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The 2002 Southern McArthur Basin Seismic Reflection Survey:

The Anglo American Seismic Traverse (02GA-BT2).

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THE 2002 SOUTHERN McARTHUR BASIN SEISMIC REFLECTION SURVEY: THE ANGLO AMERICAN SEISMIC TRAVERSE (02GA-BT2).

GEOSCIENCE AUSTRALIA
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by

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Note: The 2002 Southern McArthur Basin Seismic Reflection Survey was initially referred to as the 2002 Batten Fault Zone Seismic Reflection Survey.

Contents

Executive Summary

Reflection seismic data has the potential to make a significant impact on our understanding of the giant McArthur River mineral deposit within the southern McArthur Basin. Seismic data can image basin geometry and sedimentary architectures, on both a local scale and a regional scale, permitting ideas to be tested concerning the migration of metal-bearing basinal fluids from their aquifer sandstones, along suitable fault planes to the reductant shales to form the deposits.

To investigate the regional setting of the Southern McArthur Basin, the Northern Territory Geological Survey, Geoscience Australia and the Predictive Mineral Discovery Cooperative Research Centre jointly established the 2002 Southern McArthur Basin Seismic Survey research project.

A north-south-cross line to the 2002 Southern McArthur Basin Seismic Survey was partially funded by Anglo American as an add-on to the main regional deep seismic reflection survey. This add-on was proposed to investigate the possibility of east-west oriented structures within the middle of the Batten Fault Zone and the geometry of the sediment fill in three dimensions. The project involved the collection, processing and interpretation of deep seismic reflection data along a short north-south oriented seismic traverse that crossed a regional deep seismic reflection traverse. The crustal geometry obtained from the north-south seismic traverse was compared to crustal geometries obtained from the regional seismic traverse. Both seismic surveys examined the fundamental basin architecture of the Batten Fault Zone, McArthur Basin and nature of the underlying basement. Integration of the north-south seismic data with the regional deep seismic reflection data allowed the examination of the architecture in three dimensions in the middle portion of the Batten Fault Zone. Together, the two seismic lines were used to test existing geometric models for the formation of the McArthur Basin, to examine the sequence stratigraphy of the Palaeoproterozoic and Mesoproterozoic basin, to examine the geometry of the major structures and relevant basement structures.

This report summarises the results from the add-on seismic traverse. Key sections of the 2002 Southern McArthur Basin Seismic Survey Report (Rawlings et al., 2004) has been included for completeness.

The Southern McArthur Basin Seismic Reflection Survey

INTRODUCTION

This report contains a summary of the initial interpretation of deep reflection seismic data collected as part of an industry funded add-on to the 2002 Southern McArthur Basin Deep Seismic Survey. This add-on involved the acquisition of a short north-south deep seismic reflection traverse (02GA-BT2) oriented approximately perpendicular to the main seismic line (02GA-BT1). This add-on involved a financial contribution from Anglo American, as industry collaborator, the Northern Territory Geological Survey (NTGS), Geoscience Australia (GA) and the Predictive Mineral Discovery Cooperative Research Centre (*pmd**CRC).

The regional 2002 Southern McArthur Basin Seismic Survey is a joint undertaking of the Northern Territory Geological Survey (NTGS), Geoscience Australia (GA) and the Predictive Mineral Discovery Cooperative Research Centre (*pmd**CRC), and the results from this survey have been published in Rawlings et al. (2004). Key sections of this report are included for completeness within this report.

This add-on project is *pmd**CRC Project I6, 'Batten Fault Zone Seismic Survey, North-South Extension – 2002', with the regional 2002 Southern McArthur Basin Deep Seismic Survey being *pmd**CRC Project I5, 'Batten Fault Zone Seismic Survey – 2002'.

The survey was originally called the *Batten Fault Zone Deep Seismic Survey* but we now use the more correct term *Southern McArthur Basin Deep Seismic Survey.* All original unprocessed and processed seismic data are archived within Geoscience Australia under the title 'Batten Fault Zone Deep Seismic Survey'.

BACKGROUND STATEMENT

Palaeoproterozoic rocks of the southern McArthur region contain an unmetamorphosed, relatively undeformed succession of carbonate, siliciclastic and volcanic rocks that host the McArthur River (HYC) Pb-Zn-Ag deposit. Since its discovery in the late 1950's the deposit and surrounding rocks of the southern McArthur have been the subject of intensive stratigraphic, structural, mineral paragenesis and geochemical research, much at the local, deposit scale. The long-term objective of this research involved the generation of new exploration concepts and targets in the southern McArthur and elsewhere in the Carpentaria Zinc Province of northern Australia. From a research perspective, the McArthur deposit occupies the pre-eminent position as the best-preserved deposit in the Carpentaria Zinc Belt. Coincident SHRIMP zircon depositional ages for host sediments to the deposit and Pb/Pb model ages for galena in the deposit constrain the time of ore body formation to ~1640 Ma. A prominent hairpin bend on the Apparent Polar Wander Path provides evidence for changes in plate motion and coincident variations in the intraplate stress regime, the likely driver of fluid flow at this time.

Over the past five years the deposit has also been the subject of preliminary fluid flow modelling studies aimed at testing and constraining the range of conditions that led to its formation. These studies are dependent on our ability to reconstruct basin geometry and sediment architecture at the time(s) of fluid migration. At present the weakest link in this research concerns the lack of suitable datasets to constrain the basin geometry and sediment architecture at the time(s) of fluid flow. The Geoscience Australia NABRE project erected a chronostratigraphic framework for northern Australia. In the McArthur Basin region, surfaces of chronostratigraphic significance have been identified, but lack of regional thickness information have limited our ability to reconstruct basin geometries. Fluid flow modelling studies of the McArthur deposit at CODES, University of Tasmania, are based on a simple 2D transect model in which the stratigraphic architecture and structure require testing.

The single dataset with the potential to make the most significant impact on our understanding of this giant deposit is reflection seismic data. Seismic data will enable basin geometry and sedimentary architectures to be reconstructed, on both a local scale and a regional scale, permitting ideas to be tested concerning the migration of metal-bearing basinal fluids from their aquifer sandstones, up faults to the reductant shales to form the deposits.

AIMS AND OBJECTIVES

The deep seismic survey examined the fundamental basin architecture of the Batten Fault Zone, McArthur Basin and nature of the underlying basement. Geological field work by the NABRE project allowed the interpretation of the basin in terms of sequence stratigraphic and structural models which have been developed largely in much younger basins prospective for petroleum. Much of the seismic program is designed to test geometric models for the southern McArthur Basin, specifically to examine the sequence stratigraphy of the Palaeo- and Mesoproterozoic basins, their bounding faults and relevant basement structures. The results will have wider applicability in that the basin is an undeformed analogue of the Western Succession of the Mt Isa Province.

In particular the regional seismic program will:

- Examine whether the Batten 'Trough' exists and what is its geometry? Was this fault zone a 'rift' and if so, what was its extension direction?
- Determine the thickness, detailed stratigraphy, and structure of the Tawallah, McArthur and Nathan Groups within the Batten Fault Zone and on the Bauhinia Shelf to the west and the Wearyan Shelf to the east of the fault zone.
- Investigate the nature of the Emu Fault and its relationship to the Batten Fault Zone. Is this a strike-slip fault and does it have a decollement at some level within the upper crust?
- The McArthur Group has a projected thickness of over 4000 m east of the Broadmere Syncline, but surface geology indicates that it has wedged out to the west of the Broadmere Syncline. Does this western edge of the McArthur Group represent the edge of the depositional basin, or a postdepositional structure?
- Where is the eastern edge of the McArthur Group? What influence did the Emu Fault have on deposition of this succession?
- What is the nature of the Tawallah Fault, and what is its association with the Emu and Mallapunyah faults.
- Architecture of sub-basins in the middle McArthur Group currently implied from surface thickness variations and magnetic images (eg, Myrtle Sub-basin).
- Are there any stratigraphic or structural relationships with known mineralisation around the McArthur River Deposit and can they be extrapolated to the rest of the Batten Fault Zone to generate new SEDEX and MVT prospects?
- Thickness variations and structure of the immediate basement, which may include thick piles of volcanic rocks (Leaman, 1998).

The add-on seismic traverse 02GA-BT2 provided additional information for many of the above objectives. In addition it will:

- Determine if inferred east-west orientated structures are present within the middle of the Batten Fault Zone.
- Be used to constrain a three-dimensional architecture within the middle of the Batten Fault Zone.

RESEARCH STRATEGY AND METHODOLOGY

This project involves the acquisition, processing and interpretation of a short deep seismic traverse within the Batten Fault Zone, McArthur Basin (Figure 1). The traverse is located to the west of the Emu Fault (Figure 1). It crosses the regional traverse and extends southwards towards the McArthur River Deposit. The regional deep seismic traverse is described in Rawlings et al., (2004).

This short north-south line is approximately 20 km west of, and sub-parallel to, the Emu Fault. It is positioned within the central Batten Fault Zone (Figure 1). It is designed to test the inferred presence of an east-west striking growth-fault and sub-basin architectures in the middle McArthur Group to the west of the McArthur River Deposit (e.g. Hinman, 1996). It focuses on whether these architectures exist and if so what are their geometry?

LOCATION, ACCESS AND SETTING

The project area lies in the McArthur River or western Gulf of Carpentaria region in northeastern Northern Territory (Figure 1). The seismic lines are entirely within the Bauhinia Downs 1:250 000 scale map sheet area. The main town in the region is Borroloola, which is serviced by the bitumen Carpentaria and Tablelands Highways, linking it to Mt Isa, Alice Springs and Darwin. An all-weather gravel road (the Roper Road) also links Borroloola to Roper Bar. Physiography along the seismic lines is generally flat or gently undulating, but there are sporadic small rocky ranges with up to 300 m relief (Tawallah, Batten and Scrutton Ranges and the Bauhinia jumpup; Figure 1). Vegetation in the survey area is open savannah woodland, supporting an active pastoral industry. The seismic lines are largely within Bauhinia Downs, Billengarrah and McArthur River cattle stations, and partly within Aboriginal land trust excisions. Habitation in the western Gulf region is restricted mainly to Borroloola, but also at small settlements and Aboriginal outstations along the survey route. Nearby, the McArthur River mine employs many locals and is a major exporter of base metal concentrate via a barge service at Bing Bong. The Gulf region experiences a monsoonal climate with distinct 'dry' and 'wet' seasons. The seismic survey was carried out in late October 2002, just prior to the onset of the west season, when roads can become impassable.

GEOLOGICAL SETTING

The seismic survey area lies within the southern part of the McArthur Basin, a ~5-15 km-thick platform cover succession of mostly unmetamorphosed sedimentary and lesser volcanic rocks deposited on the North Australian Craton between ~1815-1450 Ma (Plumb, 1979). Outcrops in the basin cover an area of about 180 000 km^2 in an approximately north-northwest trend from the Queensland-Northern Territory border, along the west coast of the Gulf of Carpentaria, to the north coast of Arnhem Land. It is bounded by older Palaeoproterozoic basement of the Murphy Inlier in the southeast, the Pine Creek Inlier in the northwest, and the Arnhem Inlier in the north.

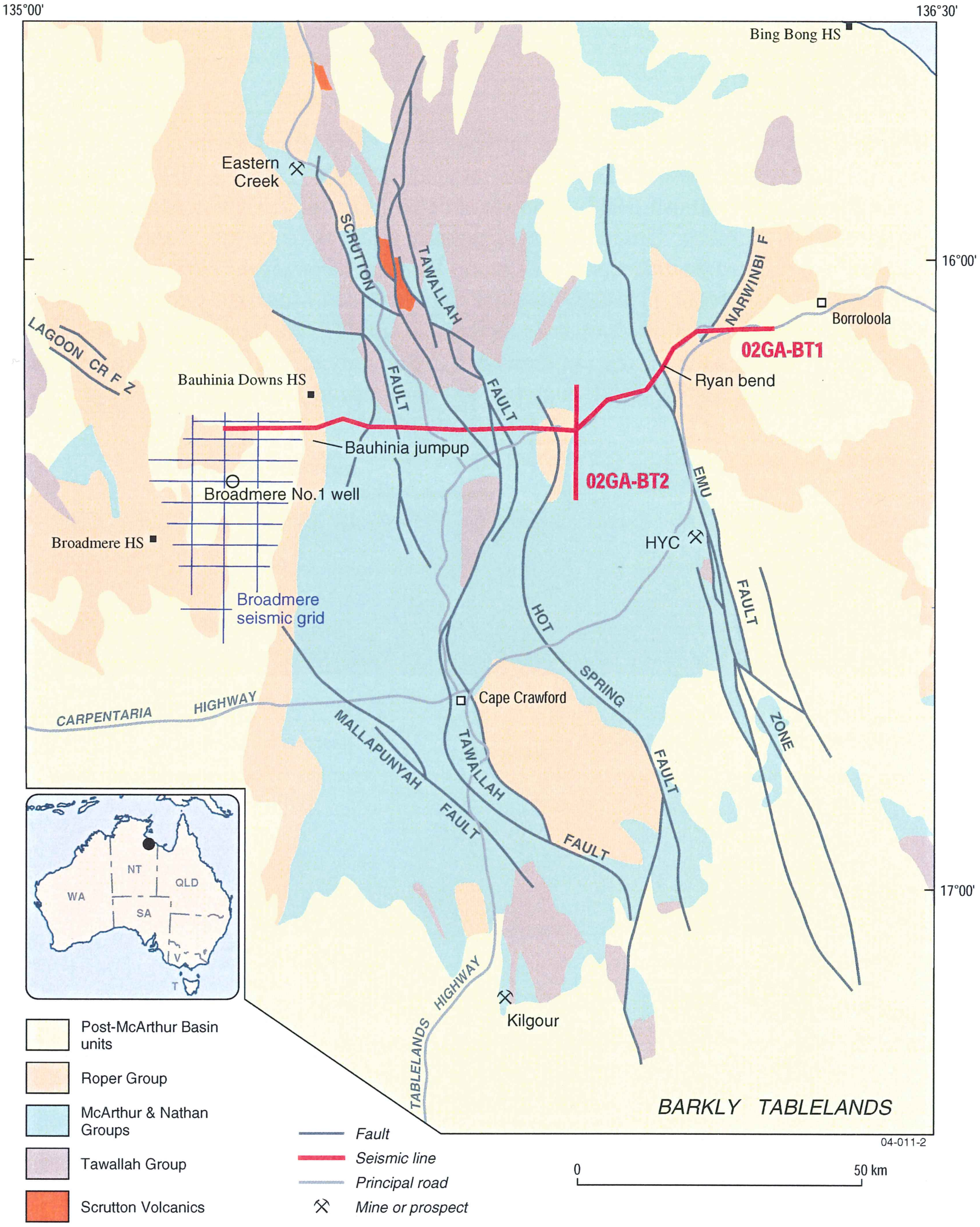

Figure 1: *Regional geological map showing schematic locations of the two Southern McArthur Basin deep seismic reflection lines. The 1984 Amoco Broadmere seismic grid (blue lines) and Broadmere No 1 well (open black circle) are also shown. The world class McArthur River Mine (McArthur River) occurs 30 km south of the main seismic line and immediately west of the Emu Fault Zone. Base map is from the Rawlings (2002b).*

The most comprehensive study of the southern part of the basin is by Jackson et al. (1987). Recent amendments to regional basin stratigraphy are outlined by Pietsch et al. (1994), Rawlings et al. (1997) and Rawlings (1999, 2002b). Interpreted correlations between the McArthur Basin and other Proterozoic basins of northern Australia are summarised by Plumb (1985) and Plumb et al. (1990).

TECTONIC FRAMEWORK

Thickening of units within fault zones was interpreted to be confined to specific sedimentary intervals deposited within intracontinental 'rift' structures, defined as the Walker and Batten Fault Zones (Plumb and Wellman, 1987; Plumb et al., 1980; Figure 2). Thickness changes appear to be greatest in the McArthur Group, which apparently thickens to ~5 km in the Batten Fault Zone. Markedly attenuated equivalents of this group lap onto the shelves. Pietsch et al. (1991a) presented an alternative model, in which the thick succession of McArthur Group preserved in the Batten Fault Zone was the result of later differential uplift of the bounding shelves, which lead to erosion of the McArthur Group in these areas. The current seismic survey (regional and add-on seismic traverses) was designed, in part, to test these two hypotheses.

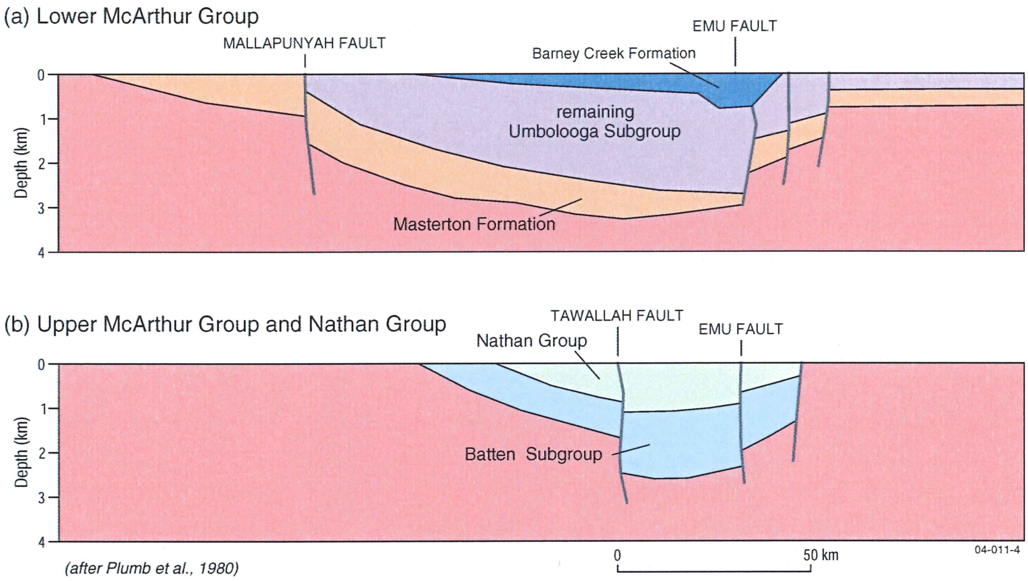

Figure 2: *Cartoon cross section of the Southern McArthur Basin by Plumb et al. (1980), showing the proposed geometry of the basin during a) deposition of the Lower McArthur Group, and b) deposition of the Upper McArthur Group and the Nathan Group.*

STRATIGRAPHY

The McArthur Basin is a mixed carbonate-siliciclastic succession with minor volcanic units near the base. Rock types include quartzose sandstone, mudstone, dolostone and minor mafic and felsic volcanic rocks. Depositional environments range from fluvial and lacustrine to shallow marginal marine in an overall intracratonic setting. The basin is currently divided into a number of stratigraphic groups on the basis of apparently major regional discontinuities, and on geographic distribution of rock units (Jackson et al., 1987; Pietsch et al. 1991a; Rawlings et al. 1997; Rawlings 1999). The stratigraphy of the Southern McArthur Basin and its immediate basement is described briefly below and summarised in Figure 3.

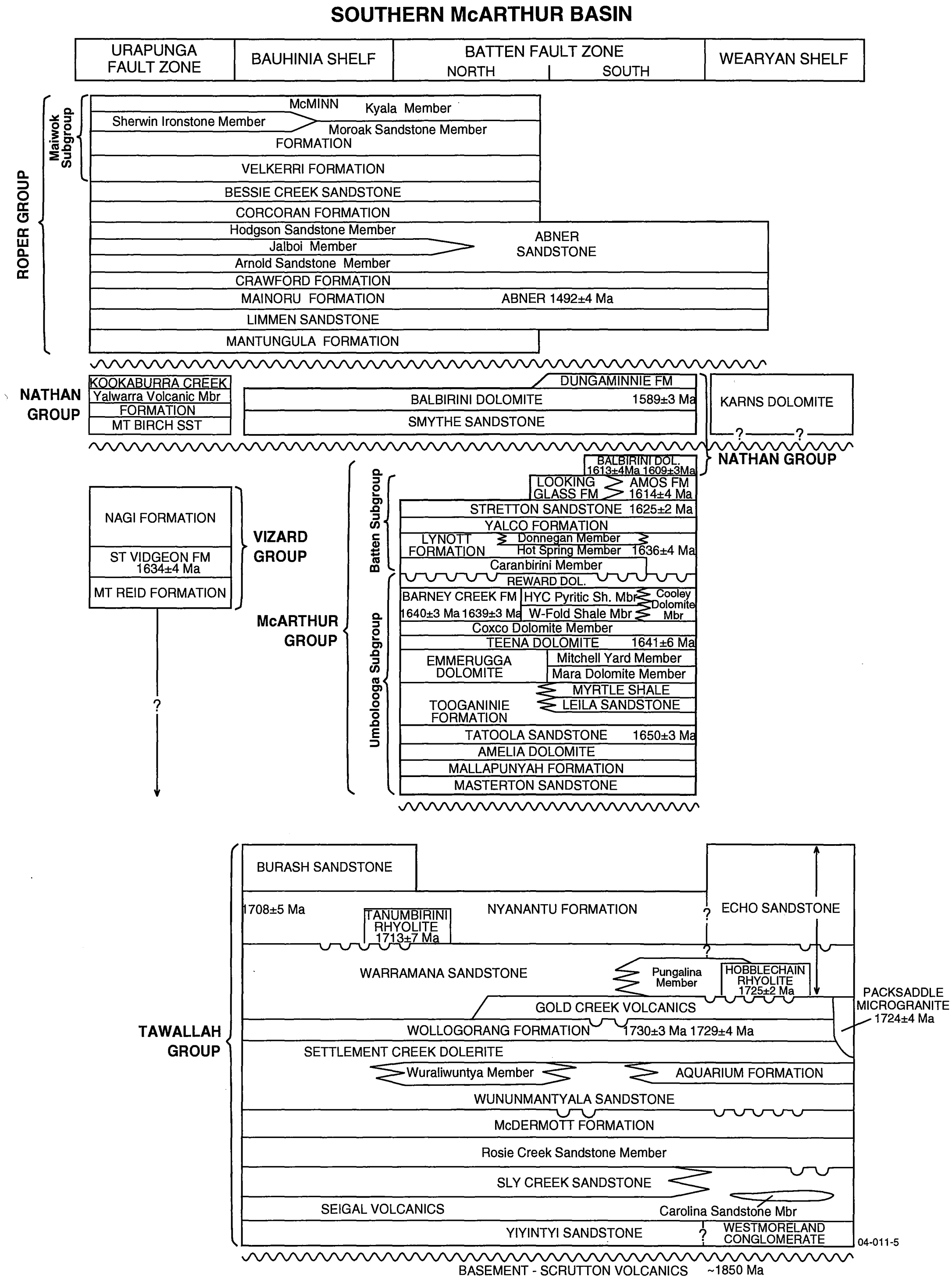

Figure 3: Stratigraphic table for the Southern McArthur Basin (after Rawlings, 2002b).

The distribution of the various stratigraphic units in the vicinity of the seismic survey can be gauged from the 1:250 000 and 1:100 000 scale geological map sheets of Bauhinia Downs (Pietsch et al., 1991a) and McArthur River region (Pietsch et al., 1991b) respectively.

Basement is recognised as a number of small fault- and unconformity-bounded inliers, collectively known as the Scrutton Inlier. These are exposed in the Southern McArthur Basin within the northern Batten Fault Zone (Figure 1).

The Tawallah Group is the oldest sedimentary unit of the Southern McArthur Basin, unconformably overlying various basement units, including the Scrutton Volcanics (Pietsch et al., 1991a), which provides a maximum age for the Tawallah Group of ~ 1850 Ma. The Tawallah Group is in turn unconformably overlain by the 1670-1600 Ma McArthur Group in the Batten Fault Zone and by a variety of younger units elsewhere (Figure 3).

The McArthur Group (Jackson et al., 1987; Pietsch et al., 1991a) is a ~4.5 km thick succession of interbedded stromatolitic and evaporitic dolostone, sandstone, mudstone and minor tuffaceous mudstone, deposited mainly in shallow water environments. The McArthur Group is weakly to strongly deformed, and outcrop is restricted to the Batten Fault Zone. It unconformably overlies the Tawallah Group, which provides a maximum age of ~1710 Ma. It is unconformably overlain throughout the McArthur Basin by the ~1590 Ma Nathan Group (Figure 3).

Outcrops of the Nathan Group are widespread in the Southern McArthur Basin (Jackson et al., 1987). Distribution is apparently largely unrelated to the pre-existing tectonic framework of fault zones and shelves.

The youngest unit of the McArthur Basin is the Roper Group, a widespread cyclic succession of fine- and coarse-grained siliciclastic rocks deposited in a variety of shallow marine, nearshore to shelf environments (Powell et al., 1987; Jackson et al., 1988; Abbott and Sweet, 2000).

The Southern McArthur Basin is unconformably overlain by a variety of younger epicratonic basins and Cainozoic regolith and soil. Late Neoproterozoic to Devonian continental and shallow marine siliciclastics and lesser carbonates of the Georgina Basin (Freeman et al., 1990) onlap the McArthur Basin and also occur as thin erosional outliers within the McArthur Basin.

SEISMIC ACQUISITION

Seismic experiments and acquisition began in late October 2002 and continued for 12 days into early November (Trace Energy, 2002). Two lines were acquired (Figure 1): Line 02GA-BT1 – east-west 110 km long, from 15 km west of Borroloola and extending westwards along the Roper Road to 15 km west of Bauhinia Downs homestead, and Line 02GA-BT2 – north-south 17 km long, centred approximately half way along Line 02GA-BT1 near Cow Lagoon.

During the program, 40 km of re-cleared gridline and 100 km of gravel or bitumen road were utilised. The station interval was 40 m and the geophone recording spread 9.6 km long. The shot interval was generally 80 m (locally 40 m), producing 60 fold data (120 fold at corners). Owing to the predicted deep Moho, 'listening time' was 20 or 22 seconds (~60 km depth).

Most of the deep seismic reflection data were acquired along the edge of public roads, but line clearing was needed for the central and western end of line 02GA-BT1 and all of line 02GA-BT2.

Clearance permits from the Aboriginal Areas Protection Authority (AAPA) obtained in 1997 were re-issued for this survey and advice obtained from the 1997 Archaeological survey (Guse et al., 1998) was adhered to. Permitting for the survey was done by officers from NTGS, who also prepared the environmental management plan (Rawlings, 2002c). Station coordinates were surveyed by Dynamic Satellite Surveys (2002) using differential GPS. A split-spread geometry was used with the source nominally at the centre of the spread. Receiver groups were centred between station pegs, while the source array was centred on the peg. Three IVI Hemi-60 (60,000 lb peak force) vibrators were used in-line, with moveup between each of three varisweeps. Further details are given in Rawlings et al. (2004) and in Trace Energy (2002).

SEISMIC DATA QUALITY

Shot point data quality varies along the seismic lines according to sediment cover and bedrock characteristics. Data quality in the north of traverse 02GA-BT2 is excellent, due to the ideal near-surface conditions. This data quality decreases southwards, due to increased variation in thickness of unconsolidated material, in which there is poor geophone coupling. In addition, data quality in the central Batten Fault Zone is variable. Shot points above shallow bedrock of Tawallah Group and siliciclastic McArthur Group units have provided good data. Carbonate units of the McArthur Group (e.g. Balbirini Dolomite) proved to have a karst landscape with deep seismic-defined 'regolith' and therefore poor transmission of energy into the crust.

SEISMIC PROCESSING

Routine data processing, including migration, was completed in April 2003, enabling a first-pass interpretation in May 2003. The processed seismic trace still has areas of poor resolution, due to the problems discussed above. However, the geometry of the various faults can be interpreted with some confidence. The McArthur Basin stratigraphy is relatively subhorizontal across the traverse, where not obliterated in the zones of poor resolution. These zones make it difficult to extrapolate geological groups and unconformities across the traverse.

Production processing utilised the Disco software package, and the interactive version Focus was used for parameter tests, first break picking and QC. Brute stacks were produced in the field, as part of the QC process, using dummy (straight line) geometry and generic stacking velocity functions, with very little additional processing. SEG-Y data on Exabyte tapes from the ARAM system were read in the field as there was no 3490E tape reader available.

The processing flow was designed with the aim of enhancing reflections and preserving amplitudes, while avoiding processes that could potentially degrade data, particularly in the shallow section. Comprehensive parameter testing was done on shot records, CDP gathers or stack panels for the processing modules used. Further details are given in Rawlings et al. (2004).

Interpretation of the Southern McArthur Basin Seismic Survey Data

AN OVERVIEW OF THE SOUTHERN MCARTHUR BASIN REGIONAL SEISMIC INTERPRETATION

The stratigraphic geometry of the Southern McArthur Basin was previously thought to reflect a simple basin fill. The seismic reflection data, however, are difficult to reconcile with the former interpretations. The main results from the seismic interpretation of the Southern McArthur Basin data is presented in Rawlings et al. (2004) are:

- The Batten 'Trough' is not a separate depocentre and hence is not a trough.
- Sedimentary successions mostly thicken gently to the east.
- The presence of a major east-directed thrust belt.
- The Tawallah Fault is an east-directed thrust within this thrust belt.
- The Emu Fault is a strike-slip fault with a positive flower structure.
- The timing of both the thrust belt and strike-slip movements are post the deposition of Roper Group.

INTERPRETED PACKAGES

The interpretation of the seismic lines is now provided in detail. The interpretation of the shallow section (4 sec, 12 km depth) for Traverse 02GA-BT2 is shown in Figure 4 and Traverse 02GA-BT1 in Figure 5. The interpretation of the deep data (16 sec, 48 km depth) for Traverse 02GA-BT2 is shown in Figure 6 and for Traverse 02GA-BT1 in Figure 7. Figure 8 shows an enlargement of the portion of Traverse 02GA-BT1 where Traverse 02GA-BT2 crosses it.

Basement – high reflectivity

- The basement appears to be represented by an unusual architecture of stacked convex-up arcuate reflections (e.g. 2 seconds TWT at CDP interval 5100-6200; Figure 5). There are numerous mutual truncations and 'on-lap' surfaces that are quite distinct from any other part of the seismic profiles (some of these are marked in mid blue).
- At least four possibilities for these basement features can be postulated:
  1. Primary depositional: the features may represent stacked high-angle fan-delta lobes or turbidite fan lobes, with internal high-relief depositional surfaces. However, the dips are too high to be depositional, unless the steep dips have been enhanced by later deformation
  2. Erosional: formed by high-relief incision at the unconformity at the base of the Tawallah Group.
  3. Volcanic architecture: the arcuate reflections may represent flow units, which when stacked, form a volcanic edifice or series of edifices.
  4. Structural: truncations and elliptical outlines look like either small imbricated thrust duplexes or extensional ramps with a basal detachment surface. Reactivation or inversion may have modified the sense of movement on the faults.

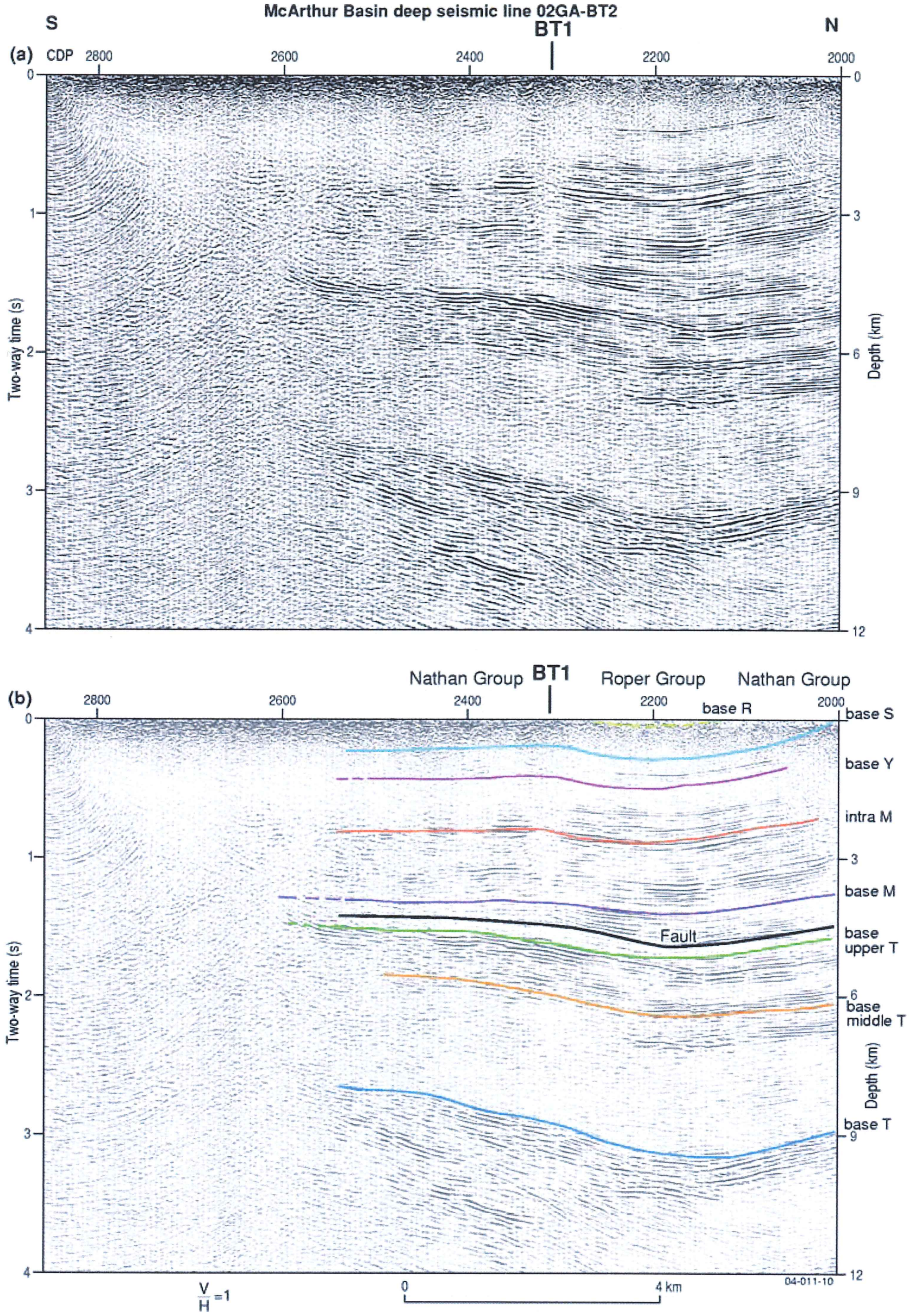

Figure 4: *Interpretation of seismic data for Line 02GA-BT2. base T = base of Tawallah Group; base middle T = base of middle Tawallah Group; base upper T = base of upper Tawallah Group; base M = base of McArthur Group; intra M = approximately Barney Creek Formation level within McArthur Group; base Y = base of Yalco Formation; base S = base of Stretton Sandstone; base R = base of Roper Group. BT1 shows the position of the main east-west line 02GA-BT1.*

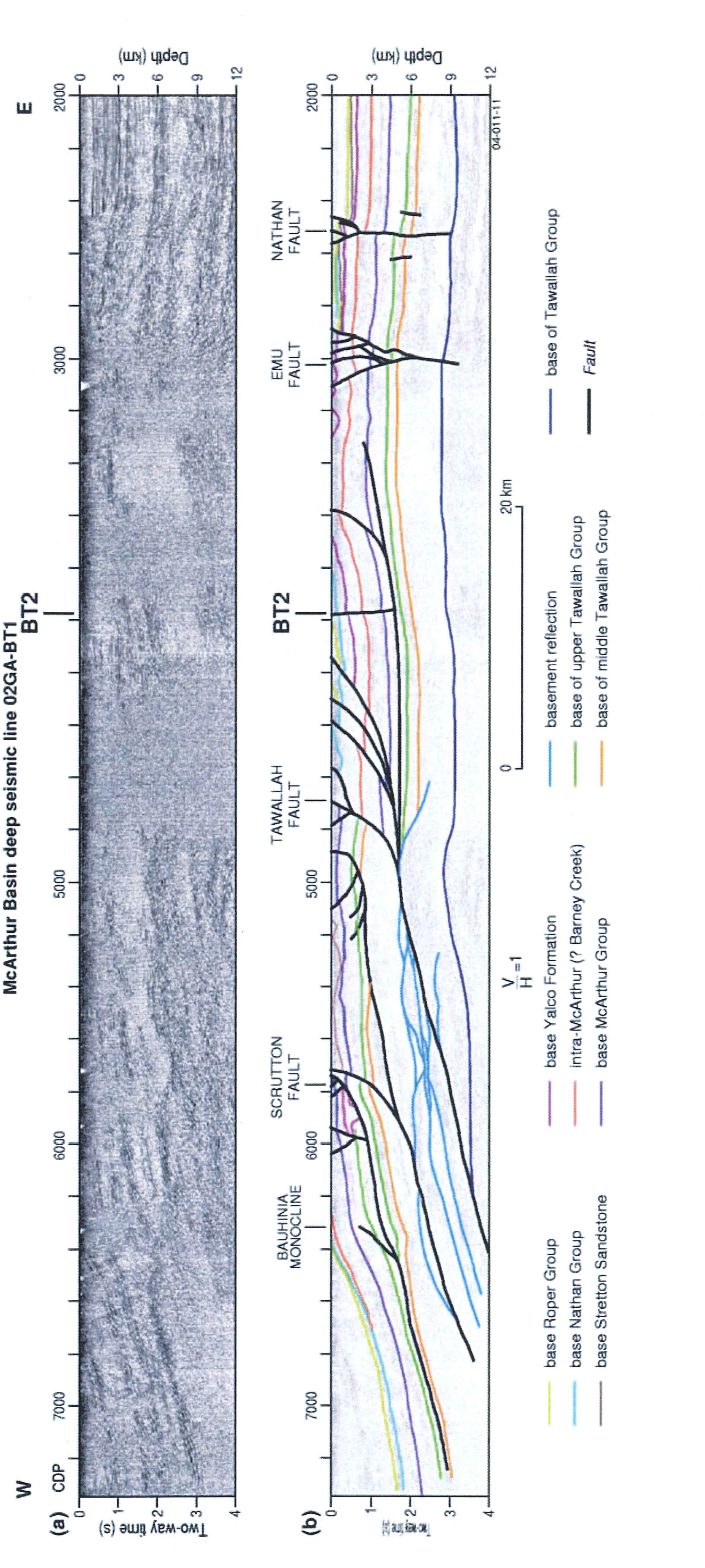

Figure 5: Interpretation of seismic data for Line 02GA-BT1. BT2 indicates the location of the short north-south line 02GA-BT2.

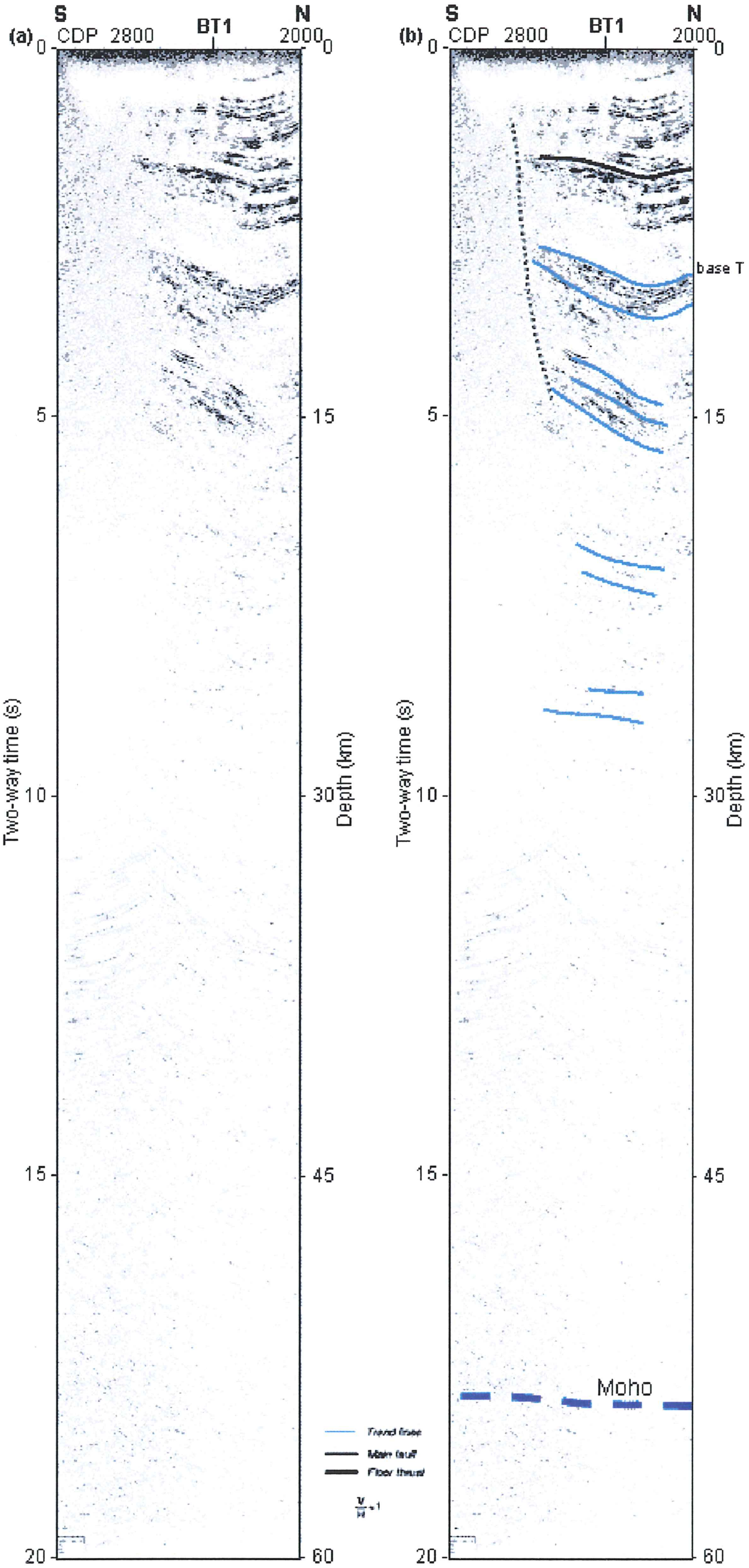

Figure 6: Whole of crust view of seismic line 02GA-BT2 showing main floor thrust (thick black line), the Moho (dark blue line) and some selected mid crustal reflectivity lines (mid blue lines).

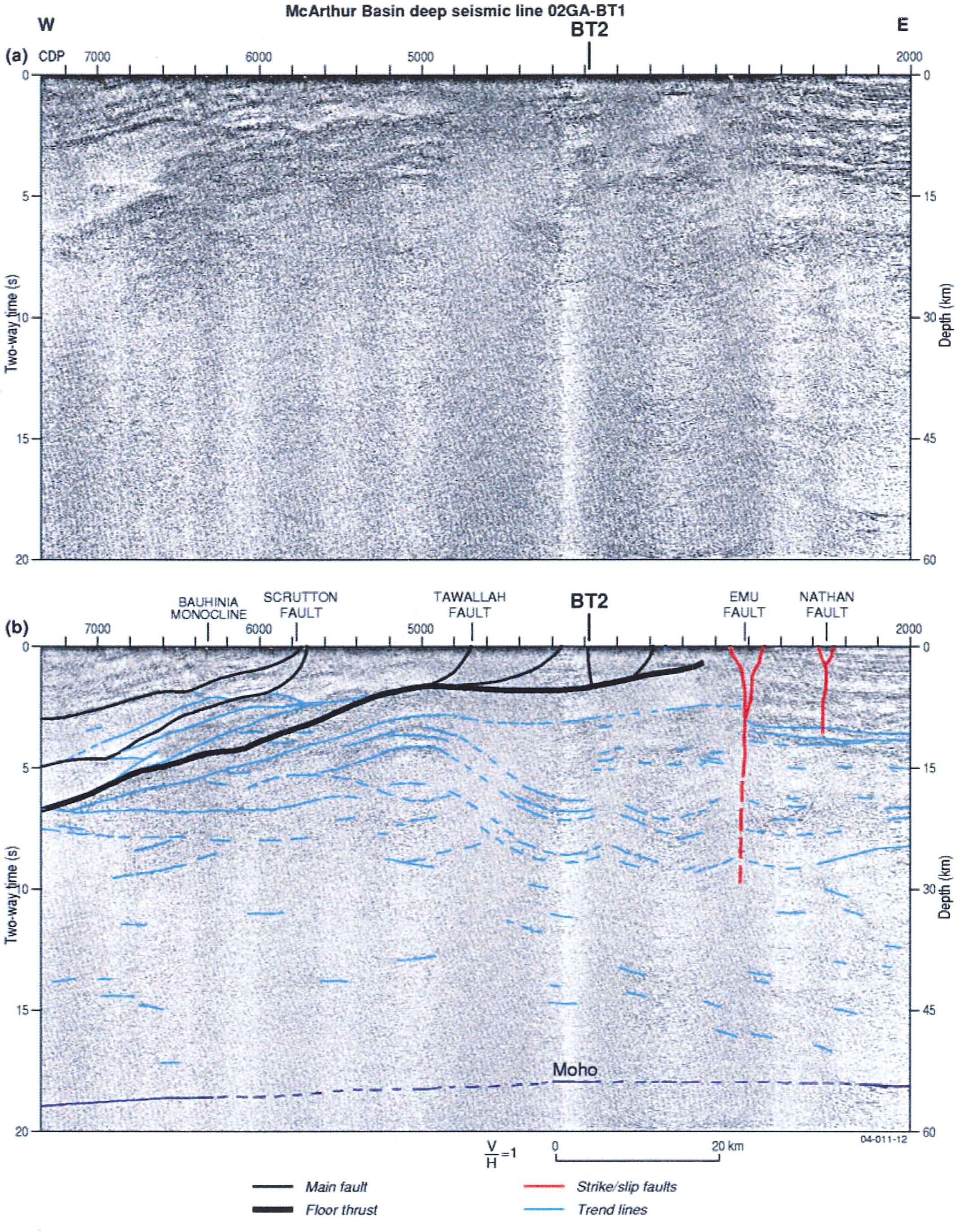

Figure 7: *Whole of crust view of seismic line 02GA-BT1 showing main floor thrust (thick black line), the strike-slip faults (red lines), the Moho (dark blue line) and some selected mid crustal reflectivity lines (mid blue lines).*

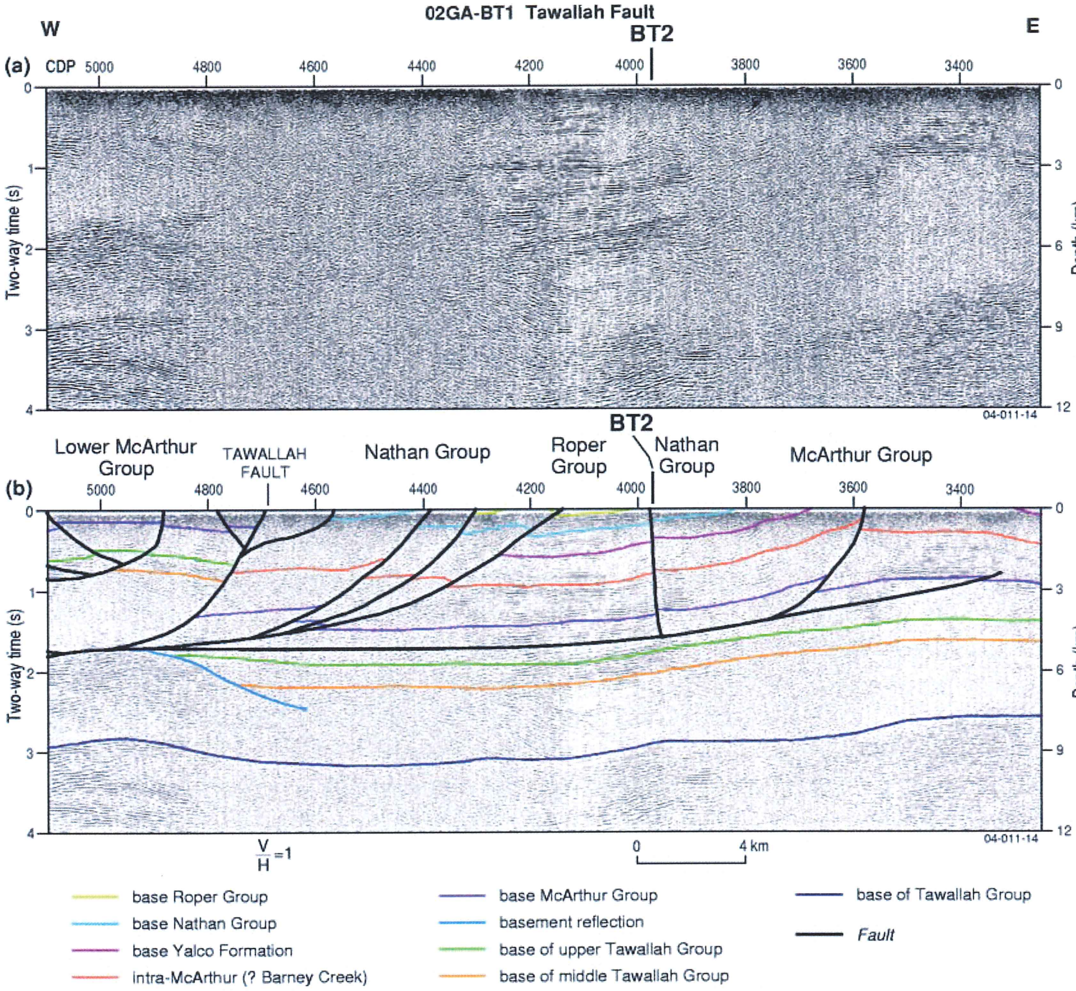

Figure 8: *Portion of seismic Line 02GA-BT1, where it is crossed by Line 02GA-BT2 (shown as BT2), showing region between the Tawallah Fault and central McArthur Basin.*

- It is important to remember that the apparent basement architecture, as viewed in the seismic profile, may be perpendicular or oblique to its principal depositional or structural axis. For example, north- or south-directed thrust architecture, if imaged in the east-west orientation of Line 02GA-BT1, may not exhibit the features typically associated with thrusting. Instead, a coalescence of sinuous thrust sheets could be visible, showing both apparent contractional and extensional geometries.

Lower Tawallah Group – low reflectivity

- The darkest blue line on the seismic profiles is interpreted as the base of the Tawallah Group, although it is difficult to distinguish along most of Line 02GA-BT1 (Figures 5 and 8). It appears better imaged on Line 02GA-BT2 (approximately 3 seconds TWT; Figure 4).
- The character of this part of the section is difficult to ascertain, perhaps because of a monotonous lithology or because it is imbricated by thrust faults that have scattered the seismic signal. Based on what is seen at the eastern end of Line 02GA-BT1, it is generally monotonous with some unusual faint 'bow tie' like internal features, which may be due to

growth wedges or they may be out-of-plane features or diffractions (e.g. 2.5 to 3 seconds TWT at CDP 2100; Figure 5). Projection of outcrop geology suggests this interval is mostly monotonous sandstone, which is consistent with the seismic character.
- At around 1.5 seconds TWT at CDP 5600 to 5900 (Line 02GA-BT1; Figure 5) there are one or two thin and discontinuous subhorizontal reflections within an otherwise characterless zone thought to be lower Tawallah Group. These may be dolerite sills like those recognised in northern Bauhinia Downs (Pietsch et al., 1991a) or they may also be analogous to the thin basalt members of the lower Katherine River Group in central Arnhem Land (e.g., Gilruth Member; Kruse et al., 1994; Sweet et al., 1999).
- Formations within this seismic package include the Yiyintyi Sandstone and possibly one or two thin un-named igneous units (Figure 3).

Middle Tawallah Group – high reflectivity

- The orange line on seismic profiles is interpreted to be the base of middle Tawallah Group.
- It is estimated to be 700-900 m thick and is reasonably consistent in thickness across the seismic section.
- The base is defined by a boundary between less reflective (lower Tawallah) and highly reflective (middle Tawallah) domains. Sometimes there is a slight discordance (unconformity or thrust) at the contact.
- The middle Tawallah Group is characterised by highly reflective anastomosing to sinuous reflections with some internal truncation.
- The distinctly stratified nature is best seen at the western end of Line 02GA-BT1 (e.g. 3.5 seconds at CDP 6800; Figure 5), where the underlying lower Tawallah Group is almost devoid of reflections.
- The lower part of this package locally consists of several stronger than normal reflections that may represent volcanics. These may have suppressed further downward propagation of the seismic signal, which may explain why the underlying lower Tawallah Group is transparent or poorly imaged on the seismic profiles.
- Formations that the seismic package includes, from base up, are the Seigal Volcanics, Sly Creek Sandstone, Rosie Member, McDermott Formation (Figure 3).

Upper Tawallah Group – low to moderate reflectivity

- The green line on seismic profiles is the base of upper Tawallah Group (Figure 5).
- This package is estimated to be 1200-1800 m thick.
- The base is possibly represented by the McDermott Formation-Wununmantyala Sandstone boundary (these should provide the best impedance contrast in the Tawallah Group).
- The base at the eastern end of Line 02GA-BT1 sits immediately above a double bright reflection set with close spacing (but we are unable to ascertain if this is the McDermott Formation or the Wununmantyala Sandstone; Figure 3). There is no evidence of discordance or unconformity.
- Wedging geometry is evident in the basal 0.2 seconds TWT at the east end of Line 02GA-BT1, showing west progradation (2.8 seconds TWT at CDP 2000; Figure 5).
- Overall subdued reflectance, but has internal parallel low amplitude reflections with some low angle truncations and sporadic sinuous reflections (representing possible internal unconformities or low-angle thrusts?).
- Formations within this seismic include, from base upwards, Wununmantyala Sandstone, Aquarium Formation, Settlement Creek Dolerite, Wollogorang Formation, Gold Creek Volcanics, Warramana Sandstone, Tanumbirini Rhyolite, Nyanantu Formation and possibly Burash Sandstone (Figure 3).

- These units represent much of the 'lateral aquifer system' proposed for the McArthur River deposit model of Large et al. (1998).

McArthur Group – high reflectivity

- The purple line on seismic profiles is interpreted to be the base of McArthur Group.
- The thickness of the entire McArthur Group increases gradually and systematically from west to east across seismic Line 02GA-BT1 (~1300 m at western end to ~3200 m at eastern end; Figure 5), although at CDP 4100 it is about 3400 m thick (Figure 8).
- A thickness of 3000-3200 m appears to continue east of the Emu Fault (Figure 5).
- There is evidence of minor onlap onto the Bauhinia Shelf to the west (Figure 5), including downward termination of a few reflections in lower McArthur Group onto the basal unconformity surface. This suggests a gently east-dipping and east-deepening ramp geometry.
- There is evidence for erosion and truncation at the base of the McArthur Group (and the base of the Nathan Group).
- One exception to the systematic westward thinning of the McArthur Group is around Emu Fault, where the thickness appears to decrease to 2500 m immediately east of the fault and to >2700 m immediately west of the fault (Figure 5). Within the Emu Fault flower structure, thickness appears to increase to >3000 m. It is important to note that the upper unconformable boundary is not preserved within or immediately west of the flower structure, so these thicknesses are considered to be minimum. The apparent stratal 'growth' is best seen in pre-stack migrated data.
- Overall, the McArthur Group is thinner on the seismic profiles than the predicted 4-5 km of Jackson et al. (1987), Plumb and Wellman (1987) and Pietsch et al. (1991a).
- In the far east of Line 02GA-BT1 (east of the Narwinbi Fault; Figure 5), the base of McArthur Group is defined by a low relief unconformity, with occasional truncation of the Tawallah Group. The lower McArthur Group is only marginally more reflective than the underlying Tawallah Group and there is no major reflection at its base, probably because Masterton Sandstone is thin or absent. Here the basal boundary of the McArthur Group is defined by truncation only. Similar truncations are seen at the base of the McArthur Group on the Bauhimia Shelf in the west.
- In the west of Line 02GA-BT1 (Figure 5), the lowermost McArthur Group is again only marginally more reflective than upper Tawallah Group and the boundary is ill-defined within a thick (500-700 m) set of sinuous reflections.
- There are several internal characteristics evident within the McArthur Group. Compared with other groups, it is made up of parallel evenly spaced reflections, but some parts of the package are more reflective than others. An interpretation is shown in Figure 5. This interpretation is as follows:
  - Poorly reflective units, presumably homogenous – Mallapunyah Formation-Amelia Dolomite; Emmerugga Dolomite-Teena Dolomite; Reward Dolomite-lower Lynott Formation; Yalco Formation (Figure 3).
  - Moderately reflective units, presumably heterogenous – Masterton Sandstone; Myrtle Shale-Tooganinie Formation; Barney Creek Formation; upper Lynott Formation; Stretton Sandstone-Looking Glass Formation.
- A main broad reflection-set (red line on seismic profiles) is present about half way up the McArthur Group in the far east (east of the Emu Fault on Line 02GA-BT1; Figure 5). It may be Barney Creek Formation (monotonous shale and dolomitic siltstone succession 100-1000 m thick). This marker is not distinguishable and is somewhat arbitrary everywhere west of the Emu Fault. It could, therefore, be interpreted to thin to the west.
- The McArthur Group extends beyond the region deemed to encompass the Batten 'Trough' and Batten Fault Zone. Similarly, there is no evidence for asymmetric half-graben

architectures (cf Plumb and Wellman, 1987), at least not in the east-west seismic Line 02GA-BT1. The Batten 'Trough' as a concept does not exist in its previously perceived form. There is a suggestion on the north-south line (Figure 4) of the succession thickening slightly towards the north, although this appears to be mainly confined to the Tawallah Group. Unfortunately, due to logistical constraints, the line was unable to be continued farther to the north to see if the thickening continued in that direction.

- Flat lying McArthur Group continues east of the Emu Fault onto the edge of the Wearyan Shelf (Figure 5) with considerable thickness and essentially parallel reflections, indicating this fault did not have first order control on deposition or post-deformational distribution. However, it remains to be seen what actually happens to the McArthur Group further east on the Wearyan Shelf proper; does it onlap the shelf, pinch out under younger unconformities, or merge laterally with the Karns Dolomite?
- In the upper part of McArthur Group there are several unconformities and wedging stratal geometries, at about Stretton Sandstone and Yalco Formation level (Figure 5). The Yalco Formation thickens from the Emu Fault eastwards towards the Narwinbi Fault. It is thinner immediately east of the Narwinbi Fault but thickens towards the eastern end of the seismic section. East of the Emu Fault, the base of the Roper Group is represented by a major erosional surface with the Nathan Group and the Stretton Sandstone thinned towards the Narwinbi Fault. East of the Narwinbi Fault, the Stretton Sandstone is thinned markedly towards the eastern end of the section.

Nathan Group – high reflectivity

- The aqua line on seismic profiles is interpreted as the base of Nathan Group.
- Based on the seismic data, the Nathan Group is up to 700 m thick.
- The position of the basal unconformity is based largely on where it is established in outcrop and extrapolated laterally on the seismic profiles. It is not particularly obvious in the seismic section, with little, if any, truncation in the east. It must be reasonably important in the west, however, because the McArthur Group is ~1900 m thick at the Bauhinia monocline but absent in the Tanumbirini Inlier, 40 km farther west of the end of seismic Line 02GA-BT1. This is presumably due to erosion at the Nathan unconformity, or it may be due (in full or in part) to onlap of the McArthur Group onto the western Bauhinia Shelf. In this western area, the boundary chosen to represent the base of the Nathan Group appears to be an angular unconformity.
- Above the base, the Nathan Group is similar to the McArthur Group, with parallel internal reflections.
- The existence, thickness and vertical position of the Nathan Group are difficult to establish on the seismic profile of Line 02GA-BT1 within and east of the Emu Fault (Figure 5). Surface geology suggests this group is locally absent (Pietsch et al., 1991a).
- The Nathan Group is generally associated with poor data quality (e.g. CDP 4300 on Line 02GA-BT1; Figure 5, and CDP 2700 on Line 2; Figure 4), probably due to vadose porosity and caving.

Roper Group – moderate reflectivity

- The yellow line on seismic profiles is interpreted to be the base of Roper Group.
- From the seismic section, the Roper Group is up to 5000 m thick.
- At the western end of seismic Line 02GA-BT1, the position of the base of the Roper Group is extrapolated westward from where it occurs near Bauhinia Downs, although a faulted contact cannot be ruled out.

- The base of the Roper Group is a low-angle unconformity with minor truncations of underlying units. However, in the west, the yellow line follows parallel to the base of the underlying Nathan Group (aqua line), suggesting no downcutting in this area (e.g. 1.5 seconds at CDP 6800-7300; Figure 5).
- Immediately above the Roper Group unconformity at the eastern end of Line 02GA-BT1, the lower Roper Group is marked by one or two prominent reflections, presumably representing the Mantungula Formation and/or Limmen Sandstone (Figure 3; Figure 5). Above this, reflections are less prominent in what may be Mainoru Formation (monotonous shale and fine sandstone).
- The remainder of the succession consists of relatively weak parallel internal reflections, which are not as prominent as those in the McArthur and Nathan Groups.
- A prominent tram-track reflection set in the middle of the Roper Group in the west (maroon line on seismic profile for Line 02GA-BT 1; Figure 5) correlates approximately to the Velkerri marker of Lindsay (2001).
- In the far west of Line 02GA-BT1, the Roper Group totals >5000 m thick (assuming a velocity of 6000 m.s-1), where it is part of the Beetaloo Sub-basin (Jackson et al., 1987). At the nearby Broadmere No 1 well (Figure 1) the lower Roper Group (below Velkerri Formation) is 2500-3000 m thick, indicating that the upper Roper Group (above Velkerri Formation) is >2000 m thick.

THRUST ARCHITECTURE

- The Tawallah and Scrutton Faults and most secondary north- to northwest-striking faults are interpreted as thrusts and coeval back thrusts (Figure 9).
- Thrust geometries are evident in the seismic profiles from discontinuous west-dipping reflections and sharp high-angle truncations.
- Thrusting is also evident in the overall monoclinal geometry of the western Batten Fault Zone (the Bauhinia monocline; Figure 5). It is essential from a geometric perspective for the Roper Group at the eastern limb of the Eleanor Syncline to have been thrust over a tectonic buttress (e.g. a palaeotopographic high; but there is no evidence for this) or a ramp marking the western edge of the Batten Fault Zone.
- Surface geology also supports a thrust model, including arcuate fault profiles of the Tawallah and Scrutton Faults (Figure 1), the regular west-younging and west-dip of strata between these main faults, and the major stratigraphic juxtapositions preserved at these faults (e.g. Batten, Scrutton and Tawallah Ranges). For example, the upper Tawallah Group section exposed at Scrutton Range has much greater affinity with the Tanumbirini Inlier 60 km to the west than it does the Tawallah or Batten Ranges, which are only 10 km to the east. The presence or absence of important markers such as the Tanumbirini Rhyolite, Nyanantu Formation, and Gold Creek Volcanics, and the differing position of unconformities between nearby ranges in the Batten Fault Zone reflects a formerly greater spatial separation, prior to thrusting.
- The kinematics of fault fibres within faults along seismic Line 02GA-BT1 generally supports west-over-east thrust movement (based on field work conducted subsequent to the seismic acquisition, see section below) or, in some cases, east-over-west thrust movement.
- The geometry and dip of the interpreted thrust faults is not really apparent from their relationship with topography or from previous field studies. They have generally been considered to be near vertical (e.g., Jackson et al., 1987; Pietsch et al., 1991a; Rogers, 1996).
- In the seismic profile for Line 02GA-BT1 (Figure 5), the thrusts at the surface have dips in the range of 30° to 80° (generally 60-70°) to the west or east. These merge and curve into a series of parallel listric thrust surfaces with a linear or mildly curved profile dipping at 10-15° to the west.

- Thrust planes appear to be mainly developed in upper Tawallah Group and lower McArthur Group, but penetrate down into basement and the middle crust.
- The main thrusting event was after deposition of the Roper Group, but some earlier thrusting is also possible. Some reasons for the post-Roper timing include:
  - The Roper Group is part of the Bauhinia monocline geometry. If deposition of the Roper Group postdates thrusting, then the Roper unconformity should cut down through the thrust sheets in the central Batten Fault Zone and lie at the same structural level across the entire section, with persistently flat-lying reflections. To balance the cross section as it is currently drawn requires that Roper Group occupy the top part of section which has been imbricated and largely removed.
  - Stratigraphic juxtapositions of Roper Group occur only adjacent to the main thrusts; elsewhere, the stratigraphic level of this unconformity is fairly consistent (see section on 'Fault block characteristics' below).
  - The Roper Group and underlying units are equally deformed in the Batten Fault Zone (including folding and faulting). For example, the fold set with north-south axes that is evident in the McArthur Group in the Batten Fault Zone is also present in the Roper Group at the Eleanor Syncline.
  - Earlier studies have identified the 'post-Roper inversion' as the most important in shaping the structural architecture of the McArthur Basin (Plumb, 1994; Rogers, 1996; Rawlings et al., 1997).
- Although similar geometries are evident in the Mitchell-Flinders Thrust Belt in northeast Arnhem Land (Rawlings et al., 1997), the thrusting there is interpreted to have occurred during the hiatus separating the Nathan and Roper Groups (i.e. Isan Orogeny). Thus the temporal criteria there need revisiting.
- The overall geometry is a set of west-over-east thrusts with flat-ramp-flat geometries. The upper part of the ramp in successive thrust sheets has been removed by either erosion or subsequent thrust sheet emplacement.
- The proposed model involves dismemberment and thrust imbrication of a broad and uniform flat-lying basin sheet, incorporating Tawallah Group through to Roper Group ~10-15 km thick, via a series of low angle west-dipping thrusts.
- Overall, the deformation is consistent with an east to north-east striking shortening direction (direction of tectonic transport).
- The seismic-derived cross sections need to balance where they are approximately perpendicular to the strike of faults. Where the cross-section is parallel to strike, there is no need for section balance or consistent kinematics. Thrust planes in strike sections may be sinuous in profile and can entail apparent thrust and normal fault movement.
- Published thrust models (e.g., Fischer and Woodward, 1992; Tanner, 1992; McClay, 1996) predict increasing deformation and transport distance of thrust sheets toward the propagating foreland, in this case to the west. They also predict a systematic timing of thrust sheet movement, such that the western-most (uppermost) thrust sheet was the first emplaced (oldest) and eastern-most thrust sheet (lowermost) was the last emplaced (youngest). This is generally consistent with the seismic-derived cross section for Line 02GA-BT1.
- To the north, in the Mount Young 1:250 000 geological map sheet area (Haines et al., 1993), the major fault set appears to encompass east-dipping thrusts and east-over-west transport (the reverse of Bauhinia Downs 1:250 000 geological map). It is not clear how this thrust set relates temporally with the set identified along seismic Line 02GA-BT1, nor how the two sets interrelate spatially from north to south (geometrical complexity), but this is beyond the scope of this report.
- The positions of faults in the Batten Fault Zone do not appear to have been directly inherited from the basement, as has been suggested by many authors (e.g. Etheridge and Wall, 1994). Instead, the current architecture is a largely a reflection of post-Roper thrust terminations.

Fault Block Characteristics

The thrust and strike-slip fault interpretation outlined above involves the juxtaposition of at least four main fault blocks (Figure 9), each of which has undergone relative tectonic transport and exhibit some degree of unique geology (i.e. allochthonous character). Some of these fault blocks are underlain by a west-dipping thrust fault and thus can be regarded as thrust sheets. Supporting an allochthonous model are a number of distinguishing characteristics that have been recognised within the individual fault blocks from integrated surface geology and seismic interpretation, and are detailed in Rawlings et al. (2004).

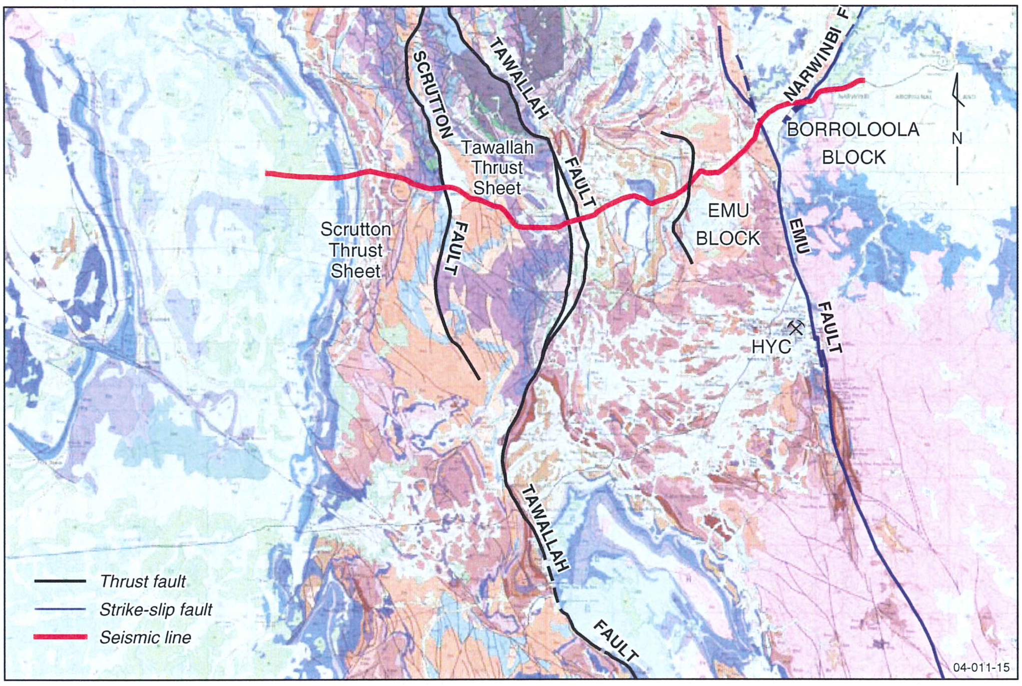

Figure 9: *Fault blocks within the Southern McArthur Basin on the Bauhinia Downs 1:250 000 geological map as defined by the principal fault systems.*

Results from field mapping undertaken subsequent to initial seismic interpretation

INTRODUCTION

The geology along the two seismic lines can be elucidated from the 1:1 000 000 scale tectonostratigraphic map of the McArthur Basin (Rawlings, 2001), the 1:250 000 scale Bauhinia Downs (Pietsch et al., 1991a) and the 1:100 000 scale McArthur River region (Pietsch et al., 1991b) geological maps. The geology is also summarised in Figure 1. To obtain a more detailed picture of stratigraphy and structure, a surface geological transect was undertaken by the Northern Territory Geological Survey (NTGS) in mid 2003 along the actual seismic survey route after the initial interpretations of the seismic sections had been completed, and after the picture of the major thrust system had been recognised in the seismic data. This entailed the establishment, along the transect, of detailed stratigraphic position, bedding attitude, orientation of mesoscopic scale faults, folds and slickenside fibres, and estimation of offset and orientation of macroscopic scale faults. Shear sense criteria from slicken surfaces follows the method of Petit (1987). Details of the seismic transect were transferred onto aerial photographs and the geology maps and used in a subsequent interpretation of the seismic lines. Full descriptions can be found in Rawlings et al. (2004), from which we extracted the following information for the area in the vicinity of seismic line 02GA-BT2.

Rogers (1996) carried out inverse palaeostress analysis across the Batten Fault Zone using fault-slip data collected in the Batten, Tawallah and Scrutton Ranges. He recognised three compressional episodes: (D_1) 'early' mid-Tawallah Group east-west compression; (D_2) mid-McArthur Group northwest-southeast compression; and (D_3) 'late' post-Roper Group northeast-southwest compression.

SMALL FAULTS BETWEEN RYANS BEND AND BATTEN RANGE

At least five relatively small faults occur along this part of the geological transect on seismic Line 02GA-BT1 (Figure 1). They are arcuate in plan, mimicking one of the two principal local macroscopic scale fold axes (1-20 km wavelength). Seismic Line 02GA-BT1 crosses these faults perpendicular to strike. In contrast, seismic Line 02GA-BT2 is parallel to these faults (Figure 1). All faults have a west-side-up sense of movement and 100-600 m of apparent vertical displacement. The intervening fault blocks each contain a west-younging and west-dipping sequence of upper McArthur Group, Nathan Group and lowermost Roper Group, with some internal north- to north-west oriented folding on a mesoscopic scale (10s of metres wavelength) and macroscopic scale (1-10 km wavelength). Dips increase systematically toward most of the faults from the east and west, and overall reverse geometry for most faults can be implied from the orientation of bedding deflections or drag folds, fault propagation folds (hanging wall anticlines) and west-side-up juxtaposition. Fault fibres are rare, but where recognised plunge toward 240-270° or 060-080° at about 25-40°. These are consistent with both west-over-east and east-over-west reverse/thrust kinematics respectively. Some fibre planes have been rotated to be shallow east-dipping with apparent extensional kinematics. The western fault block, which abuts the Tawallah Fault, consists of steeply dipping and locally overturned strata that probably involves internal structural repetition. Some stratigraphic units such as the Stretton Sandstone are attenuated to <50 m thick.

TAWALLAH FAULT

The Tawallah Fault is exposed along the eastern margin of the Batten Range, where it accompanies a substantial break in slope, and cuts north-westward through the southern Tawallah Range (Figure 1). It is a major regional north-northwest striking structure that is arcuate to sinuous in form and greater than 150 km in strike length. It juxtaposes mainly Tawallah Group on the west side against middle to upper McArthur Group on the east side (i.e. west-side-up geometry). About 25 km north of the geological transect, basement Scrutton Volcanics are juxtaposed against lower Roper Group (Haines et al., 1993), indicating up to 12 km apparent vertical displacement. The lateral continuity and scale of juxtapositions indicate at the Tawallah Fault is one of the major structures in the region. The fault is characterised at the surface by intense deformation (steep dips, cataclasite, fault gouge, folding, brecciation and hydraulic fracturing), silicification, haematisation and quartz veining. Dips in bedding within a 1-3 km wide corridor incorporating the fault tend to be greater than 70°, and decrease outward in both an easterly and westerly direction. Fault fibres were not identified in any of the localities visited and may have been destroyed during late deformation or hydrothermal activity. The map profile of the Tawallah Fault does not appear to be influenced by topography, suggesting its orientation in the shallow subsurface is steep. Its orientation deeper down is unknown.

Rogers (1996) collected fault-slip data from the Batten Range, concluding that D_1, the earliest recognisable phase of deformation, was largely responsible for the west-over-east thrust movement on the Tawallah Fault. The data also suggest that this fault subsequently underwent sinistral (D_2) followed by dextral (D_3; toward 051°) strike-slip transpressional deformation. This interpretation appears at odds with geological observations, such as the frequent juxtaposition of Tawallah Group with upper McArthur Group and Roper Group, which indicate substantial west-side-up (reverse) movement on this fault during post-Roper Group times (i.e. D_3). The sinuous nature of the Tawallah Fault is, also, not consistent with significant strike-slip displacement (cf. Emu Fault). Fault-slip data from the Tawallah Fault to the north in the Tawallah Range support the reverse fault contention, with southwest-dipping thrust fault planes prevailing (Rogers 1996). This does not preclude some earlier mid-Tawallah Group D_1 reverse movement, as proposed by Rogers (1996), followed by D_3 reverse reactivation. However, Rawlings (2002b) argues against significant mid-Tawallah deformation due to the absence of a significant unconformity at this stratigraphic level.

The seismic data in three dimensions

INTRODUCTION

The 2002 Southern McArthur Basin seismic lines followed existing roads and thus were essentially crooked. The seismic processing took this crooked line geometry into account, however, and when the data are plotted on paper it is viewed as a straight line. Unless one remembers where the bends are, it is difficult to work out where the reflections were in three-dimensional space.

To assist in the interpretation of the seismic data in three-dimensional space, a simple 3D model was constructed using GOCAD®, which is a commercially available 3D modelling and visualisation package suitable for investigating geology in three-dimensional space.

BUILDING THE 3D MODEL

The two migrated seismic lines were imported into GOCAD® and positioned according to their true CDP coordinates. The Bauhinia Downs 1:250 000 geological map and the initial interpretations were also imported as reference information. A simple model of the seismic lines is shown in Figure 10.

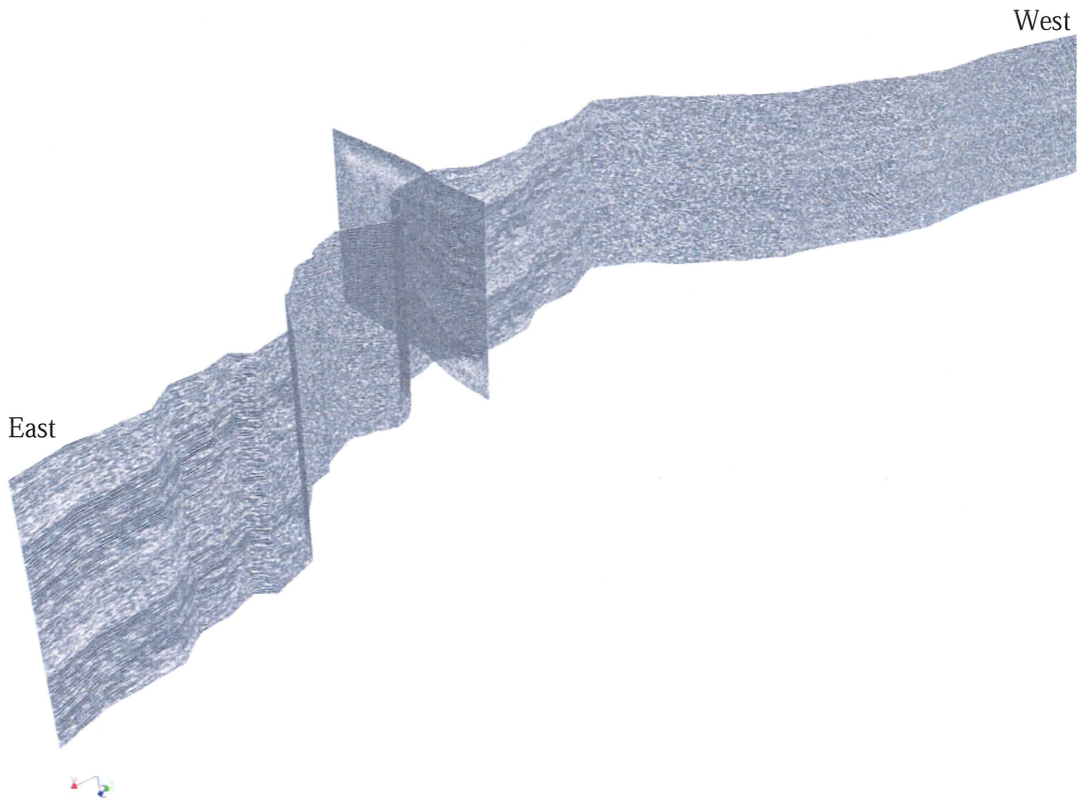

Figure 10: *Simple 3D model of the two seismic lines in 3D space. View is from the northeast looking southwest, down onto the seismic lines. The crooked nature of the seismic is apparent in this view.*

No attempt was made to construct 3D surfaces for the stratigraphy or faults. Rather, the simple 3D model was used to investigate continuity of reflections around bends and the relationships between local geology and reflections at depth.

FEATURES OF THE 3D MODEL

Figures 11 and 12 show detailed parts of the 3D model, with Figure 11 looking perpendicular to seismic line 02GA-BT2 and Figure 12 looking perpendicular to seismic line 02GA-BT1.

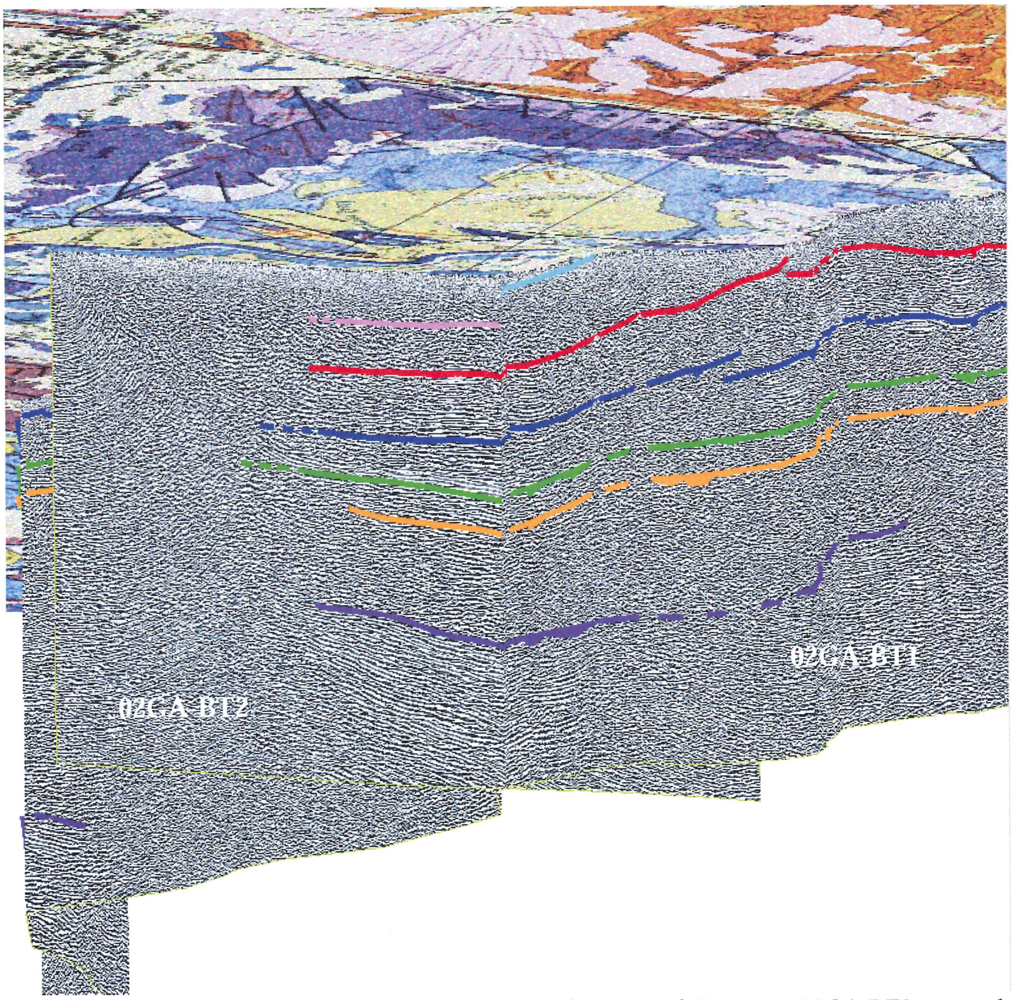

Figure 11: *Detailed view of the 3D model showing features of Traverse 02GA-BT2, viewed from depth looking north-west. The geology is shown at surface level and can be regarded as a lid to the model.*

The region of complex reflectivity that occurs between the Scrutton Fault and the Tawallah Fault was initially interpreted as a series of small thrust sheets. The 3D model showed that this region resulted from the reflection interference as the seismic line followed a sub-parallel fault plane (Figure 12).

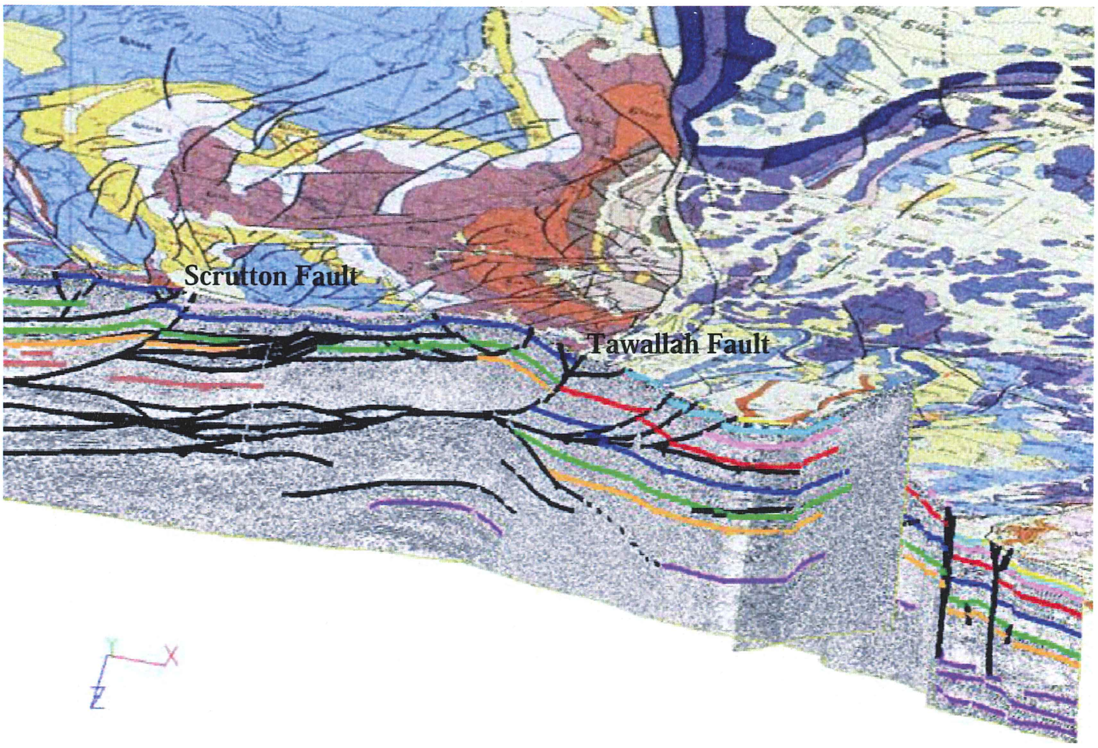

Figure 12: *Detailed view of the 3D model showing the Scrutton (left part of image) and Tawallah Faults (centre of image). Viewed from depth looking north-northwest. The geology is shown at surface level and can be regarded as a lid to the model. Line 2 can be seen at the eastern end of the image, coming out of the page towards the viewer.*

Implications of the Southern McArthur Basin Seismic Data to Mineral Systems

IMPLICATIONS OF THE SEISMIC DATA

The seismic data reported on here provide support for the concept of a steep and complex strike-slip geometry for the Emu Fault Zone, thereby allowing access to deep basinal brines. The data also suggest that sedimentary growth took place within negative flower structures along the Emu Fault during middle McArthur Group times. Rapid local deposition and growth were probably facilitated by differential subsidence along transtensional releasing bends on the fault. The resulting sub-basins were inverted during post-Roper deformation, when these areas became transpressional restraining bends. This is largely consistent with recent structural interpretations around the McArthur River deposit (Hinman, 1995; Bull and Scott, 1998; Selley et al., 2001).

The various cross-sections used for fluid flow modelling (Garven et al., 2001; Yang et al., 2001a, 2001b) vary in their consistency with respect to the section derived from the seismic data. Alternative interpretations of the seismic are possible and an east-west section at the latitude of the McArthur River deposit may be somewhat different to that at Line 02GA-BT1.

Facets of the cross-sections used for fluid flow modelling that are consistent with the seismic cross-section include:

- Emu Fault geometry. The geometry used in the fluid flow models at the McArthur River deposit is deep-rooted and steeply west-dipping, as observed in seismic Line 02GA-BT1 at Ryan Bend.
- Upper Tawallah Group aquifer. The aquifer system modelled to lie between the current positions of the Emu and Tawallah Faults (Garven et al., 2001) takes the form of a more-or-less contiguous 1500 m thick poorly reflective package in the postulated upper Tawallah Group in the seismic data. However, neither porosity nor permeability can be inferred from the seismic data.
- Thickness changes in the lower Tawallah Group clastic units (mainly Yiyintyi Sandstone). An increase in thickness across the Emu Fault from west to east, as shown in the models of Yang et al. (2001b), is supported to some extent by the seismic data (although not conclusively).

Facets of the fluid flow-derived cross-sections that appear at odds with the seismic results include:

- McArthur Group east of the Emu Fault (Borroloola block). In the fluid flow models, this block is shown to be upthrown and thinned compared to the west. In contrast, the seismic profile clearly shows a monoclinal structure with gross east-side-down movement and a continuation of thick McArthur Group to the east.
- McArthur Group in Emu Block. The overall geology is shown in the models to dip to the east between the Tawallah and Emu Faults, when it actually youngs and dips to the west (this is also evident on geological maps).
- Geometry of the Tawallah Fault. Interpretation of the seismic data at the Tawallah Fault is not conclusive, due to areas of poor data quality, but there is no evidence for any steep deep-rooted west-dipping structure, as used in the fluid flow models. Instead, a shallow-west dipping thrust is interpreted. In any case, this fault post-dates deposition of the McArthur Group and formation of the McArthur River deposit ore body by at least 150 million years (unless the unlikely 'late epigenetic' model is invoked). In addition, the current position of the Tawallah Fault reflects the current termination of a thrust sheet, not the architecture at

McArthur Group times. If the 'Tawallah Fault' was initiated upon an earlier McArthur-age structure (vertical or not), then the proto-Tawallah Fault must have existed further to the west, away from the direction of post-Roper tectonic transport. However, it is important to note that the interpretation of Line 02GA-BT1 is two-dimensional and therefore does not preclude the presence of another blind 'recharge' structure further to the south of the seismic line and west of the McArthur River deposit.

- Offset at the Tawallah Fault. This is shown as an anticline, when it should show a substantial west-side-up thrust geometry (also evident on geological maps).
- Basement lithology. This is shown on fluid flow models to change from mafic in the west to felsic in the east (after Leaman, 1998). This change is not apparent in the seismic and there is also no geological evidence for it (Rawlings, 2002b).

EXPLORATION PHILOSOPHY AND AREA SELECTION

The seismic data suggest that the potential for McArthur style base metal deposits is expanded within and east of the Batten Fault Zone. Some reasons include:

- Segments of the Emu Fault now under cover north and south of the McArthur River deposit. The seismic data have strengthened the interpreted strike slip geometry of the Emu Fault with probable stratal growth of the upper McArthur Group within some flower structures (e.g. at the McArthur River deposit and at Ryan Bend). This means that other sub-basins must have developed along the 150 km length of the fault and are prospective for base metals. The likely economics of any discoveries are also enhanced by the probability that mineralised sub-basins (typically subsidence features and therefore structurally 'deep') have been later inverted to sit at structurally 'shallow' positions.
- Areas east of the Emu Fault under cover. Contrary to most literature, the McArthur Group continues east of the Emu Fault with considerable thickness and largely parallel reflections, indicating that this fault did not have first order control on deposition or post-deformational distribution. Therefore, the exploration potential of covered area to the east is improved, as there is a much broader distribution of appropriate and thick trap rocks (Barney Creek Formation appears to be a wide high-amplitude reflection set) and other blind syn-sedimentary structures like the Emu Fault could be present. There is, however, a perception that any mineralised system will be too deep for economic exploitation, particularly under the Roper Group.
- Within the Batten Fault Zone. The current structure and thickness estimates of packages in the Batten Fault Zone do not reflect the architecture at Barney Creek time. Thrust sheets elsewhere in the fault zone may contain a thicker McArthur Group succession or may conceal an Emu-like strike slip fault that had earlier tapped fluids from deep in the basin.
- Seismic acquisition and processing was successful. Thus, direct detection of SEDEX deposits by the acquisition of shallow (1 second) reflection seismic data along the length of the Emu Fault Zone may be an economically viable option for explorers, particularly under Cainozoic cover.

MVT, PETROLEUM-PLAY AND THRUST-BELT ASSOCIATED DEPOSITS

Fluid flow modelling of foreland basins adjacent to fold and thrust belts (e.g. Garven et al., 1993; Ge and Garven, 1994; Appold and Garven, 2000) has shown that Mississippi Valley Type (MVT) districts can be explained in terms of expulsion of metalliferous fluids in an evolving orogen. Similarly, Hobbs et al. (2000) have appealed to a topography-driven fluid flow event for the formation of the Century stratiform Zn-Pb deposit, a petroleum-play McArthur 'look-a-like' (Broadbent et al., 1998). This fluid flow event is interpreted to have taken place coincident with the ~1590-1500 Ma Isan Orogeny in the Mount Isa Inlier (O'Dea et al., 1997). Large et al. (2002)

dismissed topographically driven fluid flow as a likely mechanism for the formation of the McArthur River deposit, based on the premise that there is no evidence of a regional fold and thrust belt (orogen) to provide elevation. However, it is apparent from the seismic data that a fold and thrust belt developed within the Batten Fault Zone after deposition of the Roper Group. This event may be responsible for epigenetic base metal occurrences (Cu, Zn and Pb) within the Batten Fault Zone and on the Wearyan Shelf (e.g. Redbank, Eastern Creek, Thor, Mariner; Pietsch et al., 1991a; Rawlings, 2002a; Rawlings, in prep.). The geometry, extent and timing of this thrust event increase the exploration potential for large epigenetic MVT or Century-style deposits in appropriate lithologic and structural settings in the broader McArthur Basin. Appropriate carbonaceous units occur throughout the basin succession and include the Wollogorang Formation (Tawallah Group), Barney Creek Formation, Caranbirini Member (McArthur Group), Mainoru Formation and Velkerri Formation (Roper Group). Well-developed karstic carbonate units include the Emmerugga Dolomite (McArthur Group), Balbirini Dolomite (Nathan Group) and Karns Dolomite. Importantly, because of their location on structural highs or shelves, the exploration areas for MVTs are much larger than for SEDEX deposits. Importantly, MVTs also do not have the metallurgical problems of the super-fine SEDEX ores.

Any other McArthur River aged SEDEX deposits involved in thrusting within the central Batten Fault Zone may have been remobilised and manifested as widespread diffuse anomalism or fault-associated 'late' epigenetic occurrences. A potential example is Bulman on the Arnhem Shelf (Sweet et al., 1999). The Narwinbi Fault may also have been active during Barney Creek Formation times and therefore be a possible SEDEX target, or it may be an inversion structure, which provides potential for MVTs.

Summary

SUMMARY OF THE 2002 SOUTHERN MCARTHUR BASIN SEISMIC SURVEY

- Survey funded by GA, NTGS, *pmd**CRC and Anglo American.
- Careful planning and prioritisation of route to minimise environmental, heritage and social impact.
- Extensive community consultation (pastoralists, traditional owners, Northern Land Council and regional councils).
- Acquisition: October-November 2002.
- Routine Processing: completed April 2003.
- Interpretation: May 2003 – November 2003, and ongoing
- Paper copies of the seismic data for line 02GA-BT2 (both the 4 sec section and 20 sec section) were provided to Anglo American's Perth office in February 2003 for comment and advice. An image version of the seismic data for line 02GA-BT2 as well as the intersection region for line 02GA-BT1 was also forwarded to Anglo American's London Office for comment and advice.

OBJECTIVES OF THE SURVEY

- Investigate the fundamental basin architecture of the Southern McArthur Basin, including the 'Batten Through'.
- Investigate the nature of the underlying basement and crust, including depth to Moho.
- Determine the thickness, stratigraphy and structure of Tawallah, McArthur, Nathan and Roper Groups across the region.
- If applicable, determine the direction and timing of extension and compression that shaped the basin history.
- Image the Emu and Tawallah Faults.
- Determine what influence the Emu Fault had on deposition of McArthur Group.
- Compare seismic-derived cross-section with those used for fluid flow modelling.
- Investigate what implications may exist for base metals exploration in the region.

IMPLICATIONS OF SURVEY

- The 'Batten Through' is not a separate depocentre; thus the term should be discarded.
- Sedimentary successions mostly thicken to the east; Emu Fault has only local influence on thickness changes. Based on line 02GA-BT2, there is a suggestion that the Tawallah Group thickens slightly to towards the north.
- Emu Fault is a sub-vertical strike-slip fault with inverted positive (contractional) flower structure.
- Presence of major east-directed thrust belt. Tawallah Fault is an east-directed thrust.
- Timing of both thrust belt and latest strike-slip movements is post deposition of Roper Group.
- Only partial support for postulated fluid flow models for McArthur River (McArthur River) Deposit.
- Base metal exploration plays and areas of potential exploration interest are expanded.

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