

Mechanisms for fluid transfer

Several authors have discussed the manner in which fluid may be circulated at basin scale. Processes involved may include various combinations of:

1. Gravity or topographic drive whether due directly to uplift or recharge in elevated areas.
2. Free convection, or buoyancy drive. This is thought to be rare.
3. Compaction drive due to overpressuring or displacement during consolidation and compaction in young basins.
4. Dilatancy following faulting (also known as seismic pumping).
5. Heat exchanges, changes in heat flow or magma intrusion.

6. Compression effects whether due to continental stress or thrust margins.

All processes may occur in a basin at some stage in its evolution. Some processes are long-lived or steady state whilst others are markedly punctuated and event specific.

Each process may need consideration of several subsidiary characteristics. Many of these have been alluded to in the previous section. If a brine source, whether evaporite or claystone, occurs in one sequence package and this has some distinctive hydraulic properties and is possibly confined, can that solution be circulated, can it reach a metal source and can its volume and composition be homogenised? Other questions can be posed.

1. How long does it take for homogeneity of composition to occur in the brine-sourcing unit at levels where metal solubility is significant?
2. Can that fluid fill or replace fluids in other sequence packages, especially if these contain the metal sources?
3. Can displacement or circulation occur and what constraints are implied by leaky conditions?
4. Is circulation predominantly sub-horizontal or what means permit effective sub-vertical movement? What is the relationship between fluid density, which may change laterally as well as vertically, and temperature and the combined effect in terms of convection or cross unit exchange? Do cells layer; are hydraulic boundaries rarely traversed? The combination of T-d characters within any gross package would suggest that complete homogenisation can only occur within the home package and would take a very long time. We might expect zonal homogenisation and grading laterally. If true this would mean that any tapping of a large volume of consistent composition would require a very large storage local to the outflow point.
5. If the HYC orebodies are uniform in character, implying consistent fluid character, what is the minimum volume required to allow such release given that only a fraction of the stored or homogenised volume has been tapped? Is that volume wholly in place prior to tapping or can it be generated and restored to original compositions during the life of the tapping? This writer does not believe the latter to be realistic or credible.
6. If fluids are moving in any package, for whatever reason, are they recharged at the same rate or are there delays?
7. Can the rates of sub-horizontal flow (SHF) ever be matched by sub-vertical recharge (SVR) in thick units? What happens in those cases where SHF is an order of magnitude greater than SVR and SHF is recharged meteorically? What effect would such relationships have upon flushing?

Each of these points may need further research but their implications must be considered in terms of each mechanism offered for fluid movement or each scenario proposed for the origin of the deposit.

Gravity drive

During the time of formation of the HYC deposit it is possible that both the Murphy Inlier and Tawallah Ranges were elevated. Each uplift is now of the order of 4 km but this can only be considered as an extreme maximum. This estimate is based on the relative changes in units and thicknesses but the uplift had been a continuous process within the setting of overall subsidence within the basin. Any general increase of long life would have led to a steady state condition for all practical purposes.

Thinning and onlapping of many formations suggests consistent structuring and uplift in these zones. It is very difficult to establish, however, that any post (Late) Tawallah Group formations were wholly absent from these uplifted areas but it is clear that some segments of the Early Tawallah Group, and older sequences, were never deposited or were deposited in much thinned versions.

If we were to assume that each range was uplifted by 2 km and that the hydraulic conductivity was about 10m/yr then the flow rates at HYC from the Murphy Inlier (about 200 km distant) and the Tawallah Range (about 50 km distant) would be 10 and 40 cm/yr respectively.

These values are very low. What conductivity value best represents a real bulk state at regional scale?

Garven (1994) would suggest that this might be as high as 300 m/yr. This means that bulk flow rates might be up to 3 and 12 m/yr for sources in the Murphy and Tawallah Ranges.

These estimates are, however, for steady state flow but from them we may estimate the flushing period for the aquifer. This is 66000 and 4000 years for the portions from Murphy or Tawallah Ranges. These periods would seem much too short for high TDS brine formation and must be regarded as the minimum circulation time presuming a release point at HYC. Note that the calculation is based on very extreme uplift conditions and there is no proof that anything of this scale had occurred prior to formation of HYC.

These calculations have also presumed that the uplift is present and generally unaltered leading to a constant steady state condition. But suppose, regardless of the actual elevation, that only incremental uplifts be considered. This supposition would then reflect the episodic nature of fluid flow and ore deposition. Suppose further that faulting occurs in the ranges and results in a local uplift of 3 m. If we assume that only this elevation difference is relevant; this means that it may be superimposed on whatever elevation contrast already exists, or that it is the only elevation contrast, then the incremental flow rates at HYC are 5 mm/yr and 20 cm/yr for the Murphy and Tawallah Ranges. (This calculation assumes a hydraulic conductivity of 300 m/yr, a maximum). The flushing period for the two zones is then 10 million or a quarter million years for the two zones if referenced against a base level of only the minor uplift involved. This type of background flow might well allow brines to form. **[14]**

If the aquifer cross section, of say volcanics, between each range and HYC is 5 x 100 km then 2.5 x 10^6 m^3 or 10^8 m^3could be mobilised in any given year for pressure recharge sources in the Murphy or Tawallah regions as a result of the small uplift offset. **[15]**

This calculation is a variation of Figure 6a. Note that this volume assumes that the range has a considerable length and not all of the fluid displaced would flow to a point; it would flow toward an outlet axis, if at all, and only a part would exit the system at any focal point.

These calculations assume steady state conditions framed against the limiting distances and elevations but the entire process is time dependent and contains both exponential increases and decreases in flow during any period after the imposition of the elevation change.

Two other aspects of the gravity drive mechanism must also be noted. This mechanism clearly works and there are many modern examples. The concept is sketched in Figure 7c.

1. The drive is directed. Flow is in the sense of input zone to output zone. Nothing happens if outflow is not possible or does not occur, somehow or by leakage. Where there is no discharge then the aquifer is fully pressured. In terms of an ore deposit this condition means that fluid flows to the discharge point from the recharge point; there is no radial flow. The bulk storage is not involved; only that part along the path is affected. This means that the consistency of fluid composition condition and the required volume is even more critical and must be very much greater than any estimate based on simple radial flow. This means that the capacity to yield depends on the longitudinal volume of the aquifer system and fluids of consistent composition are required along this path (which may be hundreds of kilometres for the modern Great Artesian Basin or for supply to Mississippi Valley deposits) if that is what the deposit (e.g., HYC) requires. In these conditions flows may be steady, quite slow and almost wholly confined. No pulsing of any consequence is likely but a switch on-switch off mechanism is still required at the focal site.

2. Discharge can occur at any point on the directed path, or wherever release is possible. Thus if there are several large faults or fractures between the recharge zone and HYC then each of them may lead to discharge. If there is an homogenised fluid, with metals, then much of it could be lost to these alternate paths. If this is so, then there

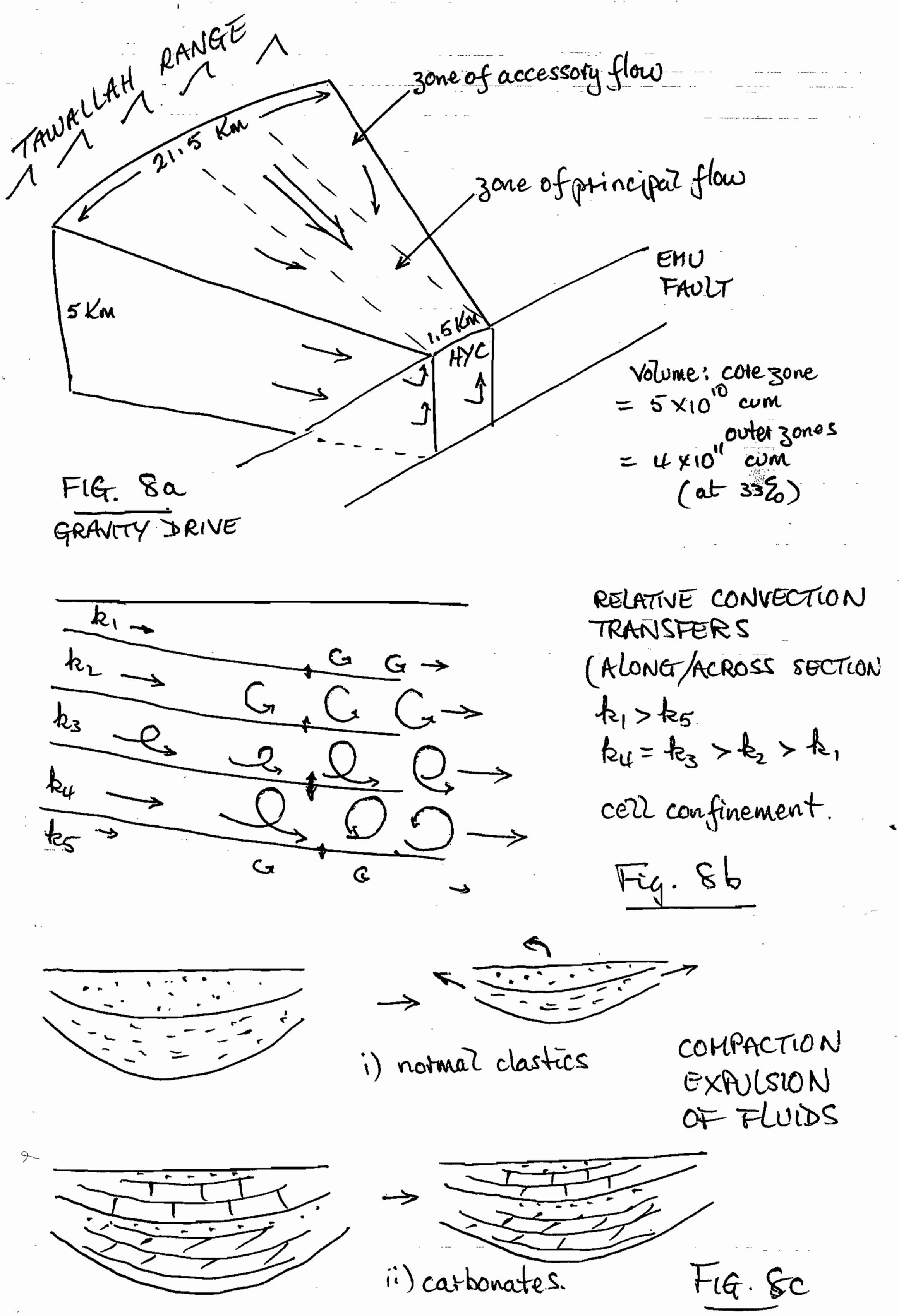

Figure 8: Examples of flow mechanisms: gravity drive, convection, compaction.

may be critical restraints upon the storage volume and indeed volume of metal sources, not to mention any problems associated with the homogenisation in the first instance. In the case of the HYC deposit, and presuming recharge in the Tawallah Ranges, it should be expected that significant fluid release would have occurred along a number of faults west of the deposit.

These problems may indicate, indeed, that gravity drive is not the solution for this deposit since the mechanism is not sufficiently site specific . It has been suggested that many deposits might be formed, or be possible, since fluid could escape elsewhere but the problems of dilution and directionality of flow, and flow period, suggest otherwise.

These issues can be summarised by the following calculations. Equations 12 and 13 have provided some indication of the volumes which might be removed from a point or fault surface focus of finite length assuming the fault fractures were open. These volumes can be used to imply a gravity feed from source either of the width of the point or the fault surface length.

Suppose that the ranges are 25 km distant and that a 21.5 km length of them can focus supply to an active fault zone 1.5 km long. This truncated pie slice if 5 km thick can contain 4×10^{11} m^3 at an extreme porosity of 33% (Fig. 8a). If the fault can remove 10^8 m^3/yr then exchange takes 4000 years. Is recharge equal to this task? Probably. **[16]**

It is clear that the most active fluid motion is enjoyed by the portion of the slice which is 1.5 km wide and centrally located. The remainder of the fluid in this volume will move more slowly but will ultimately be drawn toward the axis of discharge. Exchange in the central part of the slice is likely to occur at periods of much less than 1000 years. The 1500 m width represents the focal zone for the HYC deposit.

There are two major problems evident here; it is possible that the volume of fluid required to form the deposit is at least an order of magnitude greater than the volume of the slice (see implications of eq. 5) even at concentrations of the order of 100 ppm metal. If so, this suggests that the entire slice volume must be replaced up to ten times during the formation of the deposit, or a cycle time of 100–400 years. This is credible since the implied conductivity is then of the order of 60–240 m/yr; a figure within established ranges for many aquifers at basin scale. Is, however, this rate of flow and flushing consistent with high concentration brine production and homogenisation? Almost certainly not.

Note that all the above calculations were based upon an aquifer package thickness of 5000 m. Any reduction in thickness implies a commensurate increase in transfer rate, flushing rate and decrease in volumes available. There is also evidence that the extent of regional or local fracturing controls local versus regional flow estimates of hydraulic conductivity (Deming, 1994; Belitz & Brederhoeft, 1988, 1990). Thus any element which directs flow will determine the critical limits in the same way as the core zone flow does above.

Free convection

This process can be conceived due to temperature differences within the fluids at different depths in the basin but it is not known to be a significant process. Convection depends upon changes in density and buoyancy and the effect of temperature laterally and vertically within the aquifer package. Distinct distortions and restrictions apply at all boundaries. Convective processes are ultimately constrained by the capacity of the unit to allow fluid motions, however generated — its horizontal and vertical hydraulic conductivities. These are not generally the same. Only in uniformly porous or well fractured rocks do the conductivities equate at any scale. At basin scale it must be assumed that the horizontal conductivity will exceed the vertical conductivity generally and the only important exceptions will occur near major faults. Although convection can be conceived on the basis of physical properties its character and action are difficult to demonstrate. Water density decreases by about 8% as temperature increases from 25° to about 150°. This could occur at depths of about 5 km if thermal gradients are of the order of 25°/km. This is possible but unlikely in this basin as discussed above. If we treat 5 km as the minimum indicated depth then the pressure increase (hydrostatic) is about

50 MPa. This leads to a 2% increase in density. Thus the density difference due to temperature change exceeds the pressure effect (Deming, 1994).

Convection generated as a result of buoyancy forces is regarded as self limiting due to saline saturation and thermal constraints and may be catastrophic in nature (see Deming, 1994). It has been suggested that heat release from such circulation episodes may be important in ore formation. The length of time involved in such cycles is unknown but this may be a pulsing mechanism and some detailed modelling research is required. The real issue may be whether each layer convected involves sufficient fluid of sufficiently consistent composition since a thick section is almost certain to contain several cell layers which may reflect formations or structural changes and there may be no significant circulation across the thresholds. This is a condition analogous to modern atmospheric circulation both latitudinally and vertically. See Figure 8b.

Convection always occurs if porous media are tilted by more than 5° to the gravity vector but the magnitude of the flow involved is considered very much less than that of topographically (gravity) driven flow (Deming, 1994). Fluid flow diffusion operates at up to two orders of magnitude faster than vertical flow diffusion. This observation is crucial to appraisal of many possible models for the origin of brines, metal solutions and recharge of confined systems at basin scale and, coupled with the likely restriction on cell distribution (above), greatly restricts the capacity of such processes to supply large, compositionally uniform, coherent volumes.

Compaction drive

This process can only apply in any significant manner to the newly deposited units of the McArthur Group. Fluids derived by expulsion may well be saline, although not markedly more saline than the sea water in which they were deposited, but will not contain significant amounts of metal. The flow will also be away from the deposits, not into them. Fluid expelled is likely to rise into the overlying sea column. This process cannot be considered relevant at HYC for another reason; much of the section consists of carbonates which allow minor compaction (see Fig. 8c).

Large volumes can be involved in this process, if the materials permit. If we were to compact 3 km of sediment to 1 km then the release is 2000 m^3/m^2. If this were to occur over a sub basin area of 50 km x 50 km then the volume involved would be 5 x 10^{12} m^3. **[17]**

Note, however, that this process is a gentle steady state process with dimininishing yield with time as the material becomes less porous and more dense. The greatest expulsion occurs quite early in the compaction process.

Dilatancy following faulting

Seismic pumping has been proposed as a means to move significant volumes in short periods. The process is known to occur (Stermitz, 1964).

Consider the Hebgen Lake quake. This normal, 7.3 magnitude earthquake caused release of water from the catchment in which it occurred and the flows were monitored. The release began almost immediately after the quake and continued for many months. Rainfall events could be separated as much shorter period features. At least 5 x 10^8 m^3 was released in the first six months, or about 3 million m^3 per day. **[18]**

These are most interesting figures since a release of 10^{12} m^3 would require about 2000 comparable earthquakes, although it is not known what smaller shakes yield. If the period between such earthquakes was about 1000 years then the total volume required for HYC could be released easily in two million years.

This process is sudden, instantaneous, ***focussed*** and productive but decays rapidly in geological terms.

If we consider the layering of the HYC ore body and that each 0.3 to 0.5 mm layer of ore represents a pump pulse (Large et al., in press) then about 10^7 m^3 could yield the amount of ore involved presuming metal levels consistent with brine solubilities (see eqs. 4, 5).

It is clear from this discussion, and notes above, that seismic events driving water directly by reaction or by displacement of recharge can yield the volumes required and that, in the case of pumping, these can be focussed to the region of the active structure. More distant action would mean general release and movement with no focus and it may be very important that the Emu Fault was active at the time of ore formation — as demonstrated by the associated breccia. This raises another interesting possibility; does the breccia associated with the fault zone and the ore body represent evidence of explosive fluid release upon expulsion?

A critical aspect of this mechanism is, does the seismic event tap all fluids in a column, or only those fluids where the fault is wholly in extension? What depth does this imply? The process has important side effects which allow retention of fluid composition; namely that radial flow to the discharge point or zone is most likely and that recharge effects are both greatly reduced and less directed. A much greater portion of the total storage is thus involved in the process and much lower regional flow rates are induced.

Aspects of faulting, the associated fracturing and crustal thickness must also be considered. It is well known that fracture intersections or dilational bends are important (eg Sibson, 1994) but the dilatancy is not permanent. Sealing, elastic closure or hydo-thermal precipitation affect the capacity and length of flow activity. Subsequent events may need to re-break seals. Further, if sudden displacement occurs across jogs then there may be such a reduction in fluid pressure that the rock implodes, producing megabreccias (Sibson, 1986). Such zones may distort local temperature gradients and allow brine uplift (Fowler, 1994). In this context it should be noted that normal faults expel fluids, reverse faults do not (Sibson, 1994).

A second aspect relates to the observation that the greatest stress changes occur near the top and bottom of the seismic element; either the free surface or the crustal region in which shear and tensile forces limit extension of the fractures. In modern crust this typically occurs at depths of 10 to 15 km but may have occurred at depths of 20 to 25 km at McArthur Group times since the crust was thicker. This stress field and response character is wholly consistent with the breccias associated with the HYC ores and would also suggest that the fluids have been derived from the deeper, rather than the shallower parts of the sequence.

Fluid requirements

The outline of the deposit, the basin and possible controls within the regime means that something can be suggested about the fluids.

The amount of metal carried

If we ignore the layering or pulsing present at HYC then the total amount of metal involved is of the order of 100, 40, 2 x 10^6 t of Zn, Pb, Cu respectively. See eq. 3-4.

We may suppose that the metals are carried together in the same fluid. The carriage or location of the Fe required need not be considered here.

A concentration of 100 ppm is equivalent to 0.1 kg metal per m^3. This concentration is representative of typical neutral, oxidised, moderate to high TDS brines (above).

Thus 100 x 10^6 t of Zn requires about 10^{12} m^3 of fluid. This volume is feasible and does exist within the basin, or large sequence packages. Whether it exists with uniform properties, salinities and metal content, or whether these properties can be retained whilst withdrawing such a volume, are other matters.

Flow rates

If the mineralisation was formed in a five million year period then the rate of transfer required is about 2 x 10^5 m^3/yr. If it is presumed that the deposit was formed in only one million years, as indicated by isotopic data, then this value rises to a credible and non problematic 10^6 m^3/yr (see eq. 13).

Most significant aquifers in the basin can yield this volume on a long term basis by seismic exchange or by gravity flow if a small head can be applied.

Gravity recharge must be per highlands in which direct connection can be made to the relevant aquifers. Transfer flows across the stratigraphy will be restricted — as discussed in various sections above..

Ore layering

The layering of the ore implies an active, punctuated process such as seismic eventing or uplift perhaps associated with longer term, uniform changes involving thermal conditions. Temperature or heat flow conditions do not appear to impose any critical conditions but thermal flow channelling cannot be excluded. It could not be expected in isolation of gravity or seismically driven processes.

Chemistry

It is considered that the fluids carry most metals, including some iron, although most of the sulphur required may be fixed in the shallow, marine, pyritic mudststones. The amount of iron required, its source and its means of transport, requires a separate study in the writer's opinion since most brines carry very low concentrations and there is no reason to believe that any fluid in the immediate basin is enriched either. Most of the iron may already be present in the host rocks.

DISCUSSION OF POSSIBLE GENETIC SCENARIOS

Some fluid and flow models have been proposed for the HYC deposit. The most comprehensive has been that offered by Solomon & Heinrich (1992). This model suggests that the fluid was reduced, hot and carrying no more than 10 ppm Pb or Zn. (The calculations above show that this would require more fluid than might be available if supply were gravity driven from relatively nearby ranges.)

It is also claimed that dewatering could not produce the volume of liquid required and that it would be at low temperature. Such a fluid would not be metal rich. Calculations show that dewatering might produce the volume but clearly not the metals.

It is further claimed that high temperatures (>200°C) require abnormal geothermal gradients. This is not the case here. If the ambient surface temperature is 15° then even 13°/km could yield fluid temperatures in excess of 200° in the section established at HYC. It is the scale of the basin which is important, laterally and vertically.

Vertical convective processes are presumed to be important but the adequacy of such circulation depends upon vertical connectivity. Such circulation would be expected to layer in gross terms, reflecting the major unit or deposit patterns. There is no evidence or need for intra basement circulation which is less easily provided.

This model conflicts with much that is known or can be inferred about the fluids, namely that metal carriage is not temperature but salinity related. The fluid must also be oxidised and neutral in order not to react in passage (Cooke, pers comm) and all evidence from known oil-field, basin brines supports this implication.

Figures 9a, b, c present some sketch variations using the basin architecture models generated during this project. Figures 9a and 9b are based on the the structural solution shown in Figure 2. These diagrams sketch a number of nominal fluid paths to illustrate a concept but how many are actually feasible and what are the relative contributions from each one? The diagrams also illustrate two fluid and oxidised models but the flow notation is not specific. It must be considered conceptual, diagrammatic and not realistic.

The general circulation shown in Figure 9 is most unlikely as has been discussed in previous sections.

1. Typical cross stratification permeability is commonly less than that along stratification, often by an order of magnitude or more.
2. Confined conditions are not indicated. Any sealing at a proportion of basin scale will distort or prevent cross unit connection and flows.
3. Drive circulation of metal-carrying fluids must be slow.
4. Basic flow suggestions are sketched through and upward but most flow must be sub horizontal.
5. Complex circulation is likely at shallow depths and within the areas in which active deposition of the McArthur Group was occurring.
6. Recharge and flushing is not provided for in these sketches. If the source of water drive was in the Tawallah Ranges region then how much uplift, as seen in Figure 2, has occurred since the deposition of the McArthur Group and what

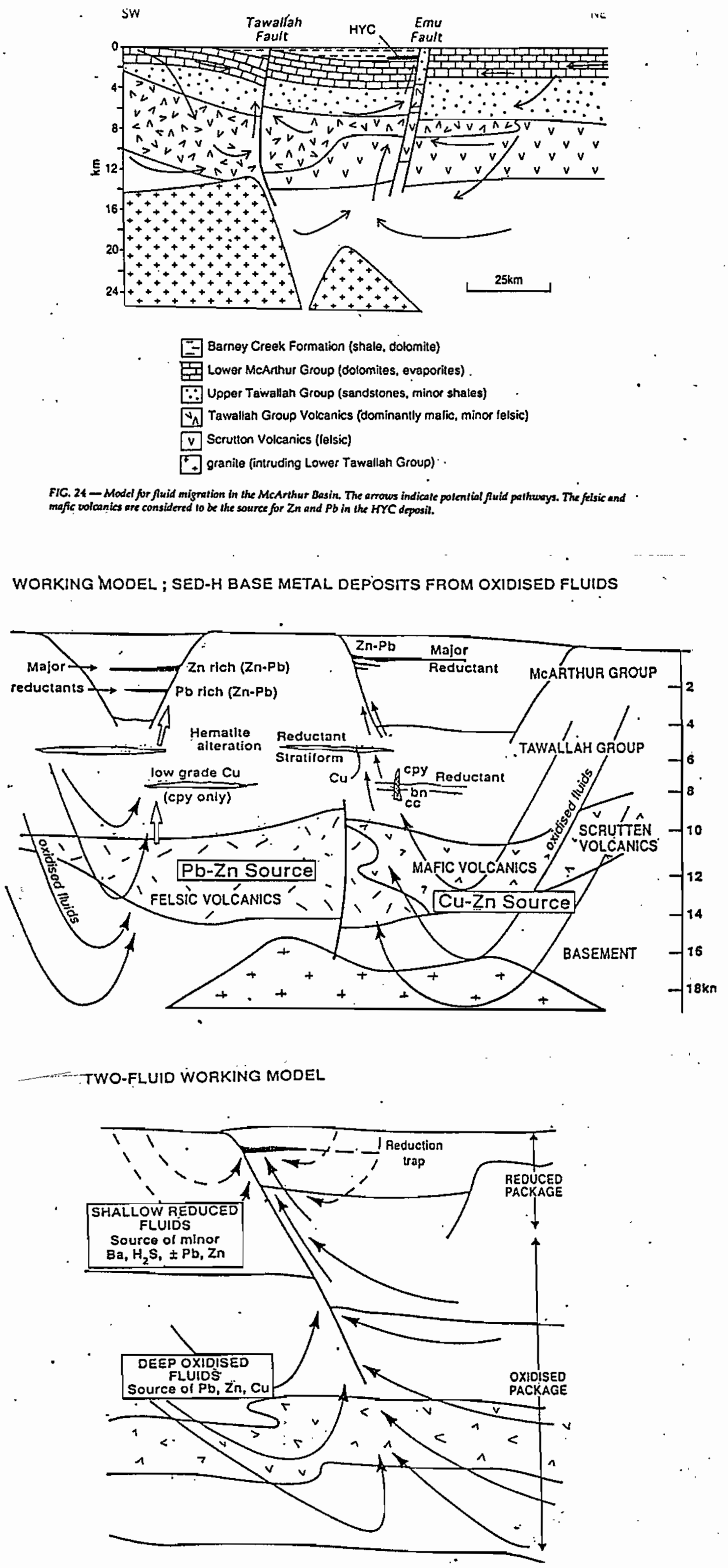

Figure 9: Style of conceptual models previously advanced by members of project AMIRA P384.

was likely at the time? Effective recharge needs to be direct.

7. How effective is convection in a strongly stratified basin?

Some of these issues can be reviewed. Concepts must be derived in terms of both mechanisms, likely hydraulic character and the basin architecture and while some of these may be local, others imply regional control.

Previous calculations show

- that the minimum background flow (steady) is 2.5 x 10^6 m^3/yr.
- the minimum steady average flow required is 2 x 10^5 m^3/yr.
- each pulse minimum volume could be 10^6 m^3 and
- a large seismic pulse could yield >10^8 m^3.

These figures suggest that neither gravity flow nor seismic pumping can be excluded as feasible mechanisms. The crucial aspects of the these mechanisms have also been outlined but may be repeated here.

A background drive process implies a steady head. Heads, however, may decrease with time. Note that uplift and erosion of scarps or catchment will either restore or diminish heads in a gravity feed situation. The gravity feed or seismic uplift options cannot be separated in terms of the source regime but clearly the exit paths are much more focussed and crucially — are satisfactorily accounted for only in the seismic mechanism. The critical process is that which affects the feeding fault system. This implies that a seismic process, possibly affecting both the subsidence and character of the basin as well as the recharge regime, may be the true origin of movements leading to formation of the deposit. The pulsed nature of the deposit is much more in keeping with the seismic history of a complex fault. Gravity feed processes are more likely to be generalised and leaky and only restricted to the recharge-discharge axis with severe constraints on volumes and hydraulic flow rates in any aquifer package (see Figs 7c and 8a).

Some suggestions have been made that the HYC system can be explained in the same manner as some deposits in the Kupferschiefer or Mississippi Valley using slow steady transfers of fluid, warming on route if necessary, by gravity mechanisms but it has, however, already been shown that the source of any head in such a system here is possibly no more distant than 25 to 40 km (for the Tawallah Ranges) and no more than 200 km for the Murphy Inlier. Other sources will be more distant but are then irrelevant. Consequently a long path or flow time is simply not available.

The possible flushing of the aquifer is an important issue. If gravity drive is operational over a long period, say 250 000 years then the water volume transfer from the ranges to HYC or the Emu Fault, seen as a pie slice with base 50 km and distant 50 km would be 1.25 x 10^{12} m^3 for the entire volcanic package with 25% porosity. Note that this is the volume required for the entire deposit and so on completion of exchange ore deposition would cease unless further solution occurs very rapidly. This is unlikely since flushing would introduce fresh meteoric waters with no significant metal solubility. Note also that this volume cannot be sustained by the three dimensional architecture established for the region and consequently the estimates are maxima. Conclusion: either this does not occur or the metal concentrations exceed several hundred parts per million. (This would need to be established before giving any weight to implications of such concentrations — see previous discussions on fluid). It may also be argued that new water can introduce more Fe and S but these occur at notoriously low levels in most waters.

Another problem in any such background mechanism is the ability of fault or fracture systems to allow fluid transfer across a depth range of 8–12 km. The ore is associated with a fracture zone at HYC and there must be some fluid capacity into the fractured zone.

If such connections are indeed made, whether by stress release, dilation and fluid pressure, then the process which drives the pulses of fluid may well be widespread and other deposits might be expected of this period, or similar activity, where pyritic shales are present in active sub basins.

If the flow wedge theory of displacement is correct then mineralisation should also change in composition upward with time since the source rock tapping should vary and the brine levels should dilute unless the entire storage has been confined for a long period. Longer contact with brine source, and consequently higher solubilities for metals, should be a function of path length and time within the aquifer system. This condition would apply along the length of any aquifer but the period involved in cross unit homogenisation, especially at sub basin scale, would be likely to be millions of years given estimates provided in previous sections and certainly much longer than the emplacement period for the deposit at HYC.

Where the resource has been tapped from great depth by seismic pulsing only then a much larger volume is available and a more uniform brine composition could be maintained and could have been generated. This conclusion may be contrasted with the previous comment that both pulsed gravity drive and seismic pumping can yield sufficient water.

All feasible scenarios must satisfy these constraints.

Although most calculations imply an average or steady state condition it must be understood that general transient conditions do apply.

Multistage transfers are most unlikely, direct fluid flow from source to reservoir is indicated. The fluid probably arrived quite hot and may have boiled.

Scenario 1 — Compactive expulsion

Compactive expulsion from any sequence in the region of HYC could only apply to the latest sediments deposited. The volumes involved might have been relatively large but all underlying units are predominately dolomitic and not subject to significant compaction (Fig. 8c). In addition any expulsion from these units would be continuous and of diminishing volume with time. It would not be significantly pulsed and nor would that fluid be an extreme brine or rich in metals; there is no source for them. All rocks older than McArthur Group would not be subject to significant compactive effects at time of ore emplacement. Scenario not viable.

Scenario 2 — Gravity drive

water source — Tawallah Ranges
aquifer — Masterton Sandstone and contiguous units.

This system essentially provides a relatively shallow aquifer system at HYC (< 2–3 km) but no inherent source of either brine or metals. Observation of evaporite cast overprint textures, as found in the associated Mallapunyah Formation, is not necessarily relevant since they could have been produced at any stage, not just the time of mineralisation, and thus these are not an indication of brine transmission. Another question might be, if this unit is a good aquifer, why these textures have not been destroyed?

Any model involving the sand aquifers must introduce the brine and must also replenish the volume of brine tapped. This may involve cross package flow which is more efficient that direct gravity drive — and raises the likelihood of this option. The overlying Mallapunyah Formation may have acted as source of salts although no whole rock comparisons seem to be available to test this hypothesis. If the brine was derived largely from this formation then density-based circulation into the sandstone must be slower than flow through the sandstone. Unless this condition was satisfied it is unlikely that concentrated brine could have formed since no concentration is likely within the main aquifer due to its siliceous base.

Variation A

Suppose gravity drive is the principal mechanism and that the Masterton package was exposed within the Tawallah Ranges at the time of ore deposition. This cannot be established given present outcrop distributions but the concept is illustrated in Figure 10a.

If the sandstone package is taken in isolation and assigned a thickness of about 1000 m then the maximum volume available is about 1011 m^3 (compare eq. 16)

Adequate flow is feasible to a fault but the exchange rate is very rapid since flushing is likely once per one hundred thousand years assuming a maximum metal content of 1000 ppm. These calculations presume

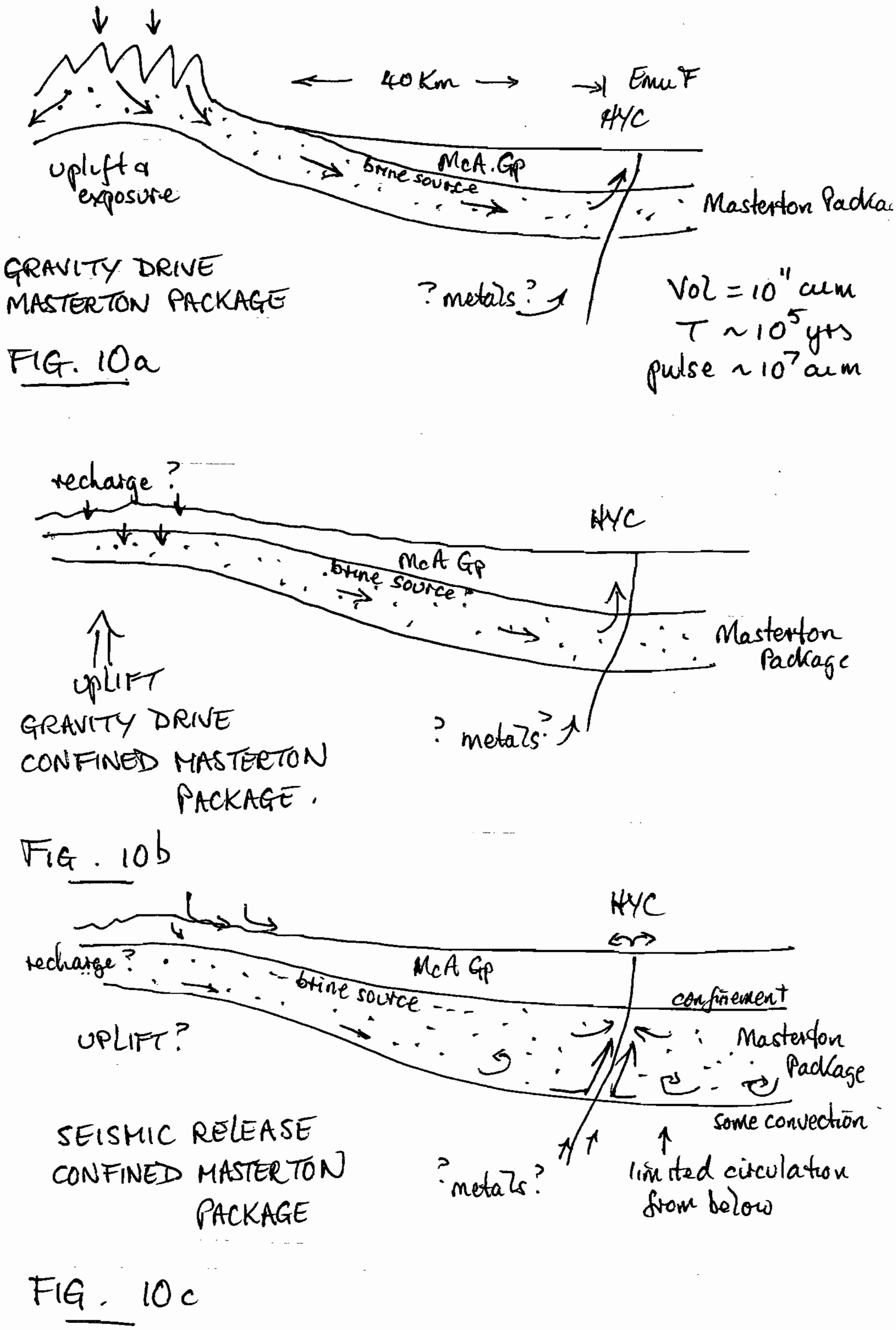

Figure 10: Gravity flow and seismic pump models for Masterton Package.

that the minimum volume of water needed is the volume available and this volume is not the integrated flow volume as explained under the conditions for eq. 16. The cycle period has to be very much shorter than suggested above.

It should also be noted that if the total number of pulses implied by eq 3 is accepted then the extraction period is no more than fifty years per pulse. Even if the minimum pulse volume indicated by eq 5 is accepted (allowing high concentrations) then the maximum slice volume would be recycled every 2000 years.

Given that the aquifer system must be leaky along the gravity path it seems unlikely that any adequate brine could form. A more serious problem is lack of metal source within the package and this requires cross stratification circulation into underlying volcanics of either the Tawallah Group or the deep section.

It must be concluded that any simple gravity model involving only the upper sandstones could neither generate, maintain nor feed fluids to HYC.

Variation B

Gravity feed using a closed or sealed Masterton Sandstone package. This option provides for the possibility that no direct recharge was possible within any modest distance due to regional cover of the McArthur Group (Fig. 10b). As noted above this can not be established with present exposure distributions.

The critical issue in this model is how to drive the fluid and arrange circulation to provide a sufficient volume of brine. Lack of direct drive for a long period and essentially stagnant conditions might have produced the brine from the Mallapunyah Formation although appropriate alternate lithologies may be more desirable.

Simple gravity drive may now be excluded even if the entire margins of the sub basin surrounding HYC were being actively uplifted. A quite complex situation is sketched in Figure 10b and recharge is now much more restricted due to the constraints upon flow into and from the overlying carbonates. This factor may have affected recovery of the storage after any release of fluids. Gravity drive does, however, remain feasible if marginal uplift and basin subsidence continues but the responses and output are limited, slow and steady and not directly matched to any tectonic events or series of events and not readily pulsed. Even were a head increment due to uplift, say, to be applied suddenly and tectonically as defined in discussion leading to eq 14 then a pulse might have ensued and been effectively terminated by limited recharge over the release period. Recharge must be delayed where flows across formation boundaries are less than those along units.

The basic problems associated with model 2A remain, however, with these additional flow restrictions superimposed.

Variation C

In this concept (Fig. 10c) the background flow may be gravity driven in accord with general basin subsidence or marginal uplift but actual, pulsed, high flow discharge is achieved locally by seismic activity. Seismically driven discharge is now considered the crucial process and the system may be open or closed; preferably closed to ensure no dilution.

The fundamental problems associated with model 2A, however, remain even though dilution and exchange are not issues. Can homogenisation occur? Possibly, if stagnant. Where have the metals come from? Is the volume adequate? All of these problems arise from the limited extent, thickness and content of the package itself as discussed above.

Seismic drive can tap 10^7 m^3 of storage per major event and the volume now available at 20% porosity (1000 m thick package) within a 20 km radius (since there is now radial release of fluid, rather than a directed flow) is now 2.5×10^{11} m^3.

This calculation assumes constant thickness at maximum property levels. For a 25 km radius this rises to 2×10^{12} m^3 but may be only 6×10^{10} m^3 if the thickness averages only 250 m. The style of these calculations is illustrated in Figure 6c. Note that flow is now radial to the release point with a small distortion in flow from the direction of applied gravity head; the gravity component being a small part of the total flow along that orientation. This is a conservative estimate of the minimum volume which can be drawn. If the system is indeed sealed then homogenisation of salinity could have taken place at any time after the Tawallah inversion, or for most of the period since there is then no time restriction on production of the fluid.

Recharge remains an issue, however, unless evacuation or gas replacement occurs since refilling across aquifer/aquiclude boundaries will be much slower (by up to two orders of magnitude) than the discharge in the absence of direct meteoric replacement.

Two issues do remain — what was the brine source and where did the metals come from?

Note that if each pulse is 10^7 m^3 then 2.5 x 10^4 pulses can be supplied by this storage — presuming it is a stable, well-mixed volume. This implies either a higher concentration of metals, that brine formation and metal supply is relatively rapid, there is substantial cross formation leakage, or there is withdrawal from a bigger area. Assumptions involving the first three of these factors seem reasonable and well constrained so that more volume and more pulses would indicate a bigger storage radius was used. This becomes problematic within the context of the local basin and its marginal uplift ranges, and the effect of meteoric recharge on the consistency and salinity of the fluid for the time and volume required. The rock volume already assumed is generous given the area quoted and the thickness presumed.

If we assume that stagnant conditions are no longer a problem and that the Mallapunyah Formation, supported by lava alteration or volcaniclastics (below?) may be candidates for brine generation while the latter materials may also have supplied metals. Unfortunately the rock volume required to supply the fluid can only supply a maximim of about one third of the metal tonnage required (see eq. 1 conditions). Ideally source conditions should be able to provide a comfortable excess since waste and loss by dispersion, or to sites without a suitable precipitating host, must have occurred. If, however the lavas were reached by the upper circulation (Tawallah Group) and were to contain 60–100 ppm Pb and Zn then this difficulty would be removed.

Scenario 2C is clearly feasible IF adequate circulation occurred in the Masterton Sandstone package and the units immediately above and below it and complete homogenisation was achieved. These elements have not been convincingly demonstrated.

Scenario 3

Aquifer: Upper Tawallah volcanics and sandstones
Background mechanism for fluid control: gravity drive

This option depends on the second sag phase volcanic package. Volcanics within this package are known to have been altered. The potential storage, however, is no larger than for the covering basal parts of the McArthur Group and the consequent flushing or cycling time is longer, but not infinite.

Variation A: Figure 11a
Suppose gravity drive is the principal mechanism. This requires uplift either near the Tawallah Ranges or Murphy Inlier. The problems outlined for model 2A arise and the path is possibly too short for brine formation and metal solution and concentration.

Variation B: Figure 11b
Since there is no evidence of meteoric recharge or elevation from the possible water supply regions then the pattern is as in model 2B — a closed system. Gravity feed does not appear to be viable due to limitations of volume, or rate of supply. Pulsing of such a system will be very difficult unless convective thresholds are involved. Whether these can release the necessary fluid to a clearly active structure is moot.

Variation C: Figure 11c
Suppose, again, that seismic drive is the extraction process but superimposed on longer term processes (gravity). As in case 2C this variation is not only feasible but also likely since it requires no essential cross unit flow or convection. Brine formation, in a

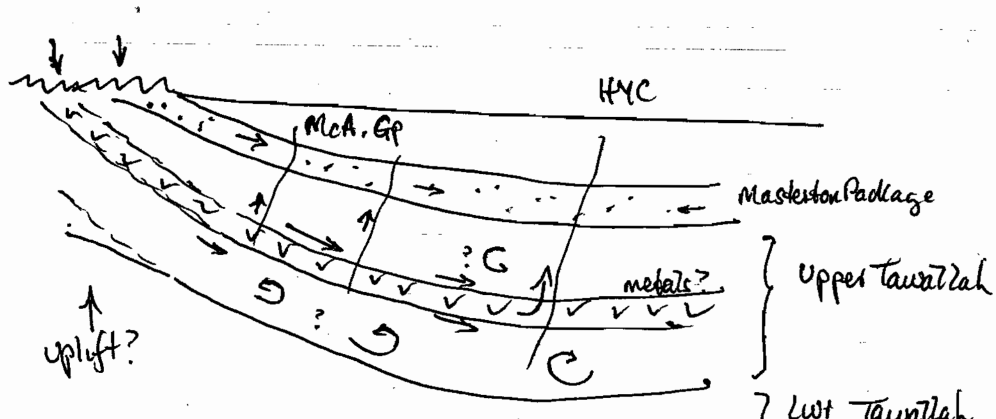

FIG 11a : Upper Tawallah exposure

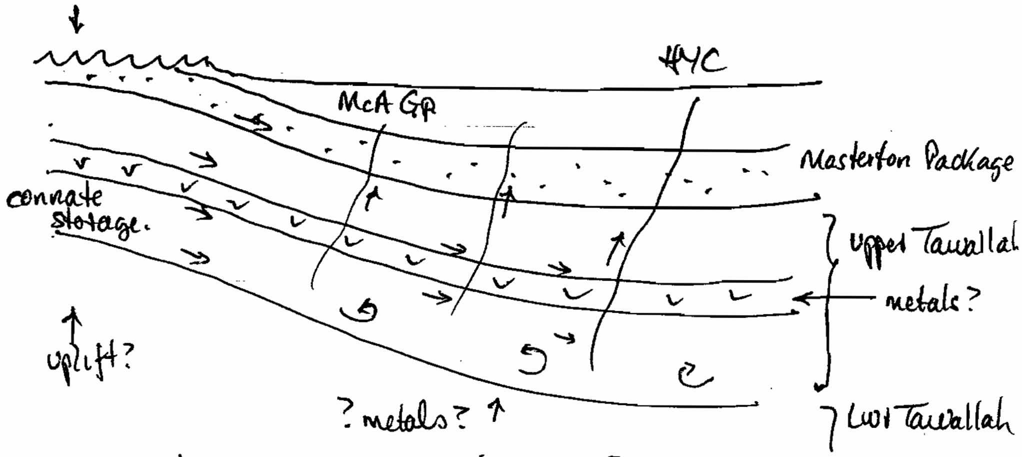

FIG 11b : Upper Tawallah confined
Flow range : ranges to HYC + volume limitation.

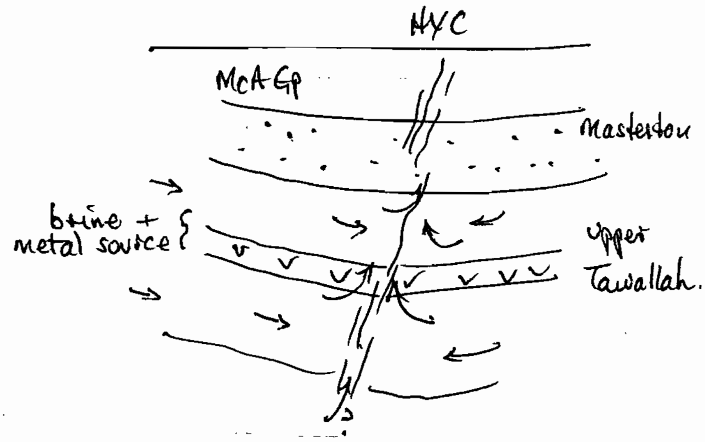

FIG. 11c Upper Tawallah.
Seismic drive superimposition.

Figure 11: Gravity flow and seismic pump models for Upper Tawallah Group rocks.

closed system lacking ready recharge, becomes wholly dependent on alteration of the volcanics — which is possible — but could be supported by other sources if entrapment has been long term. The period of formation is not critical since the sequence was undeformed and subsiding, with an ultimate McArthur Group seal, since late Tawallah compaction. In addition, the volumes available are likely to be at least 50% greater than those for the overlying package alone. This is very important.

Equation 1, however, shows that a very substantial volume of these quite thin Tawallah "volcanics" or intrusives (Leaman, 1992) must be corroded to yield the quantities of metal required. If the critical metal-host concentration is only 20 ppm (most likely for lead) then the radius of alteration must exceed more than 20 km which is, again, most of the local sub-basin east of the Tawallah Ranges.

The possible metal content of the lavas must be verified.

It should also be remarked that the alteration observed in the igneous rocks of the upper Tawallah section could be related to the ore-forming event or any other circulation event which has occurred subsequently. The later uplifts of the ranges will have generated significant gravity-driven flows and rapid flushing. Alteration is inevitable, as is repeated silicification of associated sandstones. Metals could have been removed at various stages and times.

Model 3C is, however, a viable explanation for the HYC deposit if it can be argued that a fault system can repeatedly focus motions and stress in mid section; fluids from the top part of the section alone are inadequate (2A, 2B) and all are sources are suspect if brine/metal combinations depend on cross unit circulation without transparent drive mechanisms.

Scenario 4

Aquifer: Lower Tawallah units and older rocks (lower volcanics) Figure 12

This thick volcanic system is in two parts; the upper section, almost certainly a good aquifer, does not appear to be altered generally. The lower section, equated in concept with the Cliffdale or Scrutton Volcanics, or parts of them, may well be altered (see earlier discussion). There is little exposure of most of this package and local foci of alteration cannot be assessed by direct observation or drilling results. Geophysical implications can suggest alteration volumes, which tend to be relatively small in the context of the basin, and this type of evaluation has not been undertaken in the HYC area. An indication of possibilities can be derived from the Mount Isa region.

Some estimates of metal extraction and alteration can be based on known trace copper levels of the Eastern Creek Volcanics at Mount Isa and the defined alteration volume (Leaman, 1991). The magnetic response of the 'basement' volcanics can be ranked in terms of alteration state — and presumably also as an indication of metal (Cu) removal. If the magnetic susceptibility is directly related to degree of alteration then the implied bulls-eye volume can account for all the known copper in the Isamine area. The alteration, possible source rock, and mineralisation are closely related spatially suggesting localised, focussed flow and alteration regimes. The main body of the ECV in the region, and directly beyond the mine area, is essentially unaltered.

Direct gravity drive is most unlikely in this scenario if it is accepted that overlying packages are not influential and that neither recharge nor great relief was active at these levels at the time. Seismic release must be the operating mechanism.

Consider now the lower volcanics. Within a radius of 10 km of HYC these have an average thickness of 3000 m (see Leaman, 1992) indicating a bulk volume of 10^{12} m^3 and tonnage 3×10^{12} t, which at 20 ppm of each metal implies about 5×10^7 t of each metal. This exceeds all requirements for the orebody.

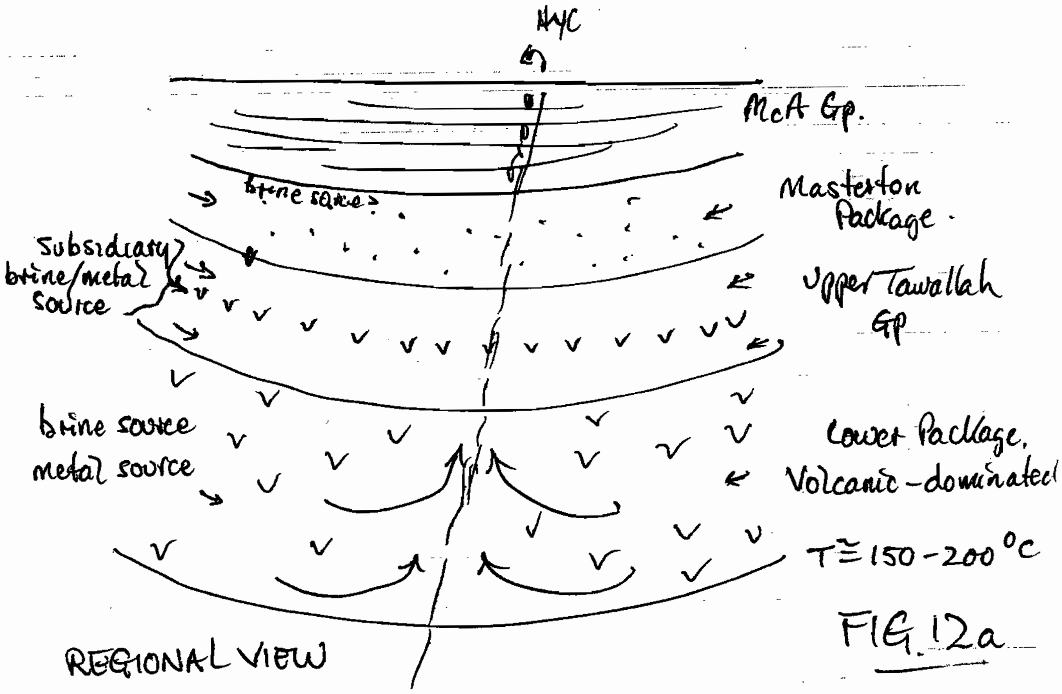

FIG 12a

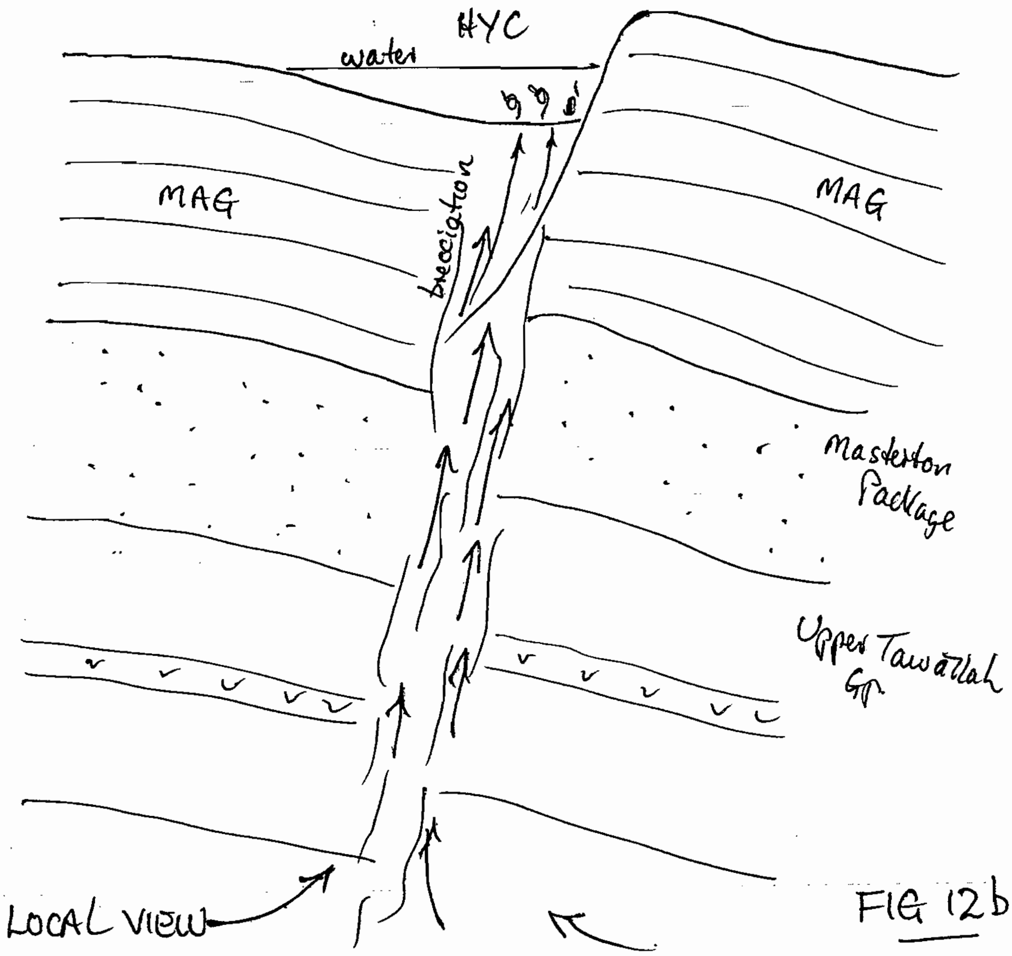

FIG 12b

Figure 12: Seismic pump model for Lower Tawallah and older rocks.

Within 25 km of HYC the volume and tonnage is increased by about six times. These are conservative estimates which also assume involvement of the whole thickness. A similar result could be achieved with only the lower third of the section with a modest increase in the area/volume involved, or a small increase in metal content.

Fluid volume within 10 km of HYC is likely to exceed 2 x 10^{11} m^3 at 20% porosity.

These values illustrate the ease with which this model can satisfy all requirements; something which is contrived and forced in all previous models.

The thick column, generating dense brines warmed by time over a very long period, could have produced and stored the necessary fluid. Evaporites are neither necessary nor known in these sequences. Time and silicate transfer and buffering are the crucial factors in brine formation in this concept.

Figure 12b provides a detailed view of the concept at the HYC site. The most recent activity on the Emu Fault has produced a small uplift to the east and subsidence to the west. Deepest water and flow is thus to the west of the fault. Brecciation occurs near the sea floor due to overpressure effects and possibly some boiling. Most water flow is associated with seismic activity and all other flow mechanisms are minor in terms of basin formation. There is thus no depletion of concentrated, homogenised brines.

It is clear from this concept that review of the properties and alteration of units away from the HYC site may be irrelevant; there is a need to know them at the site. This is particularly difficult for deep units.

CONCLUSIONS

The models suggest that:

- gravity drive mechanisms could, under very restricted conditions, provide the fluid required but there are problems associated with inter unit transfers, flow rates and dilution.

- seismic drive mechanisms can deliver the fluid required if the basic storage is large and homogenised. This mechanism is most able to provide the pulsed volumes and able to tap the root of the fault system known to be active at the HYC site at the time of ore deposition.

- no other flow mechanisms are likely to be associated with the ore deposition process in any significant way.

- the existence of an adequate storage and metal source at depth, lower volcanics of Scrutton–Cliffdale equivalence, is sufficient to account for both the fluid and metal supply. These rocks also occur at a depth which, at the time, were likely to transfer the fault stresses to shear and so allow full tapping of that reservoir.

- the brine required could be produced by long term silicate diffusion and solution processes with some convective mixing within the package. The process may have continued for one hundred million years prior to discharge.

- explanations involving the Upper Tawallah and Lower McArthur Group sandstones and volcanics are strained but brine development at this level might have been advanced by the presence of partial evaporites. Again, gravity drive solutions are not feasible and metal derivations may be marginal. Seismic release from mid crustal-shallow levels is less likely than from either top or bottom of the fracture release system.

- there is a need to evaluate formations, now exposed around the margins of the basin, in terms of their trace metal content and potential for brine formation.

ACKNOWLEDGMENT

Discussions with other members of the AMIRA P384 team have been most helpful in directing attention toward critical issues.

APPENDIX

Some conversions.

Concentration: 1000 ppm = 1 kg/m^3 of metal
1000 m^3 = 1 t metal

Fluid density: 1000 m^3 = 1 t metal = 1001 t total
= 1.001 t/m^3

seawater = 33000 ppm = 33 kg salts
33 kg in 1000 kg for 1 m^3
density = 1+ 33/1000 = 1.033

Comparative volume:
Tasman Sea 1000 x 2000 x 5 km = 10^{16} m^3

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Supplementary Notes

Considerations concerning mineralising fluids within the McArthur Basin with particular reference to the HYC deposit

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Some critical comments were offered at the AMIRA Group meeting held on Thursday, March 5, 1998.

These related particularly to

a) the emphasis on the concept of pulsed dilational or seismic release of fluids,

b) the conclusion that the volcanics would have been important or dominant aquifers,

c) the relative exclusion of the porous media as aquifers,

d) the inference that the volcanics could have been systematically decomposed to provide chemical constituents.

The following notes, including additional references to current review and research, are intended to suggest that these assumptions were neither radical nor unreasonable and that background and experience can influence belief or acceptance.

If we accept the apparent layering of the ore bodies, including the implication of sediment-enriched layers, then we must consider a fluid supply (ore fluid) mechanism which is pulsed. That mechanism must then be treated as a temporally dominant process at the time of ore formation and that other fluid flow controls were temporarily of lesser consequence. This does not mean that they did not continue to function but the pulsed supply became crucial. I conclude that only a local tectonic mechanism can achieve this requirement. I refer the reader to Sibson (1994) mentioned in the original text and to Muir Wood (1994) for supporting information about how such mechanisms may operate. Note especially Wood's Figures 8 and 9 which suggest mid crustal plumbing for fluids. This is exactly what my final scenario requires.

Igneous and crystalline rocks are, in simple theory, less porous and permeable than consolidated sedimentary rocks or other porous media. This is, unfortunately, a commonly accepted but false view because it excludes the practical influence of fracture nets and also reflects a bias derived from sedimentary basin studies where crystalline materials tend to be ignored or overlooked. It may be argued that only young, near surface volcanic piles remain good (usually extremely good) aquifers but my experience of crystalline and fractured rocks is simply put: most yield as much or more water than the sedimentary rocks they intrude when those rocks are well consolidated. We should also note that the volcanic sequences within the McArthur Basin were exposed or at shallow depth for much of their existence prior to formation of the HYC deposit and that large volumes were eroded or weathered. Volcanics do retain a higher intrinsic porosity than many other rocks regardless of whether we include their more intense jointing and fracturing component. We should expect higher yields from volcanics but even massive igneous rocks are not water free; many granites and even our Tasmanian dolerite proves this.

More recent research (National Research Council, 1996) details analysis of regional conditions in crystalline rocks (see case histories supplied) to show, that while stress conditions and changes affect flows, conductivities may be as much as 12.5 m/yr which exceeds my conservative requirements as stated in Part 2. I would maintain that the volcanics could exceed this but the scenarios do not require nything extreme. The igneous component of the section can not be hydrologically xcluded from consideration because porous media have a better press.

The discussion in the main report generally downgrades the contribution of the sedimentary sequences for two principal reasons; the igneous / volcanic sequences form a very large part of the section and very few of the sedimentary rocks can be expected to be better aquifers. Many may simply be hydrologically equivalent, such as those in the lower two thirds of the section (below Masterton Sandstone level), and others may be poorer aquifers. The various scenarios simply reflect the actual volumetric considerations and proportions of the basin section; it is not a sediment-dominated section.

Some suggestions have been made that the dolomitic sequences and units are good aquifers but all experience of, and literature about, such materials shows that they are fracture-dependent as consolidated aquifers. Since there is little evidence of fracture zone alteration we must conclude that these rocks have not either transmitted, or been affected by, large volumes of fluid.

This observation about the dolomites may be contrasted with the utter and pervasive destruction and alteration of some of the Tawallah volcanic units which have clearly been affected, at some stages in their history, by large fluid transfers. If nothing else, these observations prove that fluid can pass through the igneous rocks and that chemical transfers can be, and have been, made. Similar comments can be made about the more massive basalts of the Eastem Creek Volcanics in the vicinity of the Mount Isa mine.

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Some regional geophysical models for the Mount Isa–Cloncurry region

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SUMMARY

Five sections across the Mount Isa and Cloncurry region have been reviewed regionally. The preliminary results show that the data sets, especially the magnetic data base, contain some base level problems and that many features are not readily explained without consideration of a large number of local elements. This condition applies particularly to the Cloncurry region with its array of intensely and variably magnetised units. Gravity models are much simpler and dominated by granitoids.

Some gross structural conclusions may be drawn. The structure east of the Coolullah–Fountain Range Faults (Eastern Fold Belt) may include a repeated thrust stack but the deformation is more limited. The region immediately west of the Coolullah Fault (Kalkadoon–Leichhardt Belt) is much more altered and deformed and folding is essentially isoclinal and large pieces of the structure are wholly detached. Further west (Western Fold Belt) structures, initially detached, pass into more gently folded, long wavelength features. West of Mt Isa structures are covered by late Proterozoic to Recent materials but the gentler pattern implied throughout much of the McArthur Basin study is indicated.

The interpretation completed has not been comprehensive enough to define all stratigraphic variations in sequence but it is clear that substantial variations in thickness, some presumably primary, affect many units within the Western Fold Belt as inferred further north. It may be concluded from the present study that the principal correlation made in all previous interpretation; namely that a thick mafic sequence almost universally present within the McArthur and Isa Basins is a direct correlate of the Eastern Creek Volcanics of the Haslingden Group. Concealed extensions of this suite can be traced to outcrop.

INTRODUCTION

This is the final report in a series presenting geophysical and structural interpretations in the McArthur and Mt Isa Basins, and the Cloncurry Province, of NW Queensland and SE Northern Territory as part of the AMIRA Project P384/P384A.

The original objective of the architecture component of the project was to define elements of the region around HYC and the "Batten Trough" region in the central McArthur Basin. The initial work in this zone was effective and suggestive; to the extent that the work was expanded to cover all of the southern section of the basin and beyond, across the Murphy Inlier into the Mount Isa Basin. Many structural elements were inferred which did not crop out north of the Inlier, although many were confirmed by regional seismic reflection data, and most appeared to be consistent with formations and structures in the Western Fold Belt near Mount Isa itself. In order to test this proposition and to confirm some of the possible correlations some interpretation was extended into the Mount Isa–Cloncurry region. The first stage of this process was reported by Duffett (1996) and Leaman (1997).

Comprehensive interpretation of data in the Mount

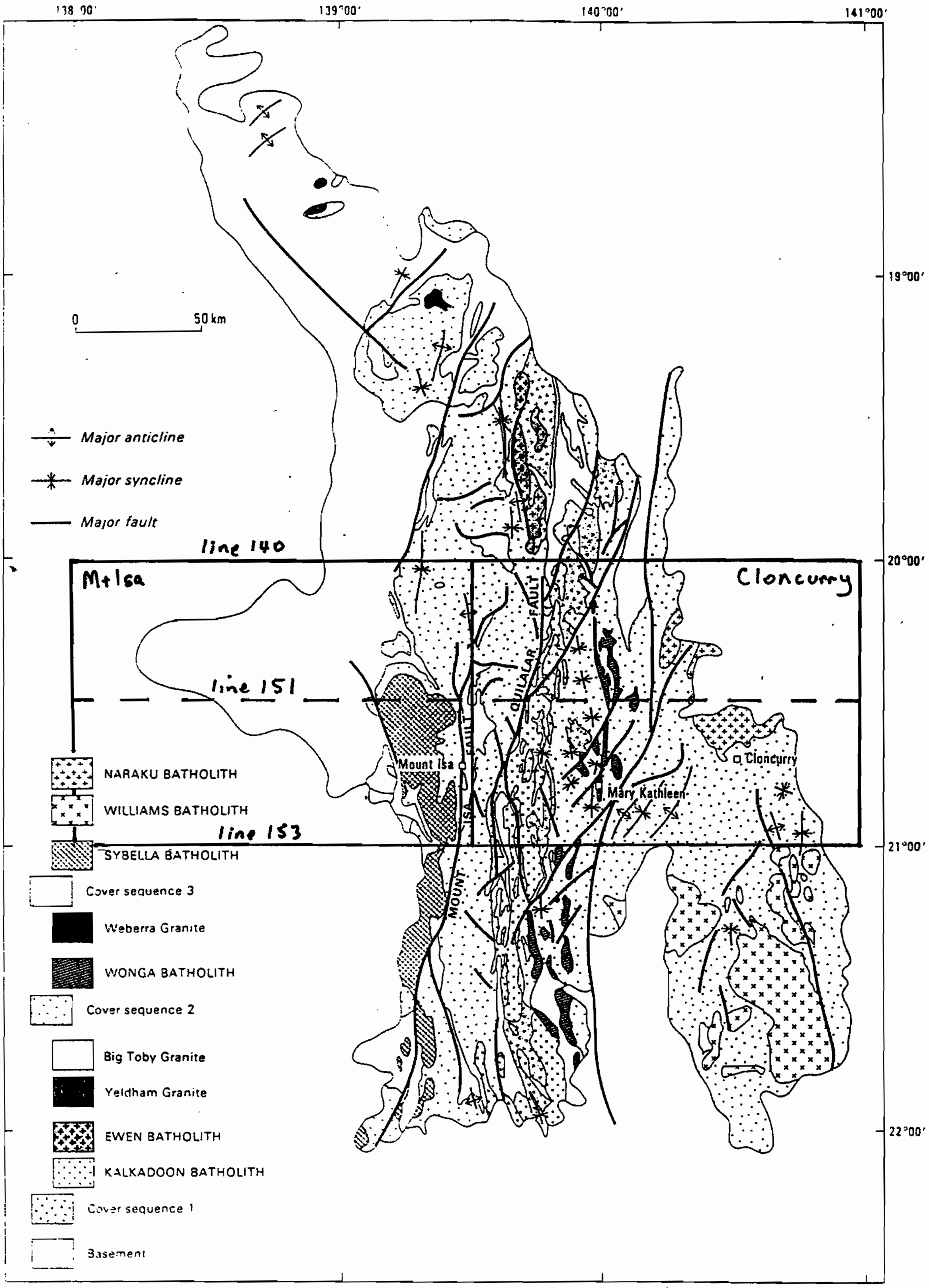

Figure 1. Geological map, Mount Isa Inlier.

Isa–Cloncurry region is beyond the scope and objectives of the present project and only enough regional evaluation has been undertaken in order to trace critical elements of the structure on infer some primary correlations. This level of study is consistent with the nature of the public domain data available to the project. The time available for this phase of the study has also been restricted by two factors beyond the control of the author; the allocation of the Camooweal area to M. Duffett led to delays, and the need to review the hydrology and fluid mechanics of the basin as defined by the interpretation in the HYC area.

DISCUSSION

This report considers five regional profiles which extend the entire width of the Cloncurry 1:250 000 map sheet and most of the Mount Isa sheet. The sheet boundary is at 143 km in each section. These are located on a simplified geological map, Figure 1.

Rock properties used are essentially as reported in previous reports. Some bulk estimates have been made of the magnetic properties of the Corella Formation and other units in the Eastern association.

Line 140: 20S

Figure 2 presents gravity and magnetic solutions for the data on this alignment.

The western end of the profile is most relevant to the project since it represents a structural and stratigraphic style consistent with previous interpretations. The model as shown resolves the data in terms of a folded, stratified, magnetic unit underlain by thick quartzites or quartz sandstones. This solution can be expressed in terms of the Eastern Creek Volcanics and the underlying Mt Guide or Leander Quartzite. The model suggests some variation in thickness from an onlap point near mid section.

This is a feasible solution but not necessarily unique. Some other sections have been resolved in terms of underlying granitoids rather than quartzites. There is no information available at this northing which might resolve the options and, in the absence of a network of modelled profiles, the matter has not been resolved. The difference in solution style does not alter any conclusions made about the volcanics or magnetic unit but do affect how the structural history, and hydrology, of the basin must be appraised. The thicknesses inferred are consistent with some known ranges.

The body of volcanics, which possess mafic (ECV) properties, has a thickness and geometry consistent with known sections and with the interpretation provided further north. There is some suggestion of folding, erosion, or primary form of the deposit west of the Quilalah Fault. The entire character of the unit and the section as a whole is transformed near 110 km and from this point the unit can be traced directly into exposed ECVs which are folded and thin eastward. Various other unit packages thin eastward mid section. Further, most implied structural discontinuities also dip eastward.

The Cloncurry terrane (Eastern Fold Belt) is both denser and thicker than the Isa terrane and large parts of it may be repeated – as implied in the Dobbyn area by Leaman (1997). Some granitoids are included in these packages and all older granitoids have be included in the deformed blocks. Only the youngest granitoids present normal discordant forms with respect to the structural grain.

The gravity profile for this line (and all others in the region, including those of Leaman, 1997) has an important property. It can not be significantly affected by gross mantle offsets since anchoring anomalies where thin recent (post Palaeozoic) cover rests on younger granitoids have similar anomaly base levels. Profile 140 may include an offset of less than 10 mgal in 300 km but other lines do not allow this amplitude change. This suggests that solutions must be generated using credible properties for exposed or concealed formations as is done here. The presence of large granitoids also limits options since the relatively thin roof rocks must explain much of any response. This is also demanded by many steeper gradients.

The magnetic solution supports these views but also suggests possible continuity of horizons within the Corella Formation complex. The extreme magnetic properties of some of these units, either regionally or locally, are not simply defined, described or modelled at this scale — or with the data available. Curve fitting on this profile implies a base offset of about 100 nT. Leaman (1997) and Duffett (1996) have noted that a clear and unambiguous base level reference cannot be provided for the data sets for the Camooweal, Dobby, Cloncurry and Mount Isa sheet areas and that up to 300 nT may be included in scalar shifts across sheet boundaries. Unfortunately this is not easily recognised due to the location of the N–S boundary between sheets and its near coincidence with the junction between the eastern and western terranes of the region. The very large change in magnetic character across this terrane boundary is able to disguise the much subtler base shift range and this issue may only be resolved by a new survey with acquisition ranges which are not tied to the terrane or map boundaries.

Line 150: 20 15S

Figure 3 provides a solution for data at this northing.

Most of the elements of the solution are as described for Line 140, above.

The western end of the profile has been modelled using a combined volcanics/quartzite solution since there is little evidence of an alternative basement but it should be noted that this data can be fitted if a granite is included in the basement.

The magnetic data have been fitted with a neutral offset and this is supported by the character of the western end of the profile. Since the data for this profile were drawn from the Isa–Cloncurry sheets it is possible that the 100 nT difference between lines 140 and 150 occurs on the sheet boundary. This problem is presently unresolved but the style of solution is not radically affected.

The substantial disjunctions in structural continuity occur mid section and structures east of them may be more intensely folded and/or detached. Most very magnetic units occur within the Cloncurry terrane. The Naraku Batholith occurs at relatively shallow depth and some alteration may be related to its roof.

Line 151: 20 30S

Figure 4 provides a solution for data at this northing.

Most of the geophysical character and its structural resolution east of the Mount Isa Fault is similar to that of previous lines described. Some large chunks of Corella Formation, or material with similar properties, are implied near the Quamby Fault Zone.

The western section of the profile is more interesting. The magnetic curve fits do imply an offset of 100 nT as observed for line 140 but there is little suggestion of any significant volume of magnetic units until the far western part of the line. The gravity profile is also distinctive. There is little suggestion of any regional gradient and the relatively uniformity implies either a huge slab of cover rocks and underlying quartzites or granitoids. The scale is more consistent with a large batholith and the exposure of parts of such a mass a little south of the profile suggests that this is the most likely condition. See also Figure 1. The general and sustained levels of the gravity field also indicate that there is little contribution from deep crust or upper mantle sources — at least in this part of the region.

The most anomalous change in character occurs within the area in which the Sybella Granite is exposed. A 20 mgal step in the gravity field occurs in this zone. The effect across the exposed granite is much higher than would be expected given the relatively low density of this pluton combination. More detailed modelling of this zone, not reproduced here, suggests that the plutons are partly detached and that the major root of the intrusion remains a little west of present exposures.

The Mount Isa Fault Zone is seen to distinctly limit extent of units to west and east.

Line 152: 20 45S

Solutions for the data along this profile northing are shown in Figure 5.

Many elements of the model are comparable to previous sections, especially east of the Mount Isa and Wonga Fault Zones. Most large structures dip east and at quite shallow dips. It should be noted that the modelled sections carry significant vertical exaggeration.

The Mount Isa Fault Zone at this northing is not as definitive a structure as that implied in line 151. The major break at this northing is several kilometres further west.

The magnetic curve fit offset for this profile is 100 nT and this consistency (with 140 and 151) suggests that line 150 could be reviewed with some removal of the mafic volcanics. This style of review is consistent with an objective modelling process where each additional model allows review of all others. As described in earlier reports, this process is most effective when extra profiles link and tie the basic network.

The gravity model shows that granitoids west of the May Downs Fault do contribute to the Bouguer anomalies and the known Big Toby Granite accounts for the variation in the field near 100 km. An additional granitoid is indicated at the western end of the section although some of the gradients observed must be related to thin, near surface cover probably Cambrian in age.

Line 153: 21 S

Models for data profiles at this northing are shown in Figure 6.

The gravity solution is consistent with all previous profiles in terms of content and base levels. The section is dominated by granitoids and elements of all but that inferred at the far western end of the profile are exposed. Again there is no consistent suggestion of any regional gradient consistent with a deep crustal source. The many small exposures of the Big Toby Granite between 80 and 120 km establish the origin of the anomalies in this area. Similar responses may be noted for the Williams Granite at the eastern end of the section although its response is muted by the denser roof rocks. The model also shows that the major structural change occurs a few kilometres west of the Mount Isa Fault. The irregular nature of the solution near this fault reflects the three dimensional character of the distribution of both Eastern Creek Volcanics and the Mt Guide Quartzite and the very high density contrast between them. Other significant changes occur east of the Ballara Fault Zone and this eastern belt has been extensively intruded.

The magnetic solution is much more imperfect and cannot be simply resolved at this scale due to the extreme properties present and implied. The curve fit shown implies an offset of 200 nT but close inspection of the western belt suggests that about 100 nT might be better. This would be consistent with other profiles. The profiles simply do not fit in the eastern belt and insufficient time has been spent on this problem in order to resolve it. Much better stratigraphic control and rock distribution maps may be required.

The solution at the western end of the section, however, is consistent with other sections and suggests a remnant of volcanics within the roof block between or above granitoids.

CONCLUSIONS

This preliminary study has indicated that the style of previous models, detached from outcrop control and which correlated a dense magnetic unit to the Eastern Creek Volcanics, is valid. This conclusion satisfies the major objective of this limited study.

Several other aspects of the structure have been considered *en passant*. The work completed shows how difficult magnetic data modelling can be in the Cloncurry region where units are varied and extreme in properties and structurally complex. There are, however, suggestions that the volcanics do continue into the eastern region, albeit much altered, and the structural and thickness patterns revealed by the modelling may be explained in this way. Most major structures dip east and at relatively shallow dips which is consistent with bulk detachment. The Mount Isa Fault is not consistently the definitive structure within the western terrane and the major break generally occurs a few kilometres west of it.

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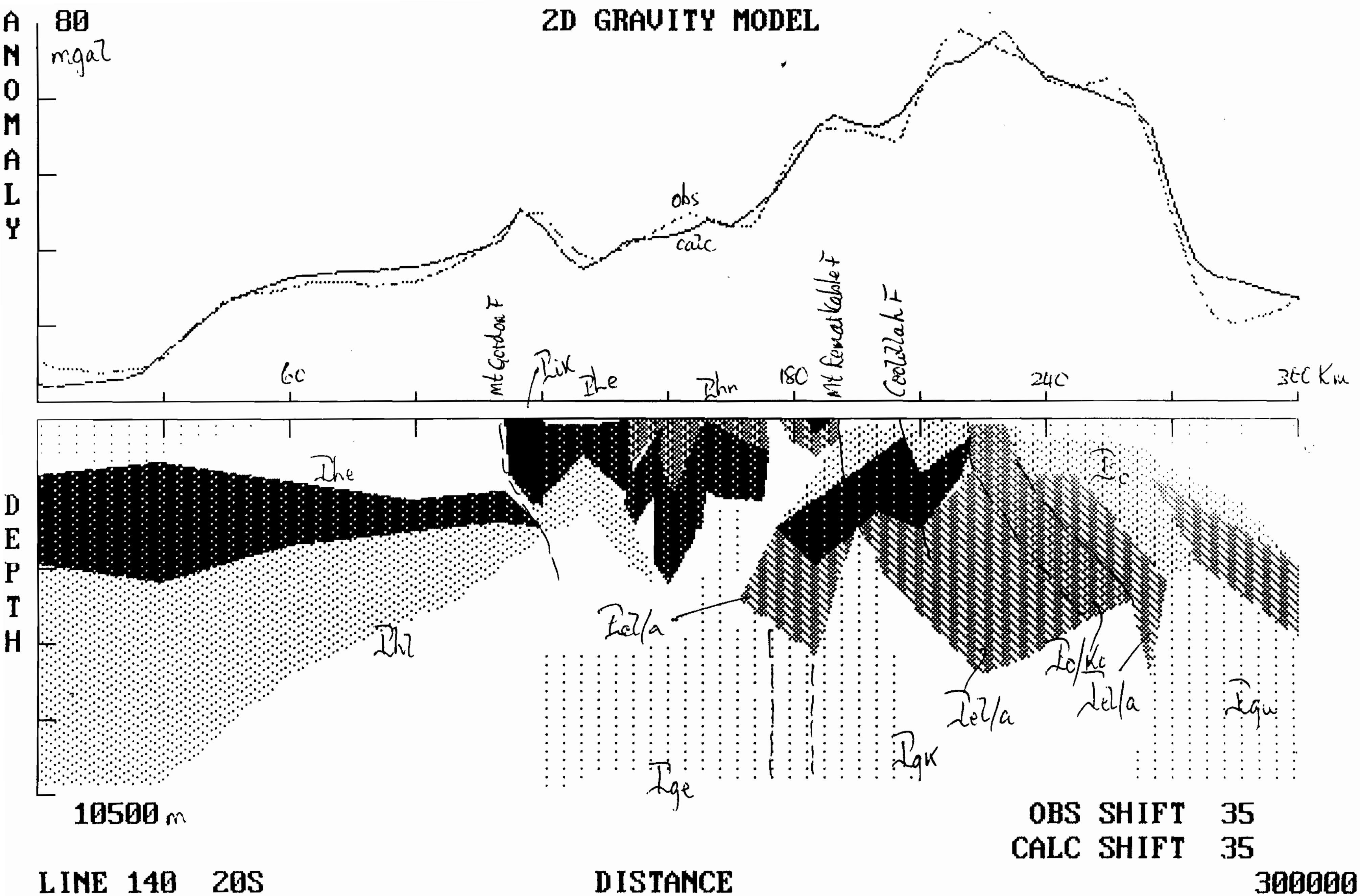


CADO5G CADO5MG

FIGURE 2A

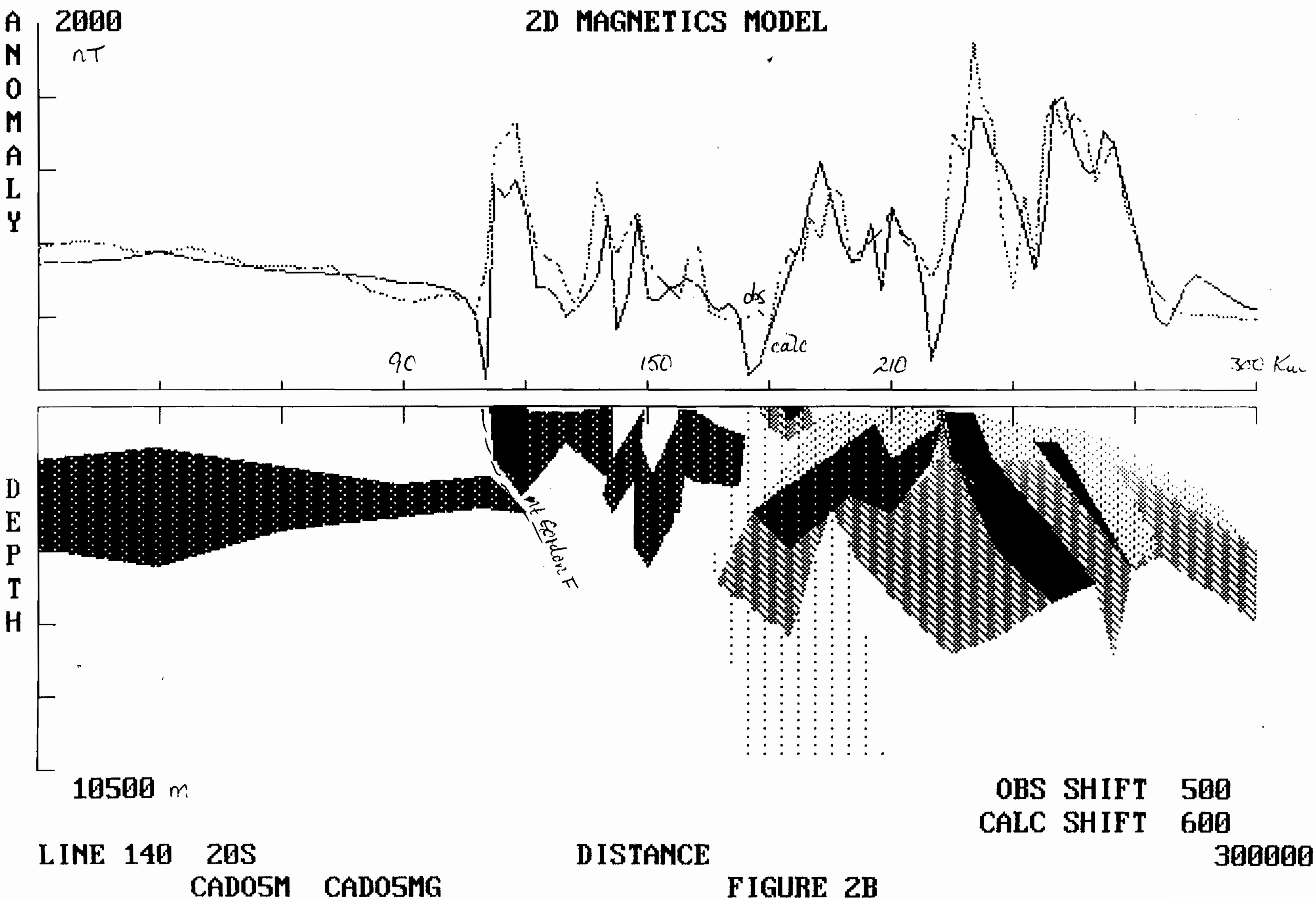
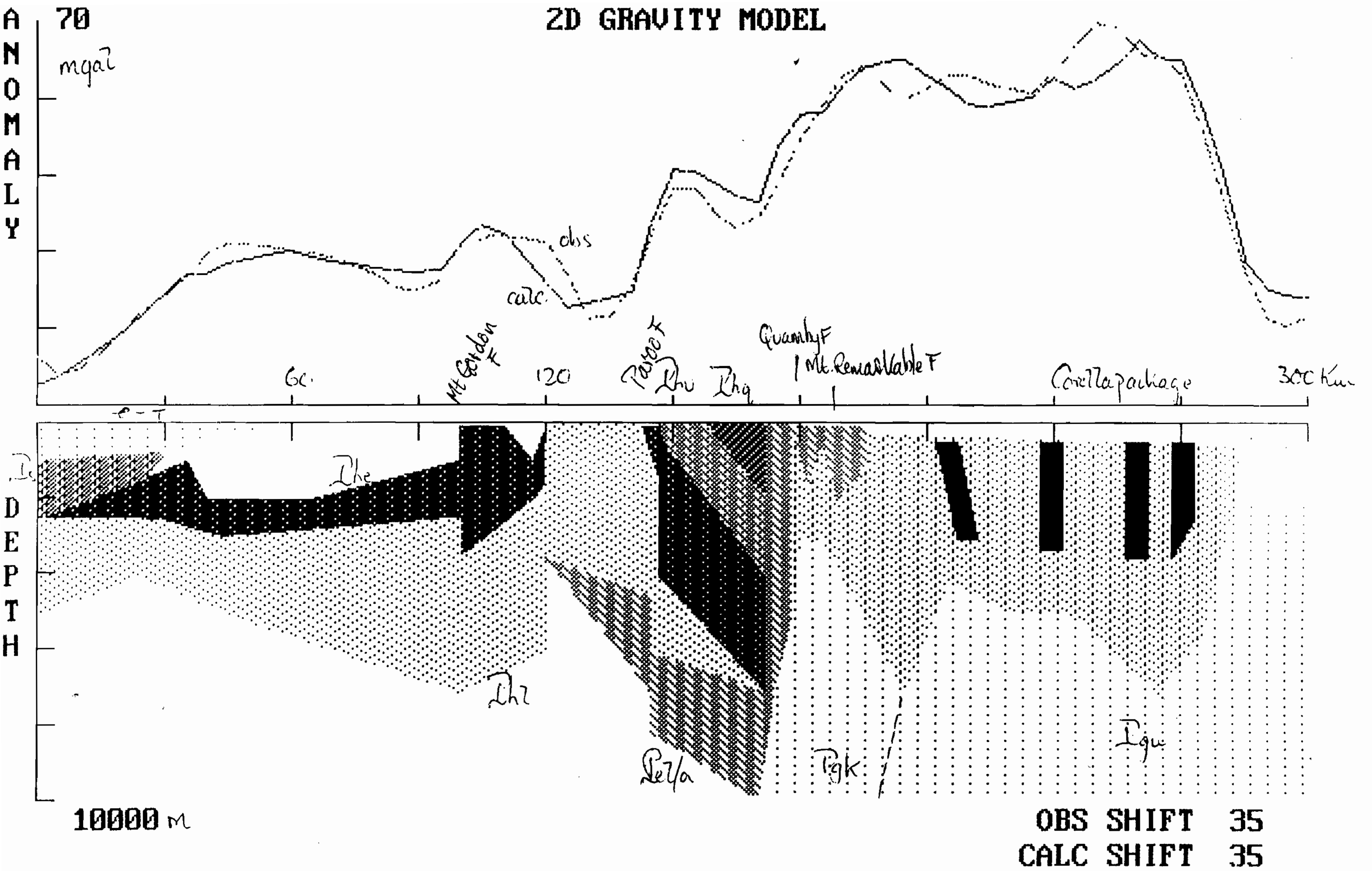

2D MAGNETICS MODEL
ANOMALY
2000
nT
obs
calc
90
150
210
300 Km
DEPTH
Mt Gordon F
10500 m
OBS SHIFT 500
CALC SHIFT 600
LINE 140 20S
DISTANCE
300000
CADO5M CADO5MG

FIGURE 2B



LINE 150 20.15S DISTANCE 300000
MIC150G MIC150B FIGURE 3A

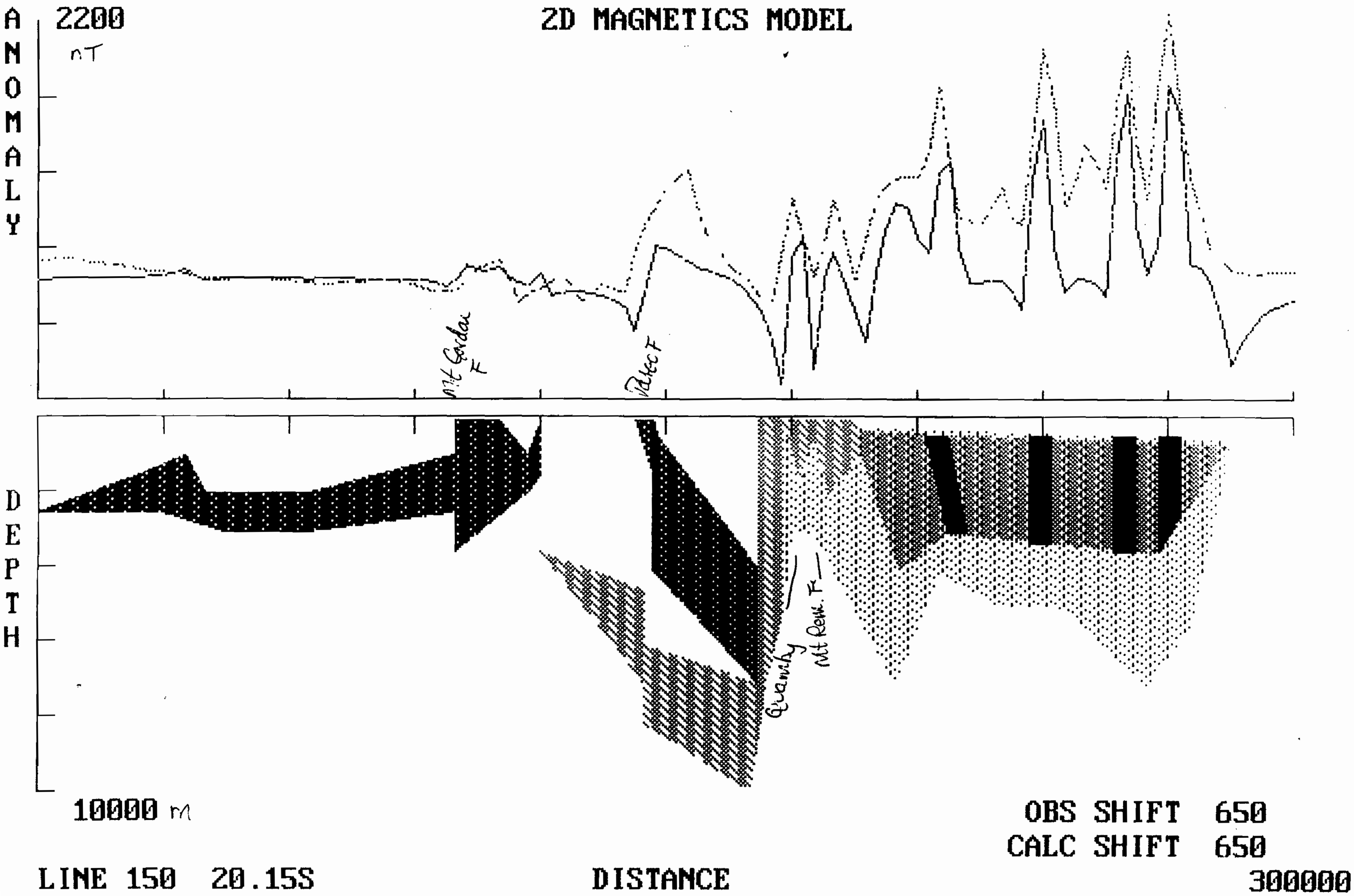
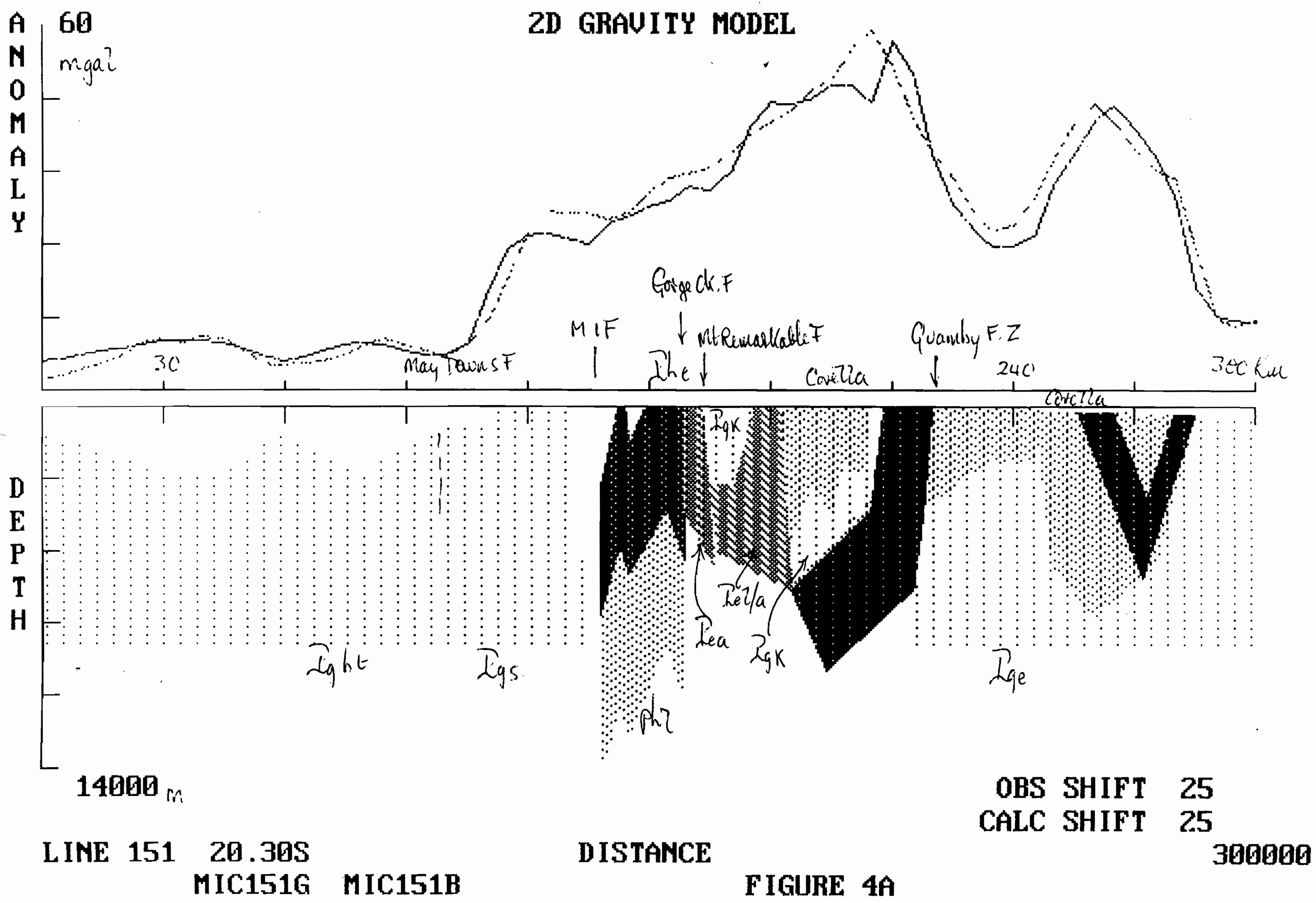
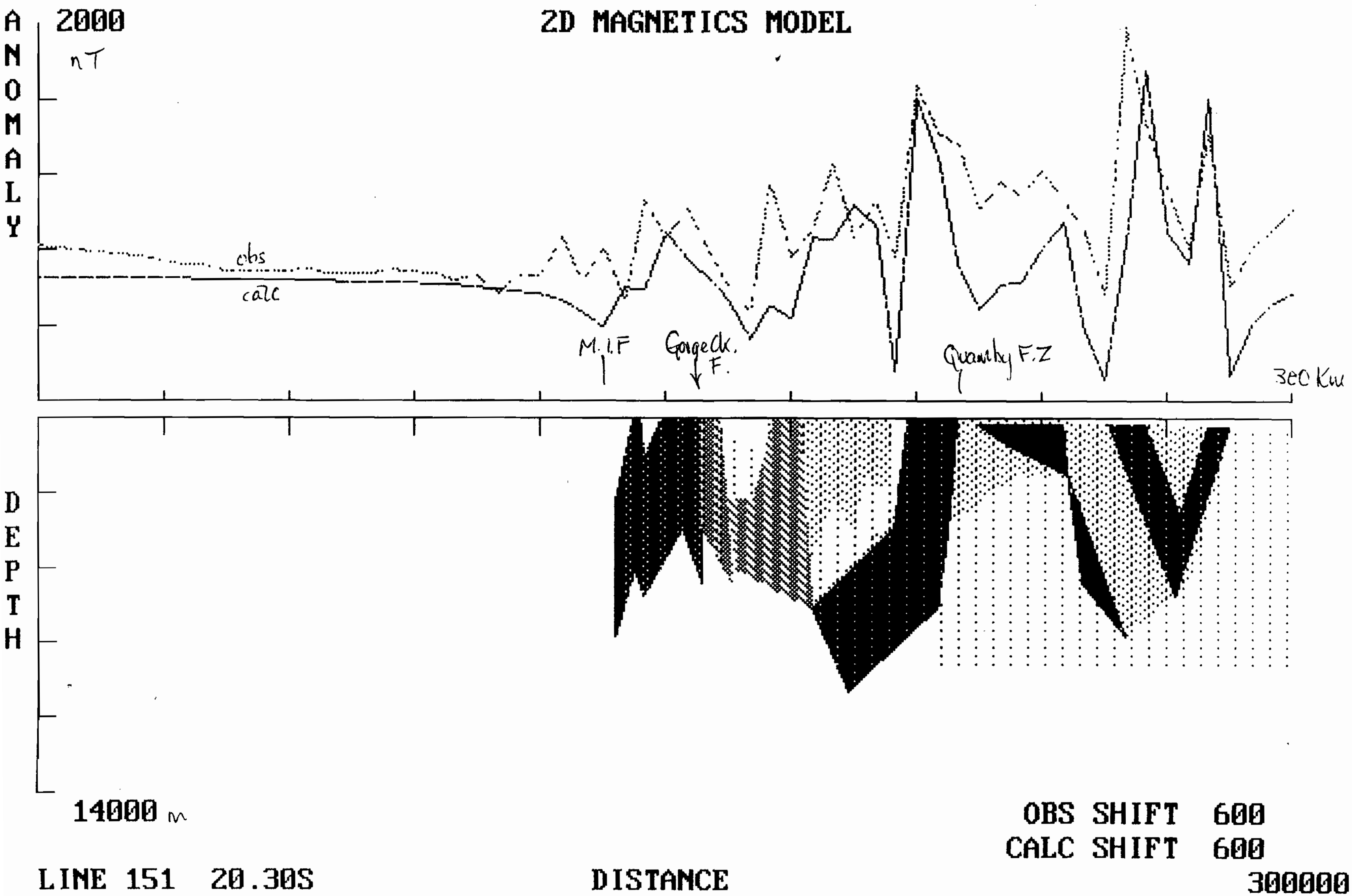

2D MAGNETICS MODEL
ANOMALY
2200
nT
DEPTH
10000 m
Mt Gordon F
Quamby
Mt Rem. F
OBS SHIFT 650
CALC SHIFT 650
LINE 150 20.15S
DISTANCE
300000
MIC150M MIC150B

FIGURE 3B



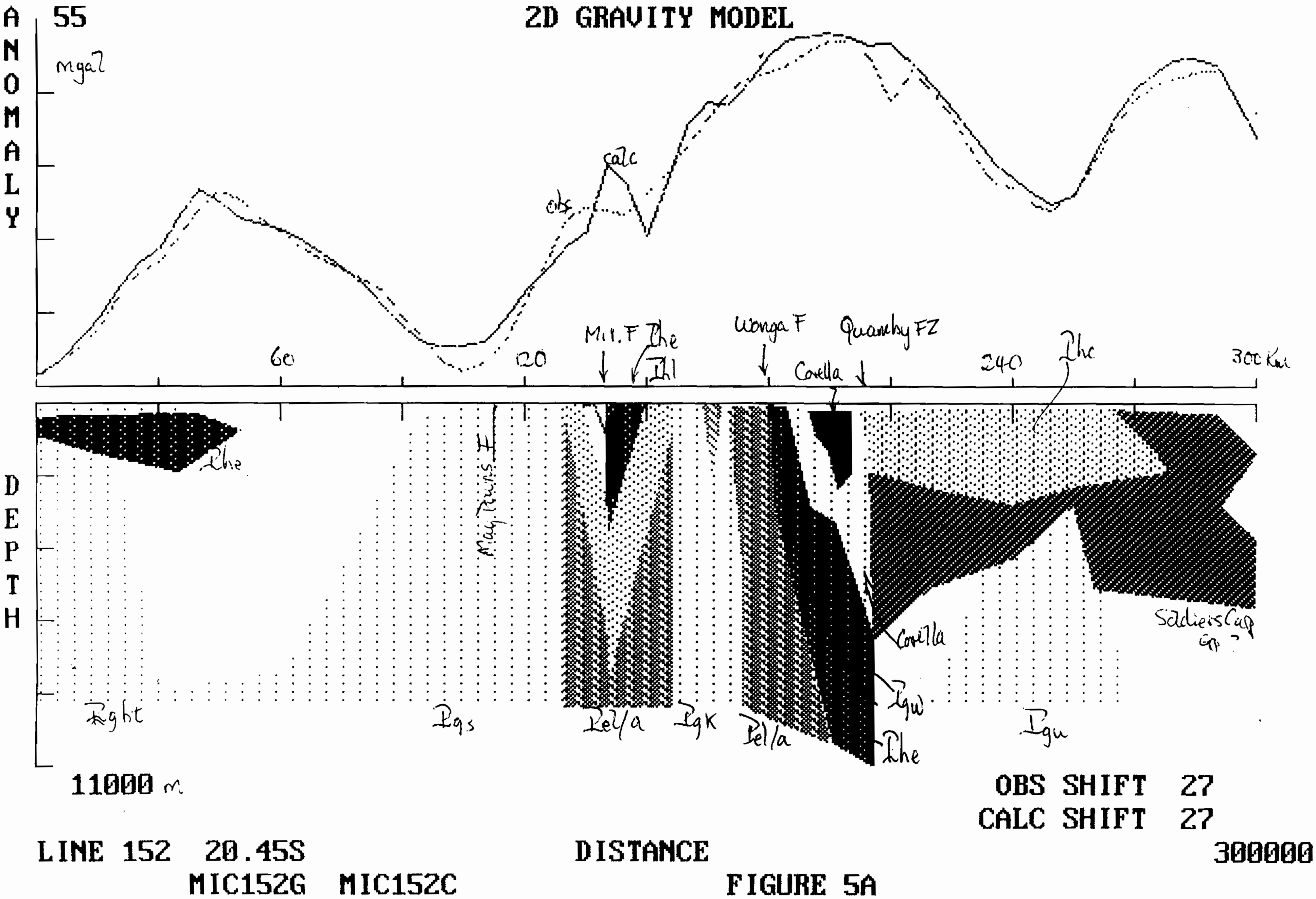
2D GRAVITY MODEL
ANOMALY
60
mgal
DEPTH
14000 m
30
240
300 km
May Towns F
M I F
Gorge Ck. F
Mt Remarkable F
Quamby F.Z
Corella
OBS SHIFT 25
CALC SHIFT 25
LINE 151 20.30S
MIC151G MIC151B
DISTANCE
300000

FIGURE 4A



MIC151M MIC151B

FIGURE 4B



2D GRAVITY MODEL
ANOMALY
55
mgal
calc
obs
60
120
240
300 Km
M11.F
The
Thl
Wonga F
Covella
Quamby FZ
The
DEPTH
The
Mary Kathleen
Covella
Soldiers Cap
Pghlt
Pgs
Pel/a
PgK
Pel/a
Pgw
The
Pgu
11000 m
OBS SHIFT 27
CALC SHIFT 27
LINE 152 20.45S
MIC152G MIC152C
DISTANCE
300000

FIGURE 5A

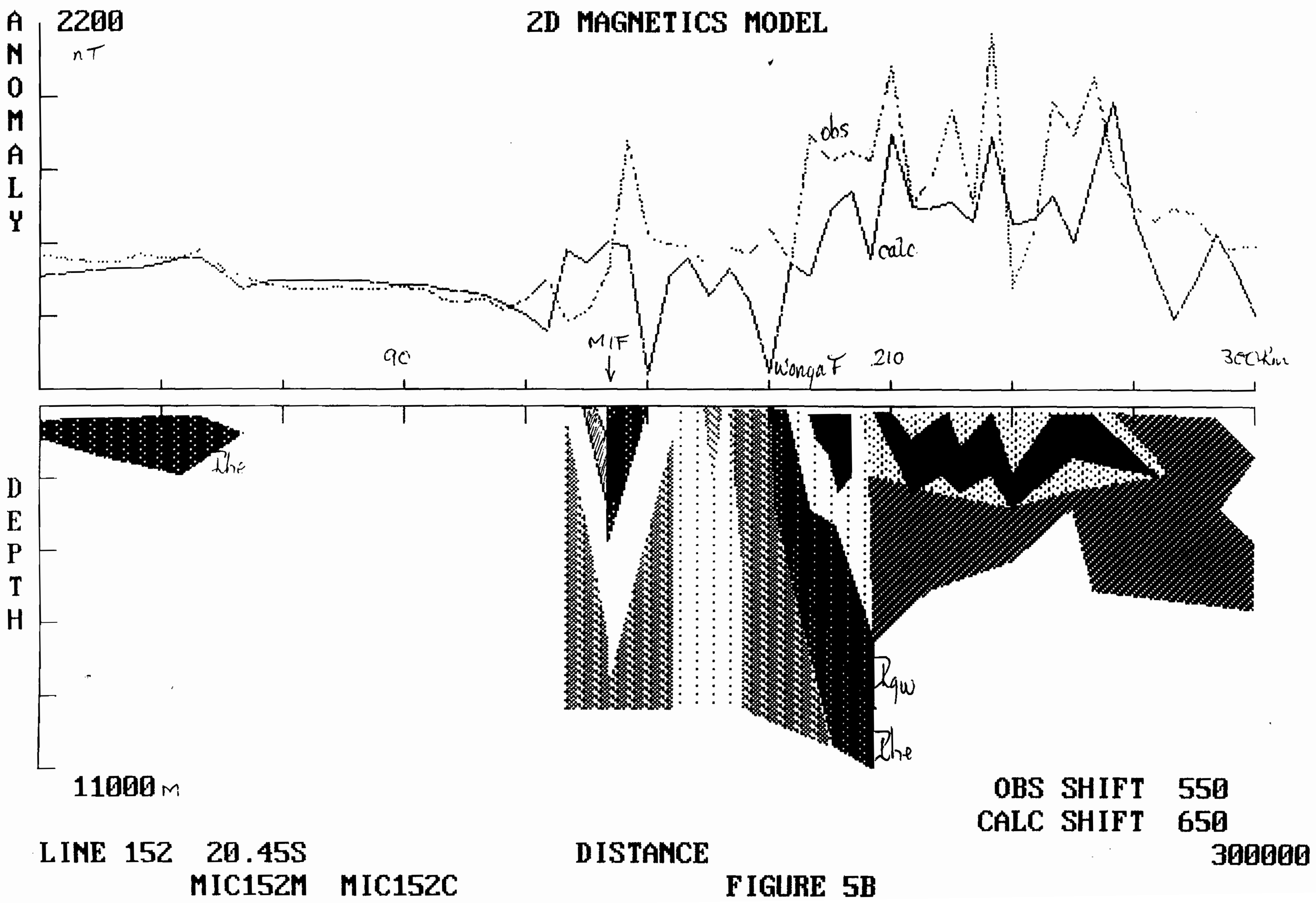
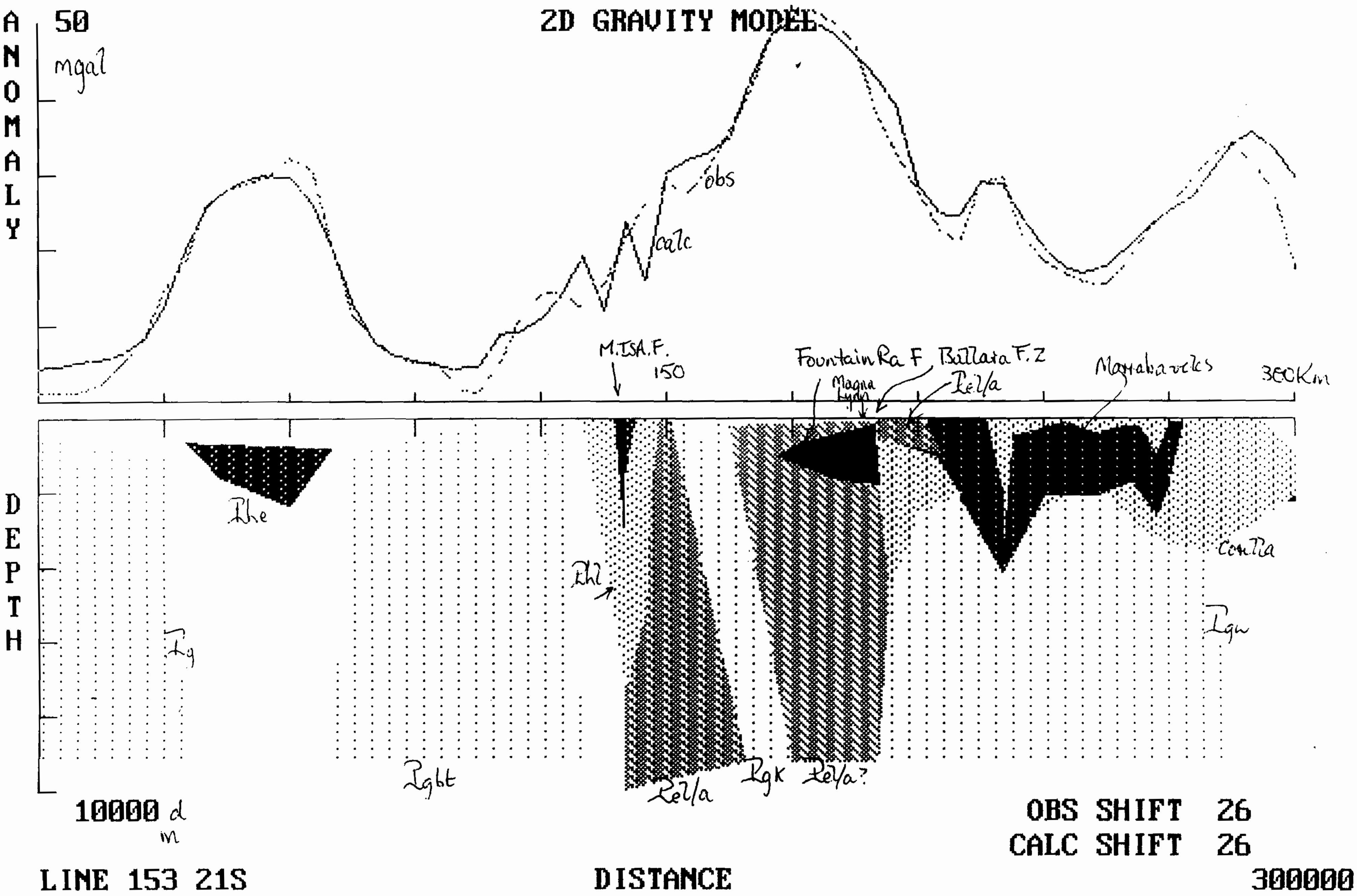

ANOMALY
2200
nT
2D MAGNETICS MODEL
obs
calc
MIF
Wonga F
90
210
300Km
DEPTH
Lhe
Lqw
Lhe
11000 m
OBS SHIFT 550
CALC SHIFT 650
LINE 152 20.45S
DISTANCE
300000
MIC152M MIC152C

FIGURE 5B



MIC153G MIC153C

FIGURE 6A

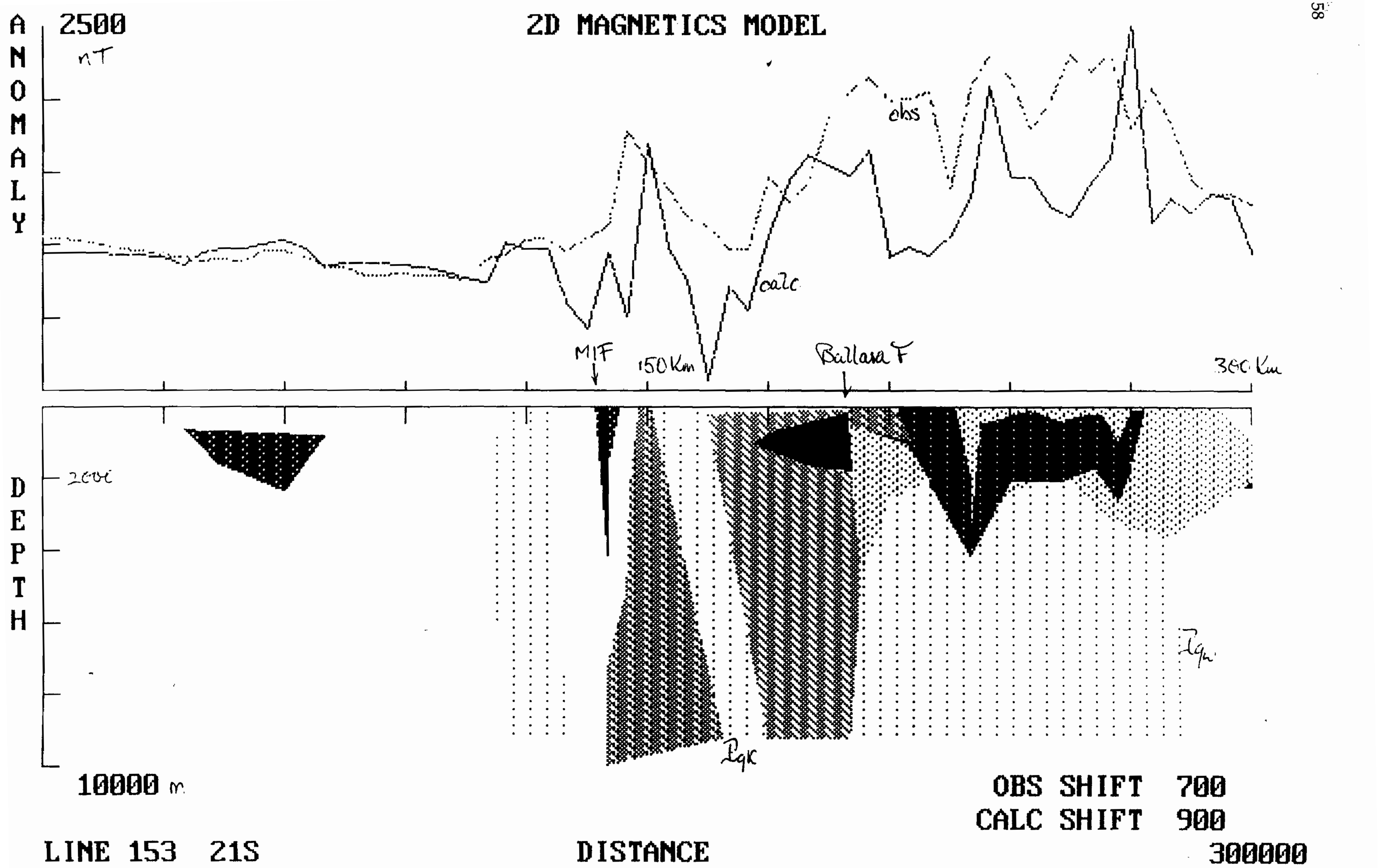

2D MAGNETICS MODEL
ANOMALY
2500
nT
obs
calc
MIF
150 Km
Ballara F
300 Km
DEPTH
2000
10000 m
OBS SHIFT 700
CALC SHIFT 900
LINE 153 21S
MIC153M MIC153C
DISTANCE
300000

FIGURE 6B

Appendix

Structure, contents and setting of Pb–Zn mineralisation in the McArthur Basin, northern Australia

D.E. Leaman

reprinted from *Australian Journal of Earth Sciences*, 1998, volume 45: 3–20. This paper is a re-titled and slightly revised version of the paper "Architecture of the McArthur basin, northern Australia" previously published in AMIRA P384, Final Report, June 1995.

Australian Journal of Earth Sciences (1998) **45**, 3–20

Structure, contents and setting of Pb–Zn mineralisation in the McArthur Basin, northern Australia

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Quantitative regional geophysical analysis of the McArthur Basin in northern Australia has shown that it includes sequences with a total thickness in excess of 20 km. Little of the deeper section, which includes thick volcanic and rift sequences, is exposed but the implied stratigraphy is consistent, and may be grossly correlated, with the adjacent western sequence of the Mt Isa Basin. Thick basal felsic and covering flood basalts can be inferred within the primary rift structures. Thinner cover sequences, including the predominantly siliciclastic Tawallah and dolomitic McArthur Groups, are developed in subsidiary basins controlled by underlying rift elements while the overlying Roper Group is much thicker and more widespread. Major erosive events are recognisable across the basin. Most tectonic activity has been focused in the zone known as the Batten Trough although this name is not appropriate because the region has been largely uplifted throughout its history. Other uplifted zones such as the Murphy Tectonic Zone tend to be oriented east-southeast to east-northeast across an original crustal grain which may have been oriented northwest–southeast and north-northeast–south-southwest. The basin may have evolved from a series of aligned convective cells which produced a disjointed rift pattern along strike. Older basin elements were not simply connected but were overtopped and the covering sequences have interlinked. No clearly defined ultimate limits have been recognised for the basin which appears to be an extension of the Mt Isa Basin to the southeast. Significant Pb-Zn mineralisation within the basin appears to be related to regions where rift margins have been persistently uplifted. Known mineralised sites lie on the rim horsts in zones where crustal fracturing is focused, and where young granitoids, which may have influenced basin circulation, are nearby.

Key words: basins, geophysics, McArthur Basin, mineralisation, structure.

INTRODUCTION

The McArthur Basin extends northwest along the Gulf of Carpentaria from the Queensland/Northern Territory border in northern Australia. Parts of it are considered to extend north into Arnhem Land (Figure 1). It is regarded as relatively undeformed, although there are open folds and evidence for local fault-related, modest compressional events. Nappe tectonics is generally absent although there have been, apparently minor, granitoid intrusions within the main basin sequences that range in age from about 1800 to 1400 Ma. Basement rocks are exposed only along the Murphy Tectonic Ridge and far to the west. The basement consists of various types of granitoid and metamorphic rocks.

While this paper suggests the structural relationships for all units at basin scale, it cannot include complete descriptions of exposed formations and these may be found in Plumb (1987, 1989), Plumb *et al.* (1980, 1990), Ahmad & Wygralak (1989) and Jackson *et al.* (1987).

Knowledge of the sequences within the McArthur Basin prior to this study has been summarised, with a comparison of the better documented western Mt Isa sequence, in Figure 2. All thicknesses are estimates based on projections from local exposures and cannot be constrained in the absence of major dipping sections or controlled seismic data.

Angular unconformities separate each group and many units within each group. Younger, post-Cambrian, cover sequences are relatively insignificant and are not discussed here. These younger cover units do, however, blanket many important zones and totally conceal all but the western limits of the basin. Each section displays evidence for crustal and atmospheric evolution with a diminished volcanic component through time. A transformation from siliceous to dolomitic sedimentation with a return to siliceous sedimentation is evident in the basin. Elements of these patterns can be recognised in some modern basins which include thick carbonate shelf phases (e.g. Rocky Mountains, North Sea).

The Mt Isa sequence demonstrates large-scale volcanism. The Haslingden Group includes up to 7 km of continental flood basalts (Eastern Creek Volcanics) with minor intercalations of siliceous sediment. No units of similar thickness are exposed in the McArthur Basin although the Seigal Volcanics have a similar areal extent. Possible correlations of mafic volcanics in the McArthur Basin are suggested in Figure 2 but it is not known if any mafic units thicken in the same way as the Eastern Creek Volcanics. No reliable evaluation of any older felsic sequences can be provided by projections from exposed sections but suggestions have been made (Plumb 1989). Two felsic sequences have been recognised (Ahmad & Wygralak 1989) with an angular relationship suggested in seismic data (McConachie *et al.* 1993).

The prevailing published view of the sequences in the McArthur Basin, based on regional mapping, is that a blanket cover of Tawallah Group was rifted locally in the region of the Batten Trough and that this continued to subside until deposition of the Nathan Group. Broader