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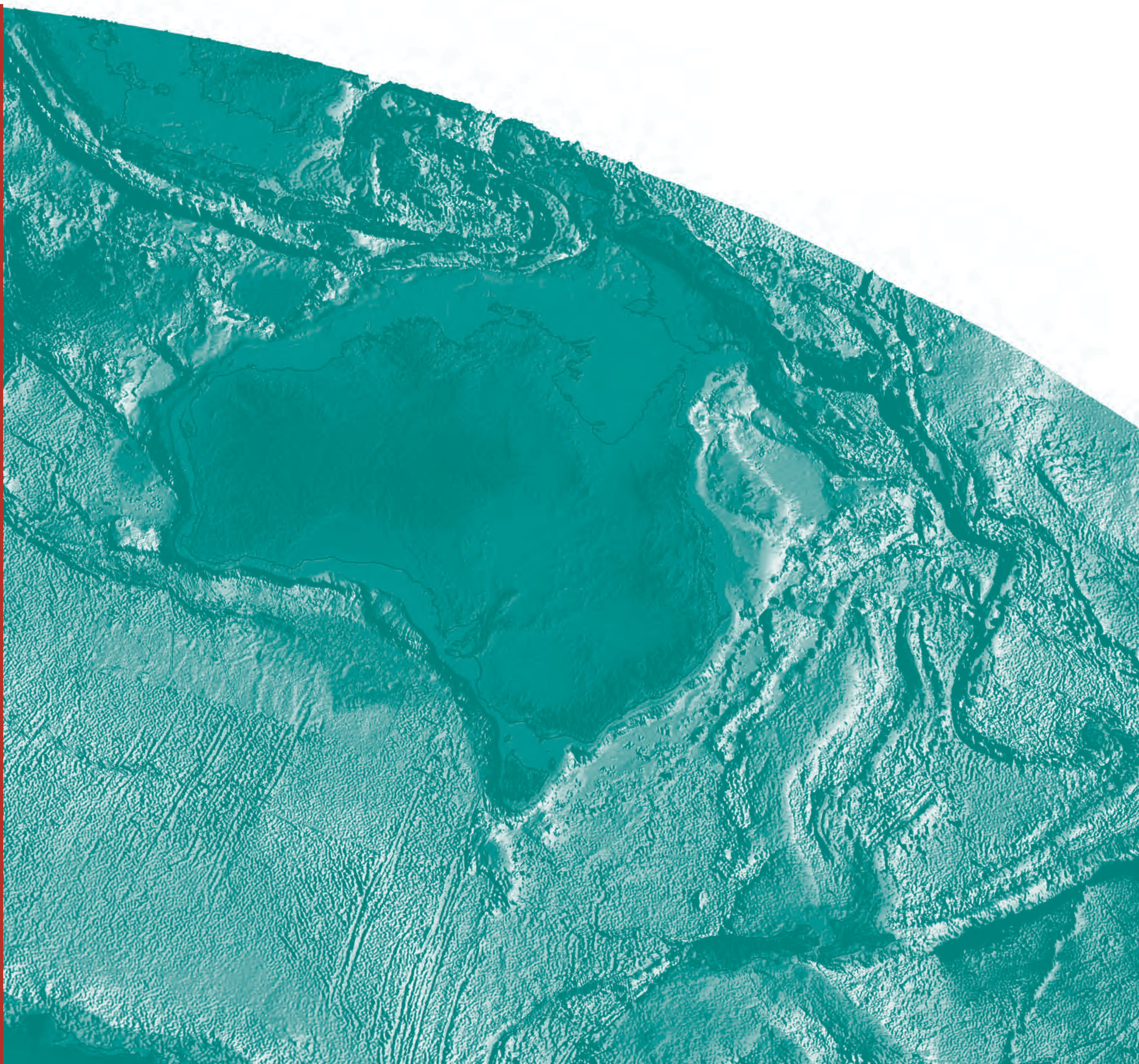

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The 2002 Southern McArthur Basin Seismic Reflection Survey

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by

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Australian Government Geoscience Australia

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

Contents

Executive Summary

The Southern McArthur Basin, host to the world class McArthur River (HYC) Zn-Pb-Ag deposit, contains an unmetamorphosed, relatively undeformed Palaeoproterozoic to Mesoproterozoic succession of carbonate, siliciclastic and volcanic rocks. Seismic reflection data obtained across this basin have the potential to revolutionize our understanding of the crustal architecture in which this deposit formed. These data were collected in late 2002 as part of a study to examine the fundamental basin architecture of the Southern McArthur Basin and the nature of underlying basement. Much of the seismic program was designed to test geometric models in this area, including tectonostratigraphy, fault systems and basement structure. The results have wider applicability because the basin is considered to be a little deformed analogue of the Western Succession of Mt Isa. The main seismic line (02GA-BT1) was oriented east-west across the Southern McArthur Basin, commenced 15 km west of Borroloola, and extended about 110 km westwards along the Borroloola-Roper Bar road. A short north-south cross line (02GA-BT2), 20 km long, was acquired within the basin itself, in collaboration with AngloAmerican.

There is very little evidence for stratal growth in the seismic data, although in gross terms the middle part of the succession (McArthur Group) thickens gradually towards the east, while the preserved thickness of the upper part (Roper Group) increases to the west. East of the Narwinbi Fault, the entire succession is essentially horizontal and at least 8 km thick, including 3.2 km of McArthur Group and 1 km preserved of the Roper Group. At the western end of the profile there is 9 km thick succession, which includes the 1.3 km thick McArthur Group and 5 km thick Roper Group. There is no evidence in the seismic data for either the Batten ‘Trough’ or asymmetric half-grabens. Rather the sedimentary succession appears to continue in both directions away from the implied boundaries of the ‘Trough’. A more likely palaeogeographic scenario appears to be that of a gently east-dipping carbonate ramp at McArthur Group times, with third-order sub-basins generated along the Emu Fault at specific time intervals.

Most of the east-west seismic profile is dominated by a series of west-dipping faults, interpreted here to be part of a major thrust belt which propagated eastward to form a forward-breaking imbricated duplex set. Within the section, displacement on the thrusts tends to be greatest in the west and diminishes to the east, with the frontal thrust of the system occurring ~6 km west of the Emu Fault Zone and having only minor displacement. In the west, the Roper Group forms the western limb of the Bauhinia monocline, which developed above the most western thrust ramp, and indicates a post-Roper timing for the thrust system. Deformation and fault geometries are consistent with an east- to northeast-striking compressional axis.

We have interpreted the Emu Fault as a near-vertical strike-slip fault, containing an inverted flower structure along seismic Line 02GA-BT1. This is supported by the overall linear nature of the fault system in plan and the rapid changes in geometry along strike. Two episodes of fault activity are postulated. The first involved sinistral movement in middle McArthur Group times, leading to possible stratal growth on transtensional fault bends. The second dextral movement postdates the Roper Group and has inverted earlier transtensional zones to form positive flower structures. The Narwinbi Fault is also interpreted as a strike-slip fault with a positive flower structure, involving at least post-Roper movement.

The seismic data support, to some extent, the genetic and fluid flow models for the McArthur River Zn-Pb-Ag deposit proposed by Large et al. (1998) and Garven et al. (2001), in which the Emu Fault was portrayed as a near vertical fault. There are also major departures however, such as geometry of the Tawallah Fault and dip of the adjacent aquifer system. The new data expand the potential for ‘McArthur style’ base metal deposits within and east of the Batten Fault Zone. The presence of a thrust belt enhances the prospectivity of large areas of the McArthur Basin for post-Roper uplift-related MVT mineralisation.

The Southern McArthur Basin Seismic Reflection Survey

INTRODUCTION

This report contains a summary of the acquisition, processing and initial interpretation of deep reflection seismic data collected in the Gulf of Carpentaria region during late October 2002. The 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). The seismic acquisition work was undertaken by the Australian National Seismic Imaging Resource (ANSIR). AngloAmerican kindly provided financial support towards the acquisition of a short cross (02GA-BT2) line perpendicular to the main seismic line (02GA-BT1).

The survey was originally called the *Batten Trough 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 Trough Deep Seismic Survey'.

AIMS AND OBJECTIVES

Through this project we aim to understand the fundamental basin architecture of the Southern McArthur Basin and the nature of the underlying basement. Seismic reflection data also provide an excellent means of testing previously proposed geometric models for the McArthur Basin architecture (including tectonostratigraphy of the Palaeoproterozoic and Mesoproterozoic basin phases) and the nature of the basin bounding faults and relevant basement structures. These have significant outcomes for understanding sediment hosted mineral deposits such as McArthur River (also called HYC for Here's Your Chance) and the future direction of base metals exploration in the basin. Interpretation of the seismic data also has the potential to influence the development of ideas and models concerning the migration of metal-bearing basinal fluids from their aquifer system, up faults to the reductant shales to form the deposits.

Seismic reflection data will also be useful in achieving a better understanding and knowledge of sub-surface geology at a regional and crustal scale. In particular, these data provide information on the regional thickness of the crust (depth to Moho) and major structures in the lower crust, as well as elucidating basement controls on basin development.

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 undulatory, but there are sporadic small rocky ranges with up to 300 m relief (Tawallah, Batten and Scrutton Ranges and the Bauhinia jumpup; Figure 2). 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, prior to the onset of the west season, when roads can become impassable.

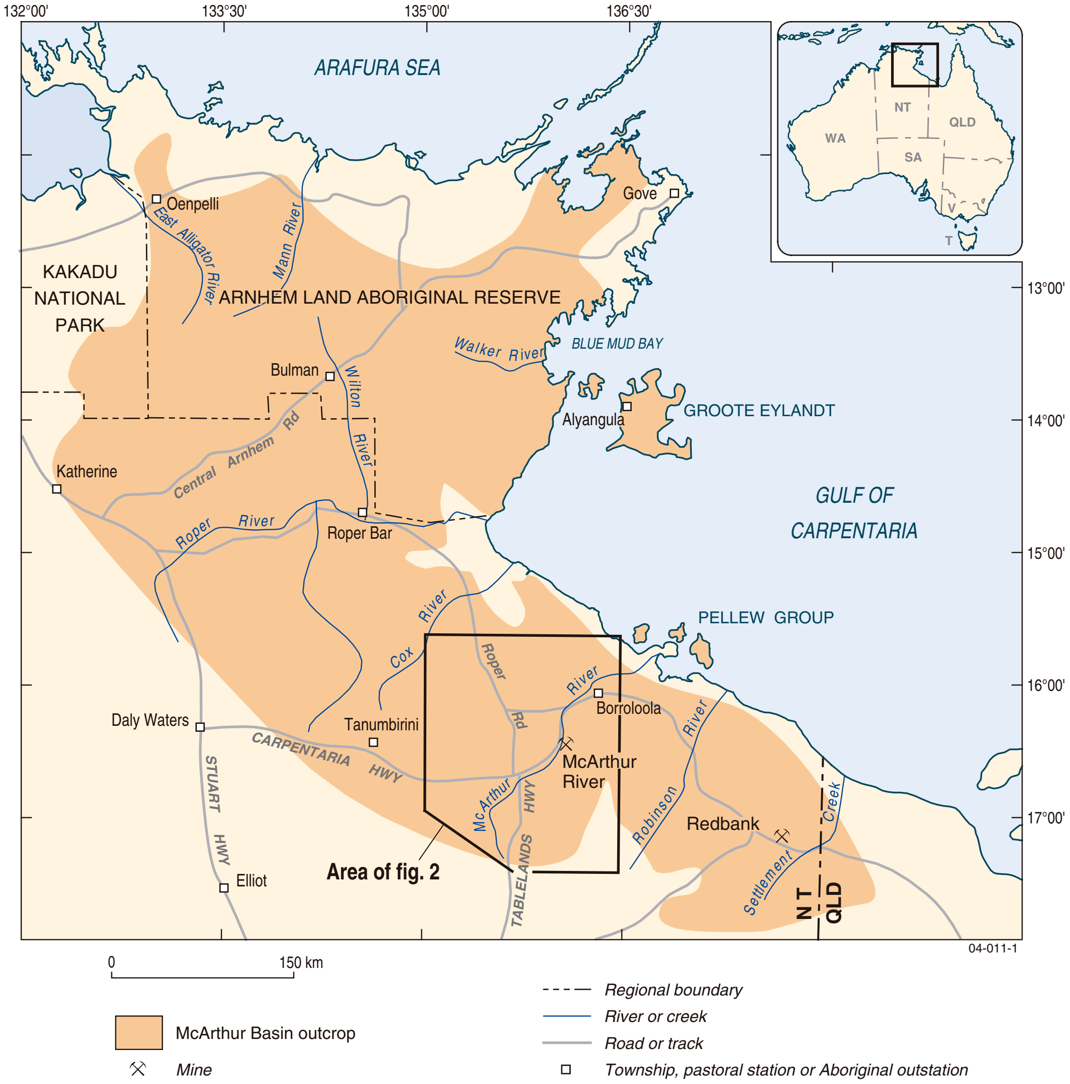

Figure 1: *Location map of the northeastern part of the Northern Territory showing the McArthur Basin and the location of the study area in its southern part.*

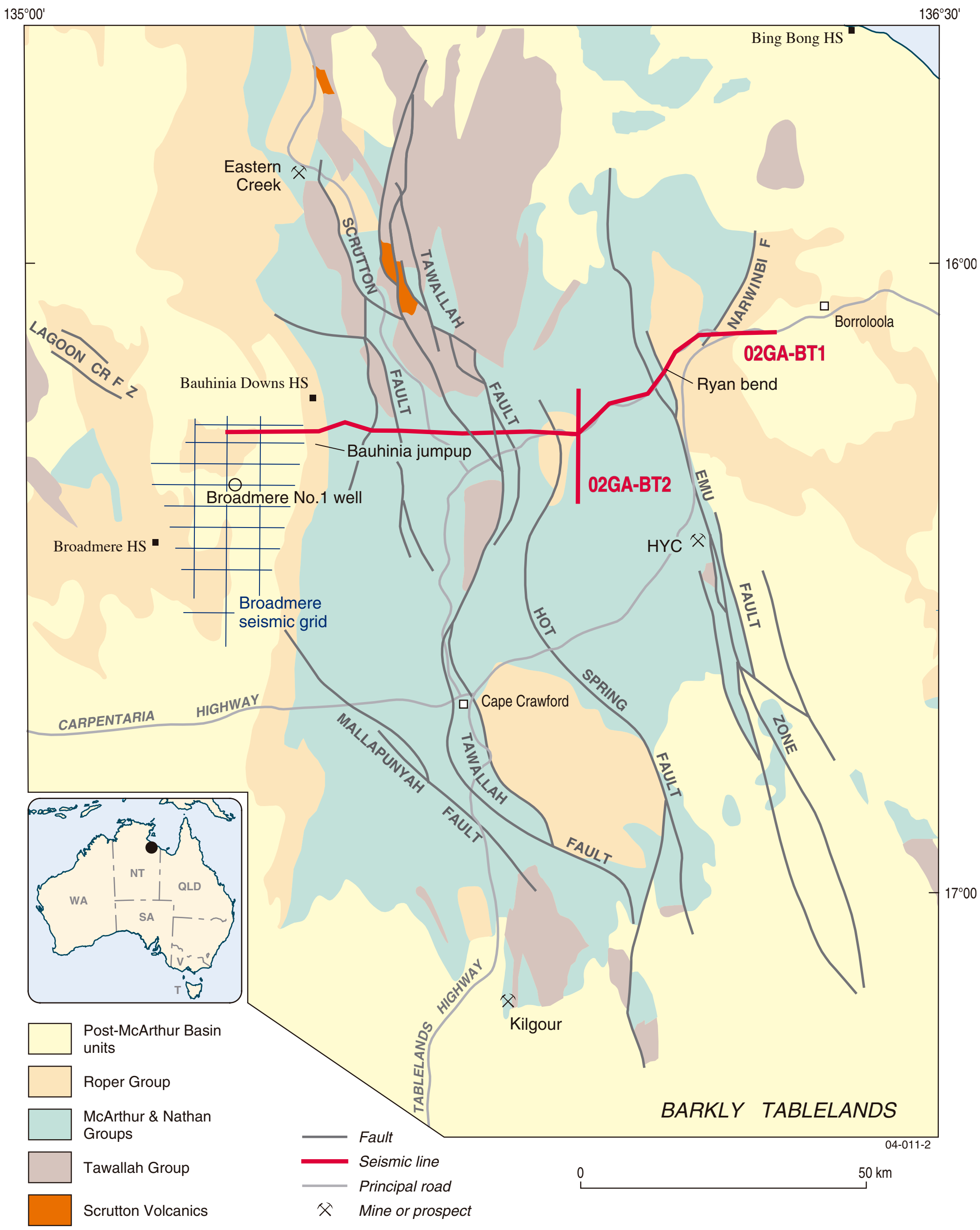

Figure 2: *Regional geological map showing locations of the two Southern McArthur Basin deep seismic reflection lines. The 1984 Amoco Broadmere seismic grid (blue lines) and Broadmere No 1 well (open black circle) are also shown. The world class McArthur River Mine (HYC) occurs 30 km south of the main seismic line and immediately west of the Emu Fault Zone. Base map is from the Rawlings (2002b).*

Regional Geology of the Southern McArthur Basin

GEOLOGICAL SETTING

The seismic survey area lies within the central-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). Exposures of the basin cover an area of about 180 000 km2 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 (Figure 3). 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 3).

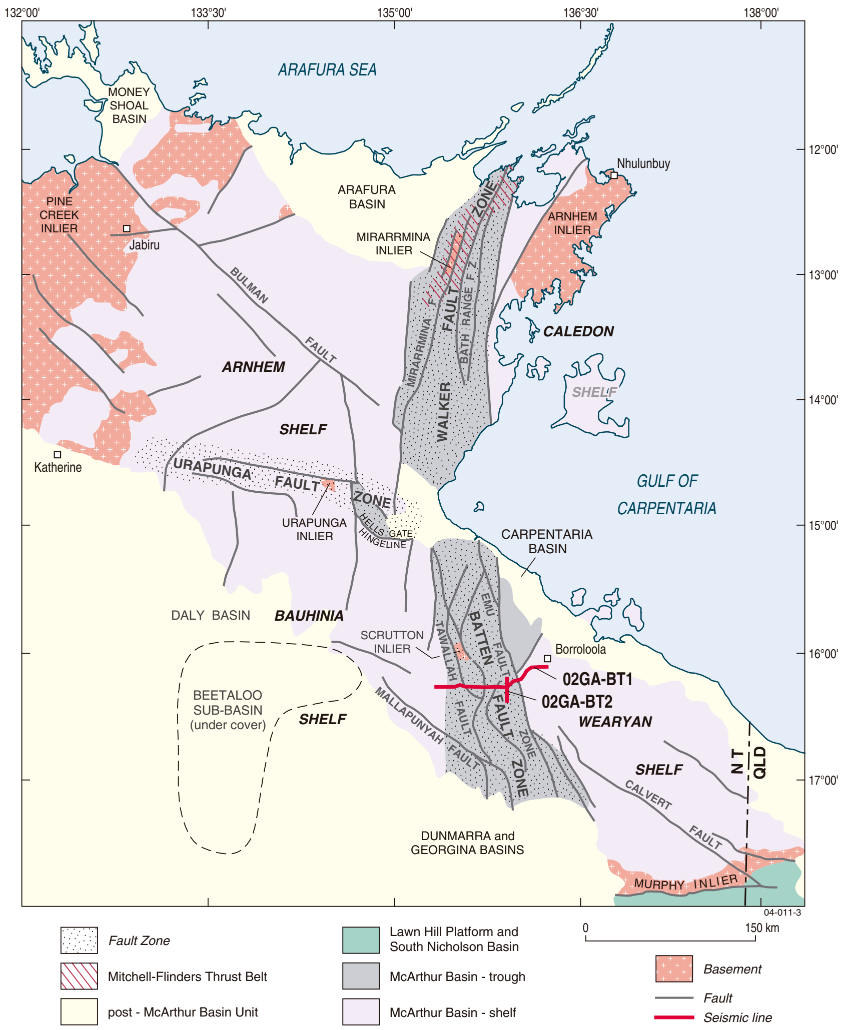

Figure 3: *Geological map of the Gulf of Carpentaria region showing the main tectonic elements (after Rawlings, 2002b).*

The McArthur Basin is divided, geographically and tectonically, into the southern and northern McArthur Basin, bisected by the east-west-trending Urapunga Fault Zone (Figure 3). Elsewhere, rocks of the McArthur Basin extend beneath Neoproterozoic and Phanerozoic cover or the sea, such that its subsurface extent is poorly known.

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

Several tectonic elements considered to have controlled sedimentation and deformation within the McArthur Basin to various extents (Plumb and Wellman, 1987; Plumb et al., 1990), are shown in Figure 3. The main features are the meridional-trending, 50-80 km-wide and >150 km-long structural corridors termed the Walker and Batten Fault Zones, which bisect the northern and Southern McArthur Basin respectively. These fault zones are separated by the east-west-trending Urapunga Fault Zone, in which basement is locally exposed. The north-south fault zones are flanked to the east and west by tectonically ‘stable’ shelves. In the Southern McArthur Basin, the Batten Fault Zone is flanked by the Bauhinia Shelf to the west and Wearyan Shelf to the east. The fault zones are characterised by an increase in deformation, faulting and steepness of dips when compared to the adjacent shelves. Previous workers have argued that these tectonic features were inherited from the underlying ‘Barramundi’ basement (e.g. Plumb et al., 1980; Etheridge et al., 1987; Rogers 1996).

According to most contemporary models, the Batten and Walker Fault Zones contain an increased thickness of preserved sedimentary section (10-12 km) compared with the marginal shelves (4-5 km; Plumb and Wellman, 1987; Plumb et al., 1980; Figure 4).

Thickening of units within the fault zones was interpreted to be constrained to specific sedimentary intervals deposited within intracontinental ‘rift’ structures, defined as the Walker and Batten Troughs (Plumb and Wellman, 1987). Thickness changes appear to be greatest in the McArthur Group, which apparently thickens to ~5 km in the Batten Trough. 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 was designed, in part, to test these two hypotheses.

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 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 5. 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.

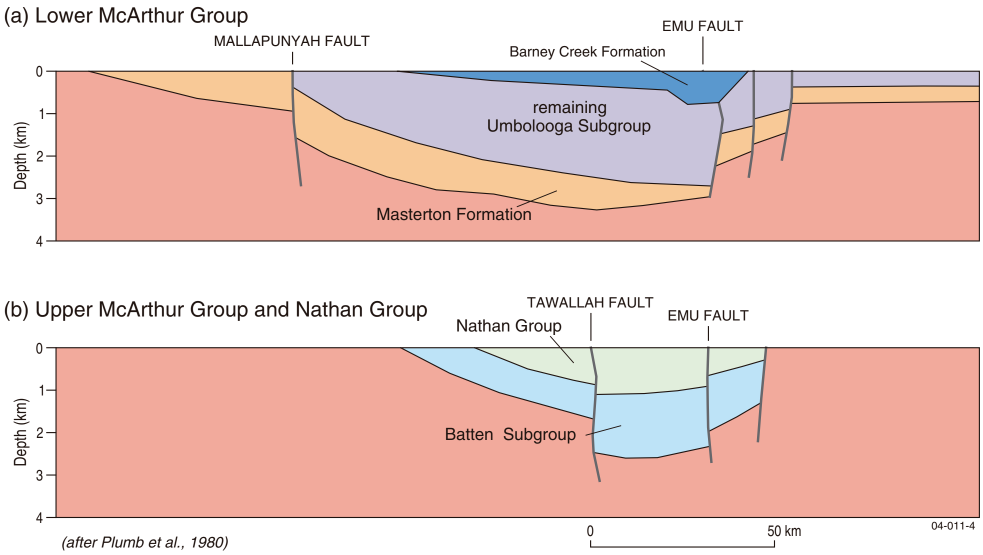

Figure 4: *Cartoon cross section of the Southern McArthur Basin by Plumb et al. (1980), showing the proposed geometry of the basin during a) deposition of the Lower McArthur Group, and b) deposition of the Upper McArthur Group and the Nathan Group.*

Basement

A number of small fault- and unconformity-bounded inliers of basement rocks, collectively known as the Scrutton Inlier, are exposed in the Southern McArthur Basin within the northern Batten Fault Zone (Figure 2). They contain mainly felsic volcanic and intrusive rocks of the ~1850 Ma Scrutton Volcanics, which have comparable composition and geochemistry to other units of the 'Transitional phase' of volcanism of northern Australia (Rawlings, 1994). At the edges of the basin, the Urapunga and Murphy Inliers (Figure 3) are basement consisting of ~1850 Ma granites and volcanics and 'Barramundi'-aged (>1880 Ma) metaturbidites (Ahmad and Wygralak, 1989; Abbott et al., 2001).

Tawallah Group

The Tawallah Group is the oldest segment of the Southern McArthur Basin, unconformably overlying various basement units, including the Scrutton Volcanics (Pietsch et al., 1991a), and provides a maximum age for the Tawallah Group of ~ 1850 Ma. It 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 5). The minimum age for the Tawallah Group is constrained by the oldest date obtained from the overlying McArthur Group (~1650 Ma; Page et al., 2000). The youngest internal SHRIMP zircon ages obtained for the Tawallah Group are 1713±7 Ma for the Tanumbirini Rhyolite and 1708±5 Ma for the Nyanantu Formation near the top of the group (Page and Sweet, 1998). On the basis of geochronology and sequence stratigraphy, Rawlings (2002b) estimates the Tawallah Group to range in age from 1790 to 1700 Ma.

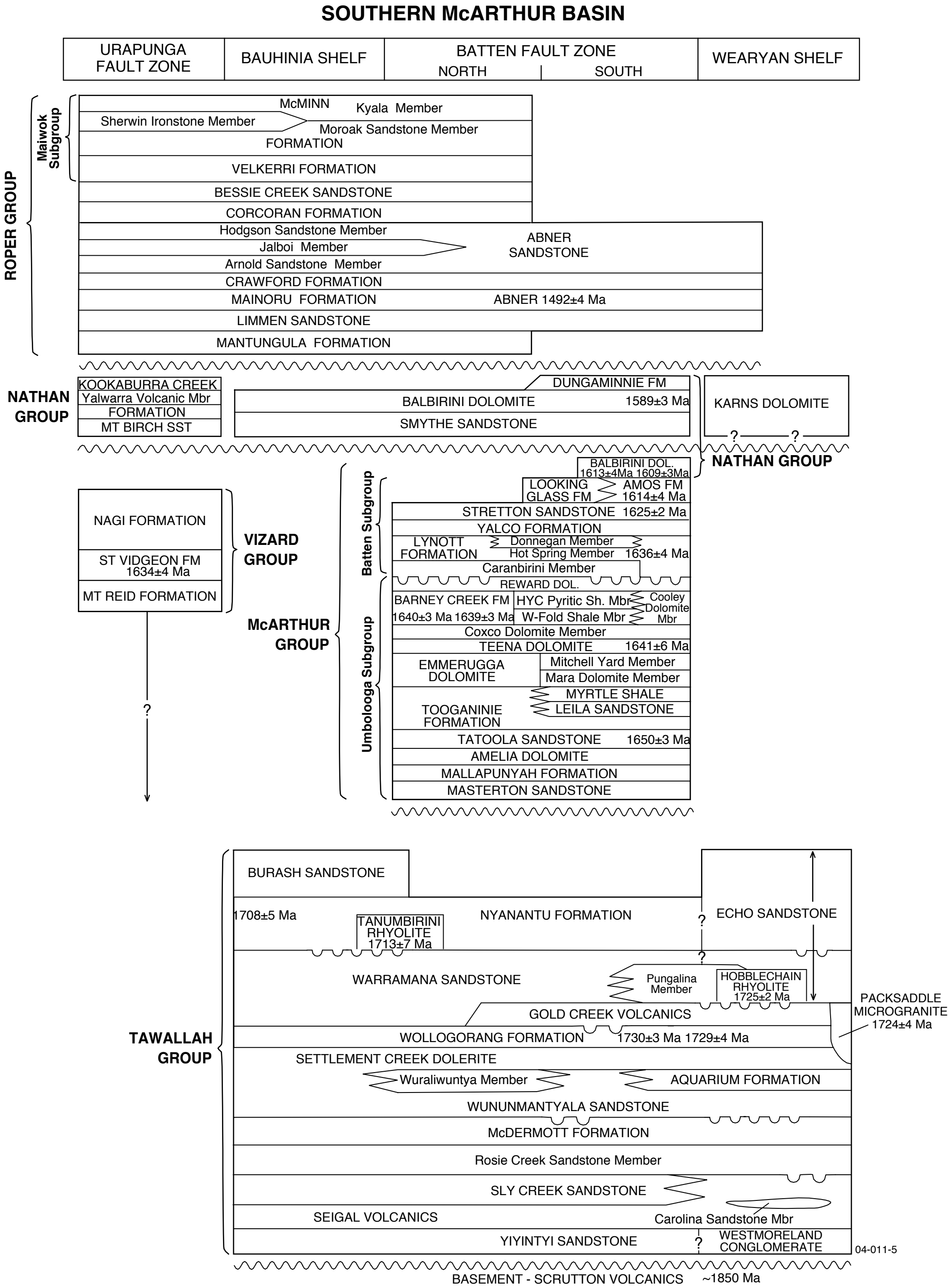

Figure 5: *Stratigraphic table for the Southern McArthur Basin (after Rawlings, 2002b).*

The Tawallah Group is dominated by shallow marine to fluvial sandstone, with lesser mudstone, dolostone, mafic and felsic igneous intervals, which together form a regionally-extensive 'platform' 2.5-6 km thick (Rawlings, 2002b). Resistant sandstone ranges and plateaux of Tawallah Group occur in a belt stretching from the Murphy Inlier (Qld-NT border) in the southeast, to the Hells Gate Hingeline in the northwest (Figure 3). Outcrop is essentially continuous over the Batten Fault Zone, Wearyan Shelf and eastern Bauhinia Shelf (Figure 3). It covers an area of ~60 000 km2 although, as it is largely concealed by younger units, it probably has a significantly broader extent. Based on geophysical evidence (Plumb and Wellman, 1987), the subsurface distribution of the Tawallah Group can be extrapolated westward onto the Bauhinia Shelf proper. The absolute northwestern and southeastern distribution limits are the Urapunga Fault Zone and Murphy Inlier respectively, although the Tawallah Group is probably contiguous with the Katherine River Group in the northern McArthur Basin (Rawlings, 2002b). It is also considered to be quasi-contiguous with the Tennant Creek Inlier to the south and Mount Isa Inlier to the southeast (Plumb and Wellman, 1987; Pietsch et al., 1994). Continuation of the succession to the north, under the Gulf of Carpentaria, is more conjectural. Field studies and geophysical interpretation (Plumb and Wellman, 1987; Haines et al., 1993) support uniform thickness and facies characteristics throughout the Batten Fault Zone and bounding shelves.

The lithostratigraphic components of the Tawallah Group are summarised in Figure 5. The oldest siliciclastic units, the Westmoreland Conglomerate and Yiyintyi and Sly Creek Sandstones, constitute about two-thirds of the total composite thickness of the Tawallah Group (~2-5 km), with an intervening 0.1-1.6 km thick flood basalt unit, the Seigal Volcanics. These are overlain by a more diverse succession of sandstone, dolostone, mudstone and bimodal volcanic and high-level intrusive units (McDermott Formation through to Burash Sandstone). A number of local and regional hiatuses and erosional unconformities are recognised within the Tawallah Group (Ahmad and Wygralak, 1989; Rogers, 1996; Jackson et al., 2000a).

McArthur Group

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 (Figure 3). 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 5). The exception is within the type section (Abner Range area) where a paraconformable contact is evident (Jackson et al., 2000b). SHRIMP zircon ages obtained for the McArthur Group include 1648±3 Ma (Tatoola Sandstone; Page et al., 2000), 1640±4 Ma (Barney Creek Formation; Page and Sweet, 1998), 1625±2 Ma and 1614±4 Ma (Stretton Sandstone and Amos Formation respectively; Page et al., 2000).

The McArthur Group is divided by a local unconformity into two approximately equal parts, the Umbolooga Subgroup and the overlying Batten Subgroup (Figure 5; Jackson et al., 1987). Most units were deposited in a restricted intracontinental lacustrine to marine setting, variably affected by tidal and supratidal processes.

At least two units are interpreted as sub-wavebase euxinic in origin, the Barney Creek Formation and the Caranbirini Member of the Lynott Formation (Bull, 1998). Deposition of the McArthur Group is generally regarded as having been fault-controlled and constrained within the Batten Fault Zone ('Batten Trough'; Plumb and Wellman, 1987; Figure 4). In particular, the Batten Subgroup is thought to have been the most restricted in its distribution, as a result of intensified marginal fault movements (Jackson et al., 1987). The current seismic program was designed to test this 'depositional trough' model.

Importantly, the McArthur Group contains the giant McArthur River sediment-hosted Zn-Pb-Ag deposit at McArthur River. Most recent workers propose a syngenetic model for this deposit. On the basis of sedimentology, geochemistry, isotopic studies and fluid flow modelling, Large et al. (1998) proposed that mineralisation formed as a result of repeated expulsions of a circulating, oxidised metal-sulphate basinal brine into a reduced organic-rich sub-basin trap site, analogous to the Red Sea brine pool. The Emu Fault has been widely interpreted as the conduit for fluid transfer (e.g. Williams, 1978).

Nathan Group

Outcrop of the Nathan Group is widespread in the Southern McArthur Basin (Jackson et al., 1987) and also extends northward onto the Arnhem Shelf (Figure 3). Distribution is apparently largely unrelated to the pre-existing tectonic framework of fault zones and shelves. The Nathan Group, including the correlative Karns Dolomite (Pietsch et al., 1991a), consists of similar dolomitic rocks to the McArthur Group, and was deposited in a shallow marginal marine or continental sabkha setting (Jackson et al., 1987). The Nathan Group consists of a basal fluvial chert-clast sandstone, overlain by 50-1600 m of shallow water stromatolitic and ooidal dolostone and minor siliciclastic sandstone. Thickness variations are largely due to extensive post-depositional erosion (Pietsch et al., 1991a). A thin basaltic volcanic unit, the Yalwarra Volcanics, is recognised only in the Urapunga Fault Zone (Figure 5; Abbott et al., 2001). The Nathan Group overlies the McArthur Group, and all older units, with regional disconformity or unconformity. The exception is the area of the Balbirini Dolomite type section, where a paraconformable boundary is evident (Haines et al., 1999). A SHRIMP U-Pb zircon date of 1589±3 Ma has been determined from the middle Nathan Group (Jackson et al., 2000b).

Roper Group

The youngest component 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). Powell et al. (1987) interpreted the Roper Group as an amalgamation of five coarsening-upward (progradational) cycles. Distribution and depocentres of the Roper Group are significantly different to the underlying units of the McArthur Basin and appear largely unrelated to the former tectonic framework (Rawlings et al., 1997). Erosional remnants of the Roper Group are common throughout the Southern McArthur Basin and range up to 5 km in thickness (e.g. the Beetaloo Sub-basin on the Bauhinia Shelf; Figure 3; Plumb and Wellman, 1987). A notable feature of the Roper Group is that it is cut by an abundance of younger dolerite-gabbro sills.

The Roper Group rests unconformably on the Nathan Group (~1590 Ma; Jackson et al., 2000b) and various older units, and is unconformably overlain by Neoproterozoic to Mesozoic cover successions (Kruse et al., 1994). Deformation is typically manifested as broad dome and basin structures, but intense deformation is recognised along the Batten Fault Zone.

The age of the Roper Group is constrained by an Rb-Sr determination of 1429±31 Ma for diagenetic illite in the McMinn Formation (Kralik, 1982) and a SHRIMP U-Pb zircon date of 1492±4 Ma for the Mainoru Formation (Jackson et al., 1999). The Roper Group is intruded by numerous dolerite sills. A SHRIMP age of ~1324±4 Ma has been obtained on the Derim Derim Dolerite (J. Claoue-Long. pers. comm., 2003). An age of ~1280 Ma comes from K-Ar dating of a dolerite sill that has intruded the upper part of the Roper Group (McDougall et al., 1965).

Younger Cover Units

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 (Figure 3). Thin remnants of marine and terrestrial siliciclastics of the Mesozoic Dunmarra and Carpentaria Basins are also widespread throughout the region (Thomas et al., 1990). Cainozoic deposits cover about 40% of the known extent of the McArthur Basin, and consist of sandy to gravelly soil, coastal deposits, dune fields and laterite, generally no more than a few tens of metres thick.

Previous Tectonic Models for the Southern McArthur Basin

INTRODUCTION

It is thought that cratonisation of the northern Australian orogenic domains during the Barramundi Orogeny was accompanied by the establishment of a fundamental framework of deep-seated northwest-, north-northwest- to north-northeast- and northeast -trending crustal structures (Etheridge et al., 1987). It is widely speculated that these structures were reactivated and became the major controlling influence on the depositional geometry of succeeding basin phases and the localisation of subsequent deformation (e.g., Plumb, 1979; Etheridge and Wall, 1994; Rogers, 1996). The majority of models for the evolution of the McArthur Basin (outlined below) promote extensional tectonics, in which specific fault orientations acted as normal or 'growth' structures and others acted as accommodation or transfer structures during various stages of basin formation. These models rely largely on the analysis of macroscopic fault and lineament trends and on comparisons with modern analogues. They differ mainly in the interpreted orientation of extension and contraction, a legacy of how difficult it is to recognise primary extensional fault families and geometric relationships when they have been largely overprinted. Field observations of mesoscopic and microscopic compressional fabrics (Plumb, 1994; Rogers, 1996; this record) are limited to small areas within the Batten and Walker Fault Zones, where post-McArthur Basin fault reactivation and overprinting have been intense. Primary evidence of depositional 'growth' is absent (Plumb, 1987), and all examples cited are inferred (Rogers, 1996). Extensional architectures proposed in all models are simplistic and assume an ideal orthogonal extending system (e.g. Gibbs, 1990). In the absence of definitive primary evidence, the most influential aspect of McArthur Basin geology that has driven extensional models is the presence of significant volcanic and coarse-grained clastic rocks at the base of the basin succession (Rogers, 1996).

Subsequent contractional reactivation of earlier 'extensional fault systems' is thought to have occurred at least three times during and after basin development (Plumb, 1994; Rogers, 1996). These contractional events appear to be better constrained than the earlier extensional events, due to better preservation of measurable structures.

THE PLUMB MODEL

Plumb (1979; 1987), Plumb and Wellman (1987), Plumb et al. (1980; 1990) and Plumb (in Rawlings et al., 1997) interpreted the development of the McArthur Basin in terms of a framework of troughs, shelves and fault zones (Figure 3). In this model, basin evolution was influenced by intermittent strike-slip faulting, block rotation and synsedimentary faulting focussed in the Batten Fault Zone, essentially related to east-west crustal extension during a period of 200 million years.

Deposition of the Tawallah Group and equivalents (the 'Redbank package' of Rawlings, 1999) has been interpreted to be controlled by segmented north-striking extensional faults, such as the Emu Fault Zone (Figure 3). These fault segments subsequently became the structural template for the Batten and Walker Fault Zones, which were the primary depositional sites ('rifts') for the McArthur and Nathan-aged packages (the Walker and Batten Troughs; Plumb et al., 1980). Although this 'Walker Trough Extension' event is poorly constrained, there is local evidence for oblique, approximately northwest- to north-directed extension (Davidson and Dashlooty, 1993; Plumb, 1994), contrary to earlier views of orthogonal east-west extension. The oblique extension model predicts right-lateral (dextral) reactivation of north-northwest- to north-northeast-trending faults and significant left-lateral (sinistral) movement along northwest-trending faults, producing 50-100 km-scale pull-apart basins. According to this model, right-lateral displacements along the Emu Fault led to depositional ‘growth’ and large variations in stratigraphic thickness. Some units (e.g. Barney Creek Formation) were interpreted to thicken into the Emu Fault and thin gradually to the west, giving rise to the view that the Batten and Walker Troughs were asymmetric half-graben (Plumb and Wellman, 1987; Figure 4). This structural evolution was used to explain the ~10-12 km of section apparently preserved in the ‘fault zones’ compared to ~4 km on the ‘shelves’.

Basin-wide, approximately east-southeast to west-northwest compression led to a post 1590 Ma inversion event during the hiatus between the Nathan and Roper Groups (‘Post-Nathan Shortening’; Plumb, in Rawlings et al., 1997). Open folding, thrusting, and conjugate strike-slip faulting can be identified throughout the Batten and Walker Fault Zones. Deformation, however, was most intense within the Mitchell-Flinders Thrust Belt in the eastern Arnhem Land (Figure 3). There, basement and lower McArthur Basin rocks appear to have been thrust westwards over the Arnhem Shelf in a 20 km-wide zone of north-northeast-striking thrust duplexes, accompanied by folding and cleavage development. This event coincides with the ~1590-1500 Ma Isan Orogeny in the Mount Isa Inlier (O’Dea et al., 1997). The subsequent ‘Post-Roper Extension and Dykes’ event is interpreted as a period of east-west extension, in which there was basin-wide emplacement of structurally- and stratigraphically-controlled mafic sills and dykes (the Derim Derim Dolerite suite; Plumb in Rawlings et al., 1997).

A second regionally-extensive compressional event, the ‘Post-Roper Inversion’ (Rawlings et al., 1997), is interpreted to have taken place in response to approximately northeast-southwest shortening. The inversion has affected all units of the McArthur Basin and basement domains, is apparent in all ‘shelf’ and ‘fault zone’ domains, and predates development of Neoproterozoic cover succession. The event involved widespread conjugate strike-slip faulting, reactivating and steepening earlier faults, and is now the dominant structural event in the McArthur Basin.

THE ETHERIDGE AND WALL MODEL

Etheridge and Wall (1994) proposed a model for the development of the McArthur Basin based on north-south extension. Large-scale structural elements of the North Australian Craton are considered to have developed during the ‘Leichhardt Event’ (1810-1740 Ma). During this event, northeast-southwest extension gave rise to a linked array of basins, accommodated and compartmentalised by northwest-trending normal faults and northeast-trending transfer faults. Extension was terminated by a period of thermal subsidence. The McArthur Basin is thought to have formed during renewed extension in an approximately north-south orientation, followed by an extensive thermal subsidence basin system (the ‘McArthur Event’; 1740-1600 Ma). This involved the formation of small east-west rift basins, linked and compartmentalised by north-trending sidewall or transfer faults (e.g. the Emu Fault). Preferential localisation of small rift basins is suggested to have occurred where the north-trending faults intersected primary northwest-oriented normal faults inherited from the ‘Leichhardt Event’.

THE ROGERS MODEL

In their studies of the Southern McArthur Basin, Rogers (1996) and Bull and Rogers (1996) agreed with the Etheridge and Wall model about the north-south extension during deposition of the Tawallah Group, followed by thermal subsidence during deposition of the McArthur and Nathan Groups. However, they further refined the understanding of compressional events that influenced basin development. Palaeostress and facies analysis led to recognition of a possible middle-Tawallah Group east-west compressional event (D_1), in which older units of the Tawallah Group were deformed and uplifted along the Batten Fault Zone, thereby controlling subsequent deposition of the upper part of the Tawallah Group. A second phase of deformation, involving northwest-southeast compression (D_2), is considered to have taken place mid-way through deposition of the McArthur

Group. It led to sinistral transpression along north- to north-northeast-trending faults such as the Tawallah and Emu Faults (Figure 3). This sinistral fault movement has also been recognised at the McArthur River deposit, where it is synchronous with mineralisation (Hinman, 1995; 1996). It is important to note the contrast with the Plumb model, which invokes oblique extension and dextral transtension on the Emu Fault at this time. The last compressional event, involving northeast-southwest shortening (D_3), took place after deposition of the Roper Group and is characterised by dextral displacement on the Tawallah and related faults ('Post-Roper inversion').

THE LEAMAN MODEL

Leaman (1998) presented a contrasting view of the structural and tectonic evolution of the McArthur Basin based on analysis of early editions of the Geoscience Australia regional gravity and magnetic datasets. His model invokes extensive piles of felsic and mafic rocks (volcanics) pre-dating the McArthur Basin succession. These volcanics are thought to have been deposited into rift structures that evolved from a network of aligned convective cells that mimicked an original northwest- and north-northeast-oriented crustal grain. In this model, the Tawallah and McArthur Groups are constrained within subsidiary basins controlled by the underlying rift elements. The Roper Group is interpreted as much thicker and widespread. In contrast to previous models, Leaman advocated that the Batten Trough had been uplifted for most of its history. Supporting evidence for the Leaman model is also difficult to find. Field evidence for an extensive volcanic pile under the McArthur Basin (Rawlings, 1999) is lacking, and any mafic volcanics present in the lower part of the succession are contained within the Tawallah Group rather that the basement. These volcanics are also substantially thinner than proposed in Leaman's model (Rawlings, 2002b). In addition, various configurations of the overlying stratigraphy are possible in Leaman's geophysically constrained profiles (Scott et al., 2000).

THE SCOTT AND RAWLINGS MODELS

On the basis of facies architecture, geochemistry, geophysics and geochronological data, Scott et al. (2000) and Rawlings (2002b) proposed models for the development of Proterozoic basin phases in northern Australia that complement the geodynamic regime envisaged for central Australia. Pivotal to their models is a convergent tectonic setting, rather than the extensional setting previously proposed. The geodynamic models involve a variety of subsidence mechanisms operating inboard of the southern active margin of the North Australian Craton (Strangways arc; Zhao and McCulloch, 1995). Subduction at the Strangways arc is interpreted to have led to deposition of wedge-shaped and magmatic-dominated basin elements, where subsidence was influenced by dynamic topography, thermally- and mechanically-driven viscoelastic behaviour of heterogeneous crust, magmatic underplating, lithospheric phase transformations, and local transtension and isostatic loading. Back-arc extension and the development of growth-fault basin architectures were limited. According to Rawlings (2002b), a long-term thermal anomaly that initiated before the Barramundi Orogeny, under the influence of a transient convective roll emanating from the Strangways arc, acted to erode the lower lithosphere and generate a magma pool. Transtension along lithosphere-scale strike-slip faults enabled migration of magma into lower-crustal magma chambers, where wall-rock melting took place, followed by extraction to the surface as bimodal volcanics. Periodic terrane accretion events at the active margin are interpreted to have generated regional unconformities, elongate and wedge-shaped basin elements, and local magmatic grabens. Subsidence in this instance was influenced largely by transmission of in-plane stress through the lithosphere to produce lithosphere-scale folding, viscoelastic deflections in the basement, transtensional strike-slip and flexural back-bulge basins, and elongate impactogens via tectonic escape. Scott et al. (2000) used the Cainozoic tectonics and neotectonics of the central Asia region as an analogue, whereby deposition and erosion were influenced largely by the Himalayan collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979).

Acquisition and Processing of the Southern McArthur Basin Seismic Data

INTRODUCTION

The 2002 Southern McArthur Basin Seismic Survey (Geoscience Australia Survey Number L157) was conducted in October-November 2002 and included the regional traverse lines 02GA-BT1 and 02GA-BT2. This survey was initially referred to as the 2002 Batten Trough Seismic Survey, but is now more correctly referred to as the 2002 Southern McArthur Basin Seismic Survey. Within the seismic data archives, it still retains the name 2002 Batten Trough Seismic Survey.

The project was jointly funded by Geoscience Australia (GA), Northern Territory Geological Survey (NTGS), the Predictive Mineral Discovery Cooperative Research Centre (pmd*CRC) and Anglo American and was carried out as a project within the Predictive Mineral Discovery Cooperative Research Centre. The Australian National Seismic Imaging Resource (ANSIR) was responsible for seismic data acquisition through its facilities manager, Trace Energy Services, as well as for field QC and preliminary in-field processing.

PRELIMINARY WORK

The project began in mid 2001 with a year of preparatory work including:

- planning and prioritisation of the route;
- land access negotiations and community consultation (pastoralists, traditional owners, Northern Land Council (NLC) and regional councils);
- development of a work and environmental management plan (Rawlings, 2002c) and;
- assessment of environmental, safety, infrastructure, utilities, government regulatory and mineral exploration risks.

In mid October 2002, line clearing took place. In late October, the route was surveyed and gravity data were collected along Line 02GA-BT1 at 240 m spacing.

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 2): Line 02GA-BT1 – east-west 110 km long, from 15 km west of Borroloola and extended 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 12 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. A summary of field parameters is given in Table 1. Further details are provided in Appendix 1 and in Trace Energy (2002).

Table 1: Summary of acquisition parameters for lines 02GA-BT1 and 02GA-BT2

LINE	02GA-BT1	02GA-BT2
AREA	Borroloola to Bauhinia Downs	Tawallah
DIRECTION	East to West	North to South
LENGTH	110.4 km	17.2 km
STATIONS	1000 - 3760	1000 – 1430
CDP RANGE	2000 - 7348	2000 – 2859
GROUP INTERVAL	40 m	40 m
GROUP PATTERN	12 in-line at 3.33 m	12 in-line at 3.3 m
# VIBE POINTS	1465	214
VP INTERVAL	80 m	80 m
SOURCE TYPE	3 x IVI Hemi-60	3 x IVI Hemi-60
SWEEP TYPE	3 x 12 s: 7-56, 12-80, and 8-72 Hz	3 x 12 s: 7-56, 12-80, and 8-72 Hz
SOURCE PAD-PAD	15 m	15 m
SOURCE MOVE-UP	15 m	15 m
# CHANNELS	240	240
FOLD (NOMINAL)	60 and 120	60
RECORD LENGTH	20/22 s at 2 ms	20 s at 2 ms

DATA QUALITY

Shot point data quality varies along the seismic lines according to sediment cover and bedrock characteristics. Data quality in the east of Line 02GA-BT1 is excellent, due to the ideal situation of bitumen road over subhorizontal Roper Group. Although shot points were also located over Roper Group in the west, quality is generally patchy due to the varied thickness of unconsolidated sand coverage, in which there is poor geophone coupling. 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, except where there is subsurface geological complexity (e.g. vicinity of Tawallah Fault). Carbonate units of the McArthur Group (e.g. Balbirini Dolomite) proved to have deep seismic-defined 'regolith' and therefore poor transmission of energy into the crust.

Overall, the seismic stacks resolve over the full 20 seconds in some areas, imaging McArthur Basin, immediate basement, middle-lower crust and Moho. There also appears to be good imaging of various faults, including the Emu and Tawallah faults, as well as basin geometry.

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, including Emu and Tawallah 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.

Table 2 shows the final processing flow, including migration, for the 22 s data for line 02GA-BT1. For adequate resolution, only 4 ms sampling was required. Essentially, the same flow was used for final processing of the data for line 02GA-BT2.

Table 2: Final processing flow for 22 s data for lines 02GA-BT1 and 02GA-BT2.

STEP	PROCESS
1	line geometry and crooked line definition (fixed CDP interval)
2	field SEG-Y to 'disco' data format; resample to 4 ms
3	quality control displays and trace ed its
4	spectral equalization (with removable 1000 ms AGC)
5	common mid-point sort (200 m bin)
6	gain recovery (spherical divergence option)
7	trace amplitude balance across user defined gates
8	application of refraction statics, datum 0 m (AHD), replacement velocity = 5500 ms^{-1}
9	application of automatic residual statics
10	bandpass filter
11	velocity analysis using Velex, first pass after refraction statics, second pass after automatic residual statics
12	normal moveout correction (10% stretch mute)
13	common mid-point stack (alpha trimmed mean)
14	trace amplitude balance
15	finite difference migration using 65% stacking velocities
16	signal enhancement (digistack 0.85)
17	display

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. The key processing steps are discussed in the following sections, with particular emphasis on those that resulted in the most improvement in data quality.

Crooked line definition and CMP / CDP sort

The geometry for each line (i.e., station coordinates and station locations for shots and receivers) was entered into an internal seismic database prior to actual seismic data processing. To avoid rounding errors in the computations a value of 533000 m was subtracted from the MGA eastings and 8190000 m from the northings of the station coordinates.

CDP (common-depth-point, or CMP, common mid point) locations were also defined. Note that the midpoint spacing along a straight line is half the receiver group interval.

Crooked line processing was used for both lines. In the crooked line case, the midpoints do not always lie along the line defined by the surveyed stations. The CDP line is defined as a smoother representation that follows the highest density of midpoints, while keeping as close as possible to the original line. Note that the CDP bins extend perpendicular to the CDP line. For both lines, the CDP line was defined with a constant CDP interval (20 m). Since the CDP line is shorter than the line of stations, the CDP number will be less than twice the station number.

The CDP line for both lines were defined manually as a series of linear segments, in order to keep closer to the surveyed line than would be achieved by a least squares fit. In this case, the CDP line generally lay within 250 m of the surveyed line. The initial choice of CDP line was refined after assessing the distribution of midpoints into CDP bins and examining the quality of the brute stack.

Edits

Documentation of manual trace edits began during field QC. Problems included shot records contaminated by earthquakes, channels intentionally left open for roads, receivers accidentally disconnected, vehicles moving along the live spread and occasional equipment malfunctions. Problem traces were omitted during processing.

Refraction statics and datums

Statics corrections remove variability in seismic travel times due to surface topography, and/or variations in regolith thickness and/or velocity. The first breaks (first arrivals) were picked on 2 s subsets of the original 2 ms shot records, using a combination of manual and supervised automatic picking. No pre-processing was done to the data. The first strong peak was interpreted as the first arrival, since the correlated traces should be zero phase.

Refraction statics are calculated by subtracting the vertical travel time calculated for the lower velocity regolith, and adding the vertical travel time calculated from datum to bedrock at a higher replacement velocity. For both lines a datum of 0 m (AHD) was used and a replacement velocity of 5500 ms^{-1}.

The results of the refraction statics analysis for line 02GA-BT1 are presented in Figure 6. Static corrections result in much sharper definition of reflections, particularly in the shallow section.

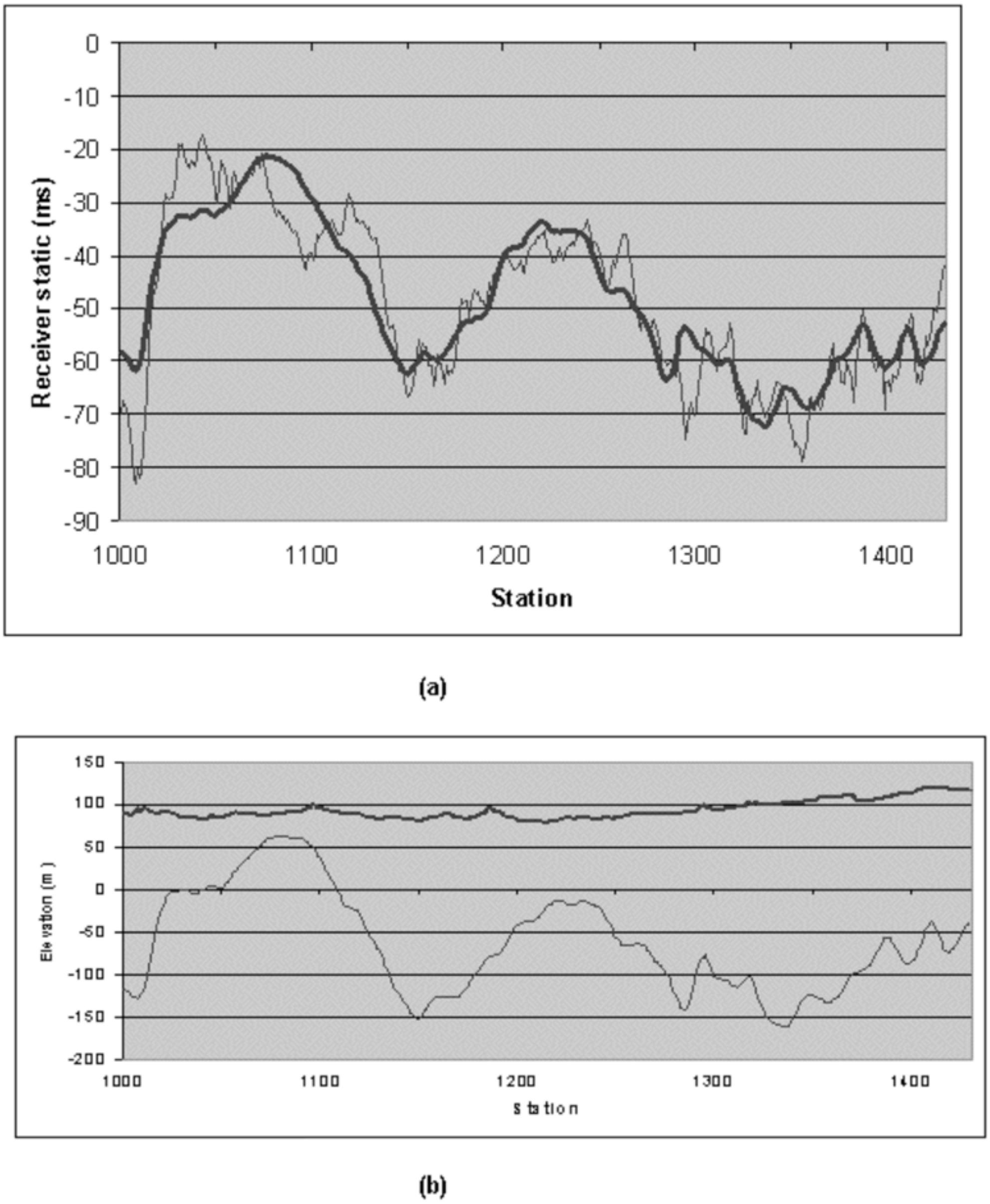

Figure 6: *Refraction statics results for line 02GA-BT1 (west to right). (a) Receiver refraction statics with long wavelength as thick line and total statics, i.e. long wavelength statics plus short wavelength statics, (fine line). (b) Elevation of surface in m (thick line) and refractor depth (thin line).*

Spectral equalisation and filtering

The spectrum balancing is carried out using a number of user-designed frequency gates, with an option to shape the output spectrum. The final spectral equalisation parameters consisted of overlapping gates of the form (4-8-12-16) Hz, with 7 subsequent repeats (outer gate values are 50% and inner gate values 100% amplitude).

Bandpass filters were also applied to suppress high and low frequency noise.

Gain recovery and amplitude balance

Corrections were made for amplitude loss with increasing time due to spherical divergence and intrinsic attenuation. All traces were multiplied by a time varying scalar dependent on velocity. The velocity function used was at t = 0 s, v = 4000 ms-1 and at t = 22 s, v = 6500 ms-1.

Instead of using an automatic gain control (AGC), amplitude balancing was performed across a number of user defined gates, with the aim of preserving true amplitudes.

Stacking velocity analysis

A critical processing step is the correction of seismic data for the offset dependence of travel time. The normal moveout (NMO) correction, which depends on seismic velocity and two-way travel time, is applied. At least every 200 CDPs were selected for velocity analysis for this project. Figure 7 shows graphically the smoothed stacking velocities for line 02GA-BT1.

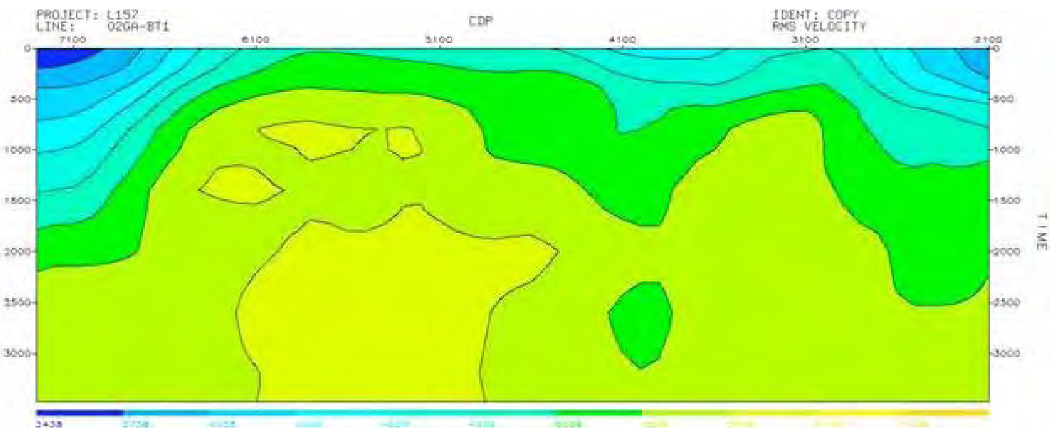

Figure 7: *Smoothed stacking velocities for line 02GA-BT1. East is to left of figure.*

Median stack and stretch mute

Stacking seismic traces after NMO correction improves the signal to random noise ratio by n, where n is the fold. An improved technique for suppressing large bursts of non-Gaussian noise, such as vehicle noise, is a type of median stack. The alpha trimmed mean stack examines trace amplitudes at each sample time, and omits a designated percentage of the highest and lowest amplitudes from the stack, in this case 15% at each end.

Prior to median stack, a 10% stretch mute was applied to zero those parts of traces distorted by the NMO correction process beyond 10%. This mute was used instead of a specific front end mute, as it satisfactorily removed most of the first arrival energy train from the stack. The mute is velocity dependent and is more severe for lower stacking velocities.

Automatic residual statics

Automatic residual statics were calculated in order to fine-tune the stack. This process operates on unstacked CDP gathers, with normal moveout and refraction statics applied, and calculates the additional time shifts (residual statics) necessary to maximise correlation across the gather in a selected time gate, such that shot and receiver surface consistency is maintained. An iterative technique is used to apply the static before the next calculation, with the number of iterations specified by the user.

A single gate was used for both lines. It was chosen from 0.25 s to 3.75 s TWT because of good reflection strength and continuity and because at later TWT the calculation is not as sensitive to NMO correction. The maximum time shift was restricted to 10 ms.

Stacking

A median stack method was use to stack the CDP gathers together. The median stack method sorts the CDP values into median order of amplitude and then rejects a user defined number from the upper and lower ends of the median sort. This method removes any spurious or atypical high or low values and produces a cleaner stack. Examples of the results of the stack are shown in Figure 8a and Figure 8b.

Migration

On an unmigrated final stack section (e.g., Figure 8), no reflections will be visible at apparent dips greater than 45º. Migration is the process of moving the recorded reflections into their true locations. Thus dipping reflections will be steepened, shortened and moved up dip. Diffractions from discontinuities, such as reflection terminations at faults, are collapsed in the process.

For both lines migration was carried out using 65% of the smoothed stacking velocity.

Migrated sections (hard copy and digital) are the end product of the processing stream. The successful application of migration is attributed to the continuity of reflections and preservation of amplitudes resulting from earlier stages of processing.

Coherency enhancement

A signal enhancement algorithm (DIGISTACK) was applied for final display only to the stacked or migrated data. DIGISTACK enhances events that are coherent across several traces, thus making reflections stand out better against background noise.

This process determines the coherency of linear events for all dips within a specified range and outputs a second set of seismic traces that is essentially a coherency section. A weighted sum is then made of the coherency section and the actual seismic section, such that a weight of zero reproduces the input seismic data and a weight of one gives the coherency section. For final display, weights of 0.85 were used.

Display parameters

The main differences between the 4 s and 22 s stack and migrated data lie in the display parameters. The 4 s data are displayed as variable area wiggle trace and the 22 s as variable area. The display scales were chosen such that the sections presented are at 1:1 scale vertical to horizontal, assuming a velocity of 6000 ms-1.

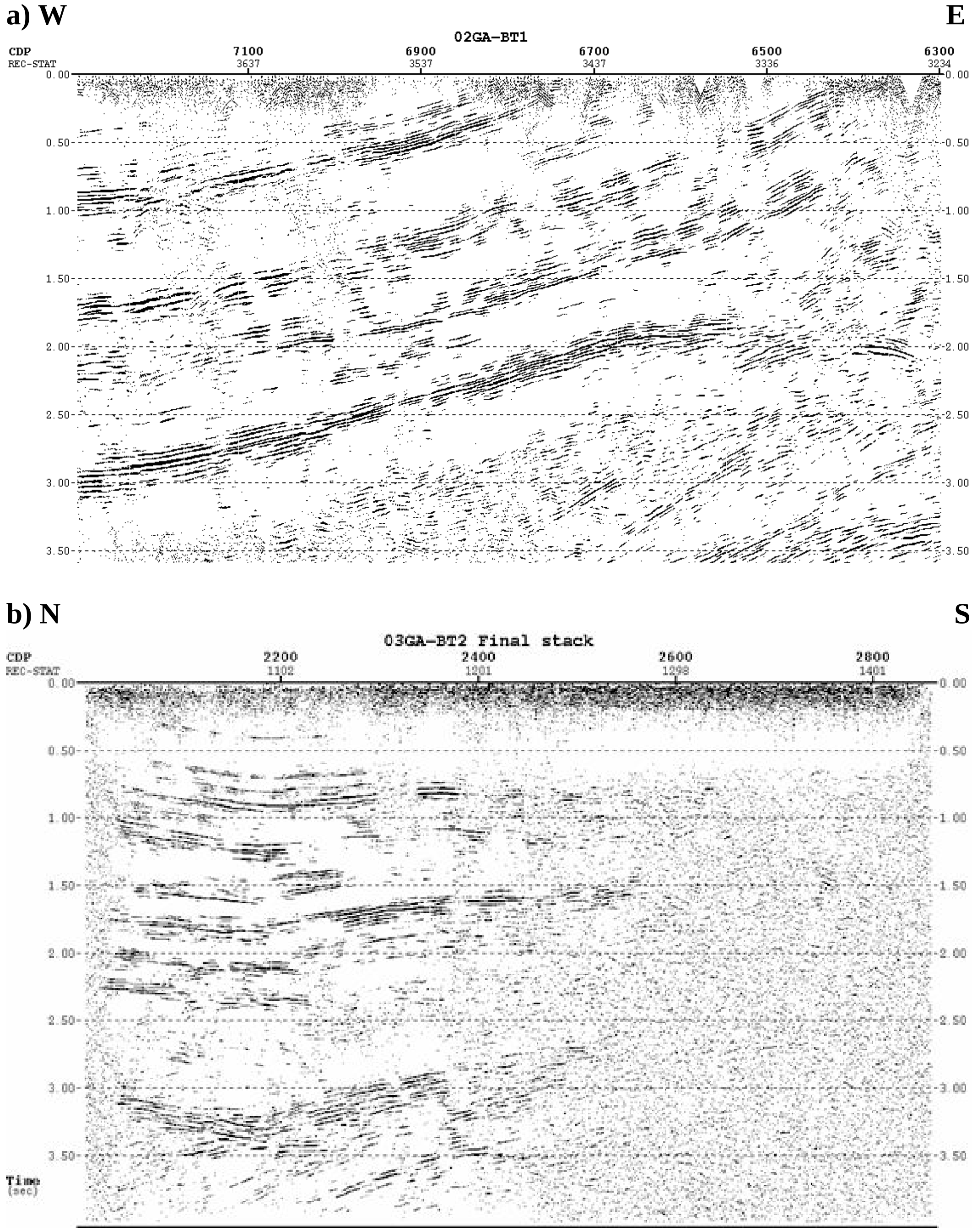

Figure 8: *a) Western portion of final stack for line 03GA-BT1 showing west dipping Southern McArthur Basin sediments. B) Final stack for line 03GA-BT2 showing gentle warping of Southern McArthur Basin sediments.*

Interpretation of the Southern McArthur Basin Seismic Survey Data

AN OVERVIEW OF THE SOUTHERN MCARTHUR BASIN 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 new interpretation for Line 02GA-BT1 is shown in Figure 9 and for Line 02GA-BT2 in Figure 10. The main results from the seismic interpretation of the Southern McArthur Basin data are:

- The Batten 'Trough' is not a separate depocentres.
- Sedimentary successions mostly thicken 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.

INTERPRETATION METHODOLOGY

The method used to interpret the deep seismic reflection data was as follows:

- Identify prominent trends in the seismic reflectivity on paper copies of various displays of the seismic data (final stack, migrated, high gain, low gain) by highlighting the main trends defined by the stronger reflections.
- Identify angular relationships between different reflective packages, which indicate an inferred discontinuity in geology.
- Draw boundaries around regions of similar reflectivity and/or between regions of different reflectivity to create packages or domains of consistent reflectivity. To be consistent, the tops of highly reflective zones were used to define the boundary to the domain (here we used similarities in the amplitude, coherency and dip of the seismic reflections to define the regions). Juxtapositions and repetitions were identified using pattern recognition or 'bar code' matching.
- Identify major large-scale trends in reflectivity, for example, reflectivity extending over large distances, either as dipping bands or sub-horizontal bands (e.g. the Moho; Figure 11).
- Using the known surface geology (1:100 000 and 1:250 000 scale geological maps), project the mapped faults and geological units to depth along previously defined reflective zones.
- Correlate reflections, rock packages and structures delineated from surface geology and the seismic data across the profile using multiple iterations.
- Identify any kinematic indicators that suggest movement directions or sense of displacement.
- Link the surface information projected to depth to the major large-scale trends and package or domain boundaries to create a crustal structure consistent with the geology and seismic data.
- Add interpretations to the section for those features identified in the geological mapping but not imaged by the seismic data. It is assumed that these structures or units are non-reflective.
- Add interpretations to the section to account for areas of strong reflectivity that do not correlate to known geological structures of units.
- Cross check the seismic interpretation against the geology, and discuss results within the project team, and evaluate against all known geological and geophysical data.

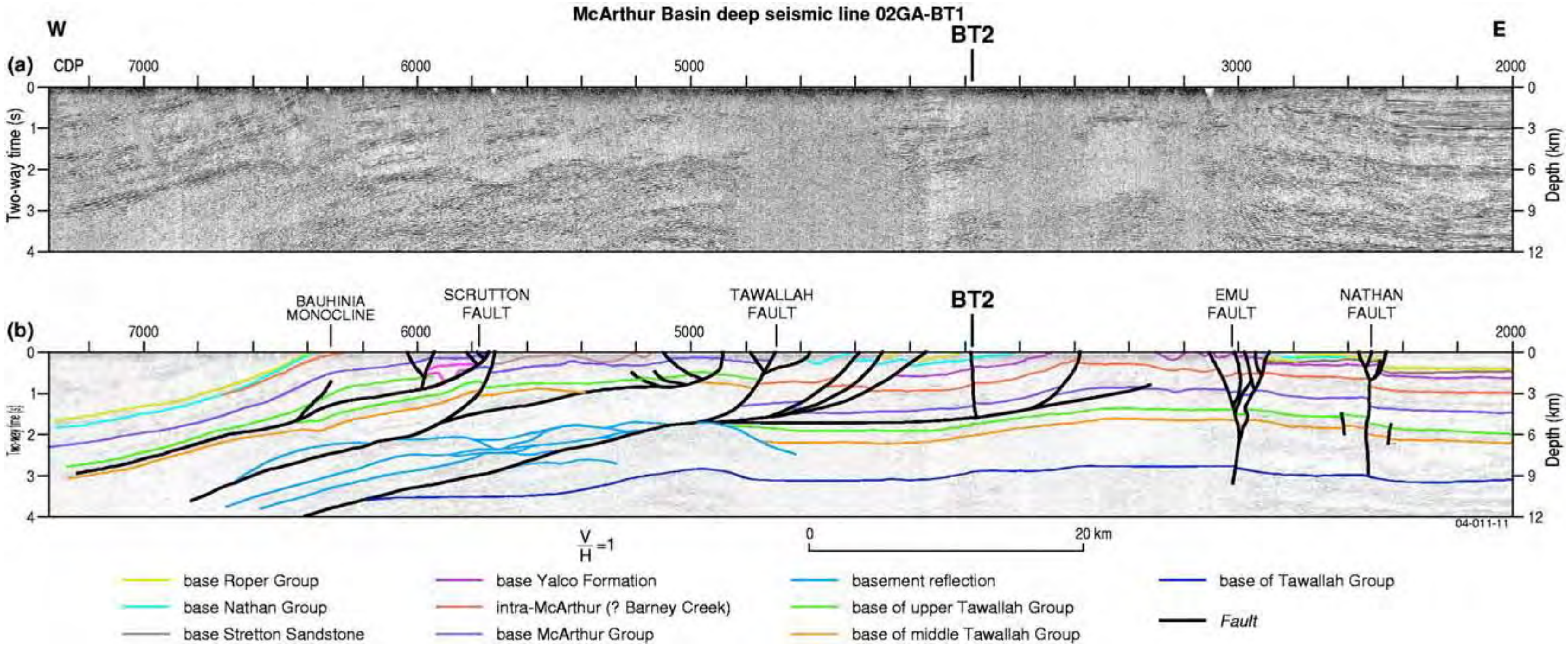

Figure 9: Interpreted seismic data for Line 02GA-BT1.

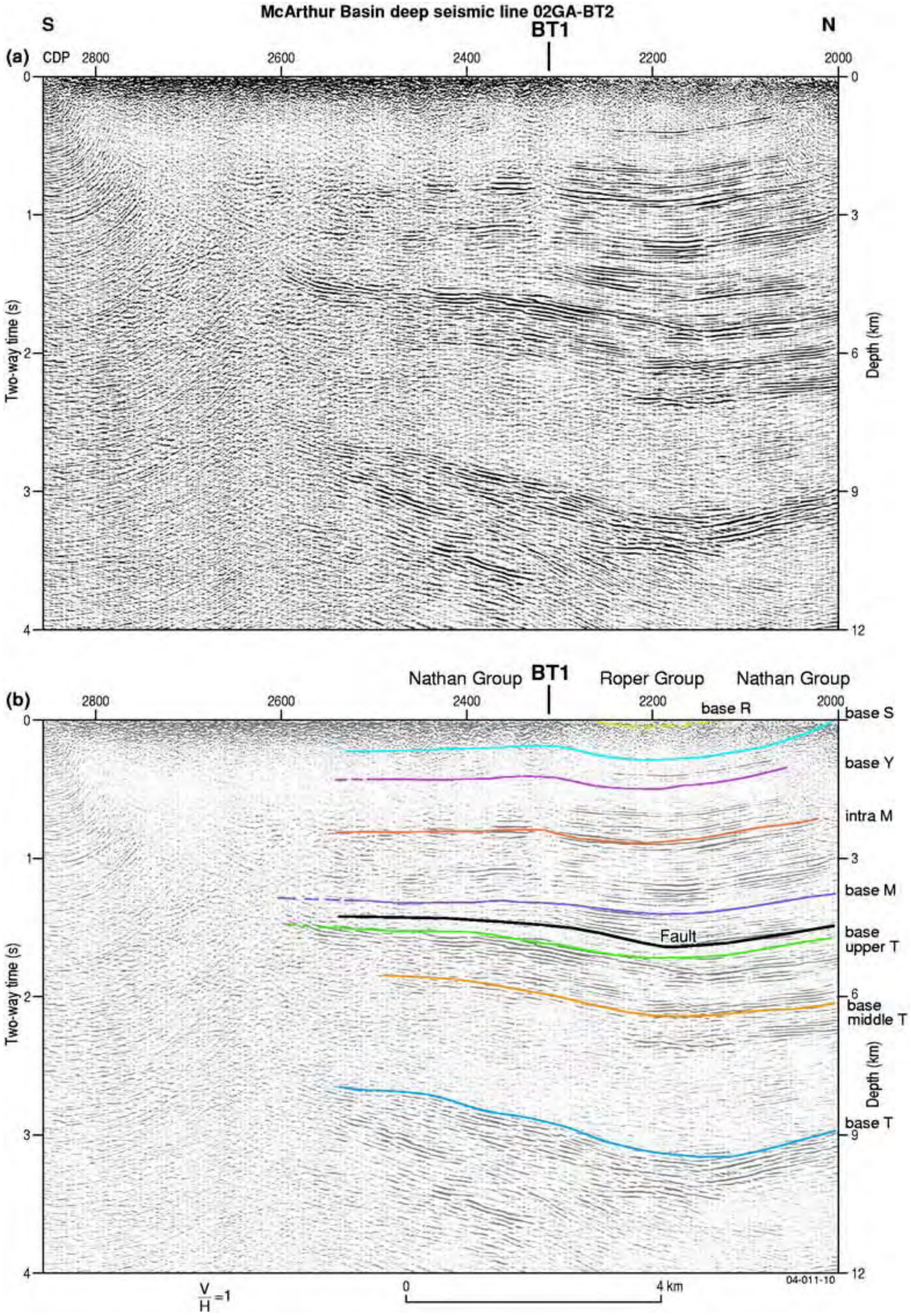

__Figure 10:__ Interpretation of seismic data for Line 02GA-BT2. base T = base of Tawallah Group; base middle T = base of middle Tawallah Group; base upper T = base of upper Tawallah Group; base M = base of McArthur Group; intra M = approximately Barney Creek Formation level within McArthur Group; base 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.

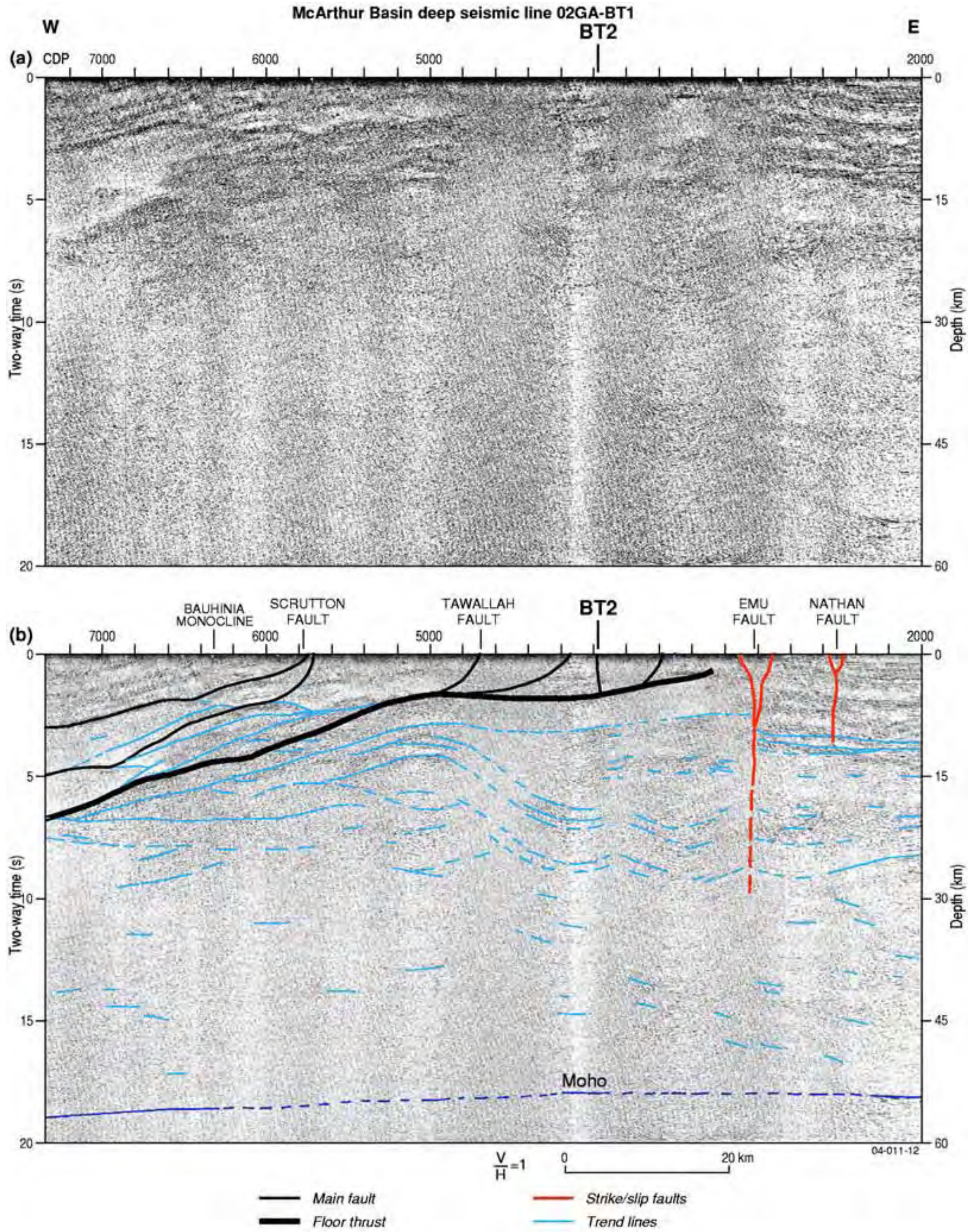

Figure 11: *Whole of crust view of seismic line 02GA-BT1 showing main floor thrust (thick black line), the strike-slip faults (red lines), the Moho (dark blue line) and some selected mid crustal reflectivity lines (mid blue lines).*

SCALE

Scale is very important. All sections were plotted at a V/H = 1, assuming an average crustal velocity of 6000 ms-1. The detailed 4 s TWT (approximately 12 km depth) seismic profiles (plotted at 1:25 000 scale) were used to identify details within the McArthur Basin succession and investigate boundaries or changes in the seismic data that could be related to the known surface geology. The smaller scaled 20 s TWT (approximately 60 km depth) seismic profiles (plotted at 1:100 000 scale) were used to interpret the larger structures and check continuity of reflectivity through the crust (Figure 11).

There were several significant bends along the seismic traverse (Figure 2). These allowed a partial three-dimensional view of the crust. These are best viewed using 3D visualisation software (for example GOCAD) in a 3D projection environment (see below).

In several areas, unusual reflectivity or reflective packages that intersected each other were regarded as suspect. In these cases, small portions of the seismic data were reprocessed to check the effects of this suspect data (for example pre-stack migration). In most cases the suspect data were inferred to result from 'out-of-the-plane' energy.

SEISMIC CHARACTERISTICS

The overall seismic data quality was good, with a good range of frequencies recorded, indicating that the attenuation of the Southern McArthur Basin sediments was low. The coherency of the returned seismic signal was variable, with some areas showing continuity of reflections for over 4 km near the surface and longer with depth. In other areas, however, particularly beneath carbonates of the McArthur Group (e.g. Balbirini Dolomite), signal within was lost.

The major cause of the reflectivity throughout the section is interpreted to be due to lithological variations between the various geological units. There are a few areas where reflections from structural features have been interpreted.

Finally, it should be pointed out that the seismic method better images horizontal and straight structures than folded or deformed structures. There is a preference to image the latest deformation over the older deformed surfaces. Late structures are imaged better because they cut across and deform earlier more complex structures.

INTERPRETED PACKAGES

The seismic interpretation of the seismic line is now described in detail. These descriptions refer to both Figure 9, which shows the 4 s interpretation for the entire Line 02GA-BT1, and one or more of Figures 12, 13, 14, 15 and 16. These latter figures show detailed views of portions of Figure 9, with Figure 12 a detailed view of the western end of Line 02GA-BT1, Figure 13 is a detailed view of the Scrutton Fault region, Figure 14 is a detailed view of the Tawallah Fault region, Figure 15 being a detailed view of the Emu Fault region and Figure 16 is a detailed view of the Narwinbi Fault and the eastern end of the line.

Basement – high reflectivity

- 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; Figures 9 and 13). 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. Reactivations or inversion may have modified the sense of movement on the faults.

- It is important to remember that the apparent basement architecture, as viewed in the seismic profile, may be perpendicular 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 compressional 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 9 and 14). It appears better imaged on Line 02GA-BT2 (approximately 3 seconds TWT; Figure 10).
- 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; Figures 9 and 16). 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; Figures 9 and 13) 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 5).

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; Figures 9 and 12), 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 5).

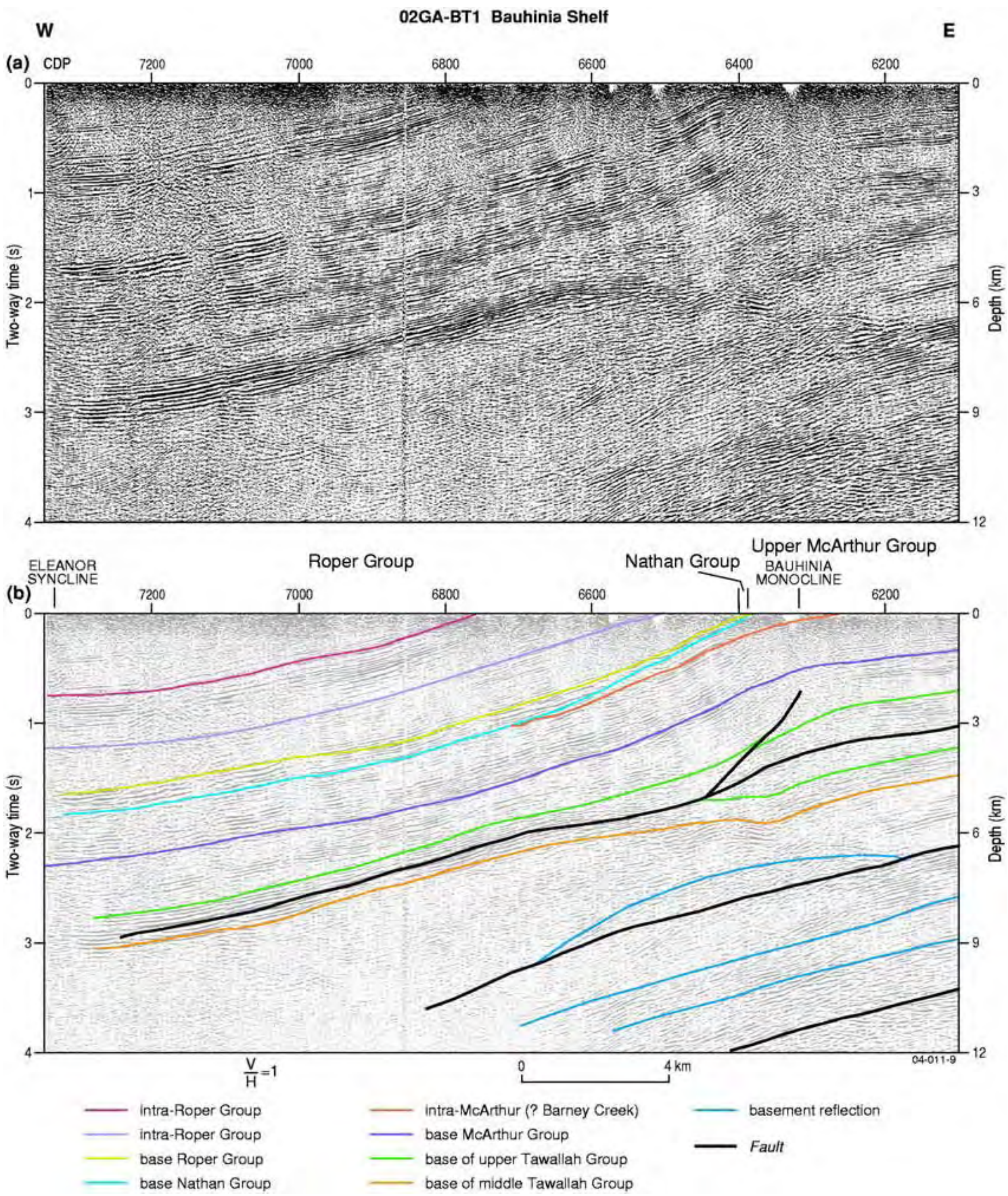

Figure 12: *Interpretation of the western portion of seismic Line 02GA-BT1, showing the westerly dipping McArthur Basin sedimentary units on the Bauhinia Shelf.*

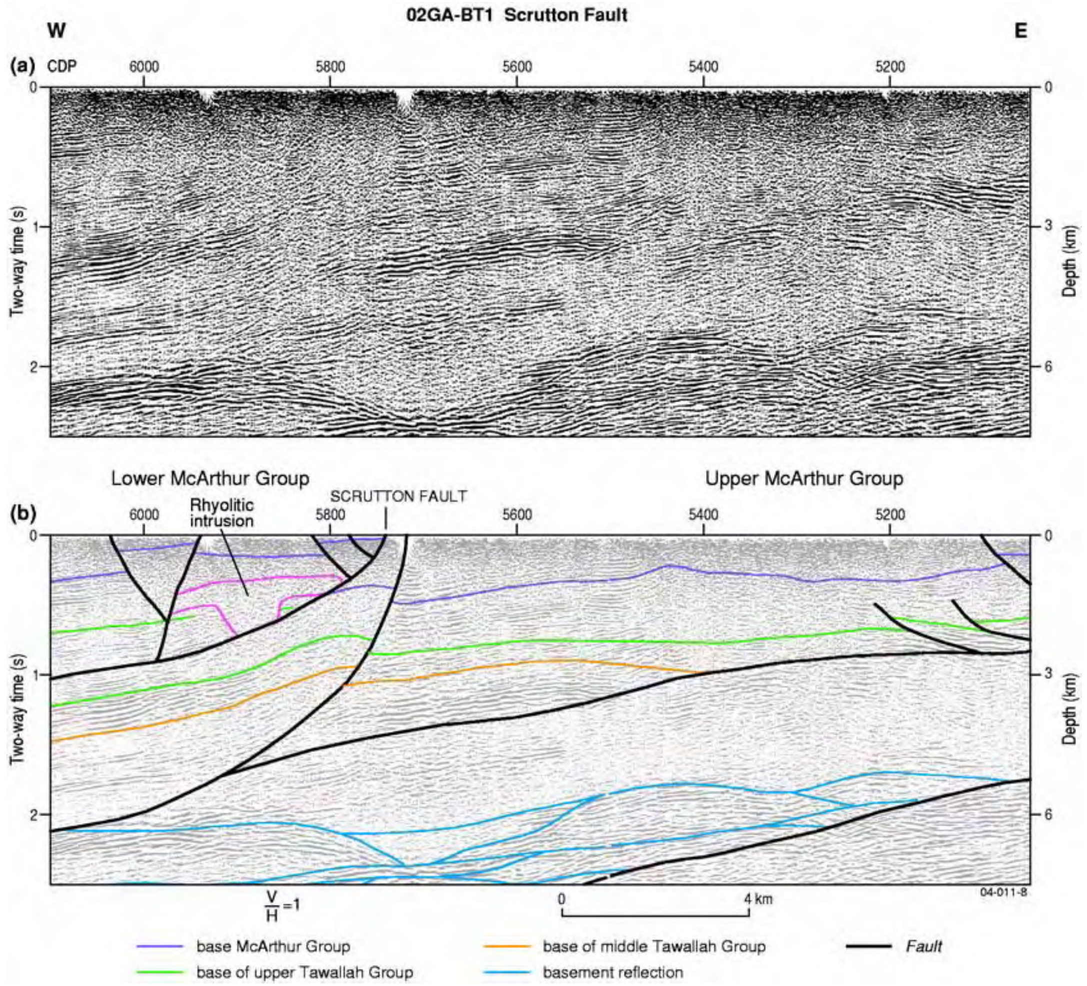

Figure 13: *Portion of seismic line 02GA-BT1 showing the region between the Scrutton Fault (west) and the Tawallah Fault (just off line to east). Section shows internal characteristics evident within the McArthur Group.*

Upper Tawallah Group – low to moderate reflectivity

- The green line on seismic profiles is the base of upper Tawallah Group (Figure 9).
- 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 16). 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 16).
- 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 5).
- 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 9), although at CDP 4100 it is about 3400 m thick (Figure 14).
- A thickness of 3000-3200 m appears to continue east of the Emu Fault (Figure 15).
- There is evidence of minor onlap onto the Bauhinia Shelf to the west (Figure 3), 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 15). 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 16), 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 12), 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 12. 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 5).
  - 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 15). 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.

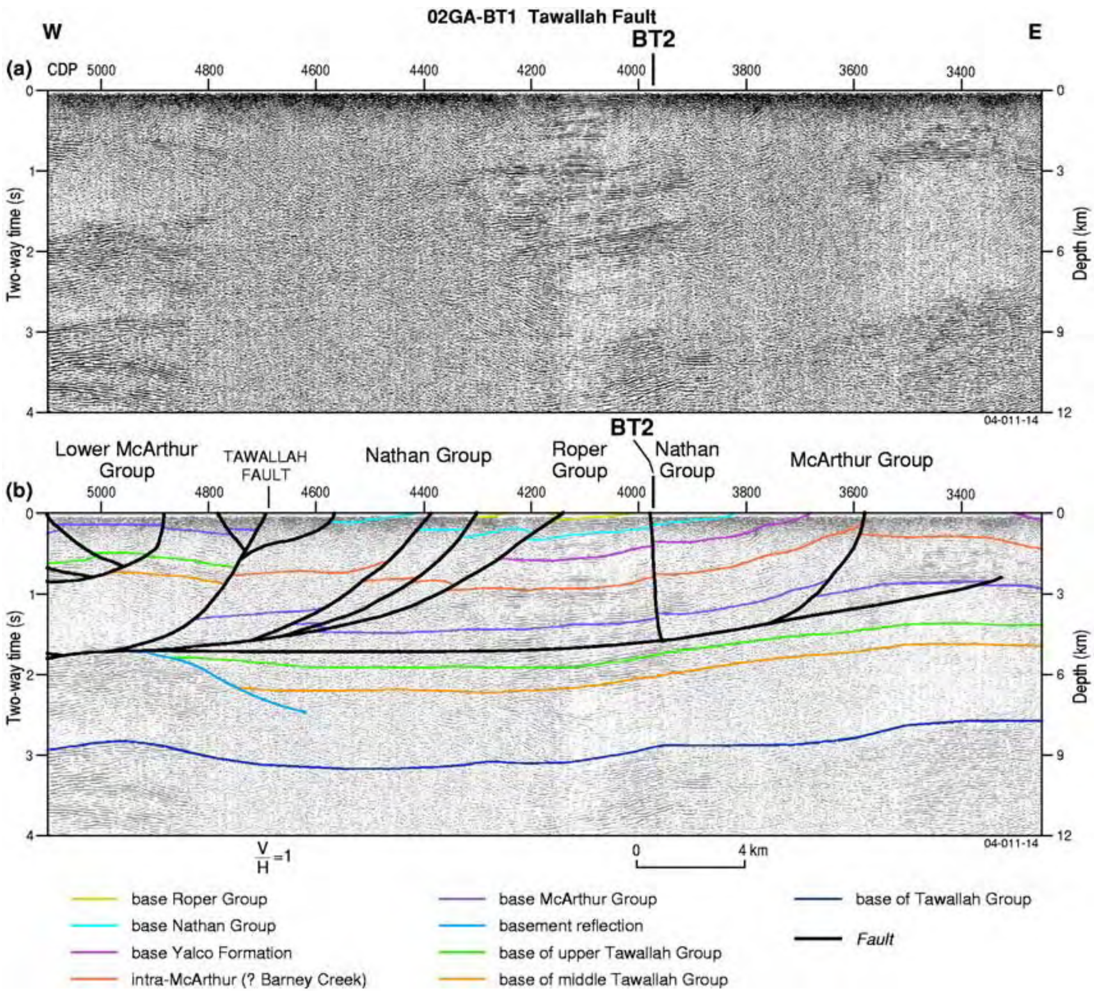

Figure 14: *Portion of seismic Line 02GA-BT1 showing region between the Tawallah Fault and central McArthur Basin. The Emu Fault is just to the east of this section.*

- 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.
- Flat lying McArthur Group continues east of the Emu Fault onto the edge of the Wearyan Shelf (Figure 3) 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 (e.g., Figures 15 and 16). 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 15). 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; Figures 9 and 14, and CDP 2700 on Line 2; Figure 10), 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 12).
- 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 5; Figures 15 and 16). 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 12) 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 2) 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.

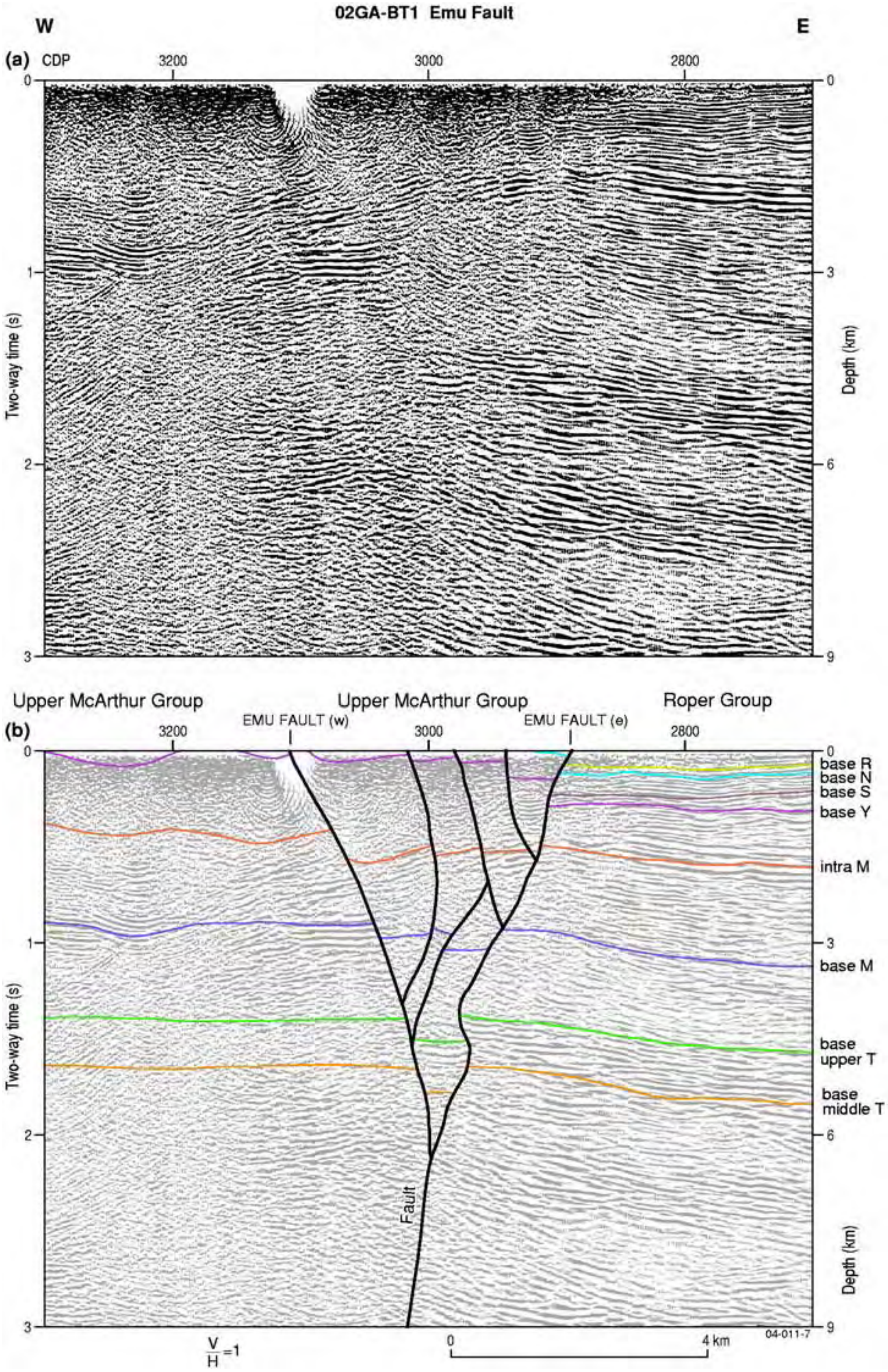

Figure 15: *Interpretation of the eastern portion of seismic Line 02GA-BT1 in the vicinity of the Emu Fault. base middle T = base of middle Tawallah Group; base upper T = base of upper Tawallah Group; base M = base of McArthur Group; intra M = approximately Barney Creek Formation level within McArthur Group; base Y = base of Yalco Formation; base S = base of Stretton Sandstone; base N = base of Nathan Group; base R = base of Roper Group.*

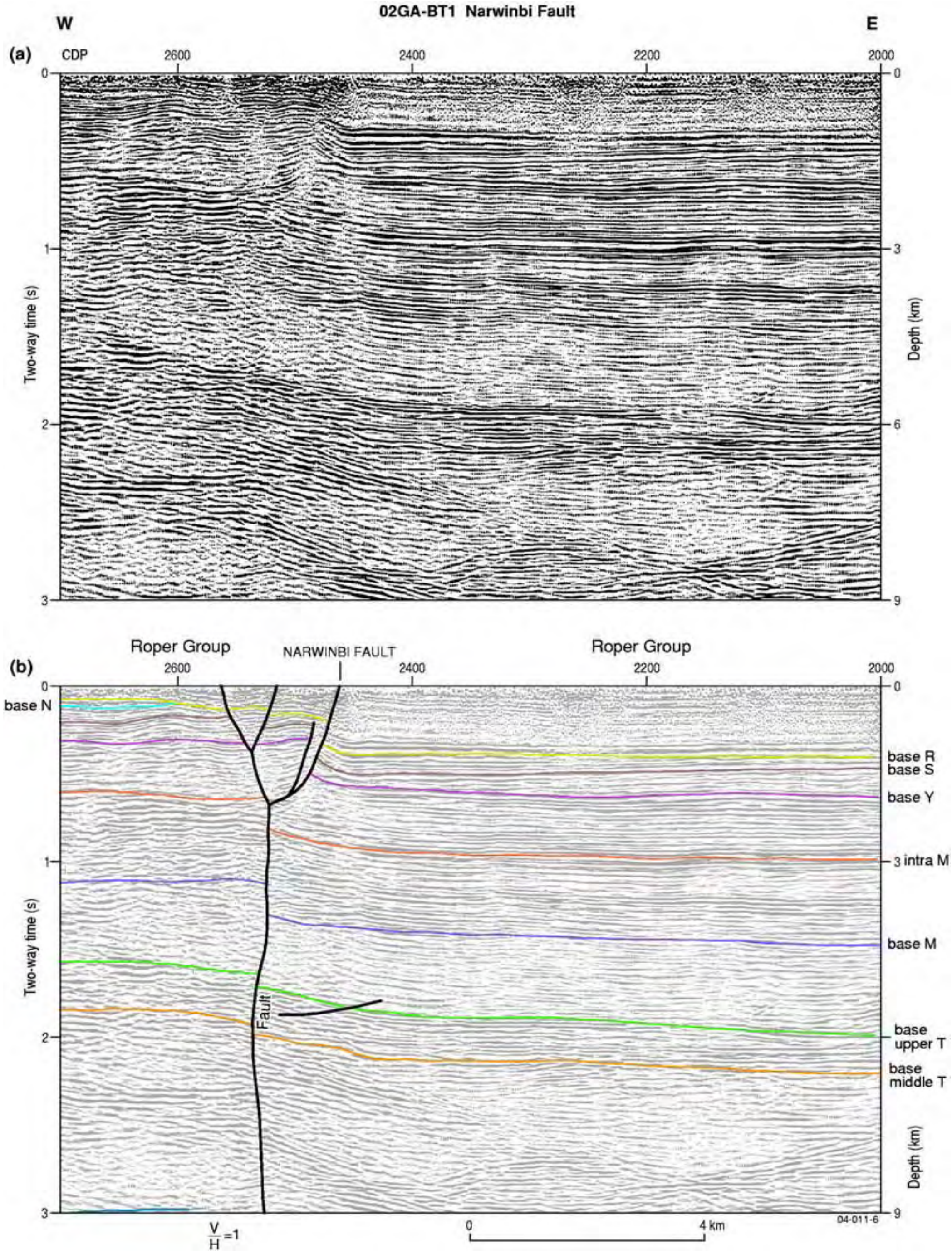

Figure 16: *Interpretation of the eastern portion of seismic Line 02GA-BT1 in the vicinity of the Narwinbi Fault, an eastern splay off the Emu Fault. base middle T = base of middle Tawallah Group; base upper T = base of upper Tawallah Group; base M = base of McArthur Group; intra M = approximately Barney Creek Formation level within McArthur Group; base Y = base of Yalco Formation; base S = base of Stretton Sandstone; base R = base of Roper Group.*

THRUST ARCHITECTURE

- The Tawallah and Scrutton Faults and most secondary north- to northwest-striking faults are interpreted as thrusts and conjugate 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 12). It is essential from a geometric perspective for the Roper Group at the eastern limb of the Eleanor Syncline (Figure 2) 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 (Figures 2, 17 and 18), 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 9), the thrusts at the surface have dips in the range of 30o 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 (Figure 3; 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.

Strike-Slip Faults

Emu Fault

- Several splays of the Emu Fault are evident from the combined geological map and seismic data, including some small subsidiary faults separating the main east and west splays near Ryan Bend (Figure 2; Figure 17). Most of these splays only penetrate part of the section and are not apparent on the surface.
- Reflections in the McArthur Group can be traced through the Emu Fault with only minor overall displacement (up to 500 m). Reflections are sometimes arched within the 'internal' fault blocks.
- Seismic and surface geology indicate an overall vertical to steeply west-dipping strike-slip fault with positive 'flower structure' geometry (Figure 15).
- There is apparent stratal growth in the middle McArthur Group within the flower structure, implying an earlier synsedimentary negative flower geometry that has subsequently been inverted.
- The latest (overprinting) movement is interpreted as strike-slip, probably with a dextral sense. This is supported by the folding present in McArthur Group immediately west of the western splay.
- The fault may well have involved sinistral strike-slip movement prior to the post-Roper dextral event, but it is difficult to identify seismic evidence for this, apart from possible inverted stratal growth within the flower structure at Ryan Bend. A variety of interpretations of the data is

possible. Rogers (1996), however, interpreted a similar sinistral mid-McArthur geometry (D_2) and dextral post-Roper geometry (D_3) from palaeostress analysis.

Narwinbi Fault

- Based on our interpretation of the seismic data, the Narwinbi Fault is a strike-slip fault with several upper crustal splays defining a positive flower structure (Figures 9 and 16).

Fault Block Characteristics

The thrust and strike-slip fault interpretation outlined above involves the juxtaposition of at least four main fault blocks (Figures 17 and 18), 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, as outlined below.

Scrutton Thrust Sheet

- Includes Scrutton Range, Eleanor Syncline and Tanumbirini Inlier.
- Bordered in the east by the Scrutton Fault, which is the principal west-dipping thrust surface (Figure 17).
- Southern border is poorly defined, as the Scrutton Fault dies to zero displacement into the middle McArthur Group.
- Scrutton Fault merges northward into Four Archers Fault on Mount Young 1:250 000 geological map sheet area (Figure 2; Haines et al., 1993).
- No western or northern boundaries defined.
- Thrust sheet maximum thickness is 9 km, thus base is defined by the Scrutton Fault at western end of seismic line. It is probably thicker farther to the west.

Basement

- Not present in outcrop.
- Not imaged on seismic profile within this thrust sheet.

Tawallah Group

- Contains Sly Creek Sandstone upward in Scrutton Range. Yiyintyi Sandstone and Seigal Volcanics are apparently absent at base of thrust sheet.
- Maximum ~2000 m total thickness above thrust plane.
- Based on surface geology, the upper Tawallah Group includes a mixed clastic and volcanic interval of Settlement Creek Dolerite, Wollogorang Formation, Gold Creek Volcanics, Warramana Sandstone, Tanumbirini Rhyolite and Nyanantu Formation (Figure 5). This appears to coincide with a >700 m thick reflective package on the seismic profile for Line 02GA-BT1.
- May contain small intrusion(s) related to Tanumbirini Rhyolite (as depicted in Figure 13).

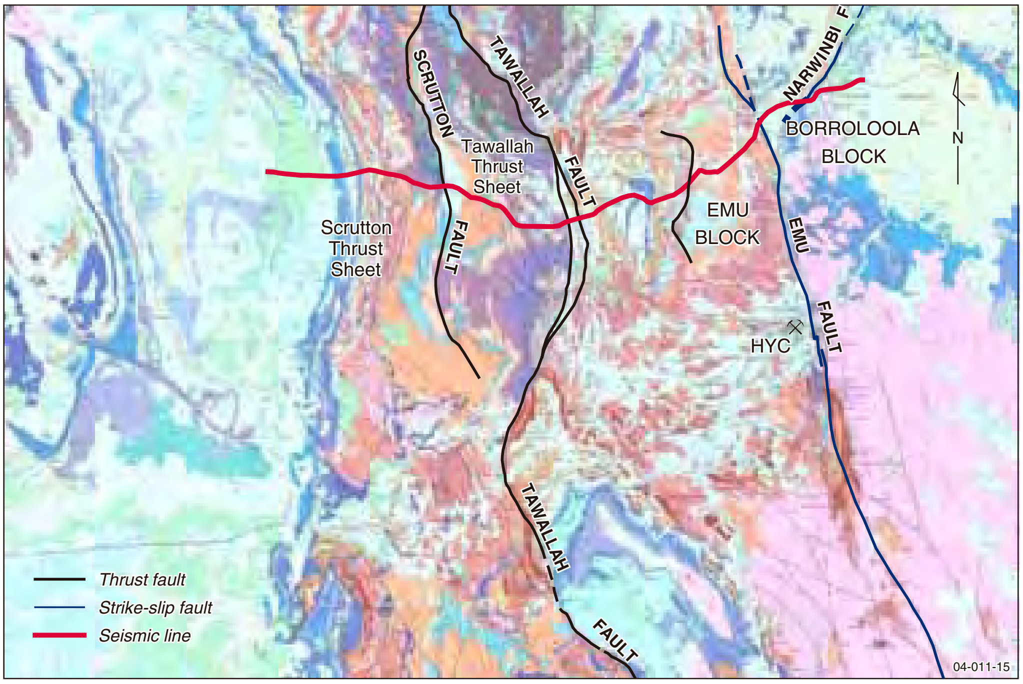

Figure 17: *Fault blocks within the Southern McArthur Basin on the Bauhinia Downs 1:250 000 geological map as defined by the principal fault systems.*

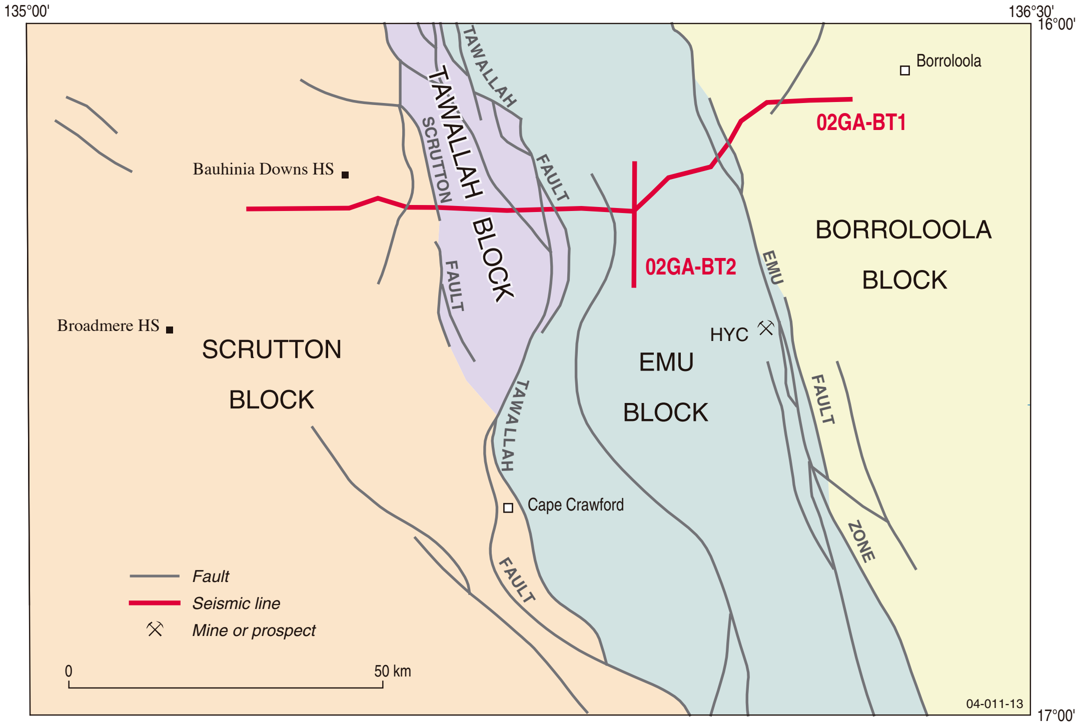

Figure 18: *Schematic version of Figure 17, showing fault blocks within the Southern McArthur Basin, shaded to show extent and principal fault systems.*

- The Masterton Sandstone clastic succession, as mapped by Pietsch et al. (1991a; 1991b) and shown on the 1:250 000 Beauhinia Downs geological map, is ~300 m thick and probably includes some Nyanantu Formation and Burash Sandstone, which are assigned to the Tawallah Group (Rawlings, 2002b; Figure 5).
- Basal thrust may occur at top of Seigal Volcanics or at Rosie Creek Member-McDermott Formation level (Figure 5).

McArthur Group

- Contains all units except Looking Glass Formation.
- Overall 2000 m thick (condensed).
- Umbolooga Subgroup ~1400 m thick (normal).
- Batten Subgroup ~600 m thick (condensed).
- Barney Creek Formation is thin and may merge with Reward Dolomite and Caranbirini Member (total thickness of <200 m; Figure 5). It therefore does not appear as distinct broad reflections in the seismic data.
- Two units mapped in Tatoola Sandstone (Pietsch et al., 1991b).
- Stretton Sandstone is quite thick (up to 300 m) when compared to rest of Batten Subgroup.
- Basal unconformity appears concordant on Warramana Sandstone, Tanumbirini Rhyolite and Nyanantu Formation of upper Tawallah Group (Figure 5).

Nathan Group

- The Nathan Group is thin or absent at the Bauhinia jumpup but is thick in the Tanumbirini Inlier (>500 m), indicating either depositional onlap onto the western Batten Fault Zone or erosion by the Roper unconformity. The seismic profile for Line 02GA-BT1 shows a mixture of these types of relationship, although it is somewhat conjectural (Figures 9 and 12 It is also feasible that the Nathan Group is structurally absent in the Bauhinia monocline and the McArthur-Roper boundary is a low-angle thrust.

- Where present at Bauhinia jumpup, Smythe Sandstone, the basal clastic unit of the Nathan Group, sits on Stretton Sandstone. Along strike to the north, the Nathan unconformity cuts down through 100s of metres of McArthur Group and sits on Yalco Formation and Hot Springs Member (Figure 5).

Roper Group

- Includes the full and thick (>5000 m) section up to McMinn Formation (Figure 5).
- Contains apparently quite thick Mainoru Formation (1000-1200 m).
- Mantungula Formation apparently occurs at base, but is poorly exposed (Pietsch et al., 1991a).
- Steady westerly dip of 15-20° to the west of the Bauhinia monocline (Figure 12).
- Lies unconformably on Smythe Sandstone (Nathan Group), Yalco Formation and Hot Springs Member (McArthur Group; Figure 5).

Other features and comments

- Loss of seismic signal at Bauhinia monocline may be due to an increase in deformation, fracturing and anisotropy in this part of the seismic profile.

Tawallah Thrust Sheet

- Includes Batten Range and western-southern Tawallah Range (Figure 2; Figures 17 and 18).
- Bounded in the east by the Tawallah Fault, which is the principal west-dipping thrust surface at the base of the thrust sheet.
- Western boundary is defined at the surface by Scrutton Fault.
- Southern border is poorly defined, where the Scrutton Fault merges into an area of coherent middle McArthur Group (Figure 17).
- Tawallah Fault merges northward into Lorella Fault on Mount Young 1:250 000 map (Figure 2; Haines et al., 1993).
- Maximum thickness of the thrust sheet is 8 km in the immediate footwall of Scrutton Fault, although apparent throw further north is >10 km (Roper Group against Scrutton Volcanics; Pietsch et al., 1991b).

Basement

- Scrutton Volcanics occur at the toe of the Tawallah Fault about 9 km to the north (Tawallah Pocket; Haines et al., 1993) and indicate that the Tawallah thrust sheet stratigraphically contains a section from Scrutton basement upwards.
- >3000 m thick in seismic profile at CDP 5900 (Figures 9 and 13), as determined by the thickest interval of ‘unique basement architecture’ present.
- Unusual seismic architecture of convex-up stacked reflections (Figures 9 and 13; see *Interpreted packages* section above for description and interpretation).

Tawallah Group

- Contains the stratigraphic sections from Yiyintyi Sandstone upward in the Tawallah Range area.
- Overall 2500 to 5000 m thick.
- Yiyintyi Sandstone is interpreted to be 500 to 3000 m thick on the seismic profile (average 2000 m), characterised by a lack of reflections (e.g. 1.5 seconds over CDP interval 5100-5800 on Line 1; Figures 9 and 13). It is interpreted as up to 4000 m thick on the geology map (Pietsch et al., 1991a).

- Thin discontinuous reflections midway through what is thought to be Yiyintyi Sandstone at 1.5 seconds near CDP 5600 and at 1.8 seconds near CDP 6100 (Figure 9) could be thin (<100 m) igneous lenses (e.g. basalt flows or dolerite sills). They probably do not relate to the >300 m thick Seigal Volcanics, as this formation would image differently in the seismic data.
- According to the geology maps, the Tawallah Group consistently includes only formations up to Wununmantyala Sandstone (Figure 5). The heterogeneous volcano-sedimentary units of the upper Tawallah Group are notably absent (e.g. Settlement Creek Dolerite, Wollogorang Formation etc). Compare this to the Scrutton thrust sheet.
- The mapped Masterton Sandstone clastic succession is 500-800 m thick and probably contains a substantial thickness of Nyanantu Formation. Combined with the underlying Wununmantyala Sandstone, this should create an 800-1200 m thick non-reflective clastic package. This is what is seen in the seismic profile for Line 02GA-BT1 immediately west of the Tawallah Fault (Figure 14).
- In contrast, in the footwall of Scrutton Fault the upper Tawallah Group consists of a moderately reflective interval (Figure 13), suggesting the volcano-sedimentary package recognised in the Scrutton thrust sheet may be present here also (despite there being no evidence for it in outcrop). If so, then a substantial discontinuity is required within the CDP interval 4900 and 5700 of the seismic profile, which has an unusually complex architecture and apparent thickening in the top 1.5 seconds (Figures 9 and 13). Possible causes include:
  - Faulting (either reverse or extensional), differential uplift and erosional removal of the reflective upper Tawallah Group, accompanied or followed by late Tawallah to early McArthur stratal growth. This interpretation is supported by apparent wedging of reflections in the seismic data and is also consistent with the presence of proximal felsic volcanism and coarse clastic facies in the mapped Masterdon Sandstone sequence (Haines et al., 1993).
  - Non-deposition of the reflective volcano-sedimentary rocks around the ranges (as suggested by Rogers, 1996). This cannot explain the overall thickening of the package, or the presence of coarse clastic sedimentary rocks.
  - ‘Out-of-the-plane’ thrusting could generate unusual structural geometries, as this part of the profile is almost parallel to the structural strike. This implies structural removal or destruction of the reflective upper Tawallah Group (e.g. a thrust at Wununmantyala Sandstone-Masterton Sandstone contact). The seismic-derived cross section as currently drawn reflects this scenario.
  - Thrust emplacement of basement into the middle Tawallah Group during an ‘early’ (mid-Tawallah Group) phase of deformation. Unfortunately, if this scenario is correct, then the structural juxtaposition will be obscured by lower McArthur Group cover.
- This problem area could possibly be resolved by field investigations (i.e. documenting the character of the Tawallah-McArthur Group boundary) and potential field modelling.

McArthur Group

- Includes Masterton Sandstone through to Emmerugga Dolomite (the latter penetrated in diamond drill hole McArthur 1).
- The Batten Subgroup is absent.
- Maximum total thickness of 1400 m preserved adjacent to Scrutton Fault.
- Relatively flat lying (Figure 9).
- One unit mapped in Tatoola Sandstone (Pietsch et al., 1991b).
- Basal unconformity appears concordant on Wununmantyala Sandstone around ranges, but the basal part of the mapped Masterton Sandstone clastic package is probably made up of Nyanantu Formation of the upper Tawallah Group (this needs field checking).
- Possible angular unconformity or complex structure preserved in seismic (discussed above).

Nathan Group

- Generally absent, but a thin (<200 m) erosional remnant is preserved in far north, where it rests unconformably on Emmerugga Dolomite (lower McArthur Group; Haines et al., 1993).
- Basal unconformity does not appear very angular.
- Consists of thin Smythe Sandstone and Balbirini Dolomite.

Roper Group

- Generally absent, but a thin (<1000 m) erosional remnant is preserved in far north, where it rests unconformably on Tooganinie Formation (lower McArthur Group) and Balbirini Dolomite (Nathan Group; Haines et al., 1993).
- Basal unconformity does not appear very angular.
- Mantungula Formation apparently occurs at base, but is poorly exposed.

Other features and comments

- The presence of basement at the toe thrust of this thrust sheet indicates it is the most highly exhumed in the Batten Fault Zone.
- Uniformly thin McArthur Group implies that it was exhumed prior to Nathan Group deposition, and >1000 m of section was removed. Either that or the Batten Subgroup was never deposited in this fault block or the McArthur-Nathan-Roper contacts are dislocations. There is no evidence in the seismic data as to what the exhumation event may have involved.

Emu Block

- Includes eastern Tawallah Range, Sawtooth Range and Abner Range.
- Bordered in the east by the Emu Fault.
- Western boundary defined by Tawallah Fault.
- Southern border is poorly defined, where the Emu and Tawallah Faults disappear under the Georgina Basin. A southern boundary may also exist at the southern edge of the Abner Range.
- Northern boundary is poorly defined, because the Tawallah Fault is truncated by the northeast-trending Rosie Fault on Mount Young 1:250 000 geological map (Haines et al., 1993).
- Adjacent to Emu Fault this block does not appear to have a basal thrust and therefore has no thickness limit. Nevertheless, the western part of this block contains the easternmost thrust sheet to the east of the Tawallah Fault.

Basement

- Scrutton Volcanics occur at the toe of a probable east-dipping thrust in the north (Rosie Fault in the eastern Tawallah Range) and indicate that the Emu Block contains at least Scrutton basement upwards.
- >2000 m thick on seismic profile for Line 02GA-BT2 (at 3 seconds; Figure 10) and at CDP’s 3400, 4000 and 5000 on Line 02GA-BT1 (Figure 14).
- Unusual seismic architecture of convex-up stacked reflections.

Tawallah Group

- Occurs in Tawallah Range, Sawtooth Range and as small isolated outcrops in the Emu Fault Zone near the McArthur River deposit. It may also contain outcrops in the Mallapunyah and Kiana Domes, however, the area south of Abner Range may belong to a discrete fault block.
- Contains Yiyintyi Sandstone up to Settlement Creek Dolerite in most places (or more rarely Wollogorang Formation), but in the Sawtooth Range it contains additional Wollogorang Formation, Gold Creek Volcanics, Warramana Sandstone and a substantial thickness of Nyanantu Formation (Figure 5). This range, however, may belong to a separate fault block in the north.

- Overall 5000 m thick.
- Yiyintyi Sandstone is interpreted to be 2500 to 3000 m thick on the seismic profiles for Line 02GA-BT1 and Line 02GA-BT2, consistent with the established geology (Pietsch et al., 1991a; Haines et al., 1993). It is best imaged along Line 02GA-BT2 at 2.5 seconds (Figure 10), where it does not appear to contain the thin internal reflections seen in the Tawallah thrust sheet and Borroloola block.
- In seismic profiles, the top of the Tawallah Group incorporates a 1500 m thick poorly reflective package, which may equate to a thickened interval of the mapped Masterton Sandstone clastic package (mostly Nyanantu Formation), as seen at Sawtooth Range. In contrast, nearby in the Tawallah Range the mapped Masterton Sandstone clastic package is thin (Pietsch et al., 1991b), and only part of this poorly reflective package can be accounted for on the geological map (Wununmantyala Sandstone). This suggests that the Sawtooth Range section is more representative of the upper Tawallah Group in the Emu Block. Therefore, Nyanantu Formation is probably more widespread than depicted on the geology map and its distribution may be antithetic to the position of many of the current ranges (except of course the Sawtooth Range).

McArthur Group

- Contains all units including Looking Glass and Amos Formations (Figure 5). Most exposure is of the Batten Subgroup.
- Overall sequence of 2800-3500 m thick (normal).
- Umbolooga Subgroup 1200-1500 m thick (normal).
- Batten Subgroup 1600-2000 m thick (normal).
- Barney Creek Formation thickens into sub-basins adjacent to or within the Emu Fault Zone to as much as 1200 m (e.g. McArthur River deposit). The McArthur Group pre-erosional thickness may also have been abnormal in these sub-basins (4500 m?).
- Two units mapped in Tatoola Sandstone (Pietsch et al., 1991b).
- Basal unconformity appears concordant on upper Tawallah Group.

Nathan Group

- Up to 700 m thick, although it may be thicker in the Abner Range area (1200 m?)
- Smythe Sandstone is present only in the north, although this is partially due to mis-mapping by Jackson et al. (1987) and Pietsch et al. (1991a) around Abner Range (Rawlings, 2002b).
- Rests unconformably (but fairly concordantly) on Looking Glass Formation in most areas, rarely transgressing down onto Yalco Formation along the Emu Fault Zone.
- South of the Abner Range, the Nathan unconformity becomes noticeably angular and Nathan Group sits as low as Emmerugga Dolomite (Figure 5). This area may belong to a discrete fault block.

Roper Group

- Generally absent, but a relatively thick (~2000 m) succession is preserved in the Abner Range (Jackson et al., 1987).
- Formations are individually condensed compared to the west in Beetaloo Sub-basin (Jackson et al., 1987; Pietsch et al., 1991a).
- Rests unconformably on Balbirini Dolomite (Nathan Group; Figure 5).
- Basal unconformity does not appear very angular.
- Mantungula Formation is apparently absent.

Borroloola Block

- Includes the Bukalara Range.
- Bounded in the west by the Emu Fault.
- Western, southern and northern boundaries not defined. Merges with the Wearyan Shelf and is largely covered by Bukalara Sandstone.
- This block does not appear to have a basal thrust and therefore has no thickness limit.
- Largely flat lying with only minor deformation.

Basement

- Basement does not crop out, but is apparent in seismic Line 02GA-BT1 at 3.7 seconds at CDP 2100 (Figures 9 and 16).
- Parallel stacked reflections that are concordant with Tawallah Group above.
- >1000 m thick.

Tawallah Group

- Outcrop occurs only in Foelsche Inlier and on adjacent Wearyan Shelf.
- Interpreted from seismic to include complete Tawallah Group (Yiyintyi Sandstone up to Nyanantu Formation; Figure 5).
- Overall 6500 m thick.
- Yiyintyi Sandstone is interpreted to be 4000 to 4500 m thick on the seismic profile for Line 02GA-BT1 (Figure 16) and appears to show a major thickness change at or near the Emu Fault Zone (from 4000 m on east side to 2700 m on west side). Yiyintyi Sandstone includes a thin internal reflector (sill or volcanic unit?).
- In the seismic profile, the upper Tawallah Group incorporates a 1400 m thick poorly reflective package, as seen in the adjacent Emu Block. It may equate to a thickened interval of the mapped Masterton Sandstone clastic package, probably the Nyanantu Formation or equivalents thereof.

McArthur Group

- Probably contains all units including Looking Glass Formation (Figure 5). Most exposure is of the Batten Subgroup.
- Overall succession of 2500-3200 m thick (normal).
- Umbolooga Subgroup 1400 m thick (normal).
- Batten Subgroup 1200-1700 m thick (normal).
- Barney Creek Formation is interpreted to be quite thick along the seismic profile, as it is equated with a broad high-amplitude double reflection set (‘intra M’ in Figure 16).
- Basal unconformity appears concordant on upper Tawallah Group.
- Wedging seismic geometry at probable level of Yalco Formation and Stretton Sandstone (‘base Y’ and ‘base S’ in Figure 16).

Nathan Group

- Thin (<200 m) or absent.
- Where Nathan Group crops out, the Smythe Sandstone is generally present.
- Rests unconformably (but fairly concordantly) on Looking Glass Formation, Stretton Sandstone or Yalco Formation (Figure 5).
- May merge to the west with Karns Dolomite.

Roper Group

- Up to 1200 m thick in seismic profile. Unlikely to be much thicker in outcrop.
- Formations are individually condensed compared to the west in Beetaloo Sub-basin (Figure 3; Jackson et al., 1987; Pietsch et al., 1991a). This is especially so for Mainoru Formation.
- Rests unconformably on upper McArthur Group (including Looking Glass Formation, Stretton Sandstone or Yalco Formation) or thin Nathan Group (Figure 5).
- Basal unconformity does not appear very angular.
- Mantungula Formation is apparently absent.

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), and the 1:250 000 scale Bauhinia Downs (Pietsch et al., 1991a) and 1:100 000 scale McArthur River region (Pietsch et al., 1991b) geological maps. The geology is also summarised in Figure 2. To obtain a more detailed picture of stratigraphy and structure, a 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. 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. The findings are summarised below, from east to west.

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.

NARWINBI FAULT

This fault was formerly referred to as the ‘east splay’ of the Emu Fault, but affords its own status here (Figure 2). The fault trace is linear over >20 km and exhibits up to 1000 m of vertical juxtaposition, with upper McArthur Group (Stretton Sandstone) on the west side and lower-middle Roper Group (Abner Sandstone) on the east side. The junction between these units is marked by a monocline, in which easterly dips increase in steepness within the fault zone, and decrease to flat lying on both flanks. The fault is a positive topographic feature characterised by cataclasite, silicification and haematisation. Dome-and-basin fold interference patterns, with 100-1000 m wavelengths, are evident immediately west of the fault within the Yalco Formation.

To the south, Narwinbi Fault ‘disappears’ under regolith where it is predicted to merge with the Emu Fault (Figure 2). Progressively shallow dips and reduced deformation in a southerly direction indicate that its disappearance is real. Perhaps displacement to the south is accommodated by a broader zone of faulting or by a complex transfer structure between the Narwinbi and Emu Faults. This fault is distinct on aeromagnetic images, suggesting that it is a reactivated basement structure.

EMU FAULT

This fault is notably linear in its surface trace (Figure 2), occurring over at least 150 km in a north-north-west orientation in eastern Bauhinia Downs and Mount Young map sheets. In detail, however, it encompasses a series of fault splays that coalesce on a scale of 1-10 km along strike. Juxtapositions across the fault and its internal complexity vary substantially along its length. For example, near the McArthur River deposit, the Emu Fault is composed of complex fault slices with apparent vertical juxtapositions of up to 5 km (Settlement Creek Dolerite against Stretton Sandstone). Small fault bounded inliers of Tawallah Group are almost certainly tectonically transported fault blocks within a positive flower structure. In contrast, near Ryan bend along seismic Line 02GA-BT1, the Emu Fault is represented by a simple elliptical plateau of flat-lying Yalco Formation bounded by a fault in the west and a monocline to the east, the latter with almost no apparent juxtaposition or truncation. The eastern monoclinal margin of the 'Yalco plateau' encompasses east dipping upper McArthur Group, thin Nathan Group and lower Roper Group. Easterly dips of up to 85° in the monocline decrease systematically toward both flanks to become essentially flat lying. Any vertical displacement is taken up by the monocline, not by any visible fault or series of faults. However, any potential lateral displacement along a blind Emu Fault at this locality is difficult to determine. The western margin of the 'Yalco plateau' is a subtle faulted juxtaposition of lower Yalco Formation and Lynott Formation of ~300 m apparent vertical displacement. Dips steepen in the vicinity of the fault, and numerous small-scale faults and cataclasite zones are evident. Based on stratigraphy, an east-side-up geometry is evident. This makes the 'Yalco plateau' a positive flower structure within the Emu Fault. Folds with >1 km wavelength and generally north trending axial traces are prolific immediately west of this fault in the upper McArthur Group.

Slickenlines and fibres are difficult to find along the length of the Emu Fault, due mainly to the propensity of cataclasite, fault gouge, silicification, haematisation and quartz veining. The few fibres identified are shallow west-plunging with kinematics of west-over-east thrusting toward 070-080°, although some have been rotated to lie on shallow east-dipping surfaces. Clearly, the last movement along the Emu Fault post-dates the Roper Group. Strike-slip movement is most likely to have been dominant, based on the linear fault pattern and presence of flower structures. However, the overall monoclinal arrangement and kinematics of fibres suggest there was at least some degree of thrust movement at this time. This may relate to a net thrust movement on a positive flower structure during strike-slip faulting or to a separate phase of orthogonal (west-over-east) reverse faulting.

Judging by the style of deformation evident in lower structural positions, such as around the McArthur River deposit, the Emu Fault also had an earlier movement history, probably during middle McArthur Group (Barney Creek Formation) times. This is consistent with the timing proposed for stratal growth, debris flow breccia formation and base metal mineralisation at the McArthur River deposit (Jackson et al., 1987; Hinman, 1995; Large et al., 1998). The presence of stratal growth within positive flower structures indicates that these structures were initially negative flowers (entailing stratal growth) that were subsequently inverted to positive flowers.

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 2). 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 2). 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 northwestward through the southern Tawallah Range (Figure 2). 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.

SMALL FAULTS BETWEEN BATTEN RANGE AND SCRUTTON RANGE

Numerous relatively short faults occur in this part of the seismic transect (Figure 2), but outcrops containing them are generally poor because they cut through the recessive lower to middle McArthur Group. There is a mixture of fault juxtapositions, some west-side-up and some east-side-up. The gross trend in this zone, however, is a gradual westerly younging and shallow (0°-10°) westerly dip. Macroscopic scale (10 km wavelength) folds are evident in north and east orientations, forming proto dome-and-basin structures at map scale. Where exposed, faults appear to be minor and involve only small apparent vertical displacements, generally in the order of 100-300 m. Dips do not appear to be rotated much within the fault zones. Local quartz blows contain cataclasite, brecciation, silicification and veining. Fault fibres identified are consistent with both west-over-east thrust movement or east-over-west thrust movement (e.g. dip 45° to 50°). These may have formed an incipient thrust and back-thrust set, within a northeast-southwest compressional regime. Further north, Rogers (1996) explained the unusual juxtapositions along the Lorella Fault in terms of a dextral contractional strike-slip duplex, relating to D_3.

SCRUTTON FAULT

The surface expression of the Scrutton Fault (the 'Bauhinia Fault' of Rogers 1996) is the sharp eastern edge of the Scrutton Range (Figure 2). It is similar to the Tawallah Fault, in that it is arcuate to sinuous with west-side-up movement, encompassing a juxtaposition of middle Tawallah Group and middle McArthur Group. The southern end of the fault appears to merge into an area of shallow-dipping middle McArthur Group (Figure 2). The fault zone contains cataclasite, fault gouge, folding, brecciation, hydraulic fracturing, silicification, haematisation and quartz veining (tension gashes). Dips are not as steep as for the Tawallah Fault, generally in the range of 15-35°, decreasing gradually to the east and west of the fault. Fault fibres are locally well developed. Fibres identified plunge at shallow angles (5-30°) to the west and show west-over-east thrust kinematics, toward 70-130° (generally 80°). Tension gashes at one locality (including dips of 20° to 180° and 30° to 350°) are also consistent with approximately east-west compression.

The palaeostress analysis of Rogers (1996) supports the thrust kinematics and timing given above (i.e., D_3), but indicates that deformation was directed more toward the east-northeast (about 74°). He interpreted the numerous second-order structures immediately west of the Scrutton Fault as tear faults, internal thrust imbrication and fault propagation folds. All structures are consistent with the toe of a thrust.

SMALL FAULTS BETWEEN SCRUTTON RANGE AND BAUHINIA JUMPUP

At least five relatively small north- to north-west oriented faults occur immediately west of the Scrutton Fault over a few kilometres of the transect, truncating the upper Tawallah Group and lower McArthur Group (Figure 2). As recognised elsewhere, there is a mixture of west-side-up and east-side-up fault movements, with only 50-200 m apparent vertical displacement. The gross trend in this part of the transect is a gradual westerly younging and shallow (5-15°) westerly dip. Most individual fault blocks also maintain the same westerly younging and dip. Thrust movements can be implied for most faults from the orientation of drag folds and stratigraphic juxtapositions. One fault has a very sinuous trace suggesting it is a low-angle west-dipping surface (thrust). An incipient thrust and back-thrust set, within a east-northeast-west-southwest compressional regime, is implied for this part of the transect.

BAUHINIA MONOCLINE (BAUHINIA JUMPUP)

The Bauhinia 'jumpup' (Figure 2) incorporates a large west-dipping monocline involving a thick package of west-younging upper McArthur Group and Roper Group. Dips increase from 5-10° to 15-25° from east to west over a distance of 5 km near the jumpup. Dips of 15-25° are maintained westward into the Eleanor Syncline. Although no faulting is obvious near the jumpup, the presence of numerous thermal springs (including Bauhinia Spring) suggests that there are blind (bedding parallel?) structures within the section.

Constraints on the Southern McArthur Basin Seismic Interpretation from Potential Field Data

INTRODUCTION

In the absence of deep drill holes, the seismic interpretation of the Southern McArthur Basin lines is not without uncertainty, particularly in estimating package densities and thicknesses at depth.

Some validation may be gained by modelling the density and magnetisation contrasts within the seismic stratigraphy and comparing the synthetic response against the observed fields. While there are an infinite number of combinations of multiple stacked bodies to explain any total field response (the basis of non-uniqueness), applying known density and magnetic contrasts to the seismic section helps to constrain the seismic interpretation.

REGIONAL MAGNETIC AND GRAVITY DATA

Magnetic data are provided by the airborne magnetic surveys Bauhinia Downs and Batten Trough. Survey specifications are outlined in the Table 3 with an image of the total magnetic intensity provided in Figure 19.

Table 3: Survey specifications for airborne magnetic surveys covering region of interest

SURVEY SPECIFICATION	BAUHINIA DOWNS	BATTEN TROUGH
Project Number	1012	573
Date	2000	1989
Boundaries	135-136.5E/15.5-17S	135-136.5E/15-16.5S
Line Direction	East-West	East-West
Flying height (m)	80	100
Line Separation (4)	400	300

Gravity data for the same window were extracted from the Geoscience Australia gravity database. Nominal station spacing is 4 km and mainly comes from regional surveying undertaken in the McArthur Basin. Figure 20 shows an image of the Bouguer Gravity in the vicinity of the seismic lines.

The Northern Territory Geological Survey has supplemented the regional gravity data base with sampling along the seismic lines at 250 m spacing. In the context of the seismic interpretation, this new dataset has not been analysed, except with respect to fault locations, outlined in a later section.

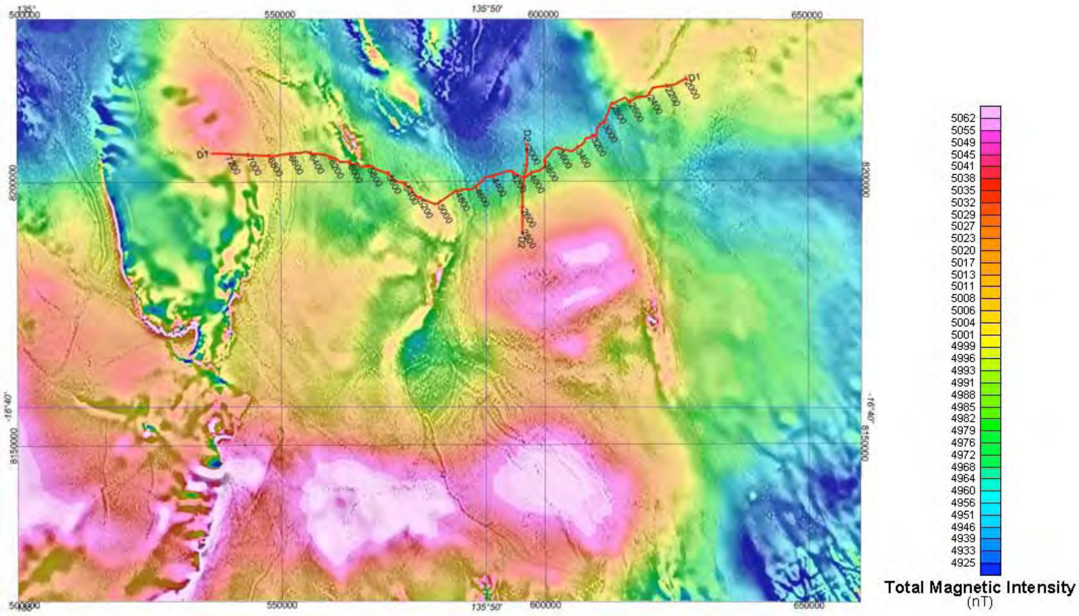

Figure 19: *Aeromagnetic image of the Southern McArthur Basin region, with vertical derivative of the TMI as shading. Seismic lines with CDP's marked in red.*

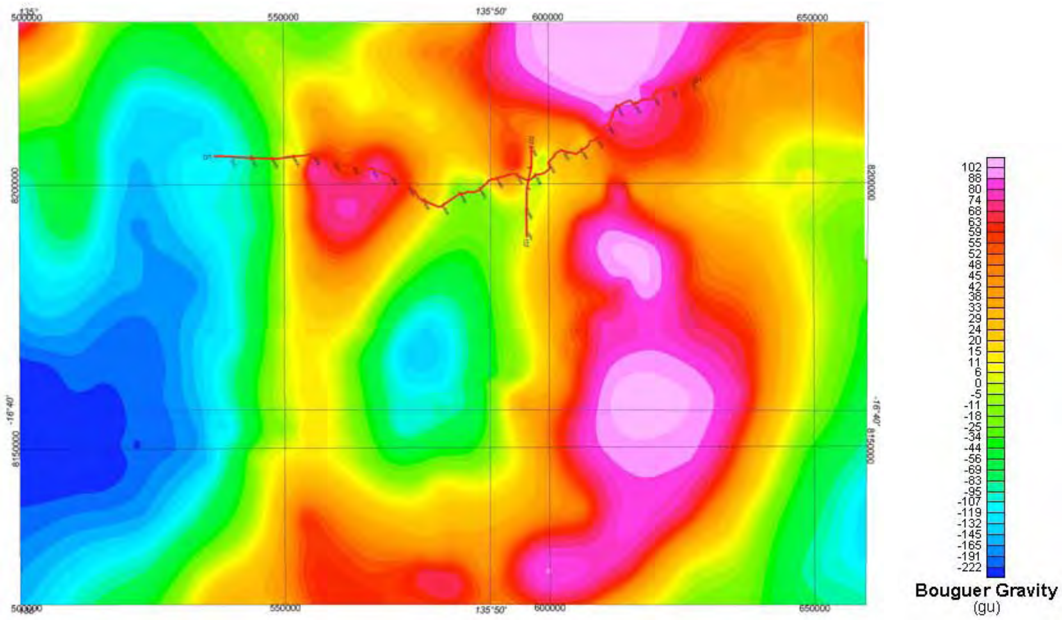

Figure 20: *Bouguer gravity image of the Southern McArthur Basin region. Seismic line locations with CDPs are shown in red.*

PETROPHYSICS

Although sampling is by no means extensive within the Southern McArthur Basin, Leaman (1998) provides a good summary of physical properties, reportedly based on numerous bulk samples. The results are reproduced in Table 4 with additional comments and actual modelled values applied, shown in the final columns.

Table 4: Magnetic and density properties of rock packages in the Mt Isa – McArthur Basin region used for modelling of seismic lines. Sourced from Leaman (1998), and applied to potential field modelling of following section. Sus = Susceptibility

* Colour code for rock units on models.

** Seismic horizon match at base of unit.

UNIT	DENSITY (T M^{-3})	OBSERVED SUS (SI*1000)	MODELLED DENSITY (T M^{-3})	MODELLED SUS (SI*1000)	*	**	COMMENTS
Roper Group	~2.6	0	2.6	0			
Nathan Group	2.74	0	2.74	0			Considered too thin to be modelled separately
Upper McArthur Group	2.77-2.78	0	2.76-2.8	0			Broadened range to effect fit
Lower McArthur Group	2.7-2.78	0	2.74	0			Used sampling average as quoted by Leaman
Tawallah Group	2.74	0	2.74	0			
Tawallah Volcanic Members	2.8	5-13	2.8	10-20			Normally 10 to 18
Tawallah – Gold Creek Volcanics			2.8	3			Mapped to outcrop
Metamorphic Basement	2.75	0	2.8	0			Density adjusted upwards after numerous testing
Background			2.74	0			Density applied to non-modelled sections for contrast

Based on the above data, a thickening of the Roper Group is the most likely candidate for regional gravity lows. Thickening of the upper McArthur Group will potentially lead to 'local' Bouguer highs and thicker volcanics potentially lead to concomitant magnetic and gravity highs.

VALIDATION OF SEISMIC INTERPRETATION WITH POTENTIAL FIELD DATA

Figures 21 and 22 present the modelled results using the colour codes and definitions of Table 4. Polygons strike north-northwest and are modelled with large strike extents (> 40 km) to minimise along-strike edge effects.

Overall, the fit of the gravity is reasonable and the interpreted thickness of sedimentary piles works remarkably well against the field data. Thickening post deposition of the McArthur

Group is clearly defined on western end of the line and to a lesser extent on the eastern end. In contrast, the magnetics requires substantial inter-horizon variation within the Tawallah Group, but neither validates nor violates the very noisy intra-package signature.

General comments and key interpretation disparities are summarised as follows:

- The break between upper (higher density - cyan) and lower McArthur Group (lower density - blue) has been made on the seismic horizon marked as intra-McArthur (Barney Creek). Based on lithology descriptions, it appears quite arbitrary in terms of density change. However, the presence of a seismic horizon in the middle of the Group does support the idea of a density-domain change.
- On the basis of observed densities, an additional section of Tawallah Group or non-metamorphic basement is required between CDP's 3000 and 5000. The seismic data are particularly noisy at depth in this section, so the possibility of a deeper sedimentary package is quite plausible.
- Likewise, a shallower section of basement is required on the eastern end of the line; alternatively, a denser sedimentary package could also be invoked.
- Gold Creek Volcanics have been modelled separately on the western edge of the line because of the tie to outcrop at CDP 5911 (Table 4; Figure 23). The thickness is considered overly large but also provides for mass excess associated with possible volcanics at the base of the McArthur Group.
- The greatest disparity with the seismic interpretation occurs between CDP's 4100 and 4500. Despite relatively conformable stratigraphy, the gravity suggests either a basement high or up-faulted block of upper McArthur Group. On review of the regional gravity and geology (Figure 24), it can be seen that the upper McArthur Group is cropping out just to the north of this location, and the feature is probably more to do with an out-of-plane structure, rather than being a feature in the plane of the seismic transect.
- Between CDPs 6500 and 6580, 'Ridge-forming' Limmen Sandstone crops out on a 25m high mesa. Bouguer Gravity dips over 2mgals, which is expected from such a topographic feature. The topographic effect is also compounded by the 50 m 'jump-up' at the edge of the Roper Group at CDP 6700 (Figure 25).
- A comment is also pertinent on the section of modelling between CDPs 6000 and 6500. The Bouguer anomaly is nearly flat but the seismic interpretation has sedimentary packages very gently dipping to the west. One way to flatten the modelled response out is to make the Gold Creek Volcanics even broader near surface, but this has the consequence of transgressing seismic horizons of the McArthur Group. Another is to include thin lenticular horizons to balance the Bouguer anomaly.

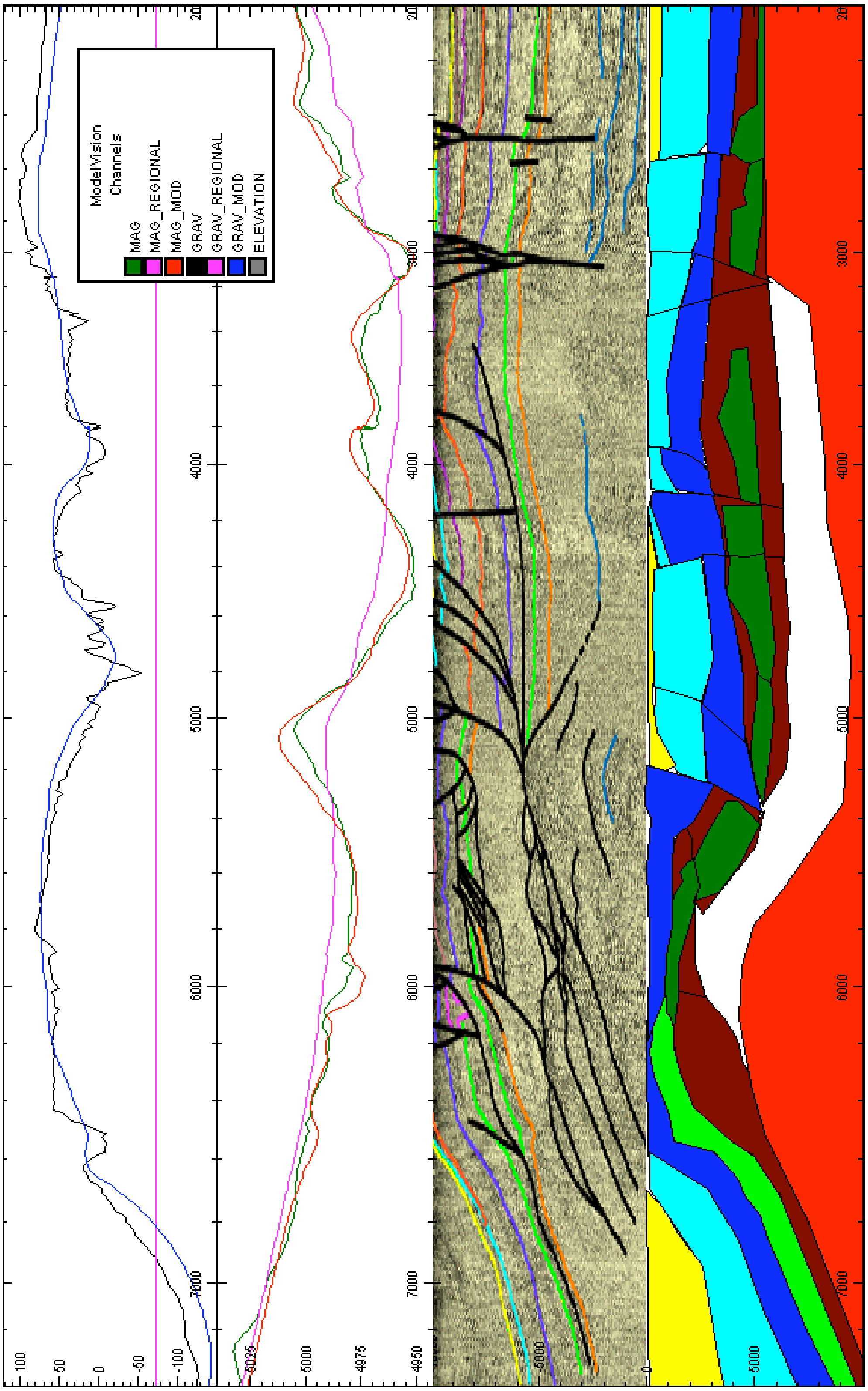

Figure 21: *Potential-field model for seismic line 02GA-BT1. Top display shows Bouguer gravity match and middle shows residual magnetics match for observed to modelled profile. Model and seismic section scaled as 0 to 10000m with colour coding explained in Table 4.*

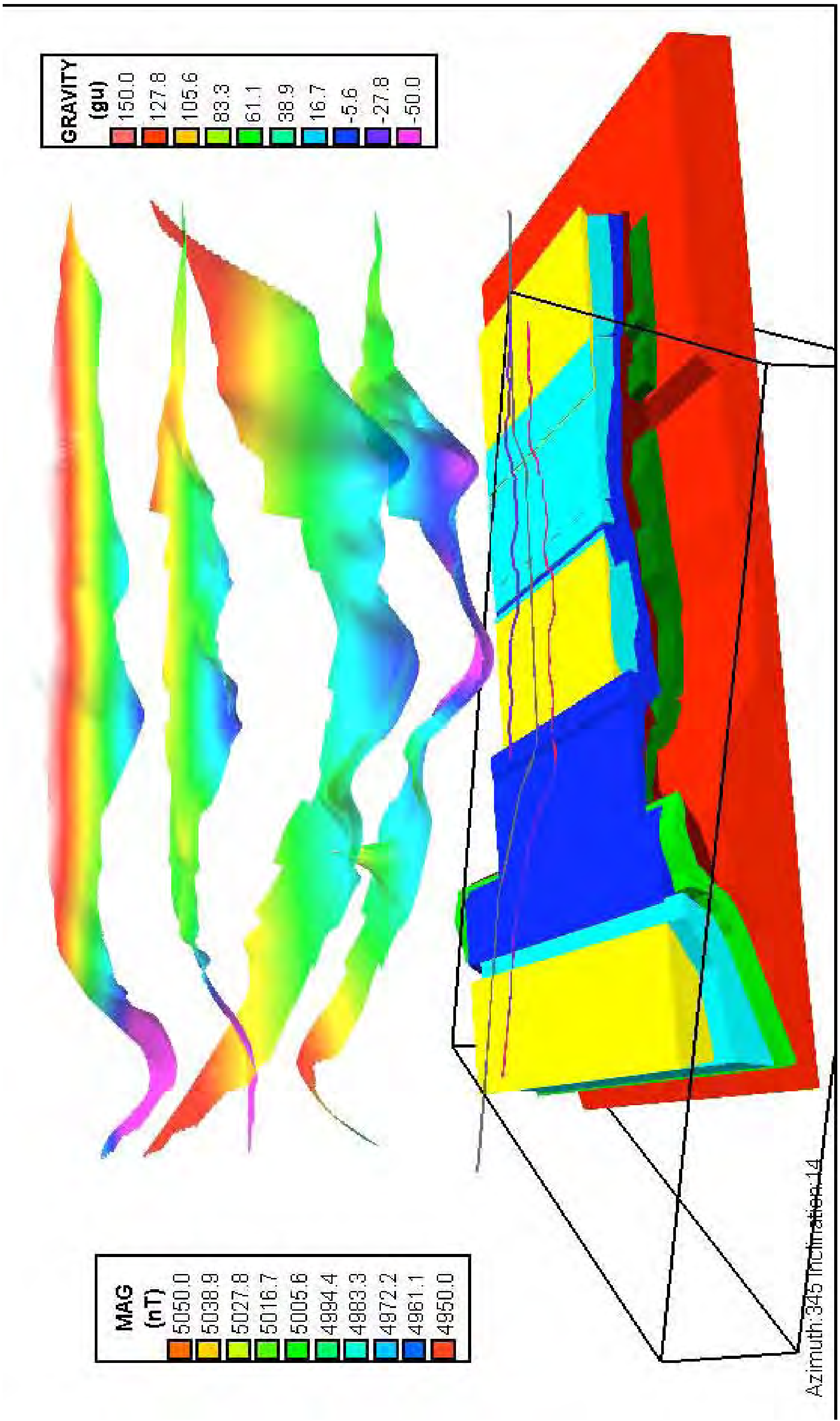

Figure 22: *Isometric projection of potential field model of seismic line 02GA-BT1 showing depth of modelling (12 km) and strike length of polygons (>40 km). Images from bottom to top are: Observed*

residual magnetic field, modelled magnetic field, observed Bouguer gravity and modelled Bouguer gravity. Pairs of images use equivalent scales.

Gravity Analysis

As mentioned above, gravity readings were recorded along the main seismic line at 250 m station spacing. While the high resolution should, for example, enable validation of fault locations (such as the Narwinbi Fault and the vertical displacement of Roper and McArthur Groups, Figure 21), interpretation is made difficult for the following reasons:

- There are clearly more density contrasts of similar magnitude than there are faults (see Figure 26).
- Positioning of the fault at the point of gravity inflection (as with the Narwinbi Fault) requires the assumption that these displacements are always near vertical at surface.
- Detailed modelling would require an equivalently detailed petrophysics database to make it worth while.

As such, the value of the detailed gravity has not been fully explored here.

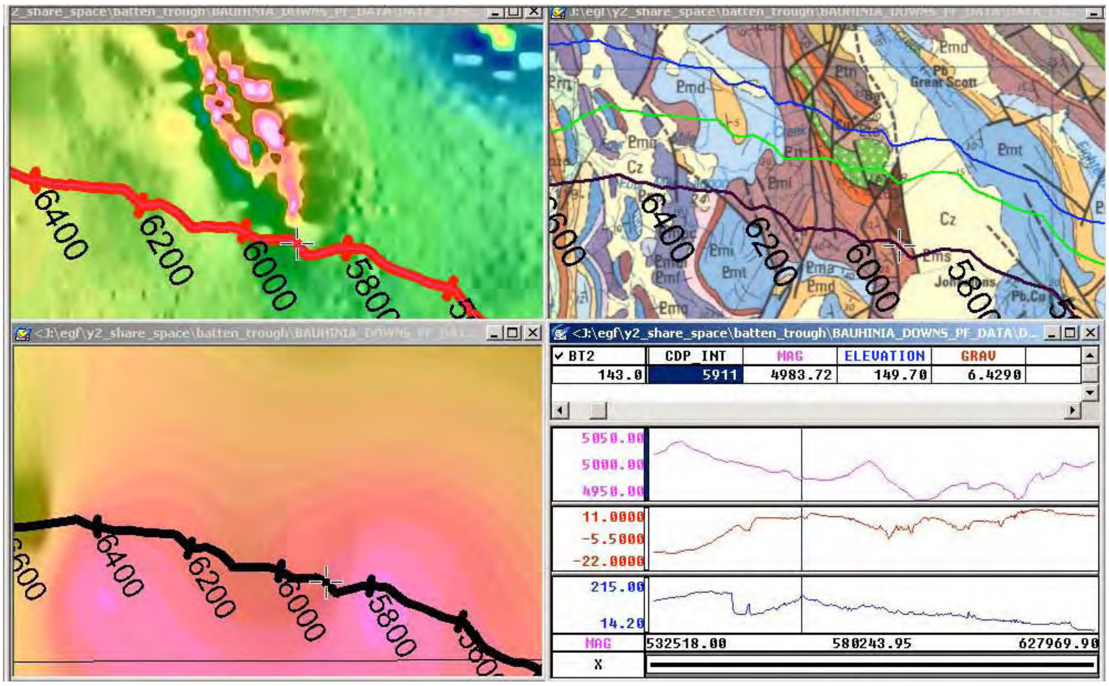

Figure 23: *Data window centred on CDP 5911. Magnetics (top left) and Bouguer gravity (bottom left) scaled with red high and blue low and shaded with vertical derivative of their respective fields. Geology (top right) from 1:250 000 Bauhinia Downs sheet showing outcrops of Gold Creek Volcanics in pale green, just to the north of CDP 5911. Profile data shown in the bottom right hand corner with magnetics in nT, Bouguer gravity in mgals and elevation as AMSL.*

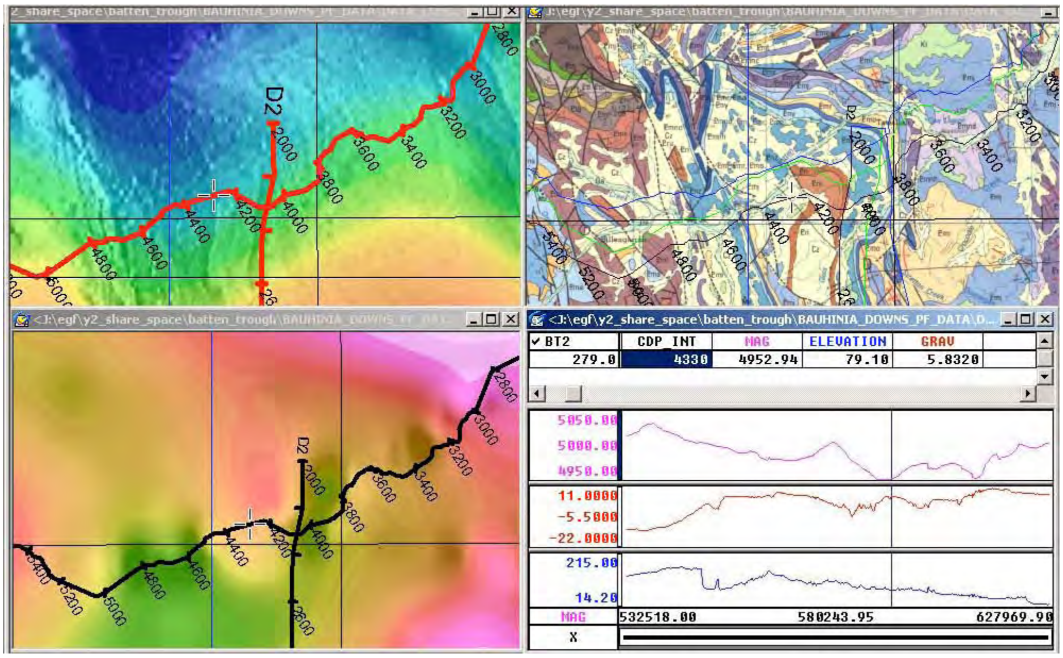

Figure 24: *Data window centred on CDP 4330. Magnetics (top left) and Bouguer gravity (bottom left) scaled with red high and blue low and shaded with vertical derivative of their respective fields. Geology (top right) from 1:250 000 Bauhinia Downs sheet showing outcrops of Upper McArthur (Batten Subgroup) in purple, to the north of CDP's 4200-4400. Profile data shown in the bottom right hand corner with magnetics in nT, Bouguer gravity in mgals and elevation as AMSL.*

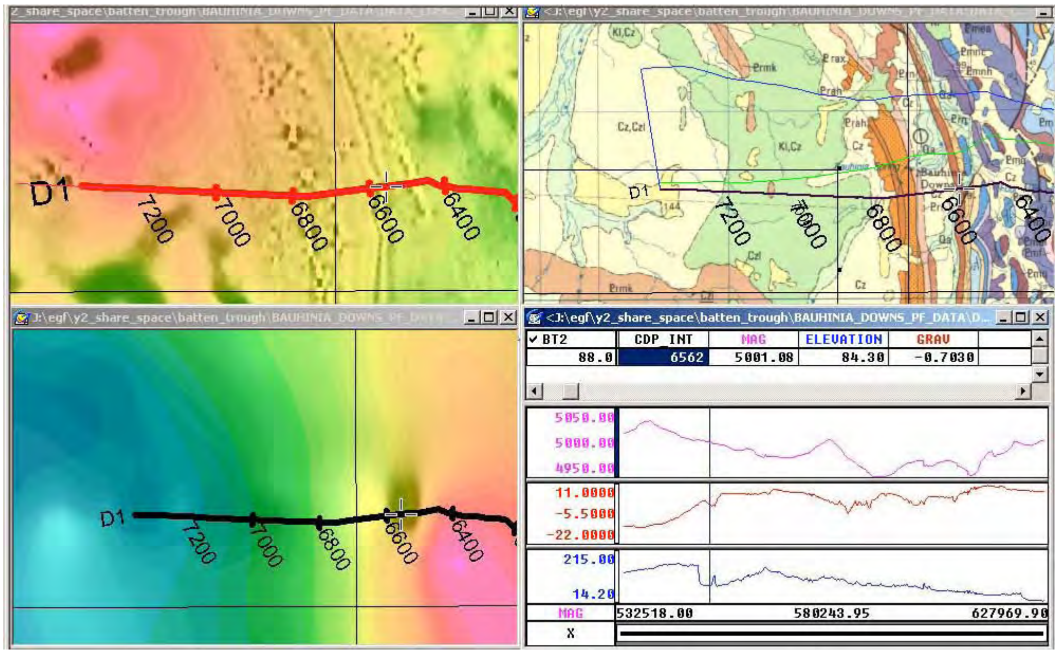

Figure 25: *Data window centred on CDP 6562. Magnetics (top left) and Bouguer gravity (bottom left) scaled with red high and blue low and shaded with vertical derivative of their respective fields. Geology (top right) from 1:250 000 Bauhinia Downs sheet showing outcrops of Limmen Sandstone (thin brown line) on CDP 6562 with Roper Group under cover to the west. Profile data shown in the bottom right hand corner with magnetics in nT, Bouguer gravity in mgals and elevation as AMSL.*

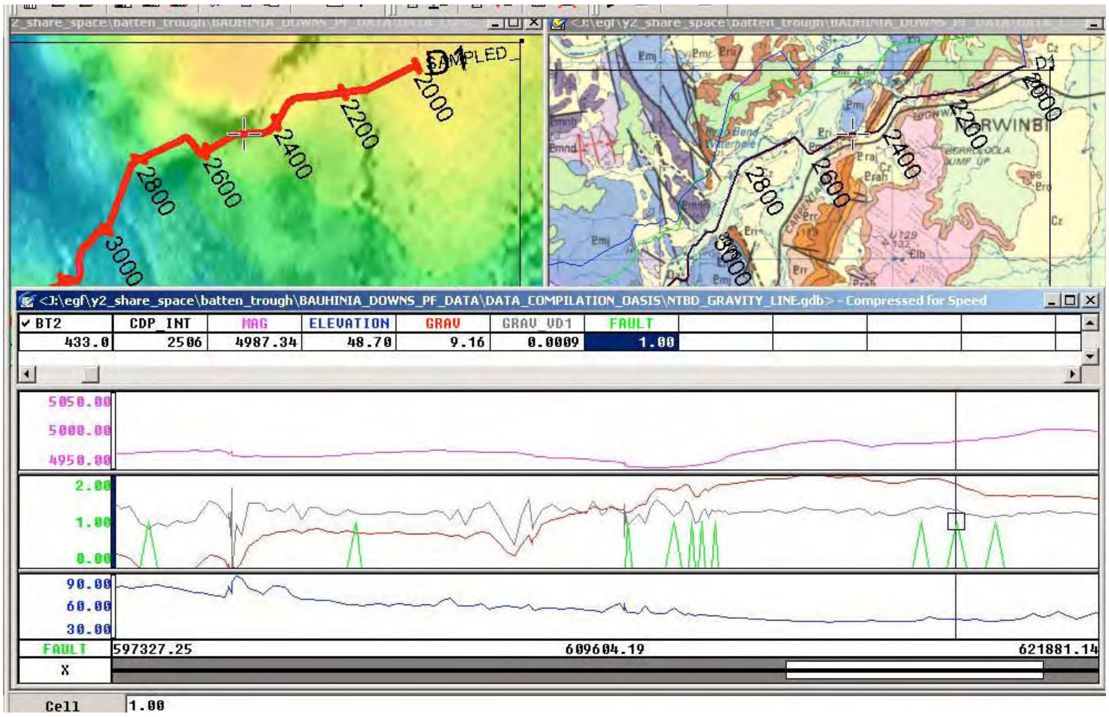

Figure 26: *Comparison of fault locations with gravity anomalies near the Narwinbi Fault (CDP 2506). Magnetics (top left) scaled with red high and blue low and shaded with vertical derivative of the fields. Geology (top right) from 1:250 000 Bauhinia Downs sheet showing Narwinbi Fault. Profile data with residual magnetics (nT/magenta) Bouguer gravity (mgals/red), vertical derivative of Bouguer gravity (mgals/m – grey), fault locations (green pointer) and elevation (AMSL/blue). The centre of the Narwinbi Fault, as indicated on the seismic section, corresponds to gravity inflection point and suspected vertical density contrast at surface.*

The Seismic Data in 3D

INTRODUCTION

The 2002 Southern McArthur Basin seismic lines followed existing roads and thus were crooked. The seismic processing took this crooked line geometry into account, however, when the data is plotted on paper it is viewed as a straight line. Unless one remembers where the bends are, it is difficult to work out where 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 27.

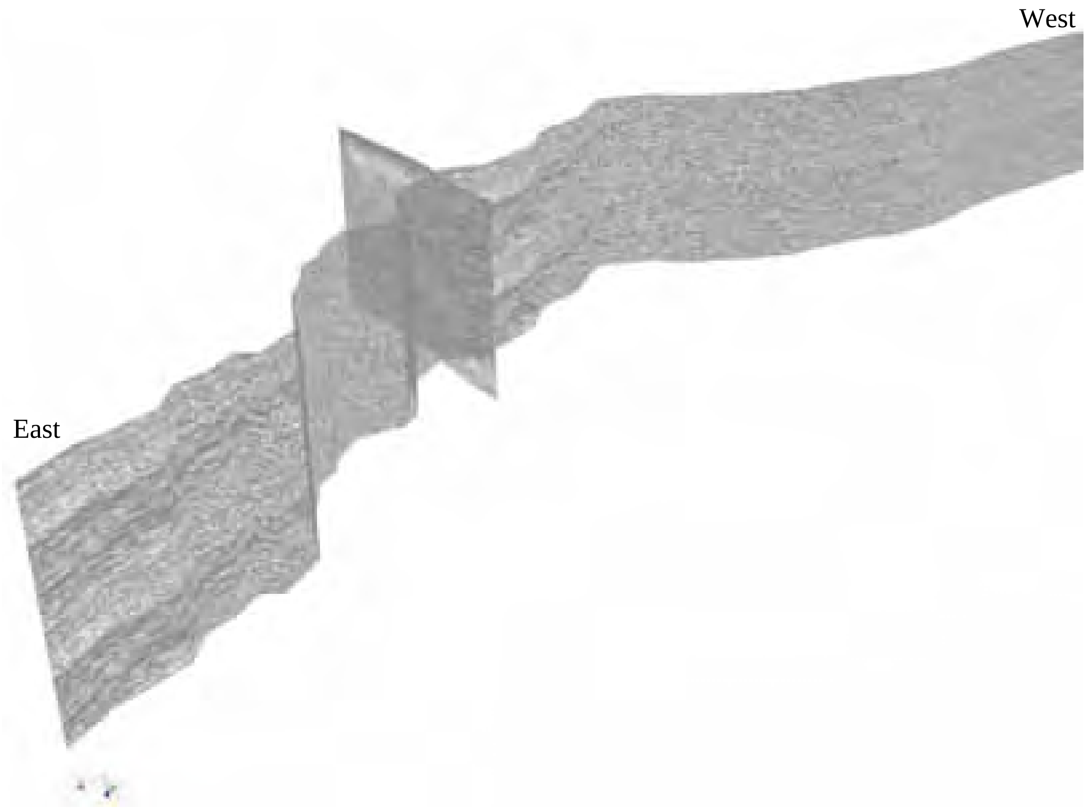

Figure 27: *Simple 3D model of the two seismic lines in 3D space. Viewed is from the northeast looking southwest, down onto the seismic lines. The crooked nature of the seismic is apparent in this view.*

No attempt was made to construct surfaces. 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 28, 29 and 30 show detailed parts of the 3D model as you move from east to west along the seismic line 02GA-BT1.

There is a marked geometrical change in that there are essentially flat lying rocks to the east in the Southern McArthur Basin region across the Emu Fault. This can be seen in Figure 28.

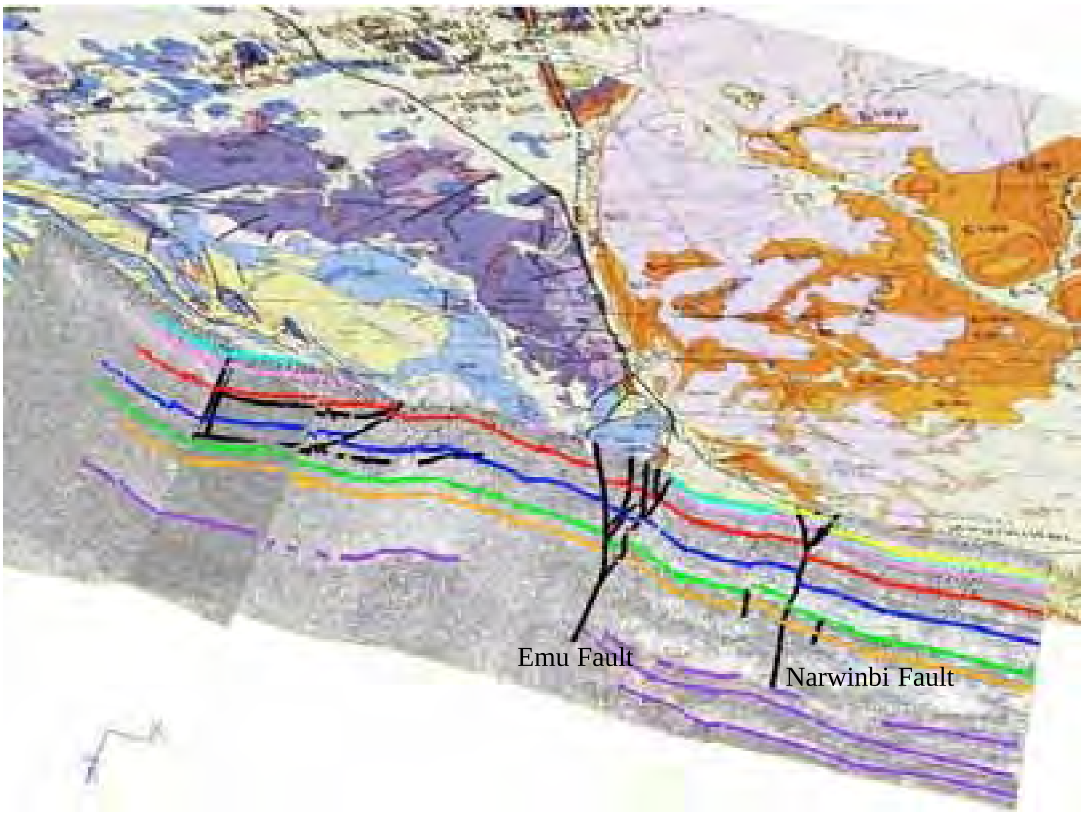

Figure 28: *Detailed view of the 3D model showing the Emu and Narwinbi Faults. Viewed from depth looking north-northwest. The geology is shown at surface level and can be regarded as a lid to the model.*

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 29).

Figure 30 shows the western end of line 02GA-BT1, with the Bauhinia Downs region to the left. The large thickness of west-dipping sediments is clearly shown.

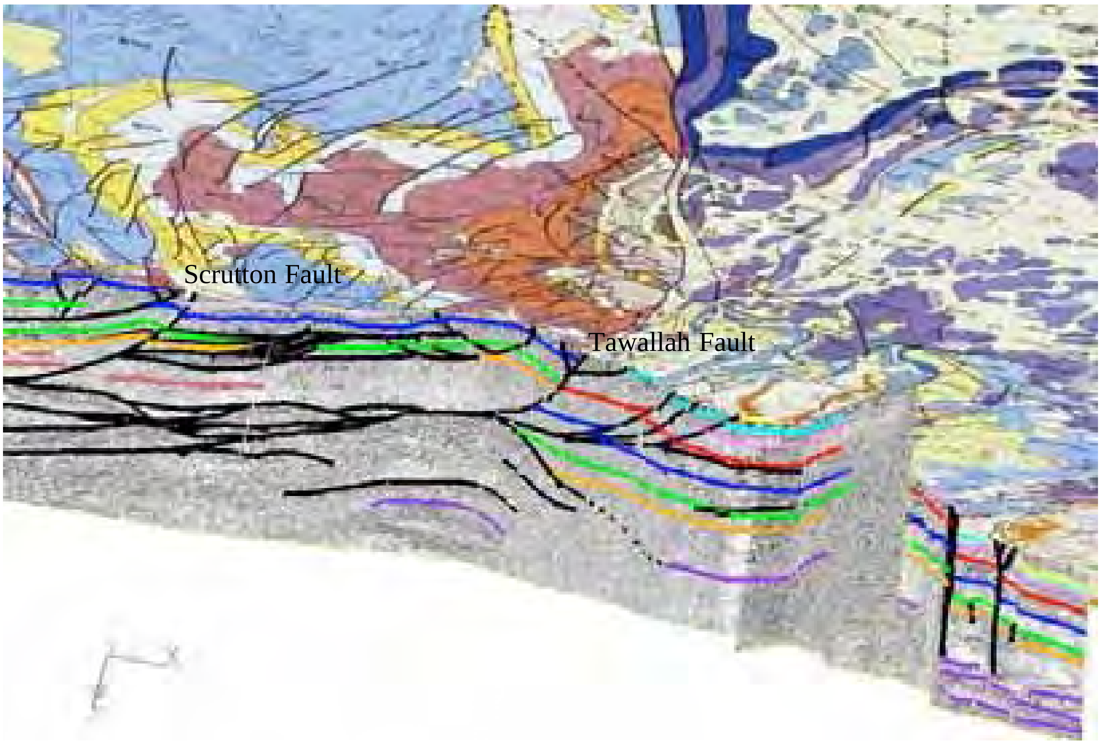

Figure 29: *Detailed view of the 3D model showing the Scrutton (left part of image) and Tawallah Faults (centre of image). Viewed from depth looking north-northwest. The geology is shown at surface level and can be regarded as a lid to the model. Line 2 can be seen at the eastern end of the image, coming out of the page towards the viewer.*

Figure 30: *Detailed view of the 3D model showing the Bauhinia Downs region. Viewed from depth looking north-northwest. The geology is shown at surface level and can be regarded as a lid to the model.*

Implications of the Southern McArthur Basin Seismic Data to Mineral Systems

MCARTHUR STYLE DEPOSITS

Genetic models

Recent models for the formation of 'McArthur style' Zn-Pb-Ag deposits in northern Australia fall into the categories of syngenetic exhalative (SEDEX; Large et al., 1998), early epigenetic replacement (Hinman, 1996; Broadbent et al., 1998) or late epigenetic structural-controlled (Perkins, 1997; Perkins and Bell, 1998). The latter is difficult to rationalise for the McArthur River deposit (HYC), based on the ore textures, organic geochemistry, isotopes, base metal distribution and lack of deformation and metamorphism (Large et al., 1998, 2001, 2002; Chen et al., 2003). The fundamental requirement for the localisation of base metals in the syngenetic and early epigenetic models is a long-lived steeply dipping syn-sedimentary fault, which penetrates the underlying sedimentary pile.

In the case of the McArthur River deposit, it has been argued that the Emu Fault was a conduit for ore forming fluids moving from source to trap (Williams, 1978). The trap for base metals is the thick accumulations of carbonaceous deep-water shales and siltstones of the Barney Creek Formation (middle McArthur Group), deposited in sub-basins adjacent to the Emu Fault. The source of metals is open to speculation, but is probably permeable labile components of the deeper sediment pile, with a contribution from altered volcanics (Pietsch et al., 1991a; Cooke et al., 1998). It can be debated as to whether metals were sourced in the immediate vicinity of the ore deposit or they were transported from far field. Cooke et al. (1998) and Large et al. (1998, 2001) favour the upper Tawallah and lowermost McArthur Groups (3-8 km stratigraphically below the McArthur River deposit) as both source and lateral aquifer.

According to the exhalative model, deep oxidised metalliferous brines ascended along the Emu Fault from their lateral aquifer source and discharged within the lower part of the water column of an anoxic ('reduced') sub-basin to form a brine pool. Sulphides precipitated via microbial and/or chemical mechanisms to form thin stratified laminae, interspersed with background pelagic sediments and carbonate debris flows emanating from the nearby Emu Fault scarp. The repetitious nature of the McArthur River deposit ore body led Large et al. (2002) to propose a process of sporadic tectonic-controlled brine pulses from the Emu Fault; this genetic model was investigated by Large and co-workers from a fluid flow perspective and found to be viable under a number of circumstances.

Fluid flow modelling

Numerical fluid flow models for base metal mineralisation at the McArthur River deposit (Garven and Bull, 1999; Garven et al., 2001; Simms et al., 2001; Large et al., 2002; Yang et al., 2001a, 2001b) rely largely on the circulation of metalliferous brines in free convective cells of 20-50 km diameter, which develop within the proposed lateral aquifer system. Fluids were restricted to the subsurface of the models within the convective cells before and during early McArthur Group time (~70 million years; from 1710 to 1640 Ma) by an impermeable cap and tectonic quiescence. At this stage, the principal faults in the basin (Emu and Tawallah Faults) were inactive and had no influence on fluid flow patterns. According to Garven et al. (2001), the circulation cells are self-perpetuating and do not require the input of any extraneous heat source or irregular topography. A similar model has been proposed for the formation of uranium deposits in the Kakadu field (Raffensperger and

Garven, 1995). In contrast, Solomon and Heinrich (1992) proposed a free convection model for the McArthur River deposit that was driven by high heat flow associated with radioactive basement.

During Barney Creek Formation time, active tectonism was introduced into the models, involving topography-driven fluid flow from the basin flanks and tilted fault blocks. The first order control, however, on ore fluid focussing was discharge to the surface along the now-active Emu Fault, and recharge along the reciprocal Tawallah Fault. Fault valve behaviour and repetitious dilation is thought to relate to discrete seismic events (Sibson, 1990), and provided the only access in 70 million years to the metalliferous brines in the lateral aquifer and circulation cells.

The success of the fluid flow models is sensitive to various aspects of the cross-section used and the estimates of porosity and permeability. The steep (subvertical) west-dipping orientation and deep-rooted nature of the synthetic Emu and Tawallah Faults is implicit to the initiation and maintenance of west-to-east brine transport and the proposed discharge and recharge points. For example, east-dipping or vertical faults would stall or reverse the circulation cell so that fluid discharge occurs at the Tawallah Fault or not at all. Thinning of the aquifer toward the Emu Fault or tilting it toward the Tawallah Fault will also modify the results for the model substantially.

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 <u>are consistent</u> 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 <u>at odds with</u> 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 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 AngloAmerican.
- 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.
- Data released November 2003.
- Report released June 2004.

OBJECTIVES OF THE SURVEY

- Investigate the fundamental basin architecture of the Southern McArthur Basin, including the 'Batten Trough'.
- 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 Trough' 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.
- 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 (HYC) deposit.
- Base metal exploration plays and areas of potential exploration interest are expanded.

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Appendix 1: Acquisition Information

RECORDING EQUIPMENT

- **Aram 24 Seismic Data Acquisition and Processing System including**
- Real Time Parallel Processor Correlator.
- One (1) 10 metre Radio Mast on Recorder with High Gain Antenna.
- Forty Five (45) Remote Acquisition Modules (360 Channels).
- Forty Five (45) Telemetry Data Cables (360 Channels), 348 metres long with 8 Take-outs spaced at 43 metres apart.
- Geospace GS-32CT 10 Hz 395 ohm vertical geophones.
- Three Hundred and Sixty (360) geophone strings (360 Channels with 12 ph/group).
- Sensor SMT-200 Geophone Tester and QC system.

SOURCE EQUIPMENT

- **Four (4) IVI Hemi 60 4x4 Articulated Buggy mounted Vibrators**
- Peak Force is 62,031 lbs per Vibe.
- Hold Down Weight is 63,000 lbs per Vibe.
- One (1) Pelton Advance 2 Model 6 PC based VIBRASIG.
- Real Time Similarity System.
- Five (5) Pelton Advance 2 Model 6 VCE's plus various spare boards.
- One (1) Pelton Advance 2 Model ESG for Recording Truck plus various spare boards.
- Three (3) Vibrators operating Online (186,093 lbs Force) with one on standby (Figure 31).
- Vibrators are equipped with Force Control and Ground Force Lock using M5 High Performance Accelerometers.
- Electronics are capable of correlating various individual sweep frequencies and compositing any range or variation of Up sweeps or Down sweeps within the same VP location. This process is Trade Marked as Varisweep.

Figure 31: *Hemi 60 4x4 Vibrator Truck on top of Bauhinia jumpup*

RECORDING PARAMETERS – LINE 02GA-BT1

RECORDING PARAMETER SHEET

Client:	ANSIR	Crew:	401
Prospect Area:	McArthur Basin, NT	Line:	**02GA-BT1**
Survey:	2002 Batten Trough Seismic Survey		
Instrument:	ARAM24 NT (Ver 1.309)	Direction of Rec:	East to West
Date Recorded:	29 October to 6 November 2002		

Recording Parameters

Traces per File	242
Record Length	20-22 sec
Sample Rate:	2 msec
Tape Format	SEG-Y
Shot Points	1000 to 3760
Rec To Rec	1000 to 3760
Files	245 to 1715

Sweep Frequency

Sweep 1	7 to 56 Hz
Sweep 2	12 To 80 Hz
Sweep 3	8 to 72 Hz
Sweep 4	
Sweep 5	
Sweep 6	
Sweep 7	

Receiver Parameters

Station Interval	40 m
Geophone Array Length	40 m
Geophone Array Centre	Mid Station .5
Geophone Type	OYO GS32CT
Strings Per Station	1
Connection	Series/Parallel
Spread Geometry	Symmetrical
# of Station Gap at SP	0

Auxiliary Traces

Time Break	241
Time Reference	242

Source Parameters

No. of Sources On-Line	3
No. of Sweeps per VP	3
Sweep Length:	12 sec
Sweep Type	Linear
Geophones Per String	12
Sweep Type Mono / Vari	Varisweep
VP Interval	80 and 40 m
Source Array Length	60 m
Vibe Spacing Pad to Pad	15 m
Vibe Move Up	15 m
VP Source Centre	On Station
Vibe Electronics	Pelton Adv II Model 6
Vibrator QC	Vibra Sig
Force Control	Peak and Trough
Phase Lock	Ground Force
High Force Output	90%
Pelton Rev. Level	6E

RECORDING PARAMETERS – LINE 02GA-BT2

RECORDING PARAMETER SHEET

Client:	ANSIR	Crew:	401
Prospect Area:	McArthur Basin, NT	Line:	02GA-BT2
Survey:	2002 Batten Trough Seismic Survey		
Instrument:	ARAM24 NT (Ver 1.309)	Direction of Rec:	North to South
Date Recorded:	27 October to 28 October 2002		

Recording Parameters

Traces per File	242
Record Length	20 sec
Sample Rate:	2 msec
Tape Format	SEG-Y
Shot Points	1000 to 1430
Rec To Rec	1001 to 1430
Files	27 to 244

Sweep Frequency

Sweep 1	7 to 56 Hz
Sweep 2	12 To 80 Hz
Sweep 3	8 to 72 Hz
Sweep 4	
Sweep 5	
Sweep 6	
Sweep 7	

Receiver Parameters

Station Interval	40 m
Geophone Array Length	40 m
Geophone Array Centre	Mid Station .5
Geophone Type	OYO GS32CT
Strings Per Station	1
Connection	Series/Parallel
Spread Geometry	Symmetrical
# of Station Gap at SP	0

Source Parameters

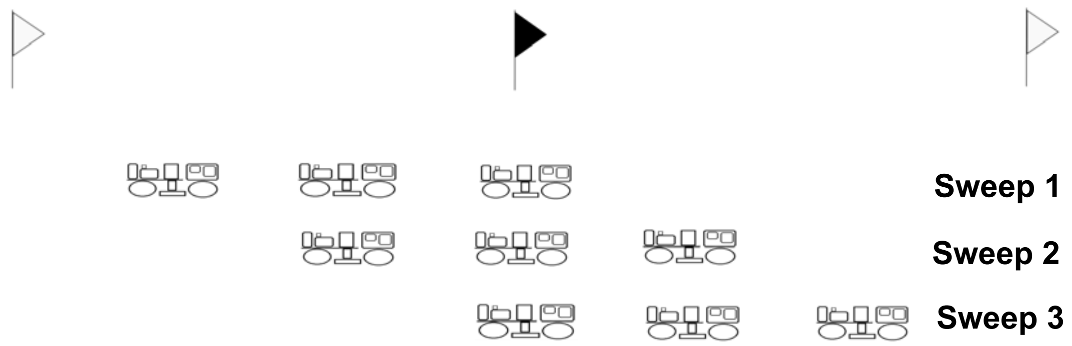
No. of Sources On-Line	3
No. of Sweeps per VP	3
Sweep Length:	12 sec
Sweep Type	Linear
Geophones Per String	12
Sweep Type Mono / Vari	Varisweep
VP Interval	80 m
Source Array Length	60 m
Vibe Spacing Pad to Pad	15 m
Vibe Move Up	15 m
VP Source Centre	On Station
Vibe Electronics	Pelton Adv II Model 6
Vibrator QC	Vibra Sig
Force Control	Peak and Trough
Phase Lock	Ground Force
High Force Output	90%
Pelton Rev. Level	6E

Auxiliary Traces

Time Break	241
Time Reference	242

SOURCE AND RECORDING ARRAY DIAGRAMS – 02GA-BT1 AND 02GA-BT2

Source Array:
3 vibes over 60m, 15m pad to pad, centred on VP 15m moveups, 3 sweeps



Receiver Array:
12 Phones over 40m, 3.33m between Phones, Centred between pegs