The Broadmere Structure

A Window into

Palaeoproterozoic Mineralisation

by

John F. Lindsay

McArthur Basin
Northern Australia

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The Broadmere Structure

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Welcome to the Broadmere Structure and a new perspective on mineralisation in the McArthur Basin. The Broadmere Structure, a small but complex inversion structure, occurs in a gently deformed part of the Batten Trough in the southern McArthur Basin. An analysis of seismic data over this well preserved area of the basin provides an understanding of the basinfill architecture and an insight into the forces determining fluid pathways throughout the evolving basin. A knowledge of this interrelationship between basin dynamics and fluid flow provides a valuable framework around which to develop exploration strategies.

Please read on….

The Broadmere Structure Report

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John F. Lindsay

Summary

An evaluation of more than 300 km of seismic data from the Broadmere Structure, a gently deformed part of the Palaeoproterozoic McArthur Basin of northern Australia, has provided a significant insight into the evolution of the basin-fill architecture which, in turn, has provided a framework for understanding the spatial and temporal distribution of mineralisation. The study, part of a joint National Geoscience Mapping Accord (NGMA) project with the Northern Territory Geological Survey, has shown that the Broadmere Structure is one of a number of complex inversion structures occurring within the Batten Trough. The flow of fluids and hence mineralisation was controlled by the timing of inversion and the geometry of the inversion structures. Concealed, potentially mineralised structures are indicated by surface exposures of the Nathan Group that occur as erosional remnants along their crests thus providing a tool to help focus exploration.

There is an accumulating body of evidence to suggest that there was an early Palaeoproterozoic supercontinent. The evidence suggests that assembly of the supercontinent began at approximately 2.0 Ga, probably in response to mantle instability beneath the Australian craton. The McArthur Basin, a complex, polyphase, intracratonic basin, was initiated at approximately 1.8 Ga as a sag basin as the supercontinent began to disperse and mantle activity declined. This shallow sag then began to accumulate a relatively mature clastic sedimentary succession with interspersed basic volcanics (**Summary Diagram**).

Subsequent extension of the weakened crust, beginning at approximately 1730 Ma, led to the development of a series of normal faults and half grabens within zones defined laterally by major strike-slip fault complexes, such as, the Emu Fault Zone. The half grabens were initially filled by a volcaniclastic sedimentary succession with associated bimodal volcanics. During subsequent basin subsidence, which occurred initially in response to thermal recovery and later to episodes of compression/transpressional reactivation ending at approximately 1575 Ma, the sub-basin accumulated a mixed carbonate and clastic succession exceeding eight kilometres in thickness (McArthur and Nathan Groups). A major change in basinal and regional dynamics between 1575 and 1500 Ma (Isan Orogeny) led to the inversion of the thickened succession overlying the half grabens and extensive erosion of earlier depositional units. Structural inversion was followed some time later by deposition of a further three kilometres of shallow marine clastic sediments of the Roper Group which were, in turn, deformed by later structural events.

The analysis of the Broadmere Structure has provided a simple basin-fill architecture or framework in which to evaluate basinal prospectivity. The primary extensional faults provide the main control on potentially prospective structures by determining deposition of the organic-rich facies that may generate petroleum or host mineralisation. The primary half grabens formed localised anoxic, sediment-starved depocentres in which organic-rich sediments accumulated. They also controlled later subsidence, whether it was related to further extension, or to later compression/transpression. The distribution of ore bodies (or for that matter hydrocarbons) is a function of the timing of fluid

movement and the nature of fluid pathways, as determined by the evolving basin-fill architecture and subsequent geohistory.

Diagenesis occurred very early in carbonate-rich intervals within the McArthur Basin succession, thus sealing them to later fluid movement. The carbonate intervals, most of which form the upper part of the highstand systems tracts, then acted as aquicludes, channelling fluids through the more permeable intervals in the transgressive and lower highstand systems tracts. Since the sequences drape over the underlying extensional faults, mineral-rich fluids could not readily move vertically through the succession from the extension faults but, were instead, introduced into the system from the major faults bounding the Batten Trough. Fluids then moved laterally through the permeable channels into the Batten Trough. Spatial data show that Pb and Zn occurrences lie close to the bounding faults, while Cu occurrences are distributed across the width of the Batten Trough, supporting a more or less syngenetic origin for the former and a much later, post-inversion, epigenetic origin, for the latter. Clearly, these conclusion must be integrated into any exploration strategy.

Introduction

The McArthur Basin covers an area of 180,000 km^2 in the central northern region of the Australian continent (**Figure 1**). The full extent of the basin is unknown as large areas extend beneath the Neoproterozoic to early Palaeozoic Georgina Basin (cf., Lodwick & Lindsay, 1990), the Cainozoic Carpentaria Basin and the Arafura Sea (Jackson et al., 1987; Haines et al., 1993; Plumb et al., 1990). However, it is bounded to the southeast by the older rocks of the Murphy Inlier, which also separate it from the contemporary Mount Isa Basin. In the northwest, the basin is limited by the older Pine Creek Geosyncline, while to the northeast, it is bounded by the Arnhem Block.

The basin, which contains a Palaeoproterozoic to Mesoproterozoic mixed carbonate and clastic depositional succession (**Figure 2**), is a broad shallow crustal depression bisected by a much deeper structure, the Batten Trough (**Figure 3 and Figure 4**). This trough, which is approximately 60 km wide, is flanked by the Bauhina Shelf to the west and the Wearyan Shelf to the east (cf., Plumb et al., 1980; Jackson et al., 1987). The Emu Fault Zone clearly separates the trough from the Wearyan Shelf (**Figure 4**). To the west, a series of less continuous faults locally defines the margin of the trough. In the southern McArthur Basin the Batten Trough contains upwards of 12 km of sedimentary rocks compared with the four kilometres of sedimentary rocks on the shelves on either side.

The data presented here are based upon a relatively small but well distributed grid of seismic profiles gathered by Amoco in 1983 (**Figure 4**) (Amoco, 1984). The survey consists of 333 km of sign-bit-recorded, 512-channel, Vibroseis data. The data were processed to 128 fold with penetration aimed at four seconds two-way-time (TWT) (see **Table 1** for processing parameters). The seismic grid is complemented by a small number of drill holes and two petroleum exploration wells (**Table 2**).

The Broadmere seismic survey extends across most of the southern part of the Batten Trough including the Broadmere inversion structure. The Amoco evaluation of the data (Amoco, 1984) was completed prior to the drilling of **Broadmere #1 well** (**Table 2**) (Amoco, 1985) and, as a consequence, is in need of re-evaluation. The gently deformed rocks of the Broadmere Structure provide a unique window into the structure of the McArthur Basin. This record, which is part of a National Geoscience Mapping

Accord (NGMA) Project in cooperation with the Northern Territory Geological survey, re-evaluates the Broadmere Structure and uses it as a basis to develop a three-dimensional framework within which the petroleum and mineral potential of the basin can be evaluated.

Basin Framework

The sedimentary rocks preserved in the Batten Trough have been divided into five, informally defined, megasequences based on major erosion surfaces within the basin fill (**Figure 5**). The surfaces were selected first, because they are seismically mappable, and secondly, because they define major phases in the evolution of the basin (cf., Southgate et al., in prep.). The megasequences, which coincide, in part, with the groups and subgroups defined by Jackson et al. (1987) (**Figure 2**), are as follows:

1. Megasequence M1 (c.1760-1730 Ma)

This megasequence includes the basic volcanic and volcaniclastic units below the Big Supersequence (Southgate et al., in prep.) (**Figure 5**). Only the upper erosion surface is mappable (base of the Big Supersequence).

2. Megasequence M2 (c.1730-1645 Ma)

The Big, Prize, Gun and Loretta Supersequences (Southgate et al., in prep.) have been combined in this thick megasequence. The upper erosion surface coincides with the event surface at the top of the Loretta Supersequence (**Figure 5**). In lithostratigraphic terms the unit includes the upper Tawallah Group, including bimodal volcanics, and part of the mixed carbonate and clastic succession of the lower McArthur Group.

3. Megasequence M3 (c.1645-1615 Ma)

M3 includes the River and Term Supersequences of Southgate et al. (in prep.) (**Figure 5**). Lithologically the interval includes the upper Umbolooga Subgroup and the whole of the Batten Subgroup (**Figure 2**). The highly mineralised Barney Creek Formation is also included in this interval.

4. Megasequence M4 (Nathan Group, c.1615-1575 Ma)

This megasequence coincides with the Nathan Group (Lawn, Wide and Doom Supersequences of Southgate et al., in prep.) and includes all of the section (**Figure 5**) to the major erosion surface at the base of the Roper Group (**Figure 2**).

5. Megasequence M5 (Roper Group, c.1500-1425 Ma)

M5 includes the post-Isan-Orogeny Roper Group. As well as the basal unconformity, a prominent sequence boundary at the top of the Bessie Creek Sandstone (**Figure 2**) has been mapped to provide additional information on the evolution of the Roper Group through time. This interval is considered to have the greatest **hydrocarbon potential** (see Amoco, 1984).

Megasequence M1 (c. 1760-1730 Ma)

The M1 Megasequence (c.1760-1730 Ma) is the earliest in the basin (**Figures 2 and Figure 5**). This chronostratigraphic interval includes the lowermost part of the Tawallah Group beneath the sequence boundary at the base of the Big Supersequence (see Page, 1997; Page & Sweet, 1998; Southgate et al., in prep.; Jackson et al., 1987). The lithostratigraphic Tawallah Group is complex but consists largely of sandstone and minor shale, siltstone and dolostone and thin intercalated basic volcanics (Pietsch et al., 1991, Jackson et al., 1987). The sandstones are predominantly mature, thick-bedded, quartz arenites, that are frequently cross bedded and locally conglomeratic. Sedimentary structures and facies suggest an overall shallow marine, possibly sub-tidal, depositional setting for the clastic units of the Tawallah Group. The prominent erosional boundary at the top of M1 separates the basic volcanics in the lower part of the Tawallah Group from the bimodal volcanics towards the top.

Regionally, M1 is very consistent in thickness, and apparently independent of the development of the Batten Trough. While the base of the succession is often poorly imaged seismically, where visible, the megasequence is uniform in thickness across the area of the Broadmere survey. Strong reflections within the megasequence (see **seismic line 83-124**) indicate large acoustic velocity contrasts, mostly between clastic and volcanic intervals. The upper contact of the megasequence was deeply dissected prior to deposition of M2 (**Figure 6**). Consequently, as discussed in a following section (**See Megasequences M2 and M3**), it has been possible to map the upper erosional contact of M1 across the seismic grid, but not the lower contact.

Megasequence M2 (c.1730-1645 Ma)

This megasequence consists of the Big, Prize, Gun and Loretta Supersequences (Southgate et al., in prep.). For the purposes of seismic mapping the event surface at the top of the Loretta Supersequence (Southgate et al., in prep.) (**Figure 5**) was selected as the upper boundary of the megasequence. This surface coincides with the top of the Tooganinie Formation in the middle of the Umbolooga Subgroup (**Figure 2**).

Thus, in lithostratigraphic terms, the M2 megasequence includes the upper Tawallah Group and part of the lower McArthur Group. Lithologically the basal part of M2 consists of volcaniclastics and thin bimodal volcanics (e.g., Aquarium and Wollogorang Formations) of the upper Tawallah Group. The section above the Tawallah Group, which begins with the Masterton Sandstone, is predominantly clastic but is predominantly carbonate towards the top of the megasequence. The uppermost formations of this interval were deposited during a period of localised structurally controlled rapid subsidence which produced a series of depositional sequences that alternate between deeper water clastic sediments that shallow upward to massive platform carbonates. Facies vary considerably from the clastic-dominated tidal settings of the Masterton Sandstone to the deeper-water marine clastic and carbonate shallowing-upward cycles of the upper part of the subgroup (cf., Lindsay et al., 1996). In the upper part, each depositional cycle began with a transgressive interval followed by a restricted, anoxic, clastic-dominated setting that shallowed upward to a carbonate platform setting in which subtidal and peritidal environments eventually evolved. These cycles, because of their inherent acoustic velocity contrasts, produce strong parallel reflections on the seismic sections in the upper part of the megasequence **(see seismic line 83-120)**. In contrast, the lower Umbolooga Group, which consists of complex alternations of volcanic and clastic units, is relatively transparent acoustically.

Regionally, the basal surface of M2 (**Figure 6**), which has considerable erosional relief, slopes from east to west, beginning at 2100 ms (TWT) (c.6100 m) in the east and extending to depths of 3600 ms (c.11400 m) in the west. The Broadmere survey area is bisected by a single, continuous, normal growth fault, the Broadmere Fault, trending approximately northwest (see **seismic line 83-120**). The fault intersects M1 and the major erosion surface at the base of M2.

Even though now largely inverted, the Broadmere Fault still displays as much as 800 ms (TWT) (c.2500 m) of displacement locally (see **seismic line 83-115**). The seismic sections indicate growth on the fault on all units up to and including the Nathan Group (M4). Poorly imaged reflectors within the lower part of M2, that is the bimodal volcaniclastic interval of the lithostratigraphic Tawallah Group, are deformed and suggest that fault displacement was initially rapid. Beyond the seismic grid, exposed faults with similar orientations align with the growth fault and are here referred to as the Broadmere Fault zone. In outcrop the faults intersect the lower part of the Roper Group (M5) to the southeast of the seismic grid (**Figure 4**) whilst to the northwest they completely cut through the Roper Group. Details of the growth are discussed elsewhere (see **Megasequence M3 and M4**). Another major fault, the Mallapunyah Fault, exposed at the surface to the south of the seismic grid parallels the Broadmere Fault suggesting that they are part of a related set associated with early extension (**Figure 4**).

The lower contact of M2 has considerable topographic relief. Regionally, the interval thickens east to west from approximately 900 to 1200 ms (TWT) (2300 to 3000 m) across the Broadmere seismic grid (**Figure 8**). Locally, however, above the growth fault, the thickness is increased by as much as 600 ms (1500 m) above the regional levels to more than 1400 ms (3600 m) as a consequence of growth on the underlying fault (see **seismic line 83-113**).

Megasequence M3 (c.1645-1615 Ma)

M3, as here used for the purpose of seismic mapping, consists of the River and Term Supersequences (Southgate et al., in prep.) (**Figure 5**) and includes part of the Umbolooga Subgroup and the Batten Subgroup (**Figure 2**). Lithostratigraphically formations from the Leila Sandstone to the Reward Dolomite at the top of the Umbolooga Subgroup (c.1710-1640 Ma) are includes in M3. The Umbolooga Subgroup is predominantly dolomitic with only a minor clastic component. The succession was deposited as a number of thin depositional sequences that alternate from a shallow marine to a peritidal setting (Lindsay & Brasier, in press; Jackson and Southgate, 1997). Suggestions that the succession is in part lacustrine and sabkha (Jackson et al., 1987, Pietsch et al., 1991) are not consistent with facies which suggest that the interval is largely shallow marine in origin (Lindsay and Brasier, in press; Jackson et al., in press). The Batten Subgroup (c.1640-1615 Ma), which rests unconformably on the Umbolooga Subgroup, consists of four formations (**Figure 9**) whose total thickness varies from 150 to 1000 m (Jackson et al., 1987) is also largely shallow marine. The Amos Formation, which has been identified as part of a younger chronostratigraphic interval (see **Figure 5**) does not appear to be present in the study area.

Structure contours of the erosion surface at the base of M3 (**Figure 5, Figure 10**) indicate that the surface has a regional westward slope extending from a maximum depth of approximately 2.4 s to 1.5 s (TWT) (c.6800 to 3300 m). The main inversion structure, which is oriented north northwest, lies above the primary growth fault (see **seismic line 83-120**). The inversion structure is disrupted by two minor faults that roughly parallel its crest for approximately 15 km. The structure contours close against these faults at a depth of approximately 2.25 s (TWT) (c.6400 m). Isochrons of M3

(**Figure 11**) indicate that, regionally, the interval is thickening west to east from around 300 ms to 800 ms (TWT) (c.660 to 1700 m). Across the inversion structure, growth on the underlying extensional fault increased the thickness from regional levels of 500 ms to more than 800 ms (TWT) (c.1100 to 1700 m). Internally, the megasequence is relatively seismically transparent, except for a few weak reflections at the level of the Barney Creek Formation as a consequence of velocity contrasts between carbonate and clastic intervals. Minor faulting parallel to the axis of the Broadmere Structure displaces reflectors by 10 to 15 ms. The faults are deceptive. Even though they are shown as continuous features on the structure contour maps, they form part of a discontinuous wrench-fault zone, that is, they outline a poorly defined flower structure (see **seismic line 83-120**). Locally, the faults appear as steep reverse faults, but elsewhere they appear as minor thrust faults that extend into more ductile shale intervals at low angles.

Megasequence M4 (Nathan Group, c.1615-1575 Ma)

This megasequence consists of the Lawn, Wide and Doom Supersequences of Southgate et al. (in prep.) and is equivalent lithostratigraphically to the Nathan Group. The Nathan Group (c.1615-1575 Ma, see Page, 1997; Page & Sweet, 1998; Southgate et al., in prep.) consists of only two major formations the Balbirini Dolomite and the Dungaminnie Formation although locally the Amos Formation is significant (Jackson et al., 1987; Page & Sweet, 1998) (**Figure 12**). The Balbirini Formation is largely dolarenite with subordinate silty sand and dololutite. Although Jackson et al. (1987) suggest a continental sabkha origin for the Balbirini Formation because of the common evaporitic textures, sequence analysis suggests a more open tidal or subtidal origin within a broad platform setting for large parts of the formation (Brasier & Lindsay, in press; Jackson et al., in press). The Dungaminnie Formation begins in sandstone, but passes upwards to dololutite and dolarenite with evidence of periods of evaporitic conditions. Sedimentary structures suggest a shallow marine setting.

The megasequence rests upon a regional unconformity (base of the Lawn Supersequence; Southgate et al., in prep.) (**Figure 5)** which separates it from the underlying McArthur Group (M3). Beneath the Broadmere seismic grid, the unconformity occurs at depths ranging from 1 to 2 s (TWT) (c.2250 to 5700 m) (**Figure 13**). The surface is complex due to the underlying inversion structure and the thickening of the underlying succession across the earlier normal fault (see **seismic line 83-120**). Immediately above the inversion structure, the structure contours close around a wrench-fault zone in the vicinity of the **Broadmere #1 well**.

M4 sedimentation was terminated between c.1575 and 1500 Ma by a major compressional event, the equivalent of the Isan Orogeny, farther to the east. As a result of erosion during this interval, the Nathan Group (M4) along with the underlying McArthur Group, was deeply eroded and is very variable in thickness. In outcrop, the group reaches its maximum thickness of 1600 m to the southeast of the seismic network in the Abner Range (Jackson et al., 1987). It is, however, considerably thinner in exposed sections to the east of the Batten Trough (**Figure 4**) where the Dungaminnie Formation has been largely removed by pre-Roper Group (M5) erosion. Seismically, the Nathan Group (M4) appears as a thin wedge of sediment paralleling the underlying growth fault (**Figure 14**). That is, the Nathan Group (M4) has survived only in areas of thickening associated with synsedimentary growth on the underlying extensional fault (see **seismic line 83-115**). Across most of the Broadmere seismic grid, less than 100 ms (c. 220 m) of the Nathan Group remains. The wedge of sediment preserved in the subsurface is exposed at the surface as a strike ridge three kilometres to the east of the seismic survey (**Figure 4**).

Megasequence M5 (Roper Group, c.1500-1425 Ma)

The Roper Group (M5), which is the youngest (c.1500-1425 Ma) of the McArthur Basin megasequences, rests on a regional unconformity that cuts into the underlying Nathan and McArthur Groups (**Figure 2 and Figure 5**). The group outcrops either side of the Batten Trough (**Figure 4**) where it ranges from one kilometre in thickness on the Wearyan Shelf to three kilometres thick on the Bauhinia Shelf. Overall, outcrop data suggest that the group thins eastward onto the Wearyan Shelf and that the main depocentre lay well to the southwest (Jackson et al., 1988). Unlike the earlier groups, the Roper Group is predominantly clastic with only minor carbonate intervals (Jackson et al., 1988). The deposition of the Roper Group marks a turning point in the evolution of the basin. While the deposition of the McArthur and Nathan Groups (M2 to M4) was centered over the Batten Trough, basin dynamics following the Isan Orogeny abruptly shifting the main depocentre some distance to the southwest. This shift is also reflected in inflections in the apparent polar wander path for the Palaeoproterozoic (Idnurm et al., 1993; Loutit et al., 1994; Idnurm & Giddings, 1995) which suggest a change in relative plate motion.

As a consequence of changing basin dynamics, the basal unconformity cuts deeply into the underlying units, locally removing the Nathan Group (M4) completely (**Figure 14**) and, over large areas, eroding the upper parts of M3. The present erosion surface (**Figure 15**) conforms to the inverted Broadmere Structure and ranges in depth from 800 ms (TWT) (c.1500 m) in the east to a maximum of 1900 ms (c.4900 m) in the west. Over the inversion structure the surface shallows to 1350 ms (c.3000 m) to produce closure around minor faults.

Following broad regional subsidence and a major transgression, the Roper Group was deposited as a series of readily identifiable depositional sequences which are well illustrated in **Broadmere #1** well (**Figure 16**) (Amoco, 1985) and the **Amoco 82-1** drill hole (**Figure 17**) (Dorrins & Womer, 1983). The sequences appear as coarsening upward successions, which begin in deeper-water, marine mudstone and siltstone settings and grading upward to quartz arenites; many are tidal in origin. Overall the sequences decrease in thickness from a maximum of approximately 1000 m near the base of the group to an average of 40 m towards the top. The decrease appears to reflect a decreasing subsidence rate in response to a decaying thermal event. Accommodation, and thus water depth, reached a maximum briefly during deposition of the 'Lansen Creek Shale' (cf., Velkerri Formation, Powell et al., 1987) (**Figure 2**). Each depositional sequence or coarsening upward cycle represents an upward shoaling succession, generally beginning in an anoxic, glauconitic, shale-dominated, shallow-marine setting which includes storm-generate turbidites and grading upward to tidally-dominated clastic sediments, which in the Bessie Creek Sandstone become aggradational. Depending upon accommodation, not all sequences progress through the full cycle. In the 'Lansen Creek Shale', for example, where accommodation was large, the cycles are incomplete and terminate in silty units.

Rb-Sr isotopic dating of illite from the Kyalla Member of the McMinn Formation suggests deposition of the Roper Group occurred at around 1428$\pm$31 Ma (Kralik, 1982). A major dolerite sill, which averages 200 m in thickness and extends over a large part of the Broadmere seismic study area, intrudes the Corcoran Formation. The emplacement of the sill occurred prior to final folding and faulting of the Roper Group as it remains at the same stratigraphic level throughout the area and is disrupted by faulting in the inverted structures overlying the growth fault at the centre of the study area (**see seismic line 83-120**). The presence of the dolerite, samples of which collected at some distance from the study area have been dated at 1323.8±3.6 Ma (Claoue-Long, pers. com.), suggests that final stage of inversion of the Batten Trough occurred after this date, presumably closer in time to 1.1 Ga, when the Rodinian supercontinent began to assemble. A magnetic high 20 km in diameter, visible in total magnetic intensity images northeast of the Broadmere seismic grid close to the **Amoco 82-1 well**, probably outlines the source of the dolerite (**Figure 3**).

The Broadmere inversion structure is well documented in the structure contours of the sequence boundary at the top of the Bessie Creek Formation (**Figure 18**). The structure, at this depth (450 to 500 ms TWT), has closure with a relief of approximately 100 to 150 ms (c.170-250 m). In 1984-85 Amoco (1985) tested the Roper Group for hydrocarbon potential. **Broadmere #1** well was drilled at the top of the inversion structure, close to the intersections of **seismic lines 83-120** and **83-117**. The well spudded in the upper Roper Group in the Cobanbirini Formation and reached total depth at 2174 m in the Mainoru Formation, just above the basal contact of the Roper Group. The primary objectives of the well was to intersect the sandstones of the Bessie Creek Sandstone and the Hodgson and Arnold Members of the Abner Sandstone (Amoco, 1985). Unfortunately, porosity in all of these units was effectively occluded by silica cementation. Isochrons of the lower Roper indicate a relatively uniform thickness for the interval of 1100 ms (TWT) (c.1700 m) across the seismic grid (**Figure 19**). Dip-meter logs suggest a westward movement of sediments early in the deposition of the Roper Group, with a shift to the east higher in the section.

Analysis

The seismic data show that the Broadmere Structure is a complex inversion structure that developed in response to a number of major tectonic events over a period of at least 600 m.y. Given this long history a full understanding of the structure can only be obtained by placing it in the larger global framework of plate tectonics.

A Global Perspective

There is a growing body of evidence to suggest that there is a periodic cycle of supercontinent coalescence and dispersal (Duncan & Turcotte, 1994; Murphy & Nance, 1992; Worsley, Nance & Moody, 1984) driven by large-scale mantle convection (Gurnis, 1988; Anderson, 1982; Kominz & Bond, 1991). The assembly and dispersal of Pangea and Rodinia are now relatively well understood in terms of such models. For example, the assembly and ultimate breakup of Rodinia is reflected in regional subsidence across Australia which began at around 800 Ma and led to the development of the Amadeus, Officer, Ngalia and Georgina Basins (Lindsay et al., 1987, Lindsay, 1999).

There is also evidence to suggest that by 2.0 Ga a supercontinent similar in significance to Pangea had also come into existence (Hoffman, 1988, 1989, 1991). Crustal accretion in west Africa began at approximately 2.1 Ga and culminated in a major series of tectonic episodes at 1.9 Ga (Boher et al., 1992; Abouchami et al., 1990; Davies, 1995). Equivalent accretion events can be identified in Laurentia and Baltica (Gower, 1985; Gaal & Gorbatschev, 1987). In particular, there appears to have been a rapid assembly of Archaean crustal blocks to form northern Laurentia between 1.95 and 1.8 Ga (Hoffman, 1988). Regional data thus suggest that the supercontinent began to assemble at some time close to 2.0 Ga and then began to disperse again at approximately 1.8 Ga, probably as a result of mantle instability (cf., Gurnis, 1988).

This major planetary event appears to have left an indelible record on the ancient Australian craton. However, in Australia crustal activity appears to have been largely intracratonic or anorogenic. The Barramundi Orogeny, a significant event across much of northern Australia, appears to be associated with the final phase of the assembly of this early Palaeoproterozoic supercontinent. Crustal shortening, voluminous igneous activity (Wyborn, 1988) and low-pressure metamorphism (Etheridge et al., 1987) during the Barramundi event produced the basement rocks underlying much of northern Australia (Plumb, et al., 1980). The crust, which probably evolved on Archaean continental crust, is at least 43-53 km thick (Collins, 1983), and may well have been thicker in the past. An alternative view put forward by Myers et al. (1996) suggesting that Australia consisted of numerous crustal fragments during this period is not consistent with observed basin architecture. The Archaean Hamersley Basin has a basin-fill architecture (cf., Krapez, 1996) very similar to that of the Neoproterozoic basins of central Australia (cf., Lindsay & Korsch, 1989; Lindsay & Leven, 1996) suggesting it is intracratonic rather than being a passive margin setting. The Hamersley Basin, which also overlies normal crustal thicknesses (Drummond, 1981), is the first clearly identifiable intracratonic setting preserved on the Australian craton in which marine sediments have been preserved in a response to broad regional crustal subsidence. Earlier basins, such as the Lalla Rookh Basin, are simply graben-like feature, filled largely by fluvial sediments (Krapez & Barley, 1987). Comparison of the Pilbara region (and the Hamersley Basin) with the Kaapvaal region of southern Africa (Cheney, 1996) suggests that by late Archaean Australia formed part of a large crustal block perhaps the earliest supercontinent.

Beginning at approximately 1.8 Ga, large areas of the Australian craton began to subside to form a series of intracratonic basins including the McArthur, Mount Isa, Victoria River, Birrindudu, Kimberley and marginally the Bangemall Basins **(Figure 1**). These basins are complex polyphase structures which continued to subside for more than 200 m.y. preserving in excess of 10 km of sediment, all with similar basin-fill architectures. It is thus speculated that the McArthur Basin (and related basins) was initiated by broad regional subsidence associated with breakup of the Palaeoproterozoic supercontinent (cf., Gurnis, 1988; Pysklywec & Mitrovica, 1998; Klein & Hsui, 1987, Wyborn,1988).

The Broadmere Structure

The McArthur Basin is, thus, a complex polyphase basin the architecture of which was determined by regional tectonic events. The sedimentary succession preserved in the Batten Trough (**Figure 2**) at the southern end of the basin is interrupted by a number of erosional hiatuses which indicate major changes in basin evolution in response to these regional tectonic events. The erosional surfaces, or megasequence boundaries (cf., Lindsay & Leven, 1996), mapped in this study outline some of the main periods of basin growth.

M1 maintains a relatively uniform thickness over much of the basin and appears to have been depositionally independent of the Batten Trough. This independence suggests that the basin was initiated, not by simple extension, but by deep mantle processes involving the evolution of a mantle plume, or at least mantle instability, which led to broad regional subsidence and the formation of a giant sag basin, much as encountered in central Australia in the Neoproterozoic (Lindsay et al., 1987; Lindsay &

Leven, 1996; Zhao et al., 1994). Upwelling of the plume initially caused domal uplifting of the continental lithosphere followed by regional peneplanation (cf., Dam et al., 1998) which, in turn, led to widespread subsidence following the output of basic volcanics and the cessation of plume activity. Pysklywec and Mitrovica (1998) have shown that the descent of a cold plume alone can result in broad regional subsidence on the scale of intracratonic basins. Alternatively, the regional sag may be associated with the intrusion of anorogenic granites and partial melting of the lower crust and upper mantle initiated by the assembly of the supercontinent (Klein & Hsui, 1997, Wyborn, 1988). The stable carbon isotope record of the McArthur Basin suggests that there was little orogenic activity during the development of the basins (Brasier & Lindsay, 1998). Given the small volumes of volcanics associated with the sag phase in the McArthur Basin, this latter mechanism appears most likely although the basinal response is likely to be similar regardless of the mechanism. The sag-phase sediments of M1 were, thus, most likely reworked from the large supply of materials generated by peneplanation associated with uplift due to the rising plume or granite intrusions (cf., Tirsgaard, 1993; Klein & Hsui, 1987). The Neoproterozoic Heavitree Quartzite and Bitter Springs Formation in the Amadeus Basin, for example, appear to be a response to a similar tectonic setting (Lindsay, 1999; Lindsay & Leven, 1996) and offer an important comparison.

Extension and associated bimodal volcanism, beginning at approximately 1730 Ma (Big Supersequence), produced a series of northeast-trending, parallel, normal faults and, as a consequence, half grabens began to develop beneath the Broadmere site and elsewhere. Crustal extension and the resultant thermal recovery led initially to rapid subsidence of the half grabens (Big Supersequence) and, then, to regional transgression (Prize Supersequence) (**Figure 5**). Synsedimentary growth on the fault resulted in the local thickening of the succession over the half graben. The fault zone acted as a local depocentre until at least the end of Nathan time (M4), at approximately 1575 Ma. Major erosion surfaces identified throughout M2, M3 and M4 and their correlation with inflections in the Australian polar wandering path (Idnurm et al., 1993; Loutit et al., 1994; Idnurm & Giddings, 1995) suggest plate interactions throughout the period from 1700 to 1575 Ma, which led to continued growth of the basin. The succession is therefore complex and results from compressional/transpressional reactivation of the basin following the initial sag and extensional phases.

At some time after 1575 Ma, following deposition of the Nathan Group (M4), but prior to the deposition of the Roper Group (M5) at 1500 Ma, the succession overlying the Broadmere extensional structure was inverted by the regional equivalent of the Isan Orogeny (**Figure 5**). Regional erosion associated with the initial stages of inversion removed much of the Nathan Group (M4) and parts of the underlying M3. The Nathan Group is, as a result, preserved only as remnants paralleling the zone of increased sedimentation over the depocentre formed above the extensional half graben (**Figure 14**), that is, along the crest of the inversion structure.

The Roper Group (M5), the product of the last major basinal episode, provides evidence for a major change in basin dynamics and suggests a basinal event centered farther to the west of the Broadmere Structure. Depositional patterns suggest that there was no further activity associated with the primary extensional faults underlying the Broadmere Structure and the deposition of the Roper Group formed the closing phase of this polyphase basin. Dolerite, perhaps derived from a source to the northeast of the Broadmere Structure (see **Figure 3**), intruded the upper Roper Group at 1.3 Ga. As the sill is both folded and faulted (see **seismic line 83-120**) it can be assumed that structural inversion continued well beyond the intrusion of the sill and at least into the assembly phase of Rodinia at around 1.0 Ga.

The Broadmere Structure is, thus, a complex, compound inversion structure that formed in response to post-Nathan time compressional events. The seismic data do not provide clear definition of individual compressional events. Overall, however, the resultant main axis of the compound domal or anticlinal structure that formed over the Broadmere site is misaligned with respect to the main axis of the depocentre associated with the underlying half graben. In response to internal strain established in the thickened areas of sedimentation, wrench faults formed along the axis of the inversion structure. These faults are shown as solid lines on the structure contour maps but in reality they are discontinuous zones (an ill-defined flower structure) of faults. The fault zones are imaged on some seismic lines as steep reverse faults cutting through much of the section whilst, on other lines, they appear as localised thrust faults extending into the more compliant shale intervals at much lower angles. The Broadmere Structure is thus likely to be simply one of a series of en-echelon structures that formed in response to the misalignment of structural axes along each inverted half graben along the length of the Batten Trough (**Figure 20**).

Play Concepts

The Broadmere survey provides a window into a gently deformed part of the McArthur Basin and offers a unique opportunity to understand the evolution of the basin. As well as providing important insights into the development of the basin, an understanding of the structure also provides a conceptual framework in which to evaluate mineral prospectivity and potential petroleum plays.

The data show that the primary extensional faults provided the main control on potentially prospective structures. The half grabens developing over the primary extensional faults formed localised anoxic sediment-starved depocentres in which organic-rich sediments accumulated. Ultimately, it is the organic-rich facies that source petroleum or host mineralisation. The same primary extensional faults also controlled later subsidence, whether it was related to further extension, or to compression/transpression. For example, even though the important mineralised Barney Creek interval developed in a transpressional environment (**Figure 2**), it was the reactivation of the underlying primary extensional structures that determined the location of the sediment-starved, organic-rich deposits in which mineralisation occurred. Similarly, even though it was later compression that formed the inversion structures that acted as potential hydrocarbon traps in the Roper Group, it was thickening of the sediment in the localised depocentres over the primary extensional faults that determined their location.

The model put forward here provides a framework in which to explore. As well as determining the location of economically important structures, the primary extensional structures also ultimately controlled fluid movements critical to petroleum migration and fluid movement during mineralisation. However, the actual distribution of ore bodies (or for that matter hydrocarbons) is, in reality, a function of the timing of fluid movement and the nature of fluid pathways, neither of which is well understood.

Mineralisation

Early genetic models for the McArthur River ore bodies emphasized a syngenetic origin, involving direct precipitation on the sea floor (cf., Cotton, 1965; Croxford, 1968;

Murray, 1975). Williams (1978a, 1978b) first put forward the possibility that the stratiform ore bodies at McArthur River were not precisely syngenetic, but were deposited in response to early diagenesis in unconsolidated sediments. Recent studies of Pb-isotope systematics are consistent with this concept (Page et al., 1994; Sun et al., 1994; Carr et al., 1996). Facies analysis of the stratiform interval at HYC is also consistent with this interpretation (Hinman et al., 1994). Recent work on carbon and oxygen isotopes, supported by major and trace element studies, suggests that diagenesis was early and that Pb-Zn mineralisation occurred in consolidated sediments following diagenesis (Lindsay & Brasier, 1997).

Sedimentation within the Batten Trough was not as restricted as was believed in the past (e.g., Jackson et al., 1987). Recent facies and sequence studies (e.g., Lindsay & Brasier, in press; Jackson and Southgate, 1997) suggest that the Batten Trough succession is almost entirely marine (rather than lacustrine; cf., Williams, 1978a, 1978b; 1990, Jackson et al., 1987) and that water depths were at times considerable, at least well below storm-wave base. Sedimentation frequently occurred in a platformal setting leading to a series of well-developed, shallowing-upward, depositional sequences, thereby assuring facies continuity over large areas. While localised closed depocentres formed over the half grabens and controlled deposition of organic-rich facies, they were simply part of a much larger marine deposystem. Only the rift-stage sediments are truncated by faulting above the half grabens, later sediments all drape over the faults.

Overall, sequence architecture throughout the trough is very consistent, suggesting that, even though sediment thickness increases over the extensional structures, there is regional continuity of facies resulting in the potential for regional fluid movement. There is clear evidence that diagenesis occurred very early in the carbonate-rich intervals and that they were sealed to later fluid movement (Brasier & Lindsay, 1998; Lindsay & Brasier, in press). Carbon and oxygen isotope studies support this view and suggest that fluid movements were tightly constrained by sequence and hence, facies boundaries - fluids thus moved laterally through the more permeable parts of sequences over large distances (Lindsay & Brasier, 1997). The consolidated and sealed carbonate intervals thus acted as very effective aquicludes, channelling later fluids through the more porous intervals of the transgressive systems tracts and lower parts of the highstand systems tracts. Since the sequences drape over the underlying extensional faults, mineralising fluids were introduced into the system from the major faults bounding the Batten Trough, rather than through the extensional fault system. This then implies that fluids moved laterally from the major bounding faults through the sharply defined channels, into the Batten Trough.

If the mineralisation was strictly syngenetic, fluid flow problems can be readily understood. Fluids released onto the sea floor at the time of sedimentation could have been trapped in the closed depocentre formed over the half grabens, producing localised syngenetic ore bodies in the organic-rich depositional environment. However, since indications are that the ore bodies are not strictly syngenetic, but are post depositional and formed at some depth below the sediment water interface (cf., Eldridge et al., 1993; Hinman et al., 1994) it appears likely that fluids moved laterally within tightly constrained depositional intervals over large distances (Lindsay & Brasier, 1997). The difficulty with such an interpretation is that it would require significant over-pressuring in order to move fluids into the locally depressed depocentres along the half grabens. This would require a significant depth of burial (at least of the order of the depth of the half grabens) and that the sediments be lithified. The latter is at least supported by micro-fabric and geochemical data suggesting that diagenesis in the form of dolomitization and silicification were both very early (Brasier & Lindsay, 1998; Lindsay & Brasier, in press). Overall, this suggests that any mineralising event earlier than 1575 Ma (but post depositional) would result in mineralisation within the organic-rich zone associated with the extensional faults, but close to the main regional faults, such as, the Emu and Western Faults at the McArthur River deposits (cf., Williams, 1978a, 1978b). Otherwise, excessive overpressuring of the sediments would have been necessary to drive the system, eventually resulting in failure of the aquifer and escape of fluids onto the sea floor through hydrothermal vents. The data also limit petroleum potential as, in lieu of a structural trap, any hydrocarbons generated from the McArthur Group early in basin development (before 1575 Ma) would be dispersed or lost from the system.

Alternatively, if mineralisation is a late-stage phenomenon, we can conclude that movement of fluids into the Broadmere Structure was more likely to have occurred following the onset of inversion, as closure developed on the structure some time after 1575 Ma. This requires that, either we ignore the Pb-isotope systematics, or conclude that there was more than one mineralising event. Ongoing multivariate analysis of geochemical data from carbonate intervals suggest the possibility that Cu is independent of Pb and Zn and may result from later fluid movement (cf. Hinman, 1995). In this situation, fluid flow is much more readily understood as fluids would migrate laterally into the structural high of the inversion structure where the section is thicker and the organic carbon content higher, thereby increasing chances of mineralisation along the axis of the structure. The tightly constrained nature of the fluid conduits again suggests that wrench faults (flower structures) along the crest of the inversion structures were probably not involved in fluid flow as movement on these faults was minimal and the fault planes are discontinuous. It is likely then that fluids flowed laterally from the cross-cutting faults bounding the Batten Trough (e.g., Emu Fault) rather than from the extensional faults below the structure. Under these conditions overpressuring would not be a problem and fluids could have moved much greater distances along the inversion structures, potentially resulting in the formation of ore bodies across the width of the Batten Trough. This is supported by spatial data (**Figure 20**) which show that areas of Cu mineralisation are widely dispersed across the Batten Trough while the main areas of Pb-Zn mineralisation are confined to the margins of the trough.

The primary extensional faults, such as the Broadmere Fault, were deeply buried during basin development and for the most part are either, not visible at the surface, or are difficult to identify as a result of later structural complexity. If the architecture identified in the Broadmere Structure is representative it should be possible to recognise the likely sites of buried grabens by mapping the distribution of the erosional remnants of the Nathan Group (M4) left along the crests of the en echelon inversions structures. Remnants of the Nathan Group (M4), for example, also parallel the Mallapunyah Fault suggesting that it is associated with an inversion structure at depth (**Figure 20**). Similar outcrop belts of Nathan Group appear at intervals along the Batten Trough suggesting other more deeply buried extensional faults. It seems logical that the Broadmere Fault is simply one of a set of parallel faults. Evidence of remnant Nathan Group appears northwest of the McArthur River site, then again further north near the Limmen Bight River and, finally, associated with the Urapunga and Bulman Faults (**Figure 20**). If each remnant overlies a buried half graben, fault spacing is approximately 30 to 50 km. Prospectivity is likely to be greater along any of these structure within the Batten Trough.

If fluid flow was more or less syngenetic, ore bodies could be expected in the Barney Creek interval, where it occurs in association with exposures of the Nathan Group, but close to the bounding faults. If, by contrast, fluid flow was post inversion, ore bodies could again be expected to occur in association with the Nathan Group (M4), but across the width of the Batten Trough, because of the greater mobility of the fluids as they migrated into the structural highs. Spatial data (**Figure 20**) show that Pb-Zn mineralisation lies close to the bounding faults, while Cu mineralisation occurs across the width of the Batten Trough, supporting a syngenetic origin for the former and a much later post-inversion, epigenetic origin for the latter. Clearly, any exploration program must integrate this geohistory into its strategy.

Petroleum Potential

Hydrocarbons are found in trace amounts in rocks much older than those encountered in the McArthur Basin (e.g., Buick et al., 1998). However, it is the Roper Group that hosts the world's oldest hydrocarbon accumulations that, to date, hold any economic potential (Jackson & Powell, 1987; Powell et al., 1987; Goldstein, 1991). It was this interval in the Batten Trough that Amoco (1985) explored for hydrocarbons in 1984-85 (see **seismic line 83-120**), focussing in particular on the potential source rocks of the 'Lansen Shale'. The temporal equivalents of the 'Lansen Shale' (Velkerri Formation) (**Figure 2**) are widespread and are present in at least three other structurally defined sub-basins including, the Maiwok, St. Vidgeons and Beetaloo Sub-basins (see Warren et al., 1998). As discussed above, this interval was deposited at the time of maximum accommodation and thus maximum water depth.

The hydrocarbons occur, in large part, in situ, associated with deeper water shale and silt deposited either side of the maximum flooding surface of a number of depositional sequences. In the Beetaloo Sub-basin Warren et al. (1998) have shown that TOC values (up to 8%) parallel the gamma logs through the organic-rich middle Velkerri Member. They attribute this correlation to changing sea-water chemistry. However, it is more likely that the correlation relates to reduced clastic sedimentation rates and the more anoxic conditions associated with rising sea level. This depositional setting is expressed in the sedimentary record in the form of a condensed interval that brackets the maximum flooding surface (corresponding to the gamma-ray maxima) of each depositional sequence. The gamma-ray peaks (see **Figure 17**), which are not exceptionally strong, simply reflect increased clay content in the less-energetic, sediment-starved, deeper-water environment. This interpretation is also consistent with the evidence of anoxia provided by sulphur isotope data (Lambert & Donnelly, 1992).

While the source rocks are overmature in proximity to the dolerite sills in the Corcoran Formation, organic matter in the Roper Group is generally marginally mature, although there is a general increase in maturity with depth (Crick, 1992; Crick et al., 1988). Source rock geochemistry is comprehensively summarised by Warren et al. (1998) and Summons et al. (1988). While the source rock potential of the Roper Group has been confirmed, suitable potential reservoir intervals remain elusive as a result of silicification, which fills the pores of most sandstone intervals. Given the age of the Roper Group and its geohistory, it is unlikely that any potential seal could maintain its integrity for the necessary length of time. Petroleum prospects are thus relatively poor.

Conclusions

The Broadmere Structure is a complex inversion structure formed over a period of more than 600 m.y. (**Figure 21**). The structure provides a window into a gently deformed part of the McArthur Basin, which allows insights into the evolution of the basin and provides a spatial and temporal framework within which mineralisation and hydrocarbon potential can be evaluated. The main conclusions are:

1. The McArthur Basin was initiated at approximately 1.8 Ga as part of a regional crustal response in the wake of supercontinent assembly and dispersal (**Figure 21A**). Subsidence following mantle instability or the intrusion of anorogenic granites resulted in a broad regional sag and the accumulation of a mixed clastic and basic-volcanic succession.

2. Extension of the weakened crust beneath the McArthur Basin and associated bimodal volcanism, beginning at approximately 1730 Ma, resulted in the development of a series of northeast-trending normal faults and half grabens which were laterally confined by northwest-trending strike-slip fault complexes, such as the Emu Fault zone (**Figure 21B**).

3. Subsidence in response to thermal recovery following extension, combined with subsidence associated with transpressional events in the interval from 1730 Ma to 1575 Ma, resulted in the accumulation of a mixed carbonate and clastic succession. This succession, which reached a maximum thickness in excess of eight kilometres, was deposited in a largely shallow-marine setting.

4. Increased subsidence over the half grabens resulted in the development of localised, anoxic conditions within the sub-basins and the accumulation of organic-rich, clastic sediments (e.g., Barney Creek Formation) that formed the site for later mineralisation (**Figure 21C**).

5. Structural inversion of the half grabens (Isan Orogeny) (**Figure 21D**) began prior to deposition of the Roper Group (**Figure 21E**), that is, no later than 1575 Ma. Inversion of the structures continued well beyond the life of the McArthur Basin.

6. Timing of fluid flow determined the spatial distribution of mineralisation. Pb-Zn mineralisation occurred early in basin history, post early diagenesis, but well before structural inversion. The potential for overpressuring limited movement of Pb-Zn mineralising fluids to the zone close to the major bounding faults. Overpressuring may well have resulted in loss of fluids to the sea floor through hydrothermal vents. Later mineralising fluids moved laterally through the inversion structures across the width of the Batten Trough resulting in widely dispersed Cu mineralisation.

7. Mineralisation is most likely to occur in association with inversion structures formed above the primary half grabens (**Figure 21F**). These structures are generally obscured by later sedimentation and by later structural complexity. However, erosion following initial structural inversion (c.1575 Ma), but prior to Roper Group sedimentation (c.1500 Ma), left distinctive remnant wedges of Nathan Group above the half grabens providing a distinctive flag to help focus exploration.

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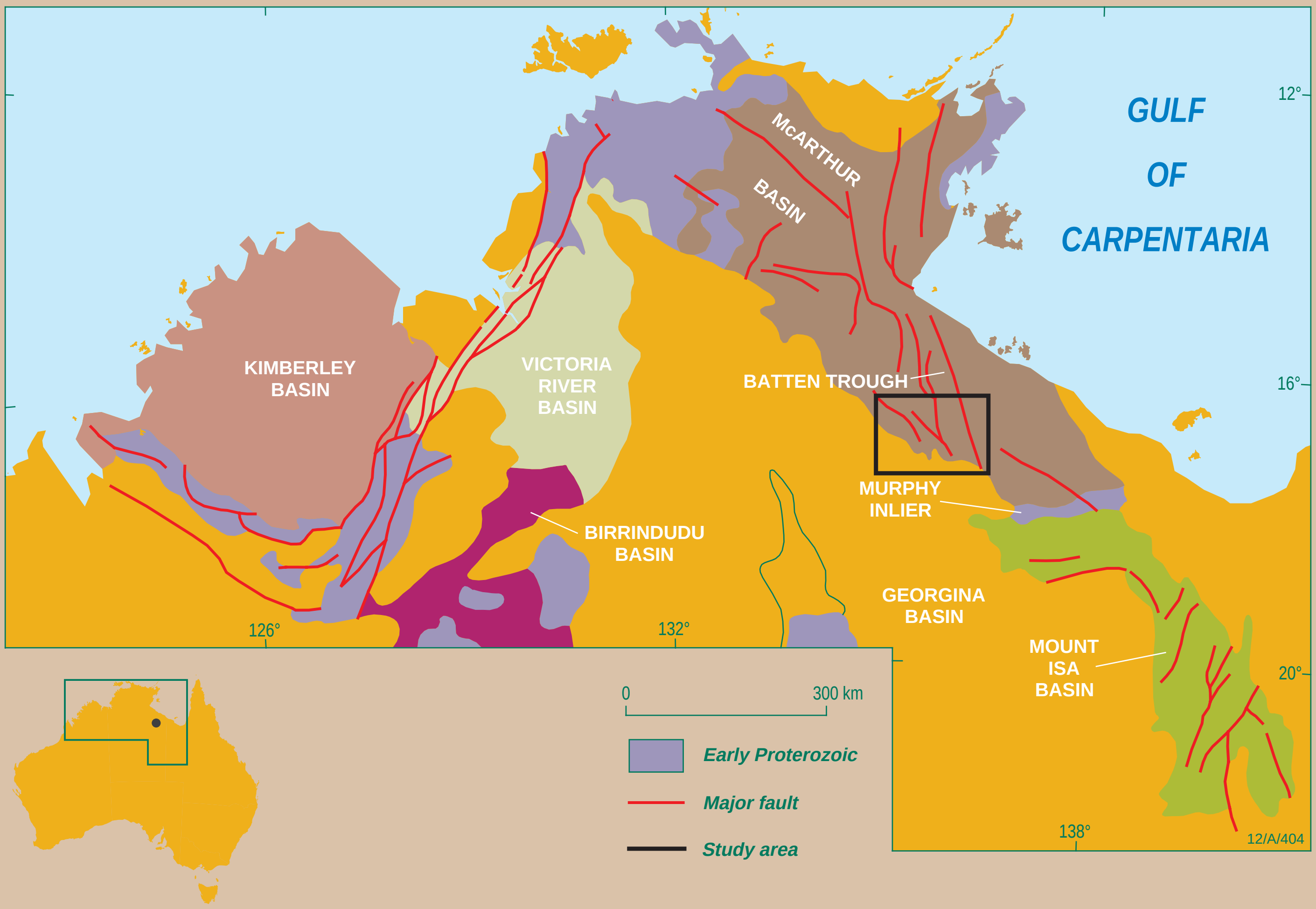

Figure 1 LOCALITY MAP SHOWING THE DISTRIBUTION OF PALAEOPROTEROZOIC BASINS ACROSS NORTHERN AUSTRALIA

geology map of study area

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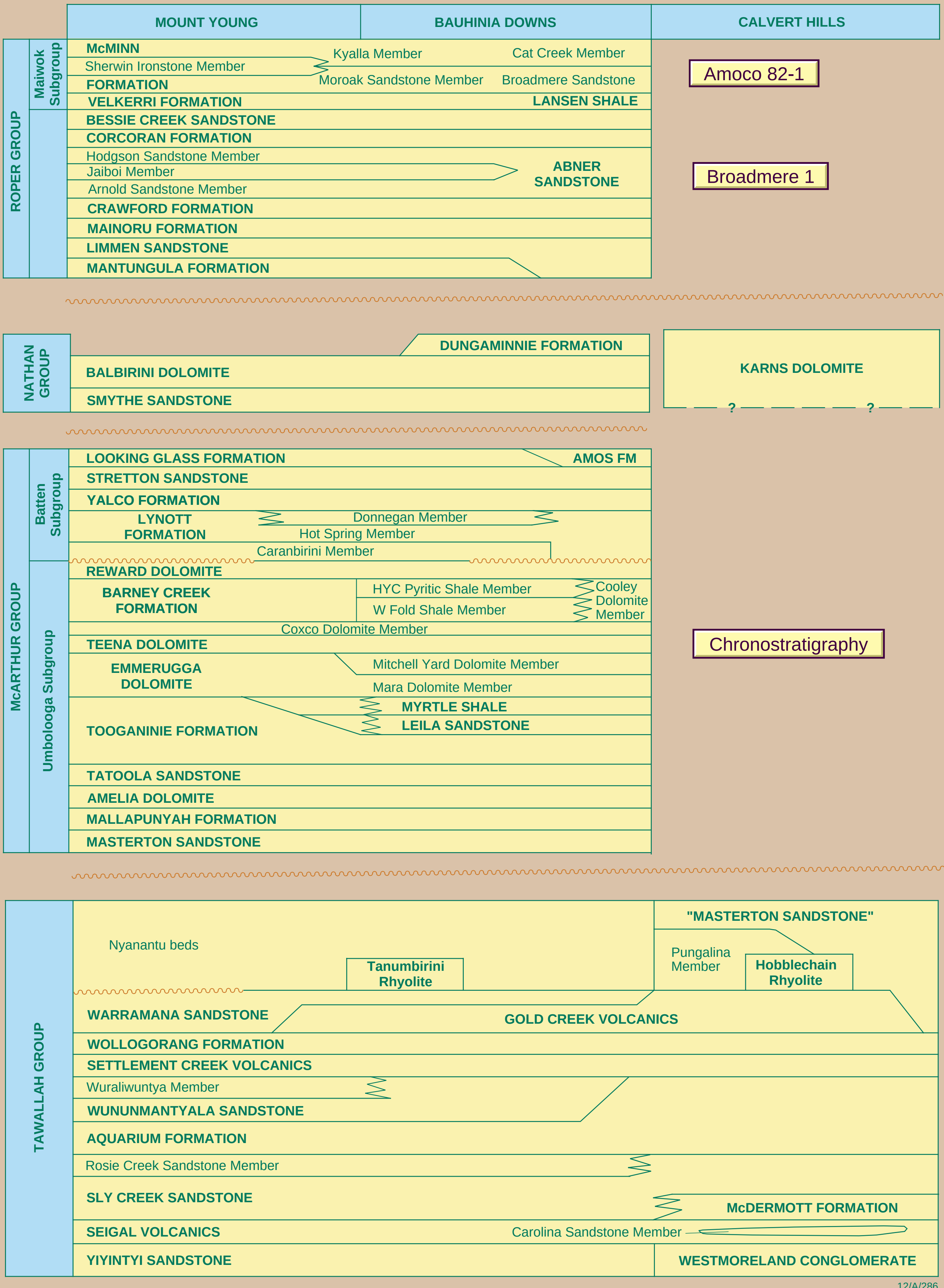

Figure 2 GENERALISED LITHOSTRATIGRAPHY OF THE McARTHUR BASIN (AFTER JACKSON et al., 1987; PIETSCH et al. 1991) (cf. Figure 5)

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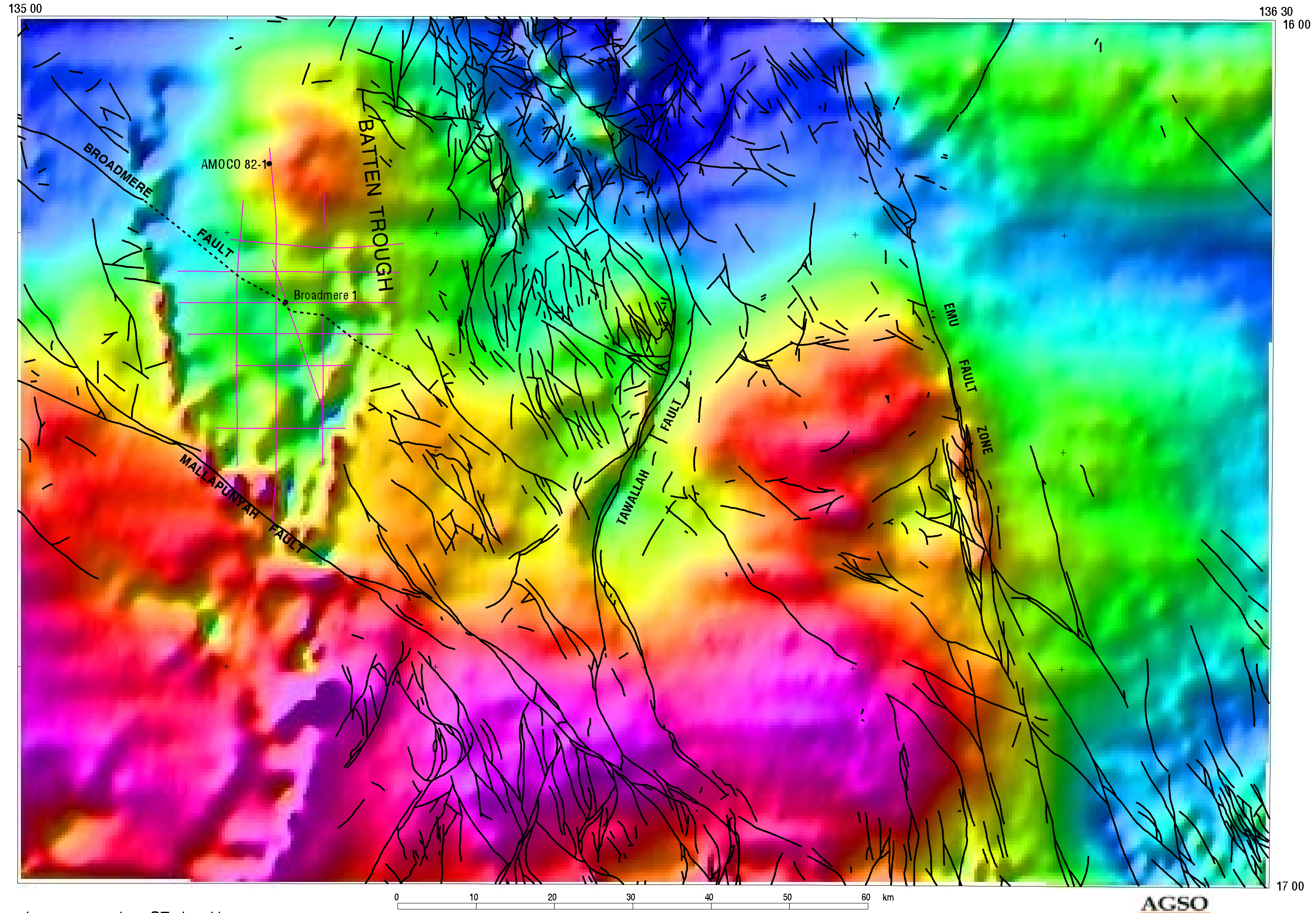


Image processing : CTarlowski
NABRE GIS database: AJRetter

Geology map of study area

Fig 3 Total magnetic intensity image of Bauhinia Downs sheet (derived from Tarlowski et al., 1996) showing the location of the Broadmere seismic survey. The prominent circular structure to the north of the seismic grid may indicate the source for later dolerite sills intruding the Roper Group

AGSO

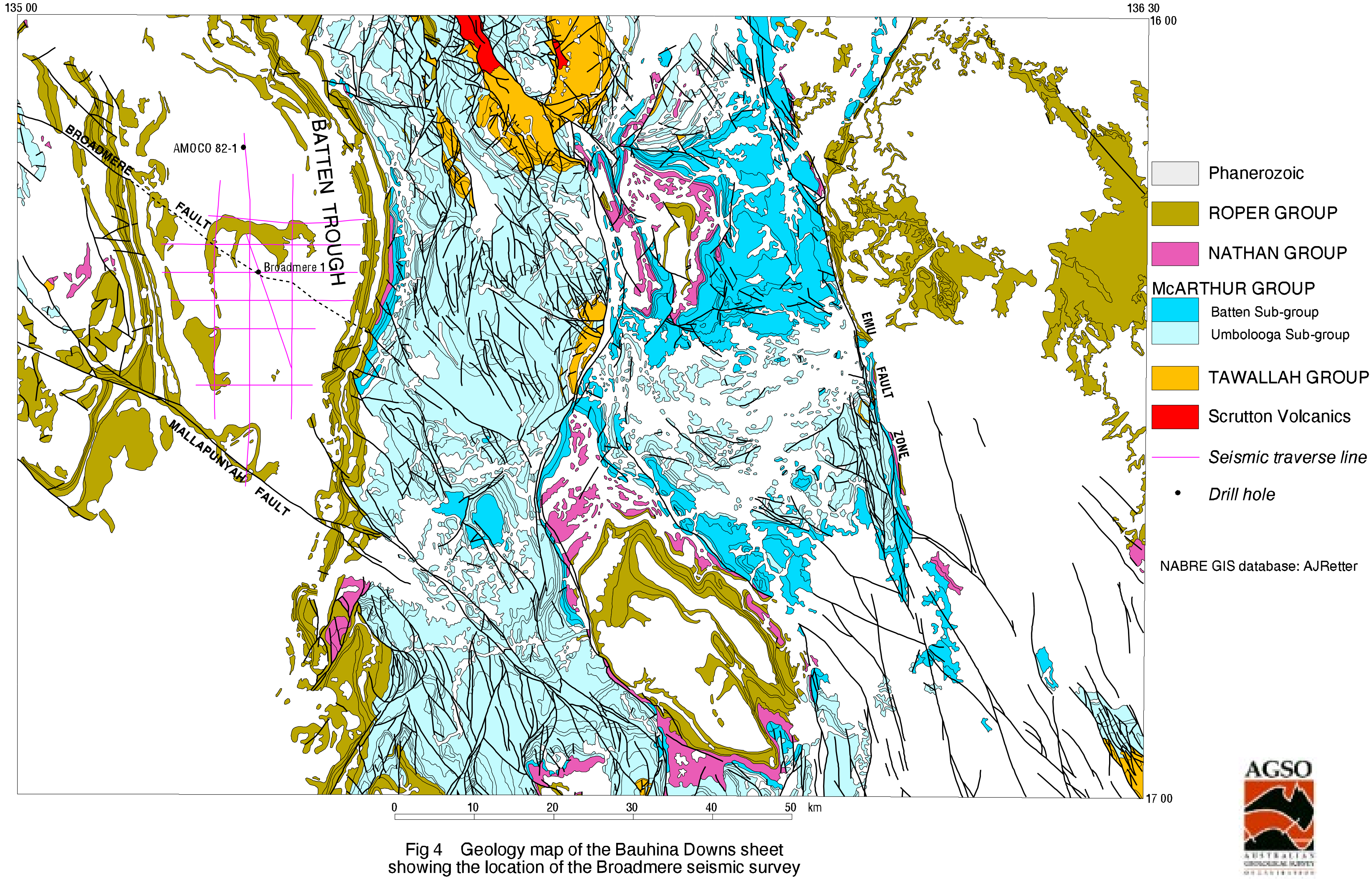
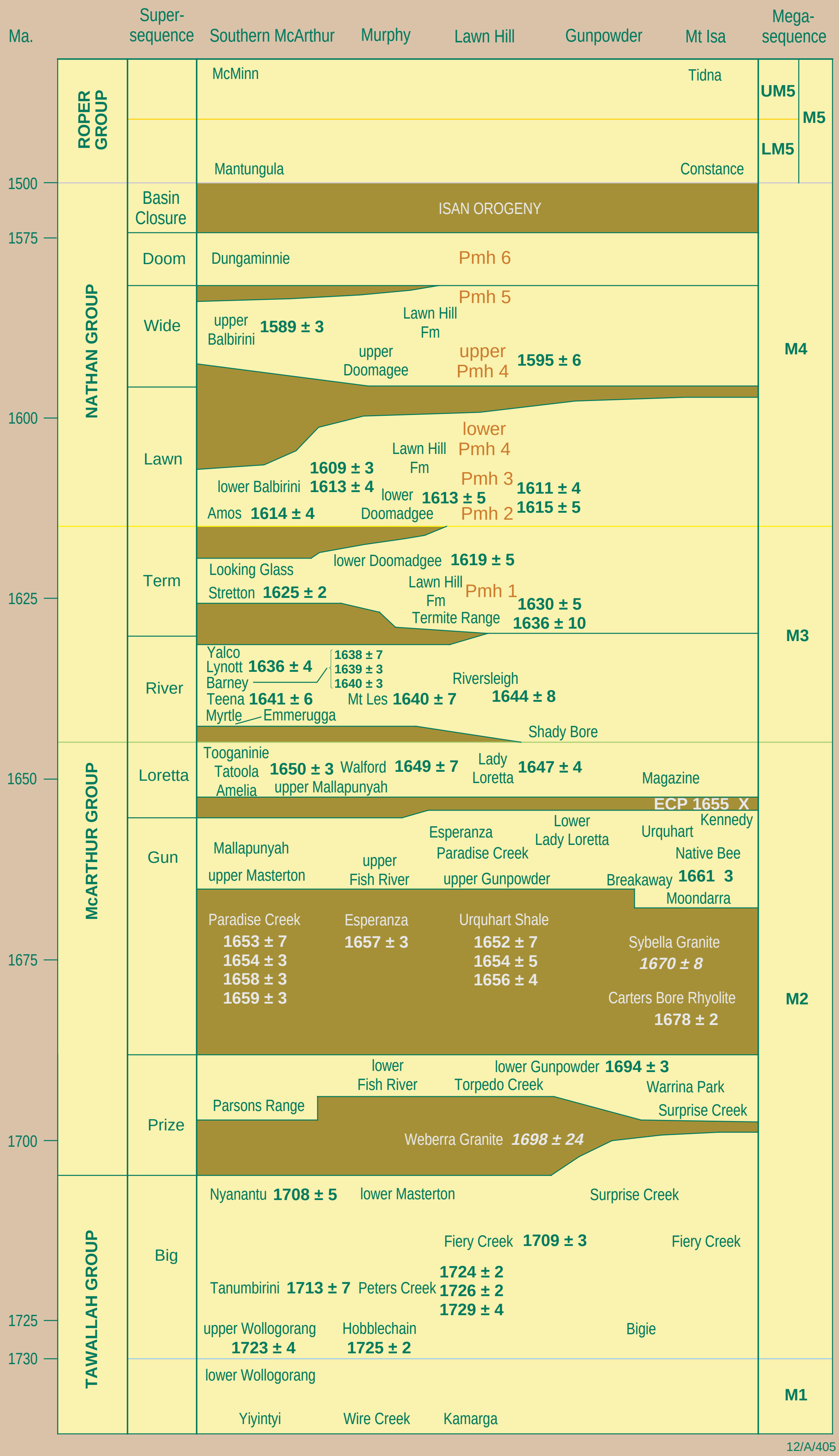


Fig 4 Geology map of the Bauhina Downs sheet
showing the location of the Broadmere seismic survey



Lithostratigraphy

Figure 5 CHRONOSTRATIGRAPHY OF THE MOUNT ISA SUPERBASIN

SHRIMP AGES ARE SHOWN IN NORMAL FONT WHILST U-Pb AGES ARE SHOWN IN ITALICS (AFTER PAGE, 1997; PAGE AND SWEET, 1998; SOUTHGATE et al., in prep.) LITHOSTRATIGRAPHIC GROUPS FOR THE McARTHUR BASIN ARE SHOWN TO THE LEFT, WHILST THE MEGASEQUENCE MAPPED IN THE PRESENT STUDY APPEAR TO THE RIGHT. MEGASEQUENCE BOUNDARIES MAPPED IN THE PRESENT STUDY ARE COLOUR CODED IN COORDINATION WITH THE INTERPRETED SEISMIC LINES.

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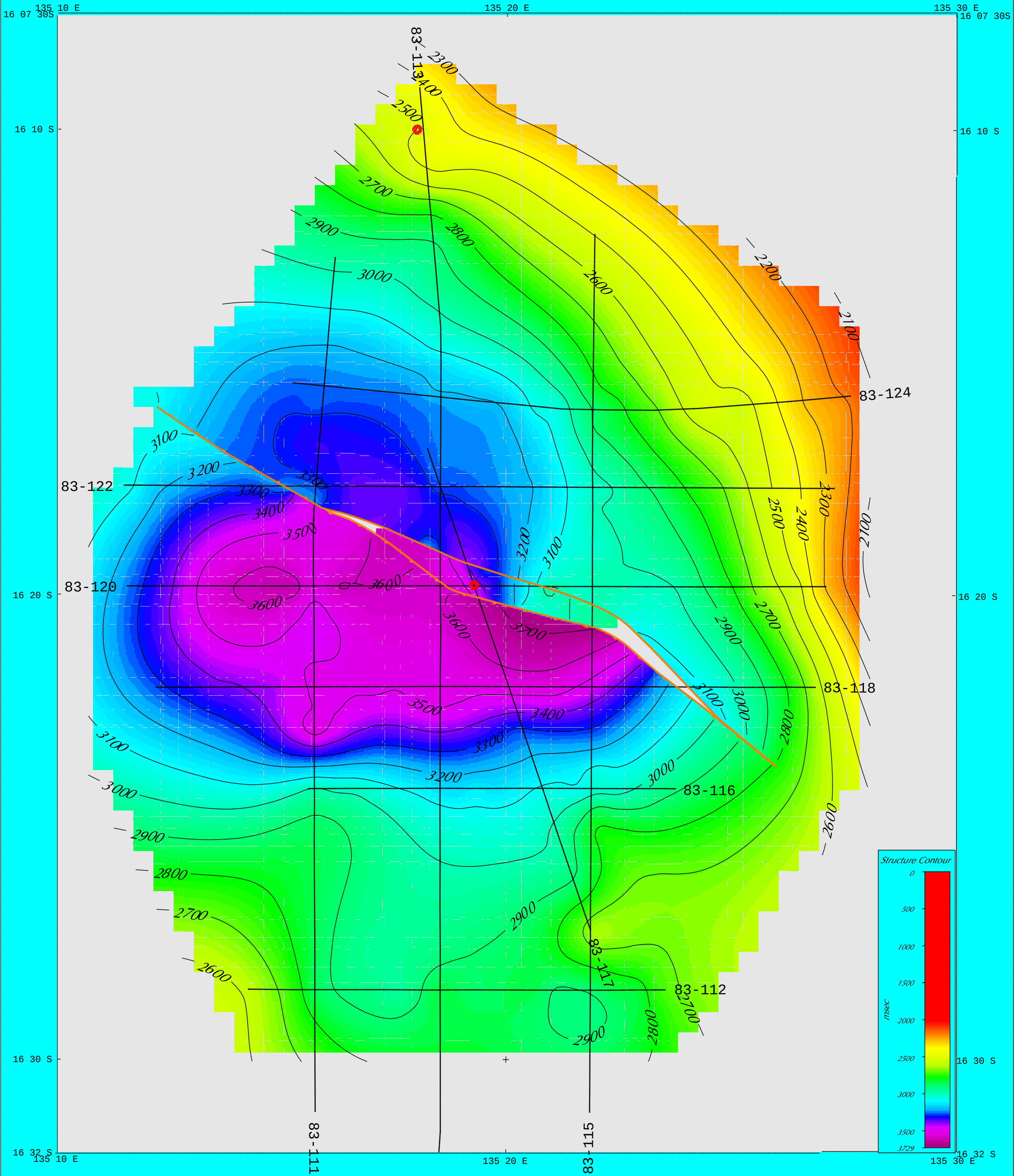
BROADMERE STRUCTURE



Contour Interval 100 msec
Two way time
Interpretation by John Lindsay
Petroseis Version 7.62b
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Date : Oct 1998

Fig 6 Two way time to the erosional surface at the top of Megasequence M1 (c. 1730 Ma). Note the northwest-southeast oriented Broadmere Fault, now inverted, but still exhibiting considerable displacement.

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AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 135 E

AGSO

Perspective view

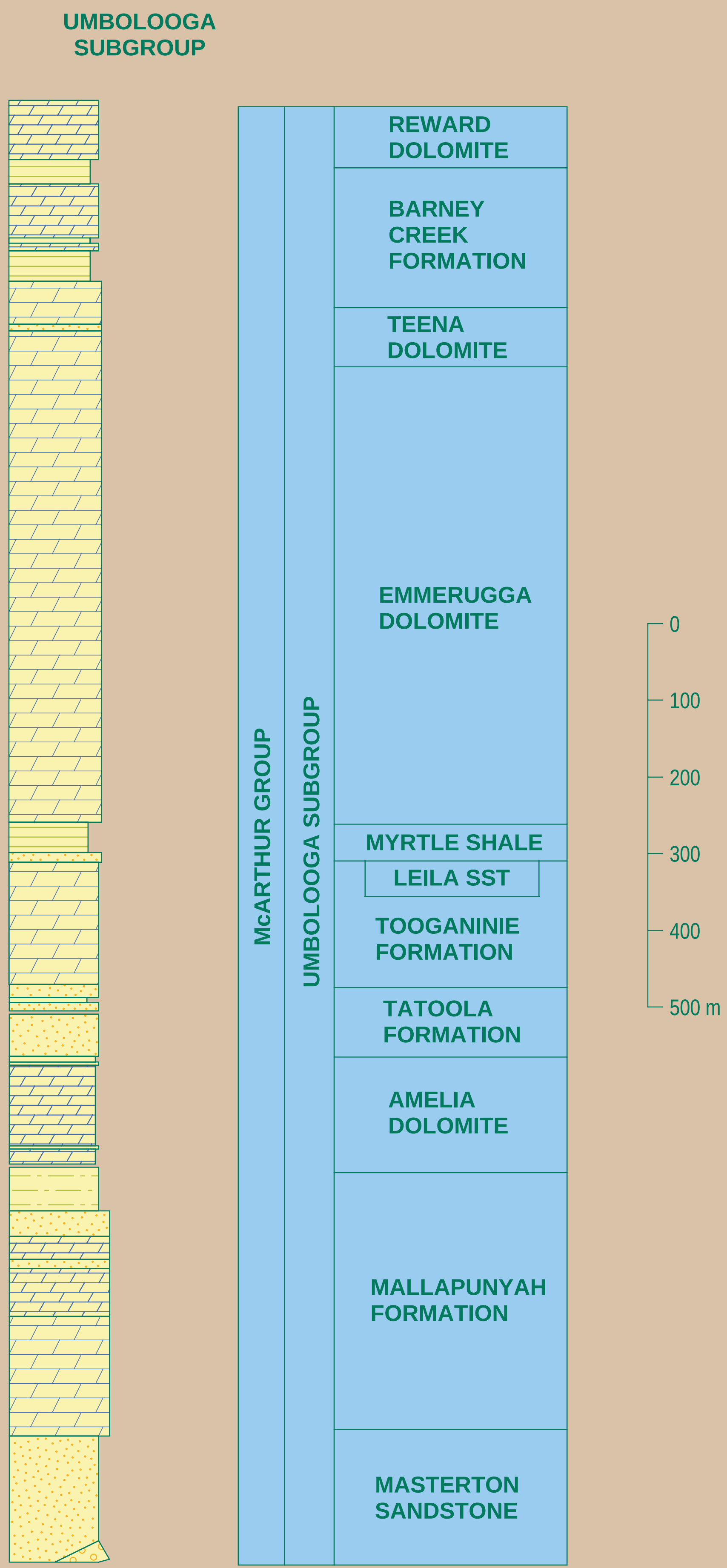

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Figure 7 SIMPLIFIED AND IDEALISED LITHOSTRATIGRAPHY FOR THE UMBOLOOGA SUBGROUP (c. 1710 - 1640 Ma)

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BROADMERE STRUCTURE

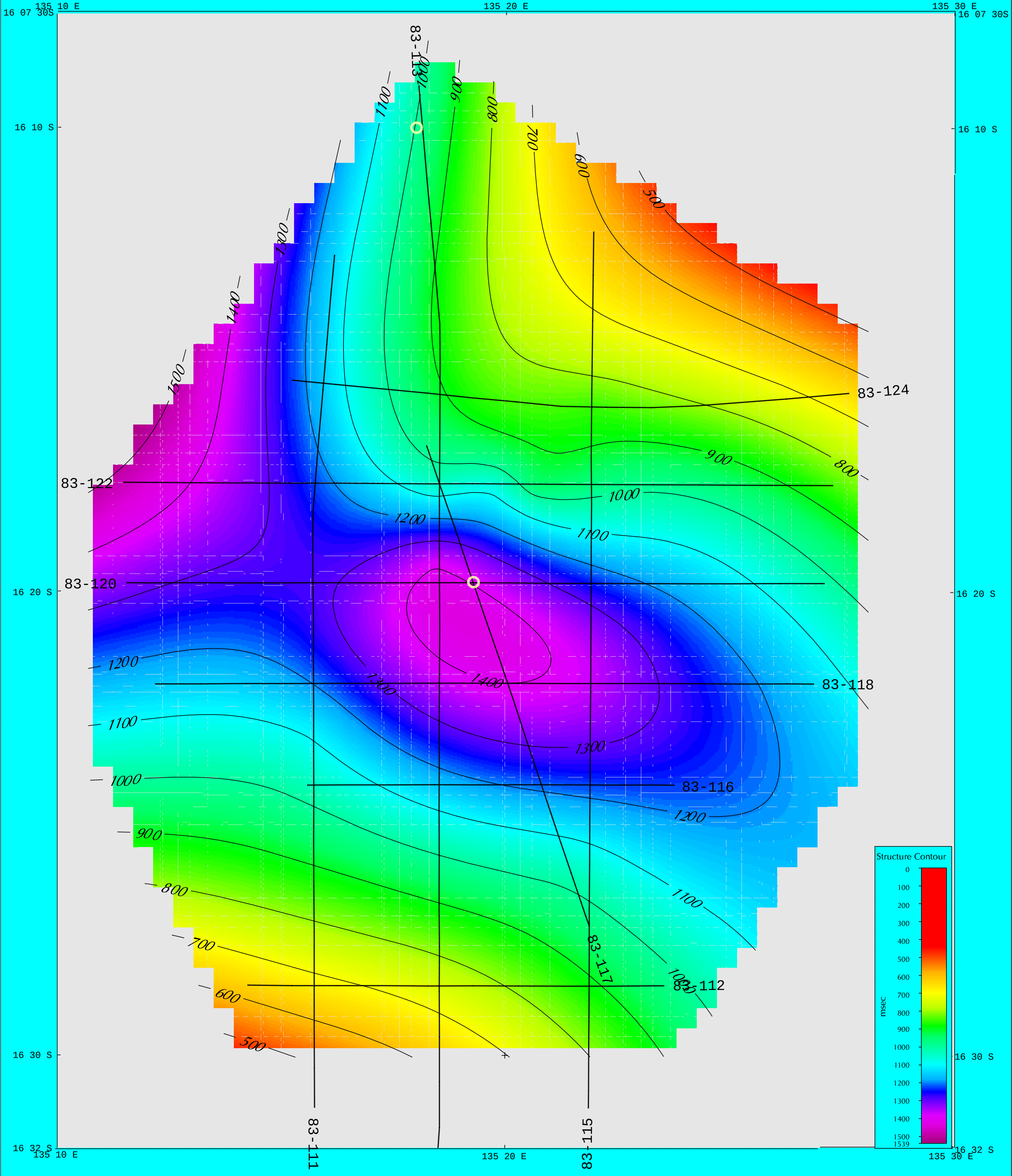

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Fig 8 Isochron in two way time for Megasequence M2 (c. 1730-1645 Ma). Note marked thickening of the interval in the zone above the half graben associated with the Broadmere Fault (cf. Figure 6)

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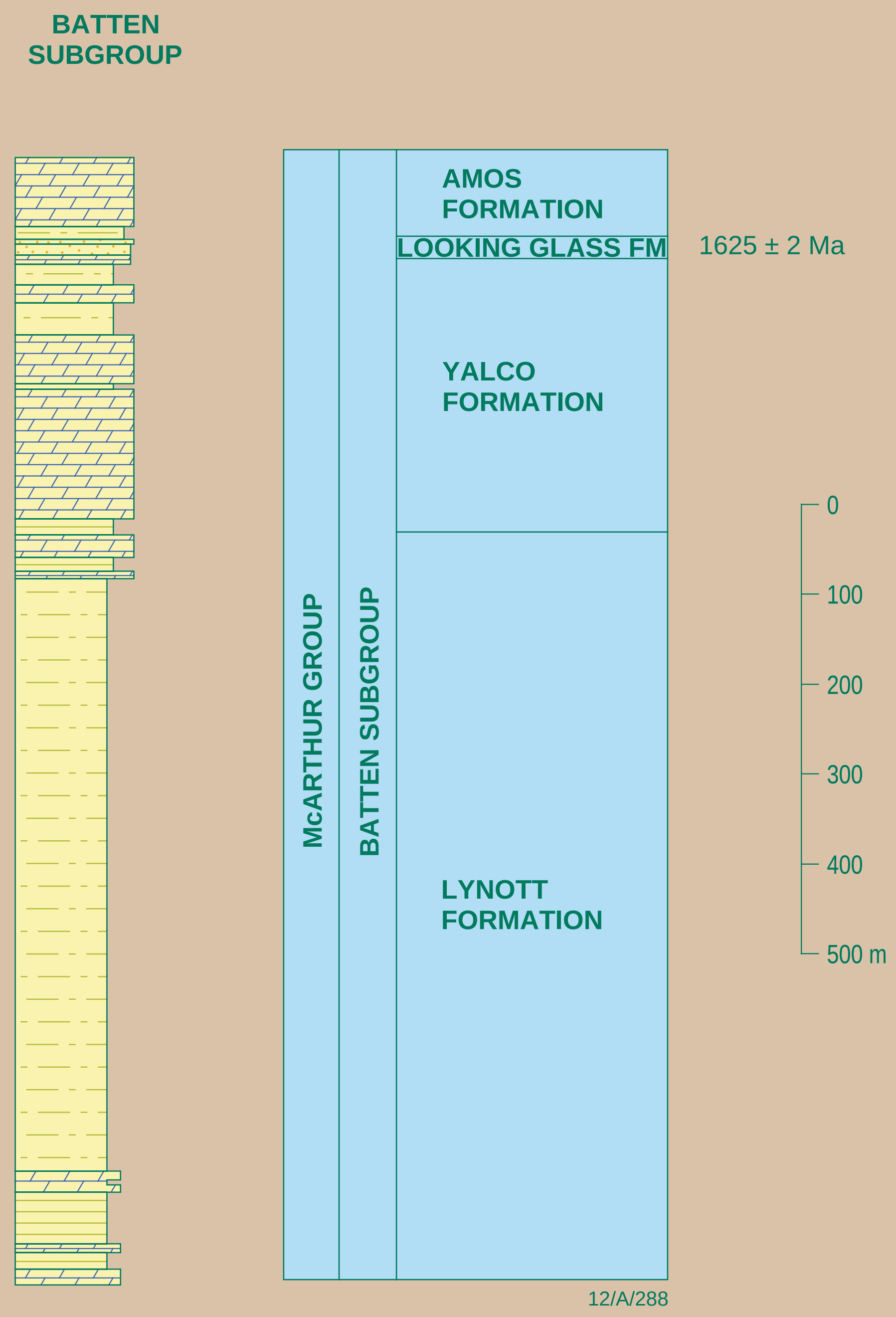

Figure 9 SIMPLIFIED AND IDEALISED LITHOSTRATIGRAPHY FOR THE BATTEN SUBGROUP (c. 1640-1615 Ma)

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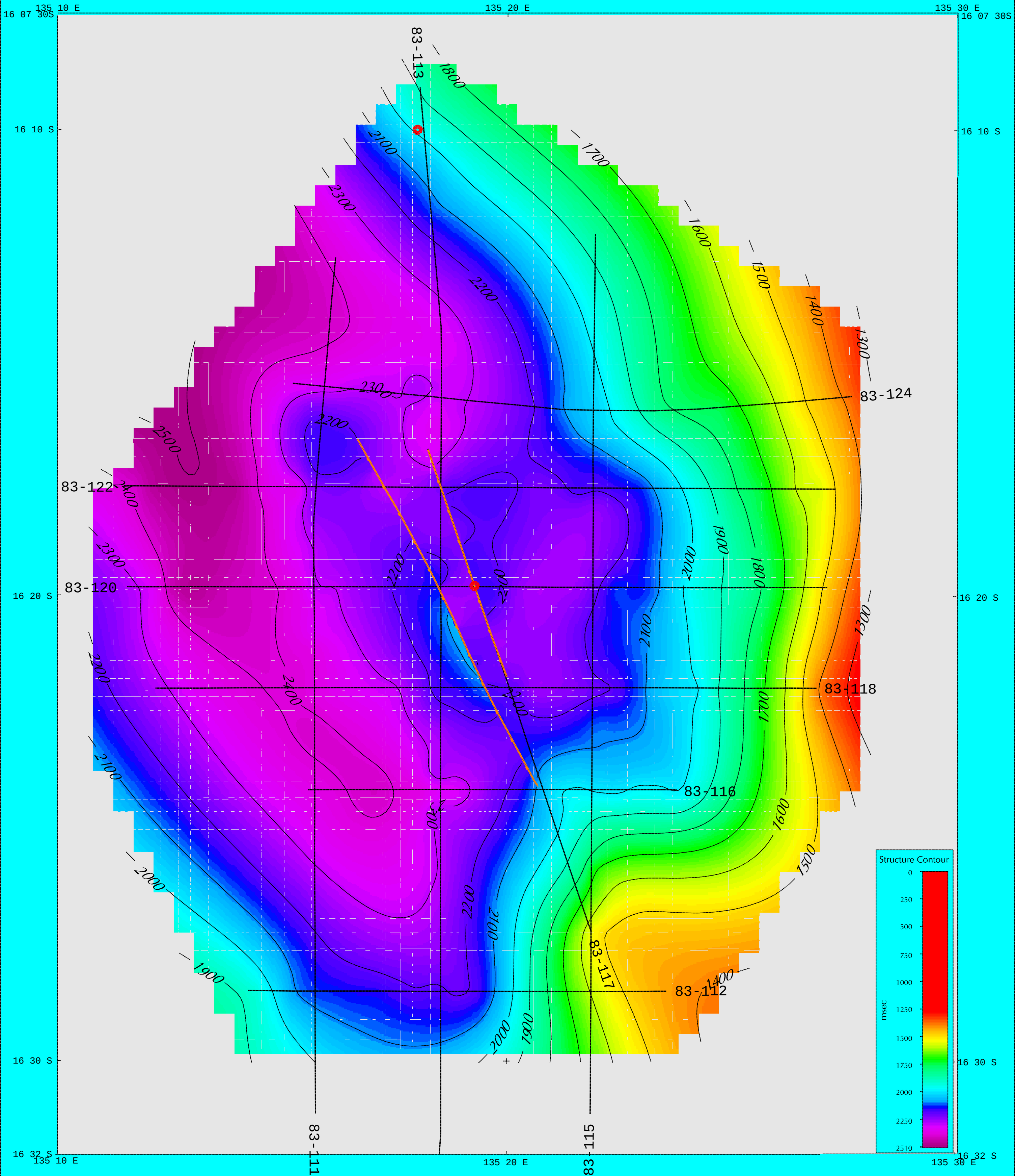
ORGANISATION

BROADMERE STRUCTURE



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Interpretation by John Lindsay
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Fig 10 Structure contour in two way time for the erosion surface at the top of Megasequence M2 (c. 1645 Ma). Note discontinuous faulting along the crest of the Broadmere Structure.

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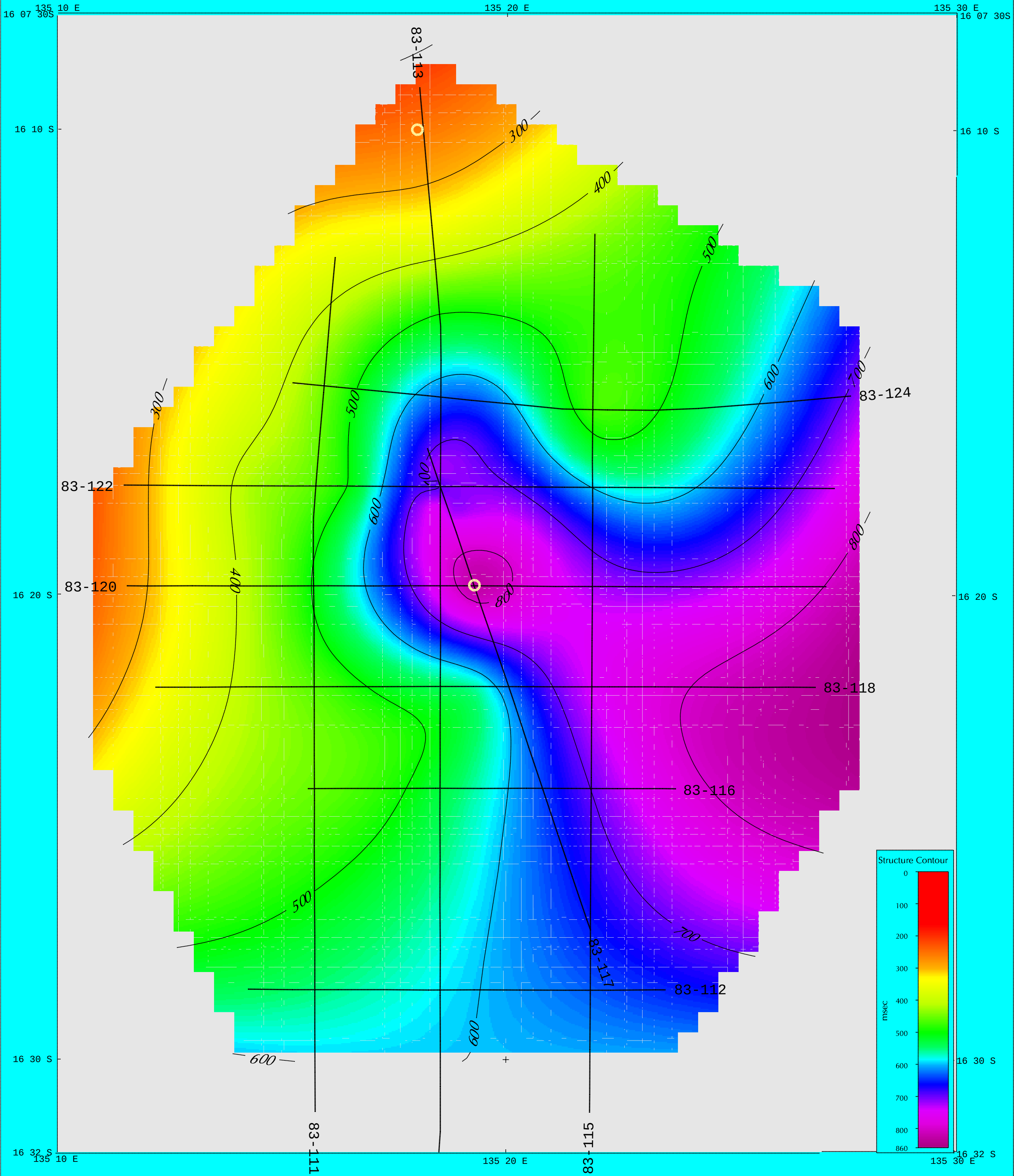
AGSO

Perspective view

BROADMERE STRUCTURE



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Two way time
Interpretation by John Lindsay
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Fig 11 Isochron in two way time for Megasequence M3 (c. 1645-1615 Ma.) Note thickening of the succession in the area above the Broadmere Fault (cf. Figure 6).

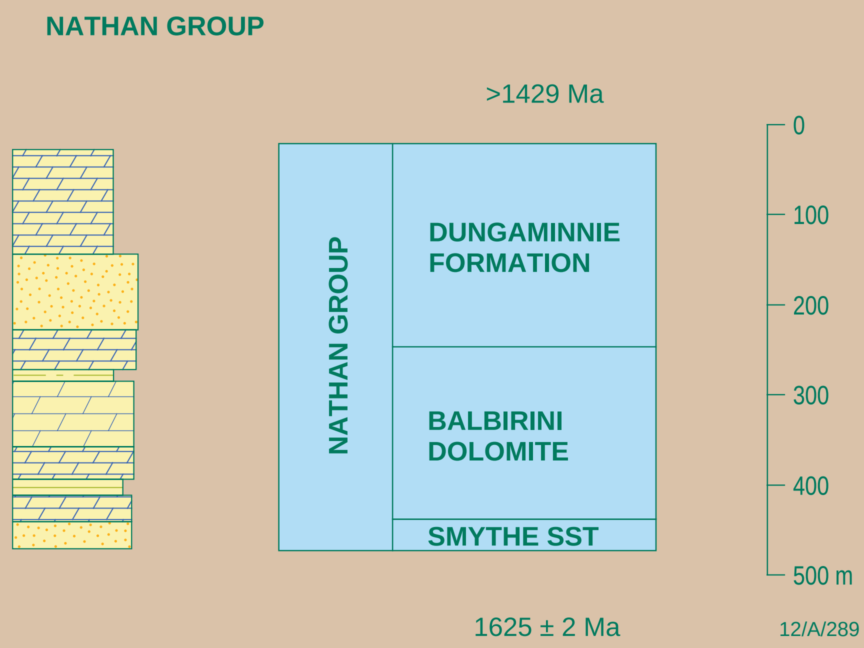

Figure 12 SIMPLIFIED AND IDEALISED LITHOSTRATIGRAPHY FOR THE NATHAN GROUP (MEGASEQUENCE M4, c.1615-1575)

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BROADMERE STRUCTURE

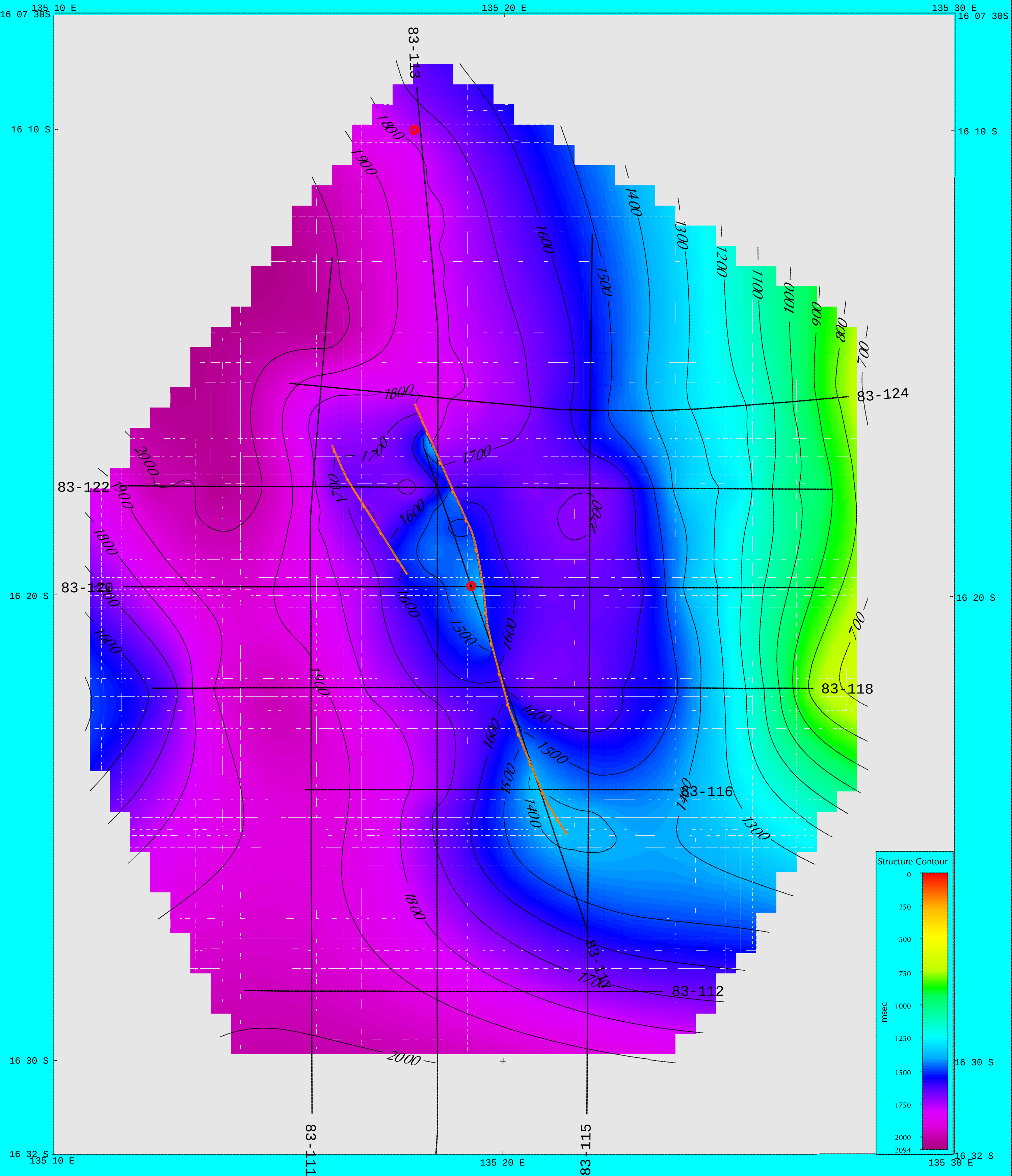

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Fig 13 Structure contour in two way time for the erosional sequence boundary at the top of Megasequence M3 (c. 1615 Ma). Note faulting along the crest of the Broadmere Structure.

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AUSTRALIAN NATIONAL SPHEROID
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Perspective view

BROADMERE STRUCTURE

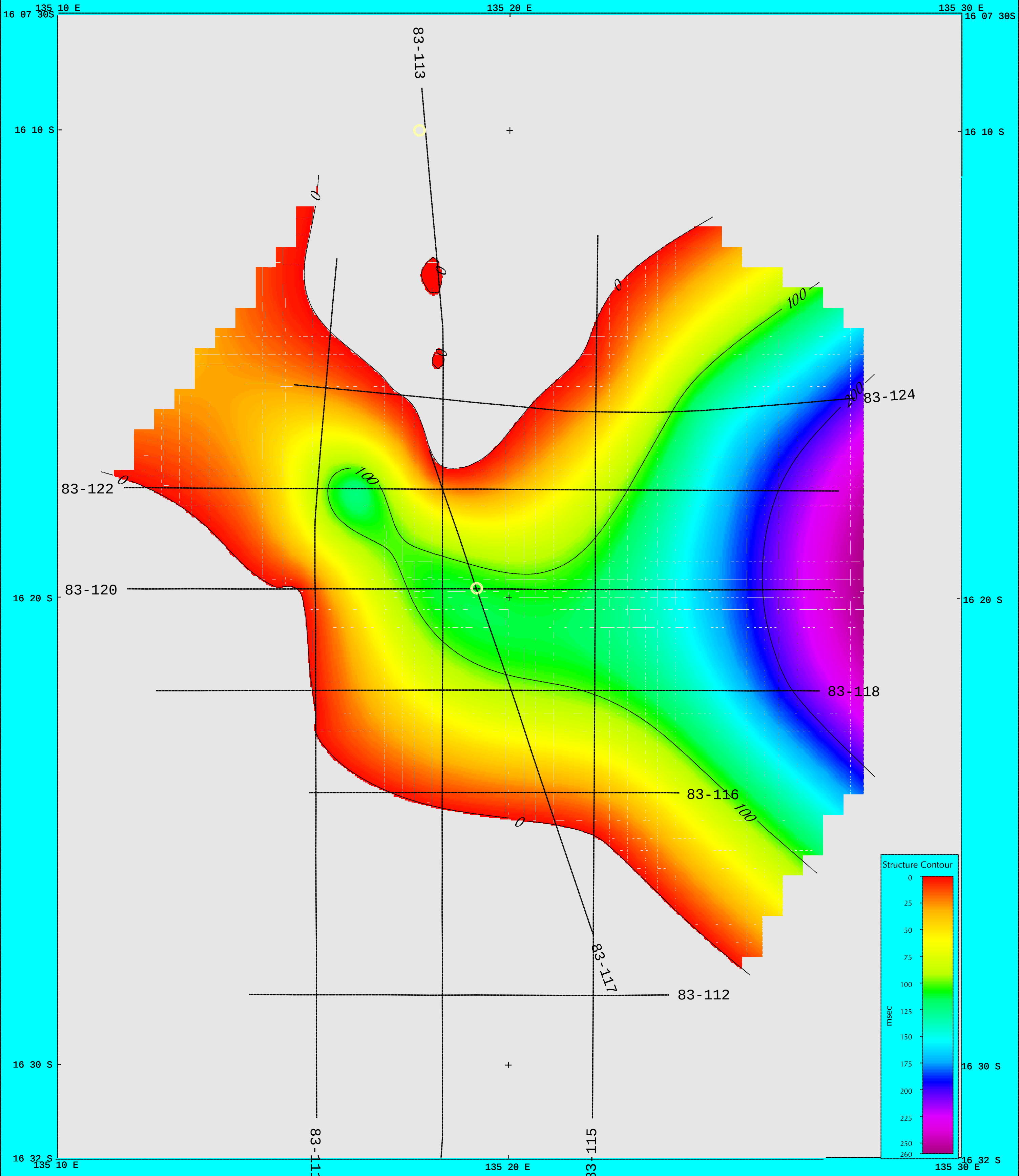

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Fig 14 Isochron in two way time for Megasequence M4 (Nathan Group c. 1615-1575 Ma). Note that much of the succession was eroded prior to deposition of the Roper Group (Megasequence M5). Remnants of the Nathan Group only survive over the Broadmere Structure where accommodation, and, hence sedimentation was greater.

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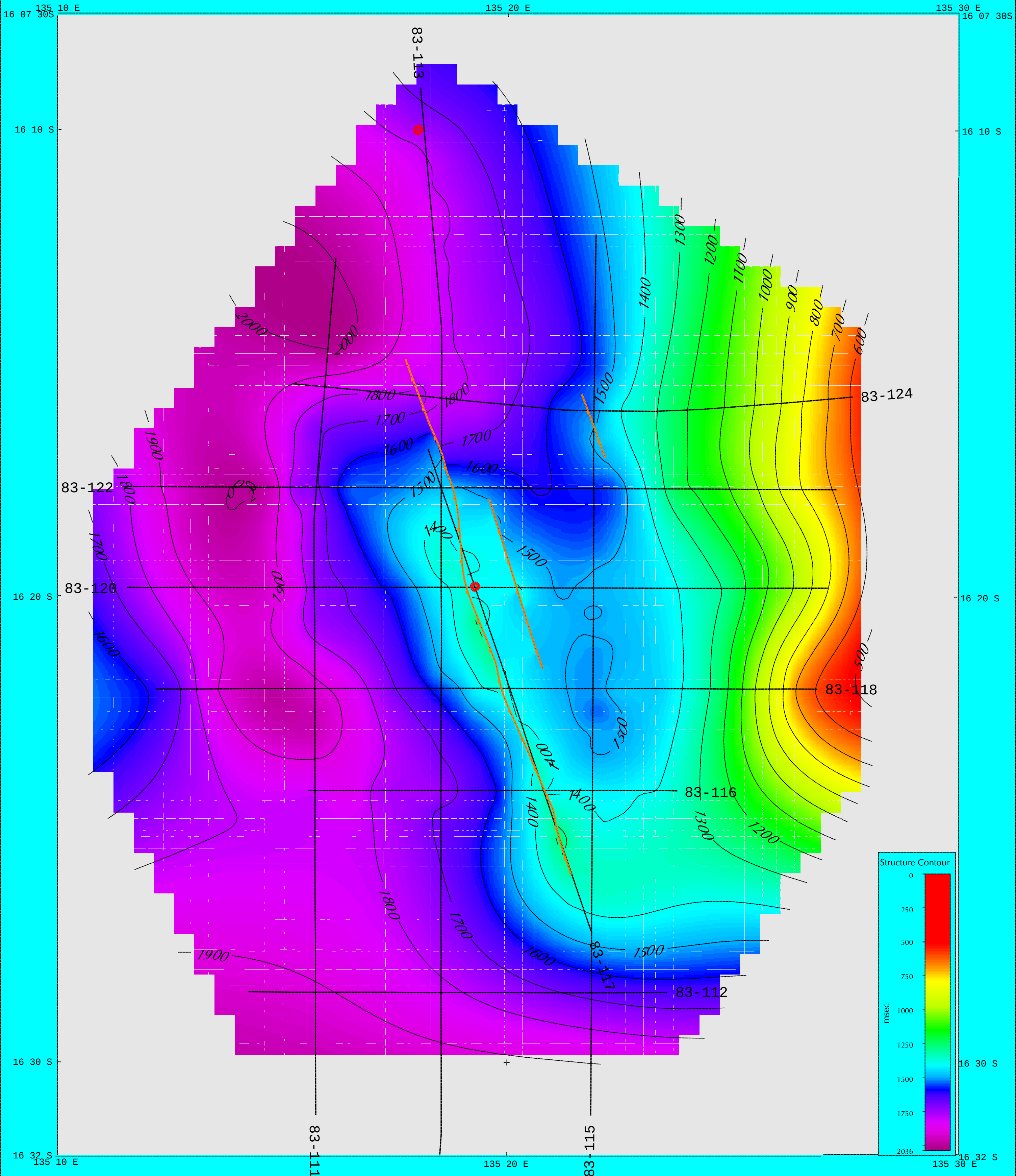
BROADMERE STRUCTURE



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Two way time
Interpretation by John Lindsay
Petroseis Version 7.62b
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Date : Oct 1998

Fig 15 Structure contours in two way time on the erosional sequence boundary at the top of Megasequence M4 (c. 1575 Ma). Note the zone of discontinuous faulting along the well-defined crest of the Broadmere Structure.

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AUSTRALIAN NATIONAL SPHEROID
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Perspective view

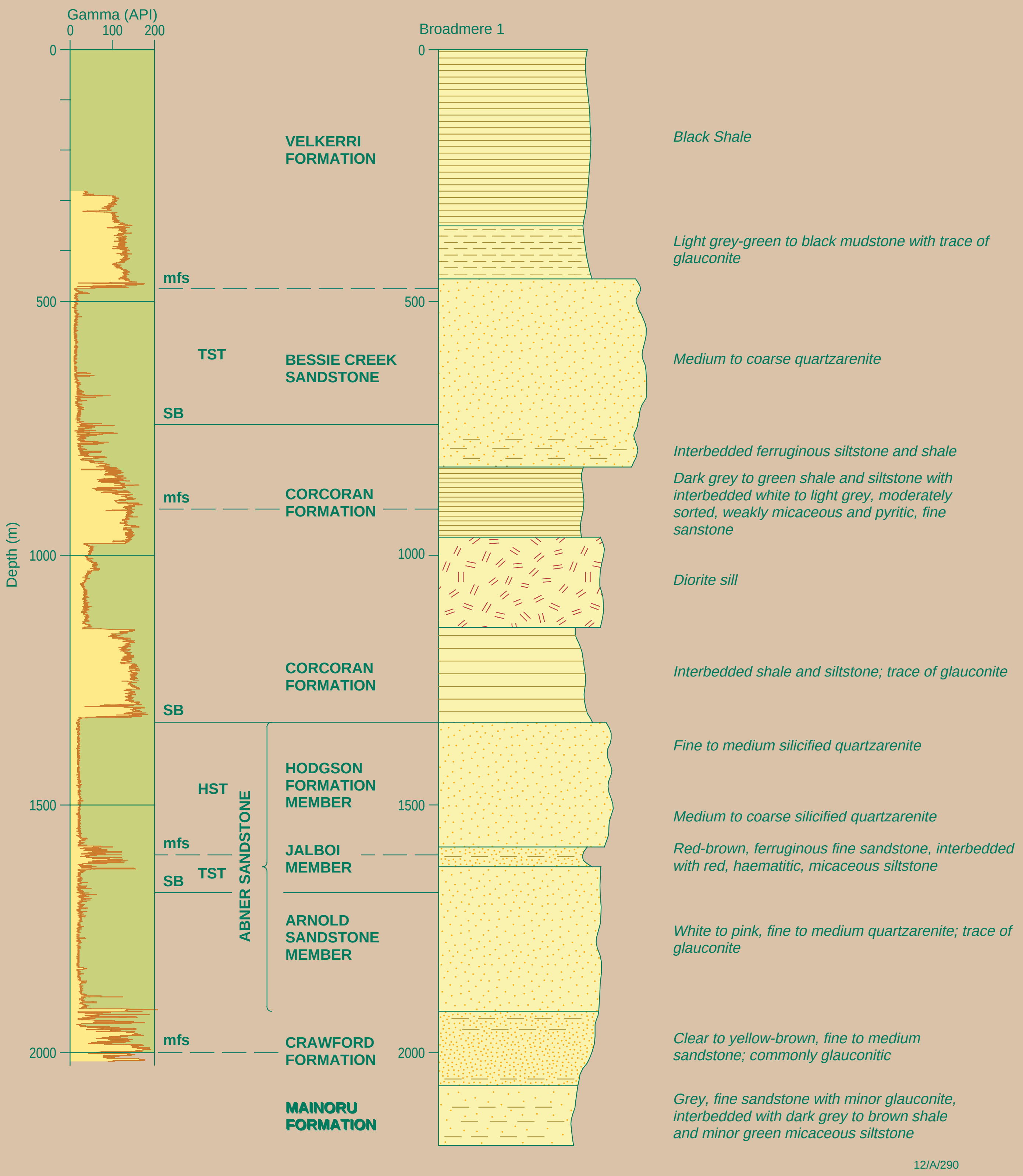

Figure 16 BROADMERE No.1 WELL LOG OUTLINING THE LITHOSTRATIGRAPHY AND SEQUENCE OF THE LOWER ROPER GROUP

Lithostratigraphy

Seismic line Amoco 83-117

Seismic line Amoco 83-120

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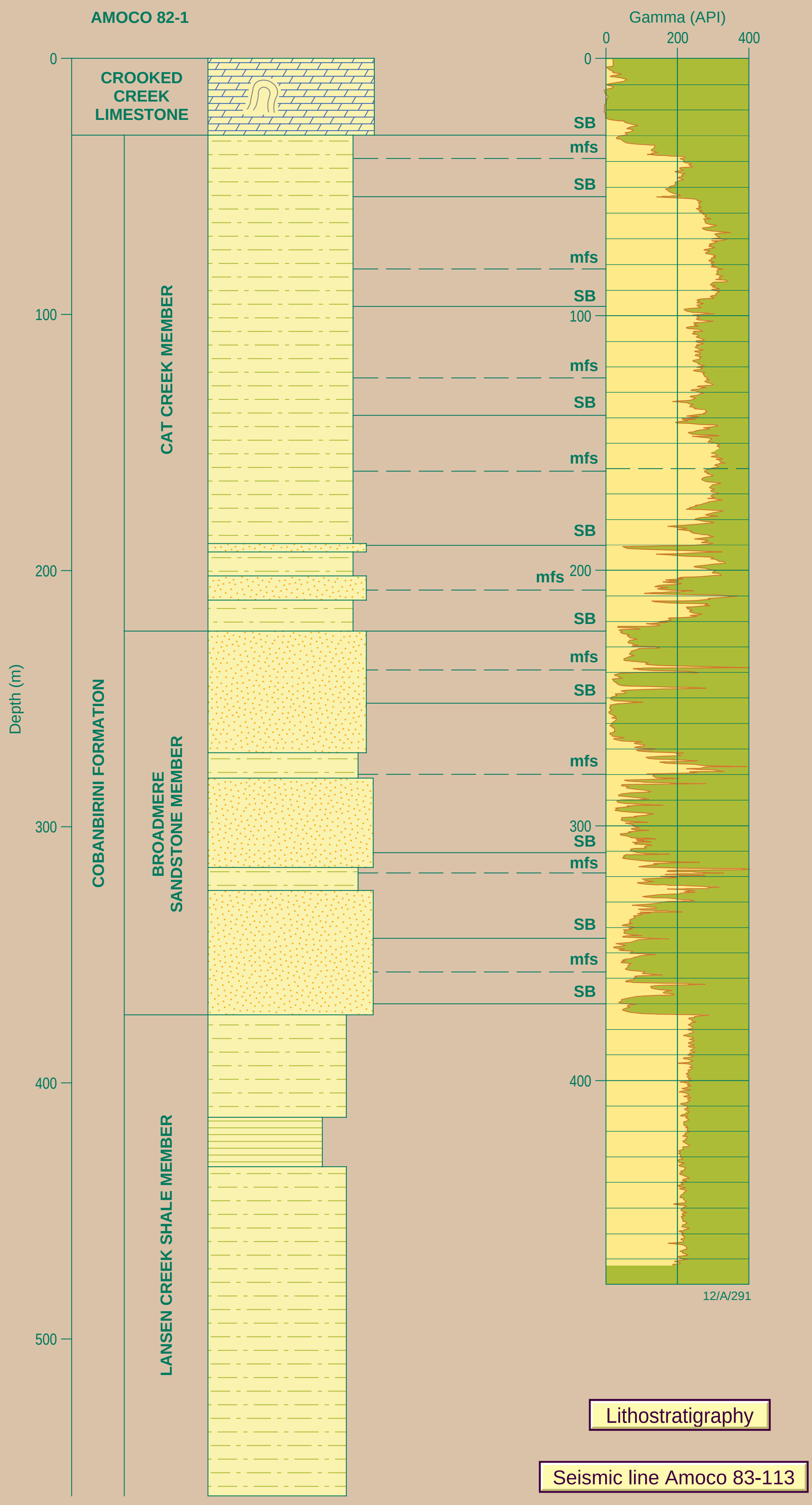

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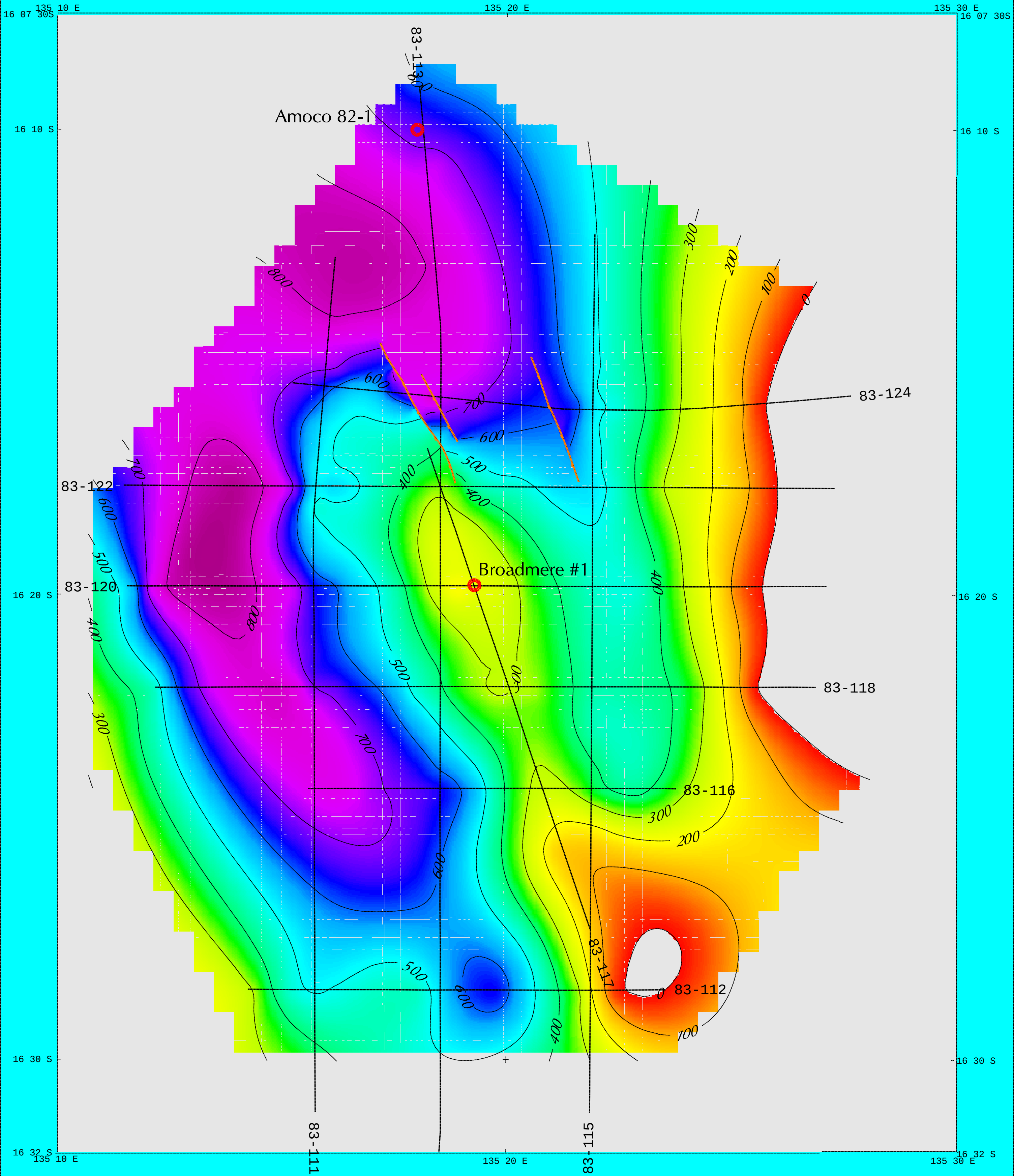
Figure 17 AMOCO 82-1 WELL LOG AND THE LITHOSTRATIGRAPHY AND SEQUENCE OF THE UPPER ROPER GROUP

BROADMERE STRUCTURE



Contour Interval 100 msec
Two way time
Interpretation by John Lindsay
Petroseis Version 7.62b
Generated by I Zeilinger
Date : May 1998

Fig 18 Structure contours in two way time on the sequence boundary near the top of Bessie Creek Sandstone. Note the positioning of the Broadmere #1 well at the crest of the well defined Broadmere Structure.

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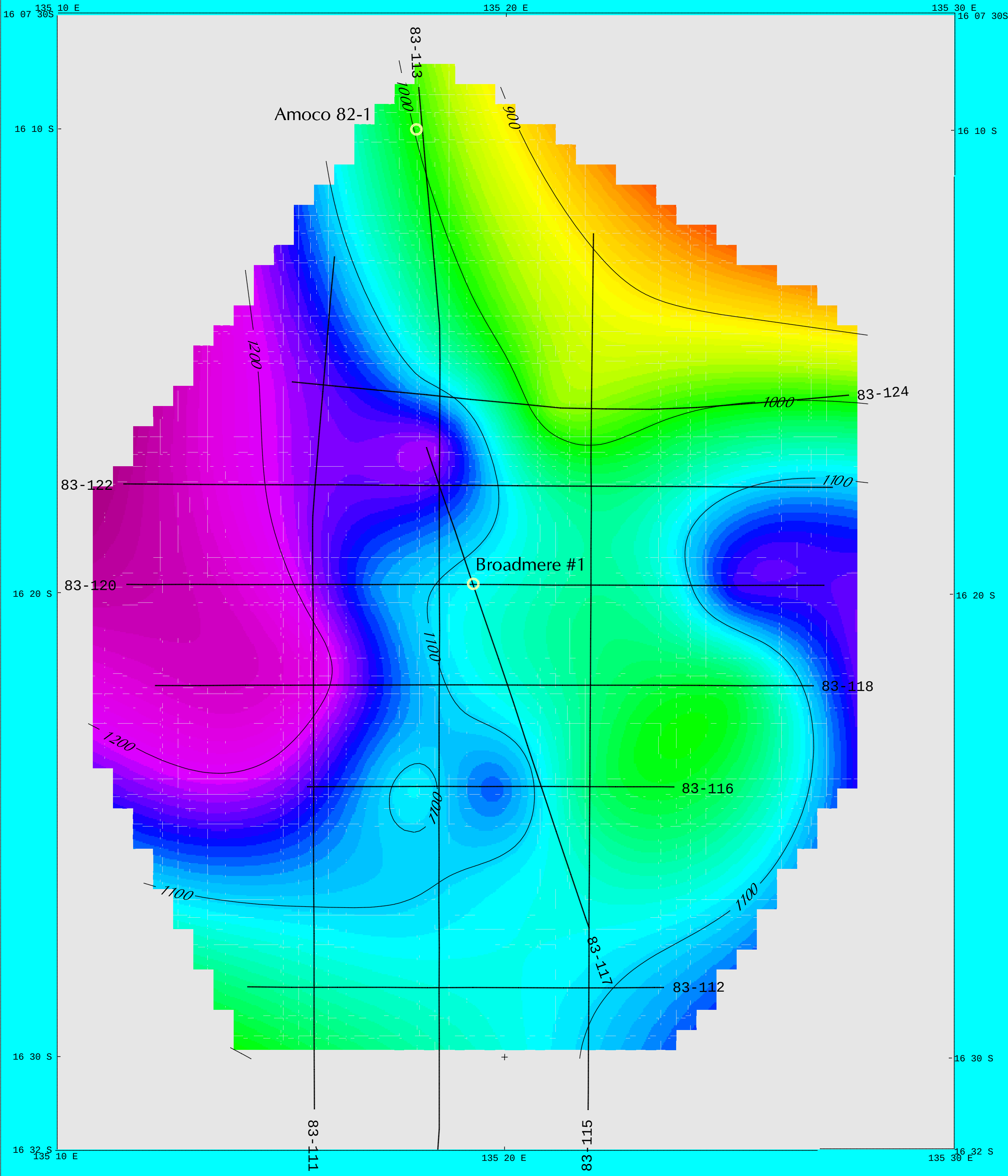
UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 135 E

AGSO

Perspective view

BROADMERE STRUCTURE



Contour Interval 100 msec
Two way time
Interpretation by John Lindsay
Petroseis Version 7.62b
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Date : Oct 1998

Fig 19 Isochron in two way time for the Lower Roper. Note that, by comparison with the earlier megasequences, the Lower Roper Group is relatively uniform in thickness.

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UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 135 E

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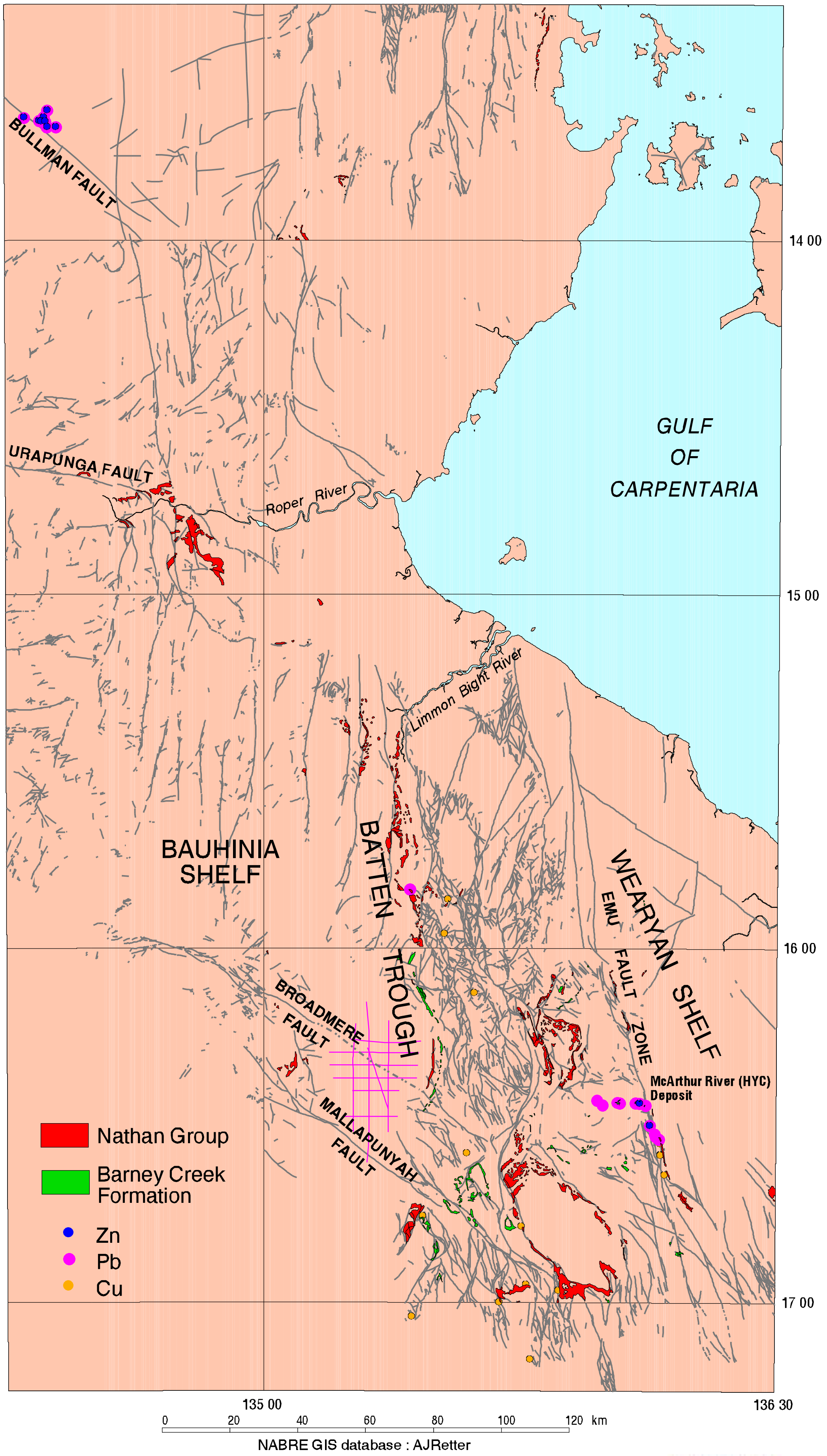


AGSO

Fig 20 Regional map of the McArthur Basin showing the distribution of Nathan Group (Megasequence M4) in relation to mineralisation. Note that Pb/Zn occurences are restricted to areas close to the major bounding faults, such as the Emu Fault, whilst Cu occurrences are distributed across the Batten Trough (primary data from Ewers and Ryburn, 1997) in association with the inverted zones above the underlying half grabens

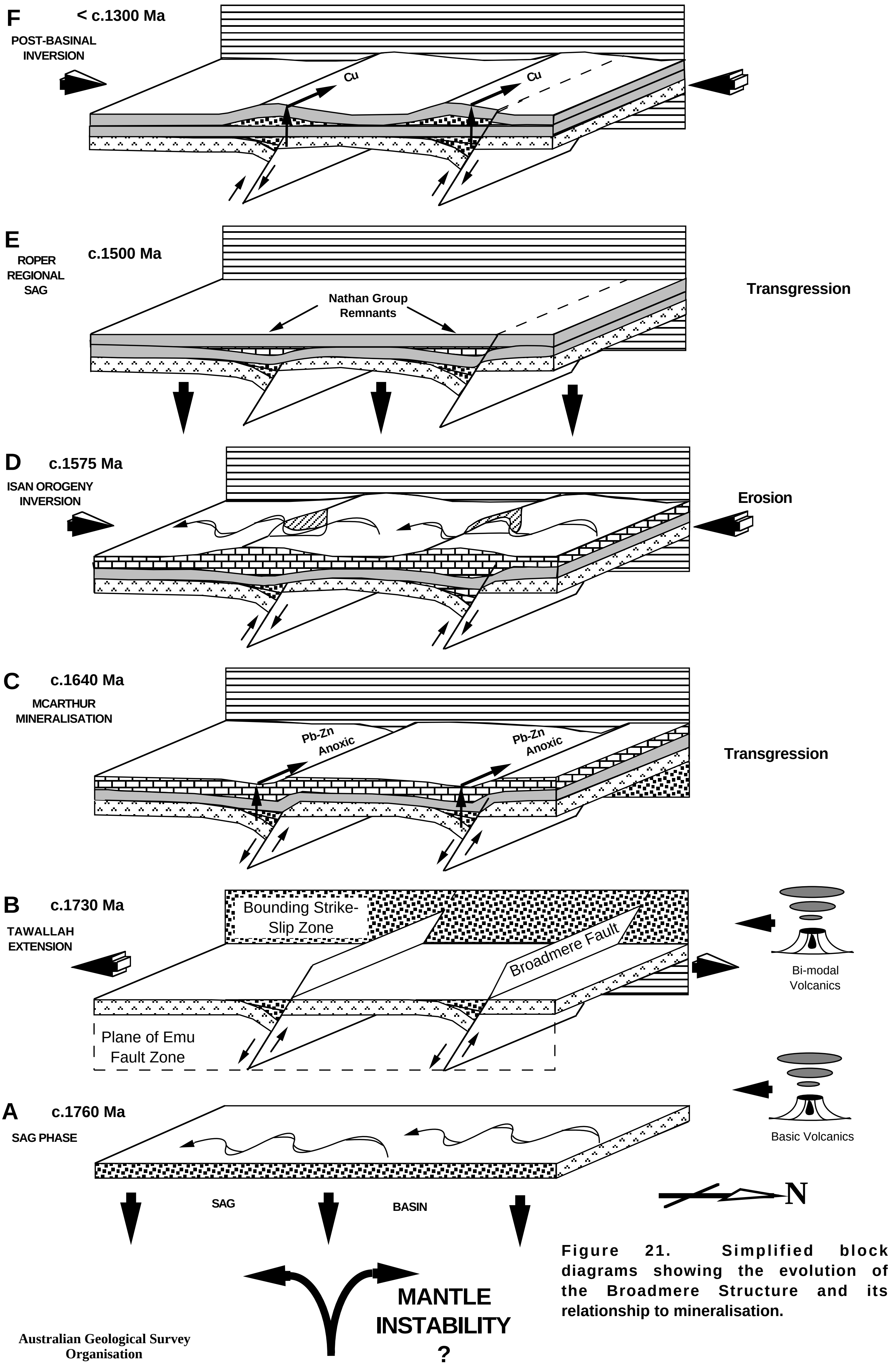
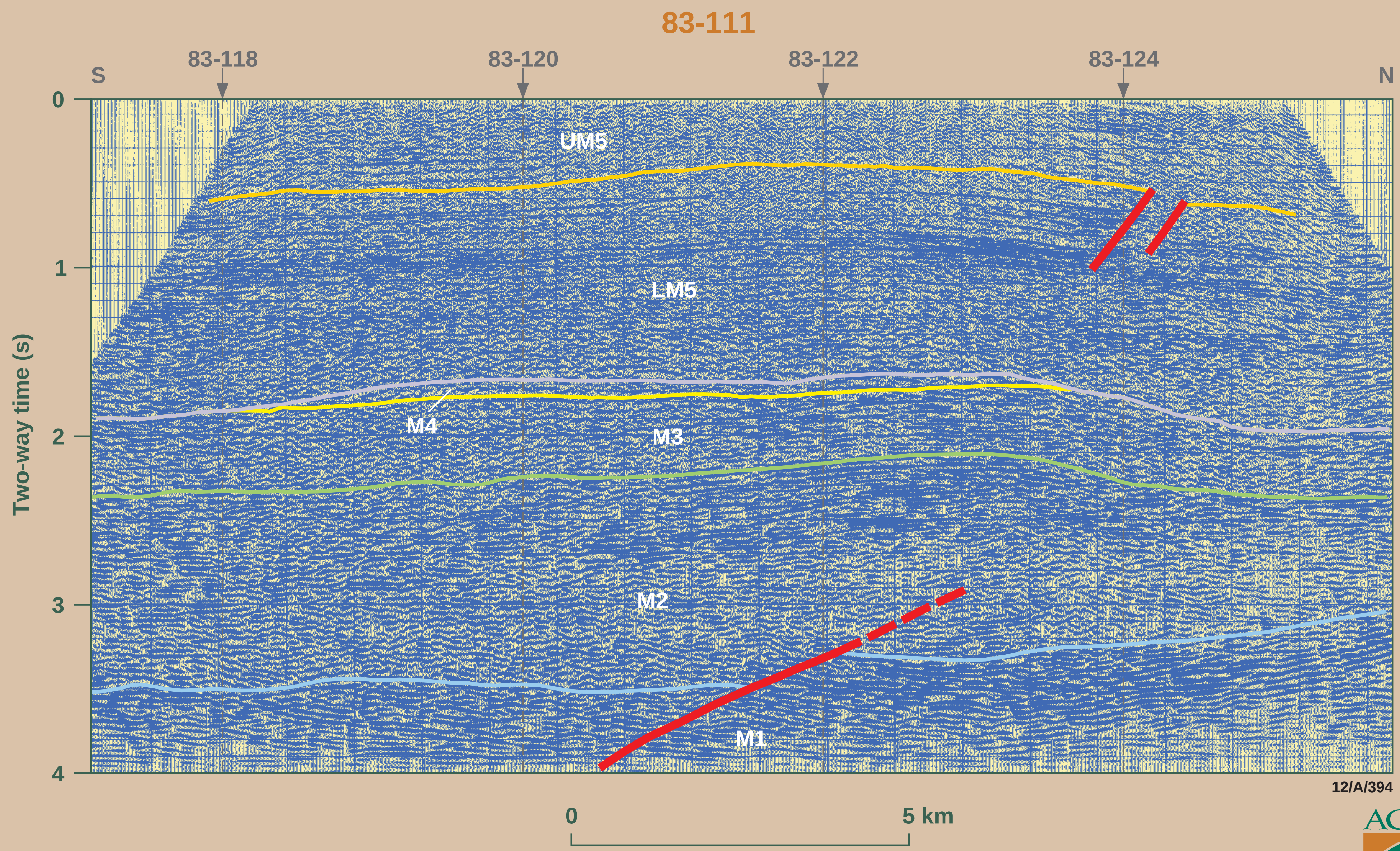


Figure 21. Simplified block diagrams showing the evolution of the Broadmere Structure and its relationship to mineralisation.

Australian Geological Survey
Organisation



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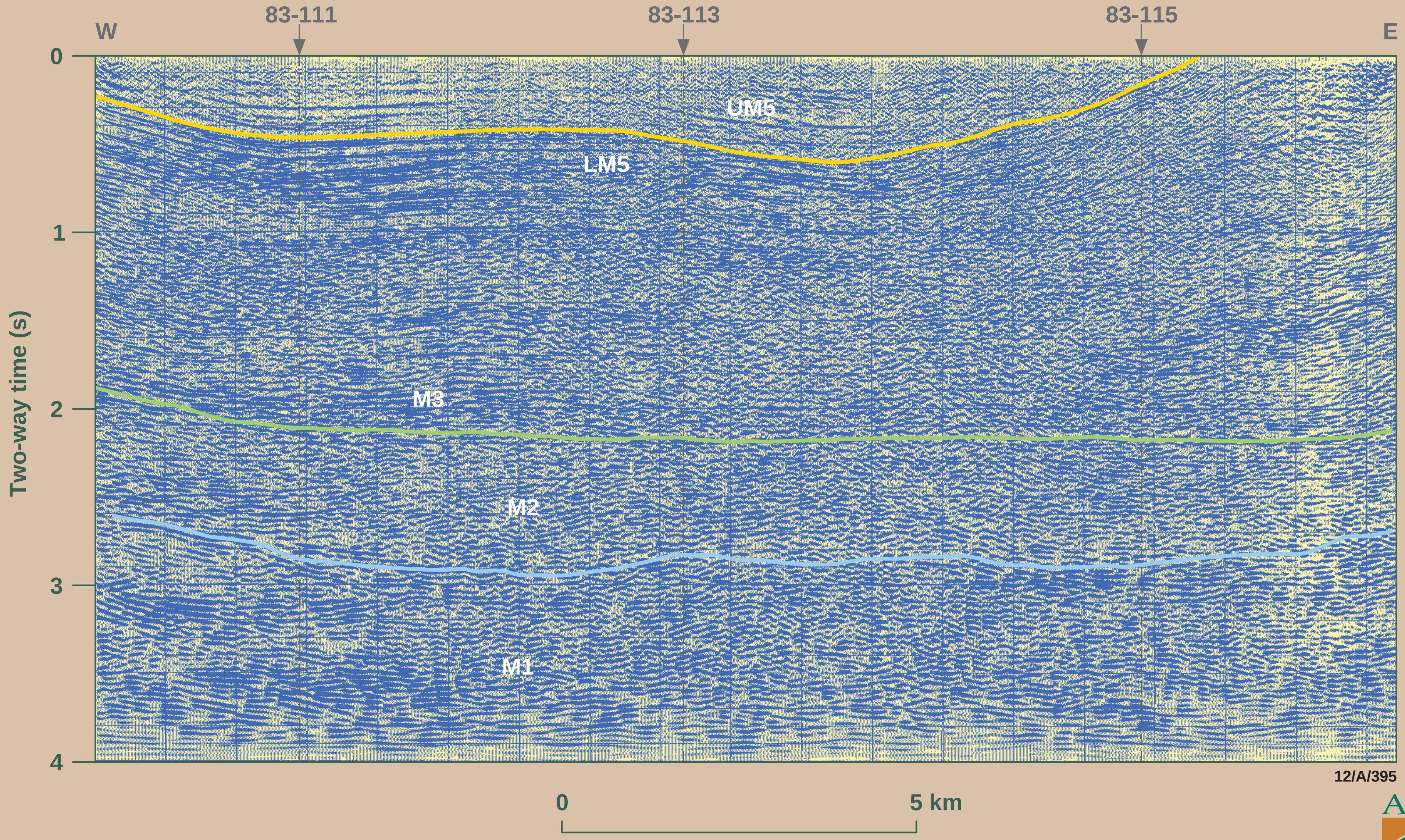
Seismic parameters

83-112



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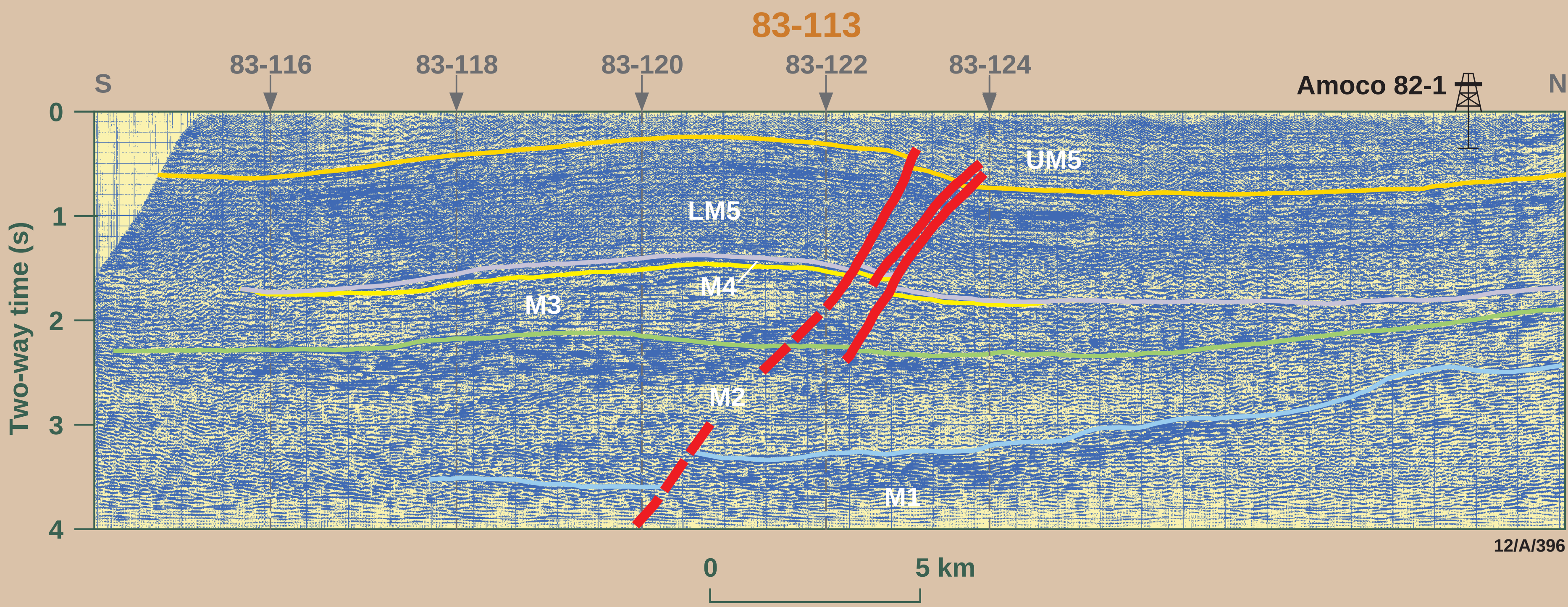

Amoco 82-1

Seismic parameters

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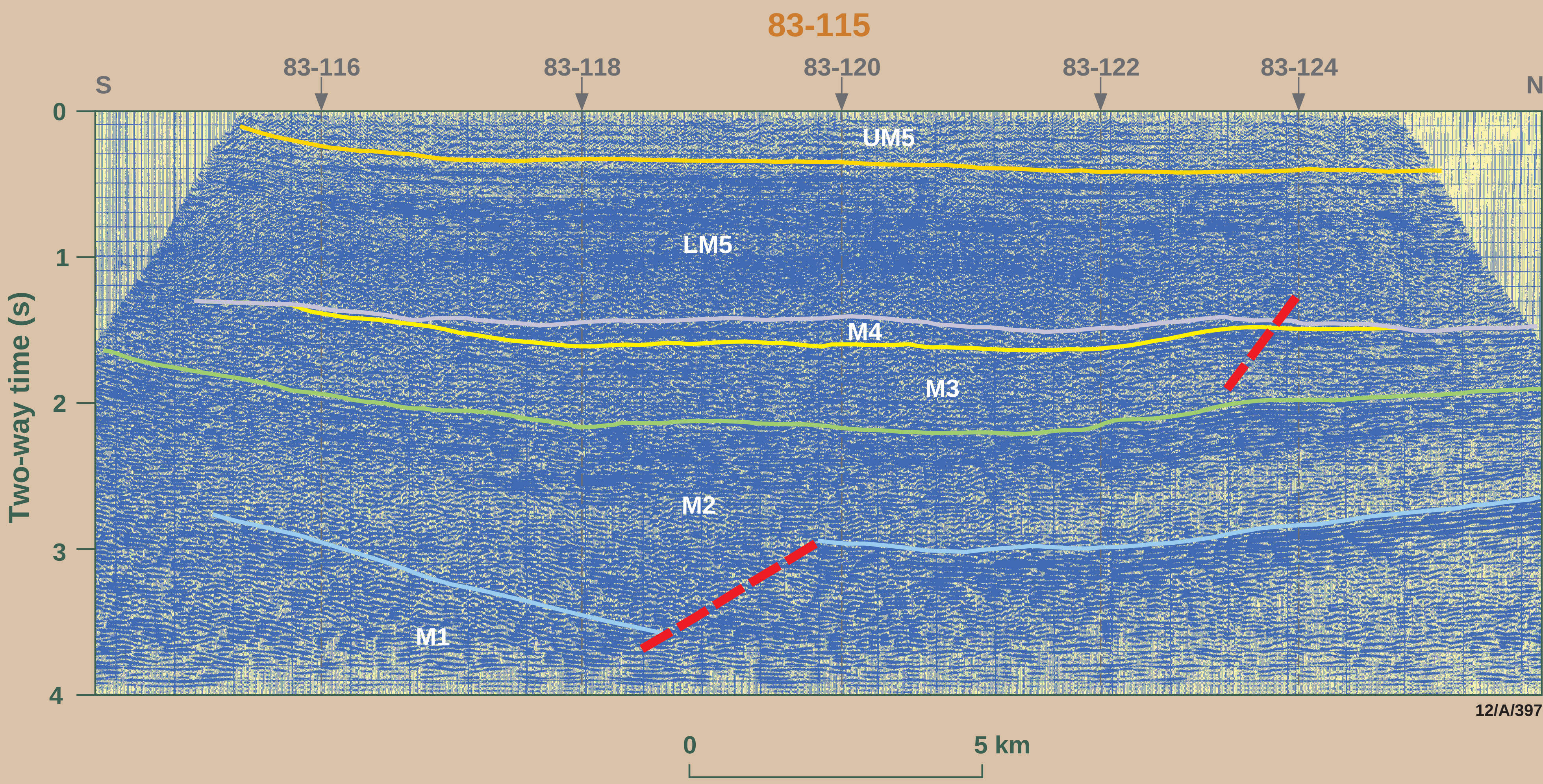

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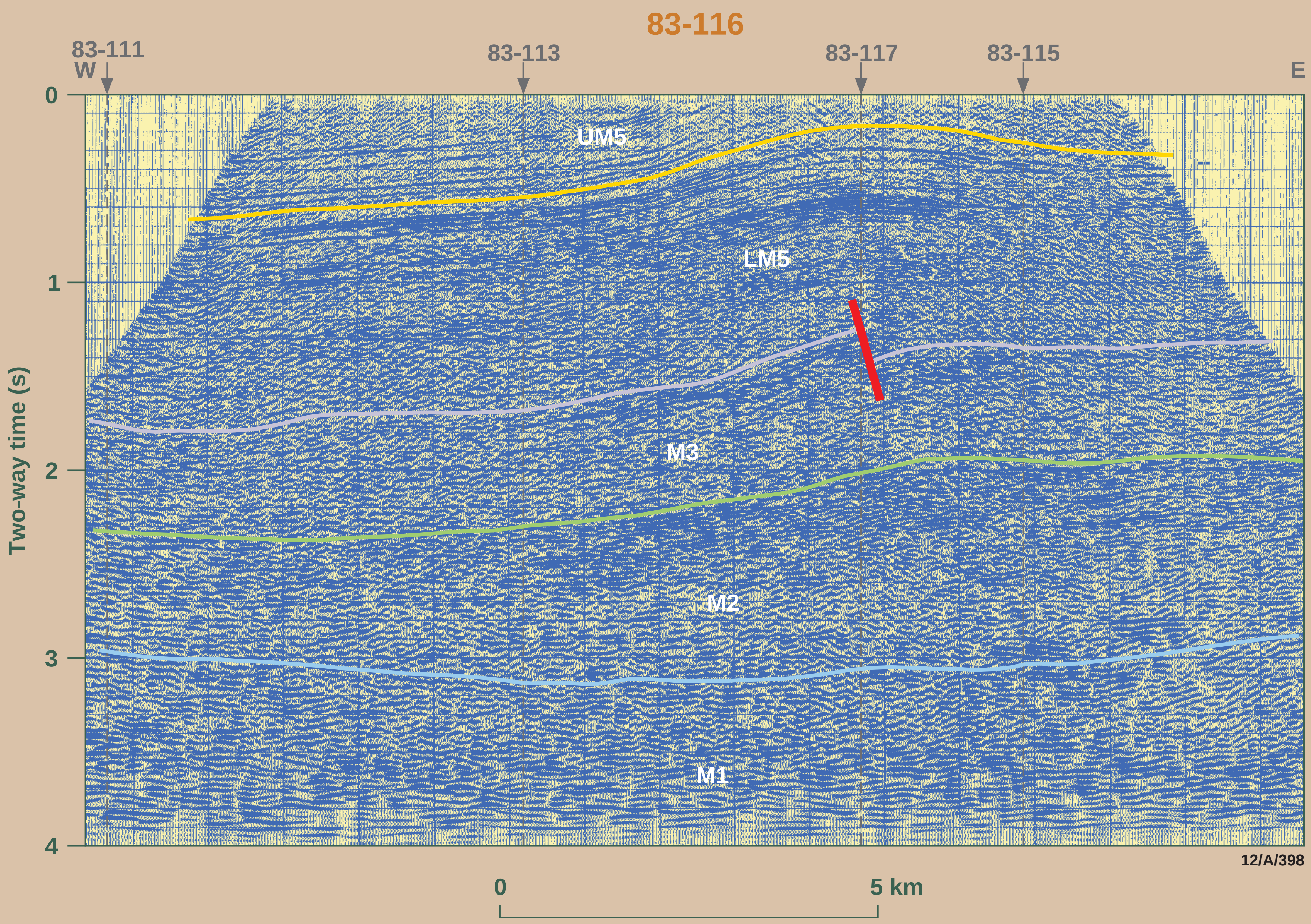

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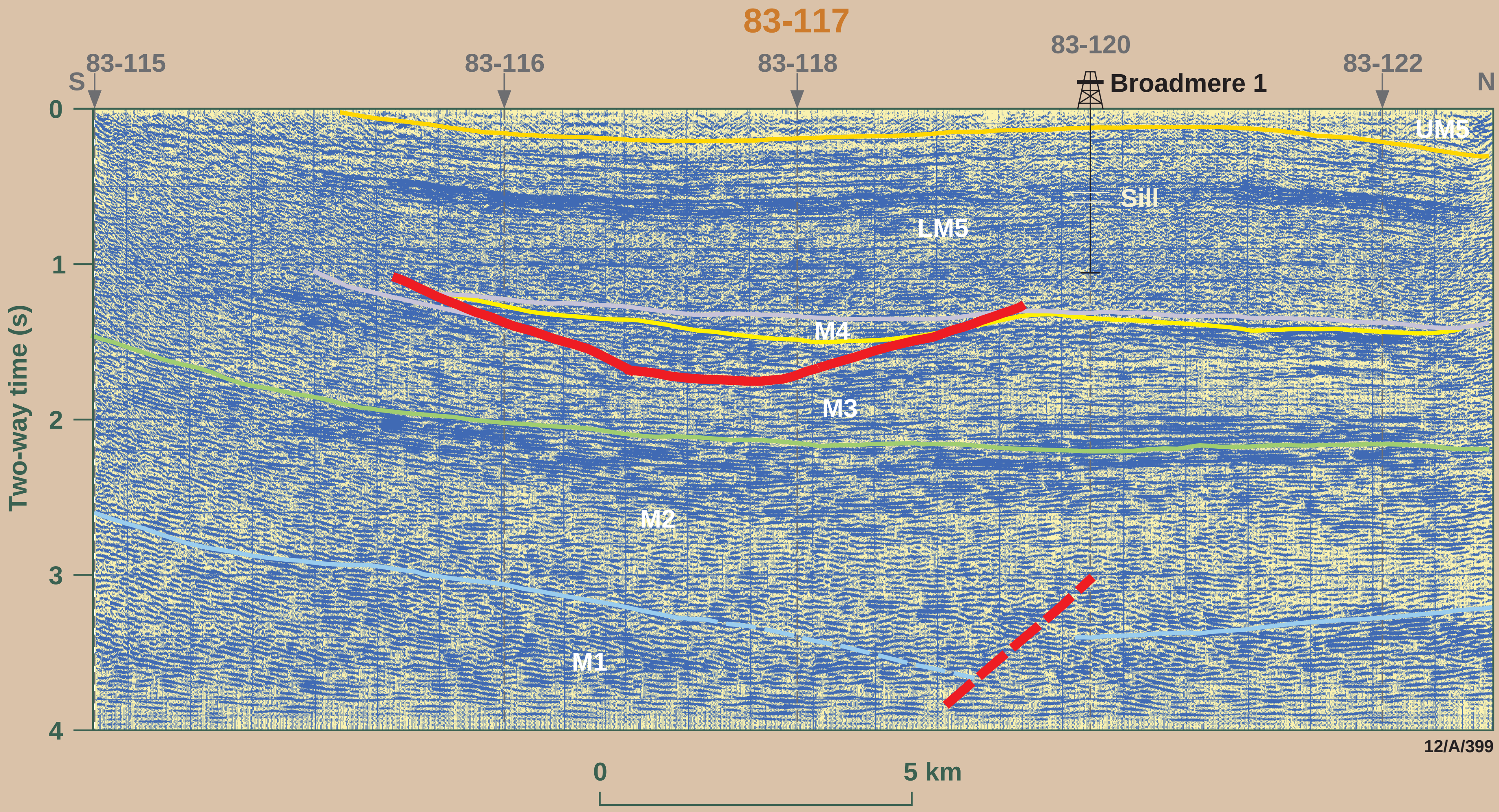

Broadmere 1

Seismic parameters

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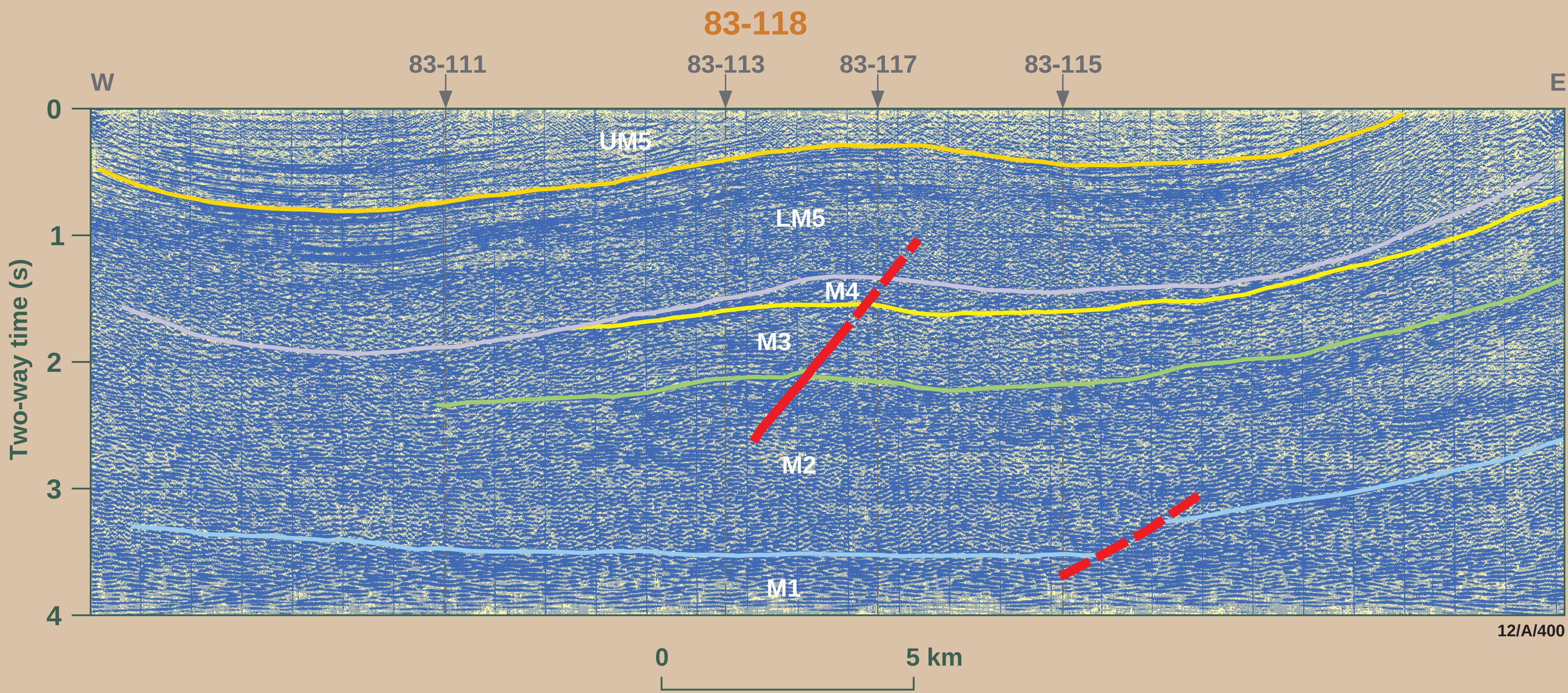

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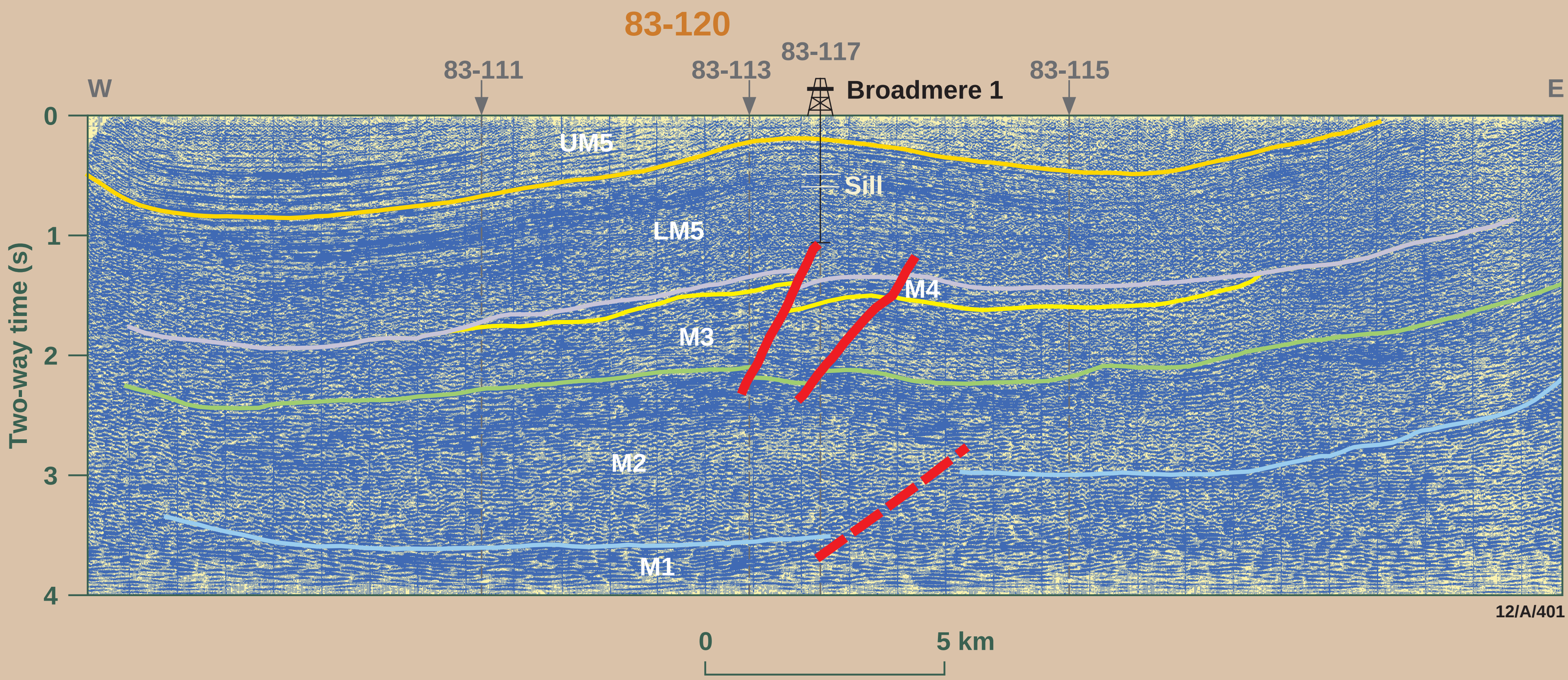

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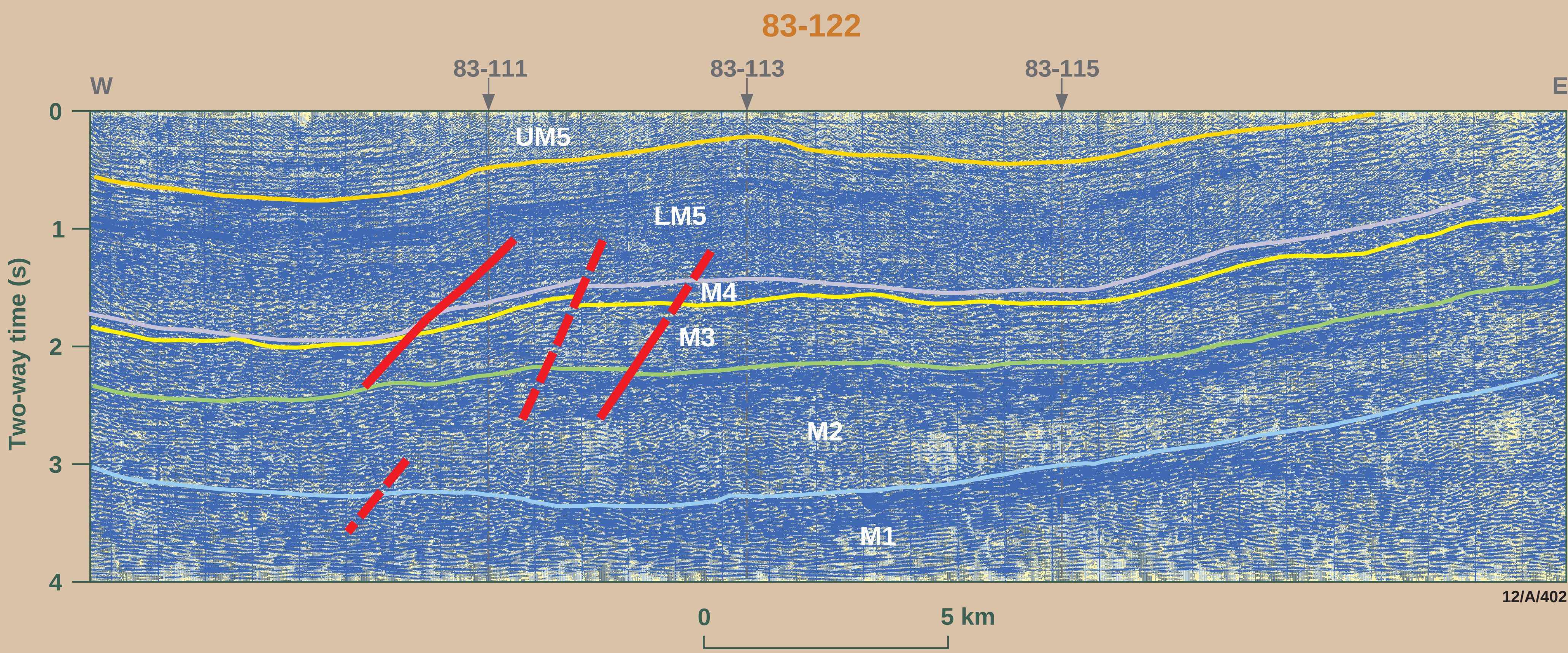
Broadmere 1

Seismic parameters



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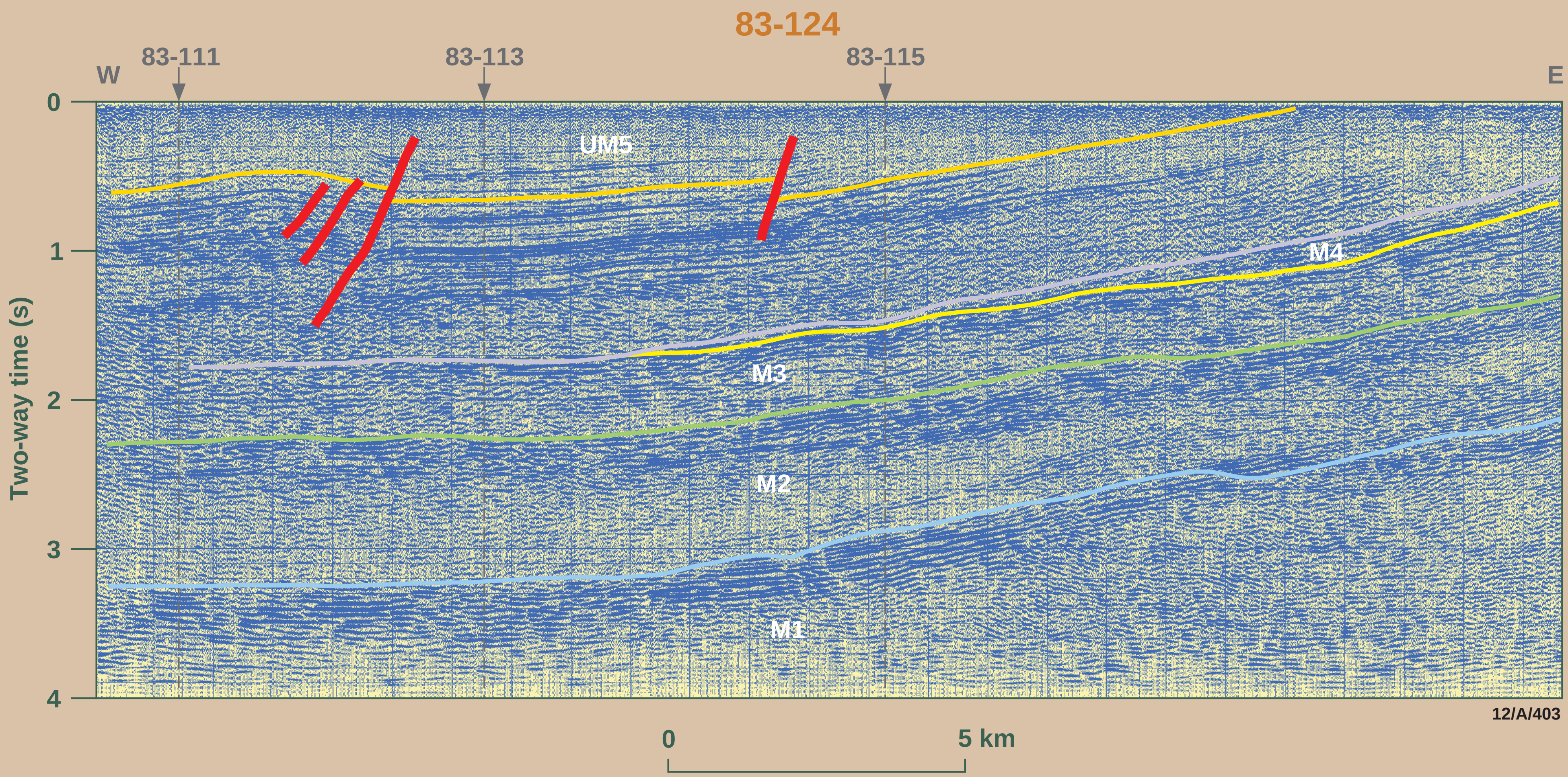
Seismic parameters



Seismic parameters

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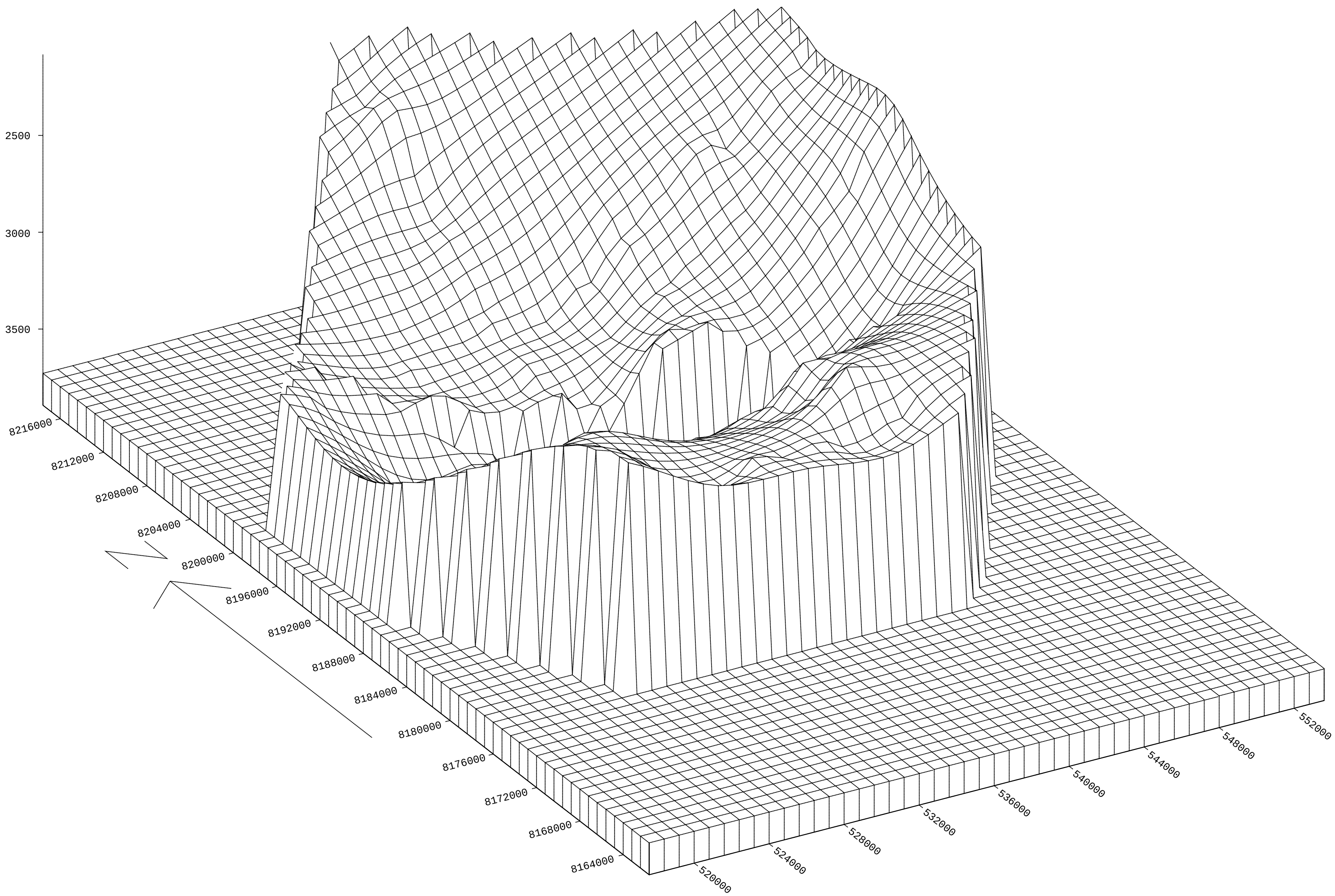
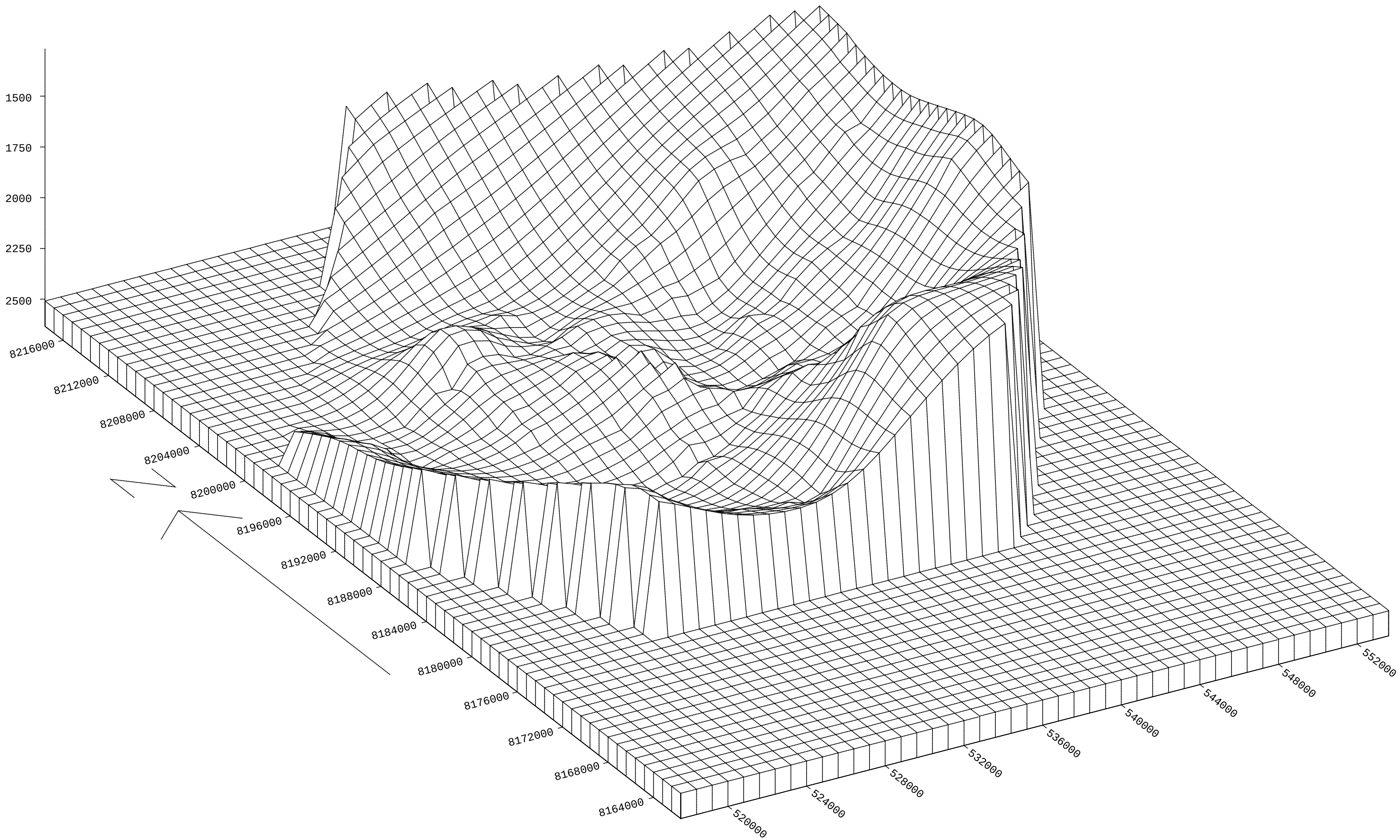
Fig 6 Perspective view of the erosion surface at the top of Megasequence M1 (c. 1730).



VIEWING ANGLE 30 DEGREES

VERTICAL EXAGGERATION 10.00

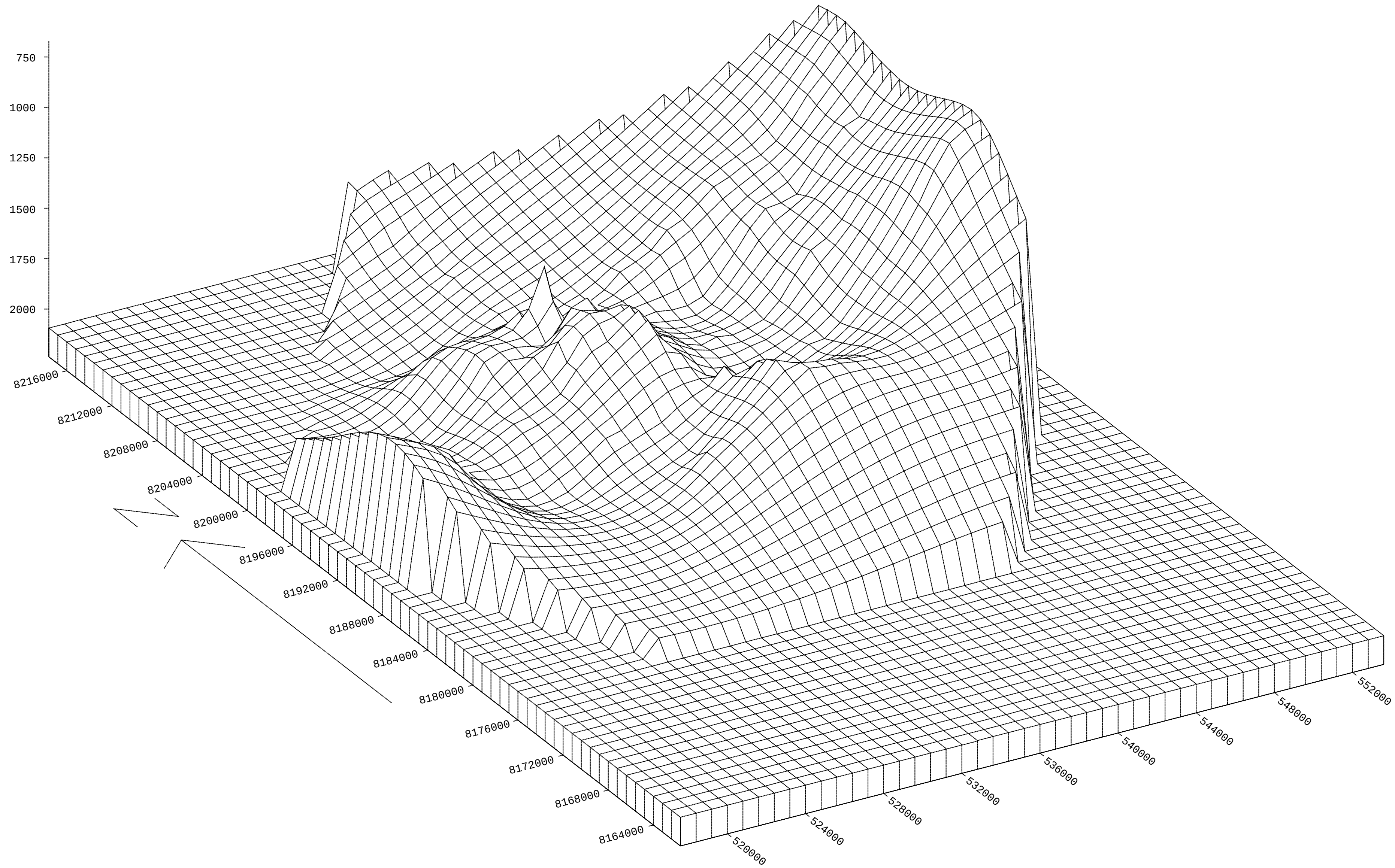
Fig 10   Perspective view of the erosion surface at the top of Megasequence M2 (c. 1645).



VIEWING ANGLE 30 DEGREES

VERTICAL EXAGGERATION 10.00

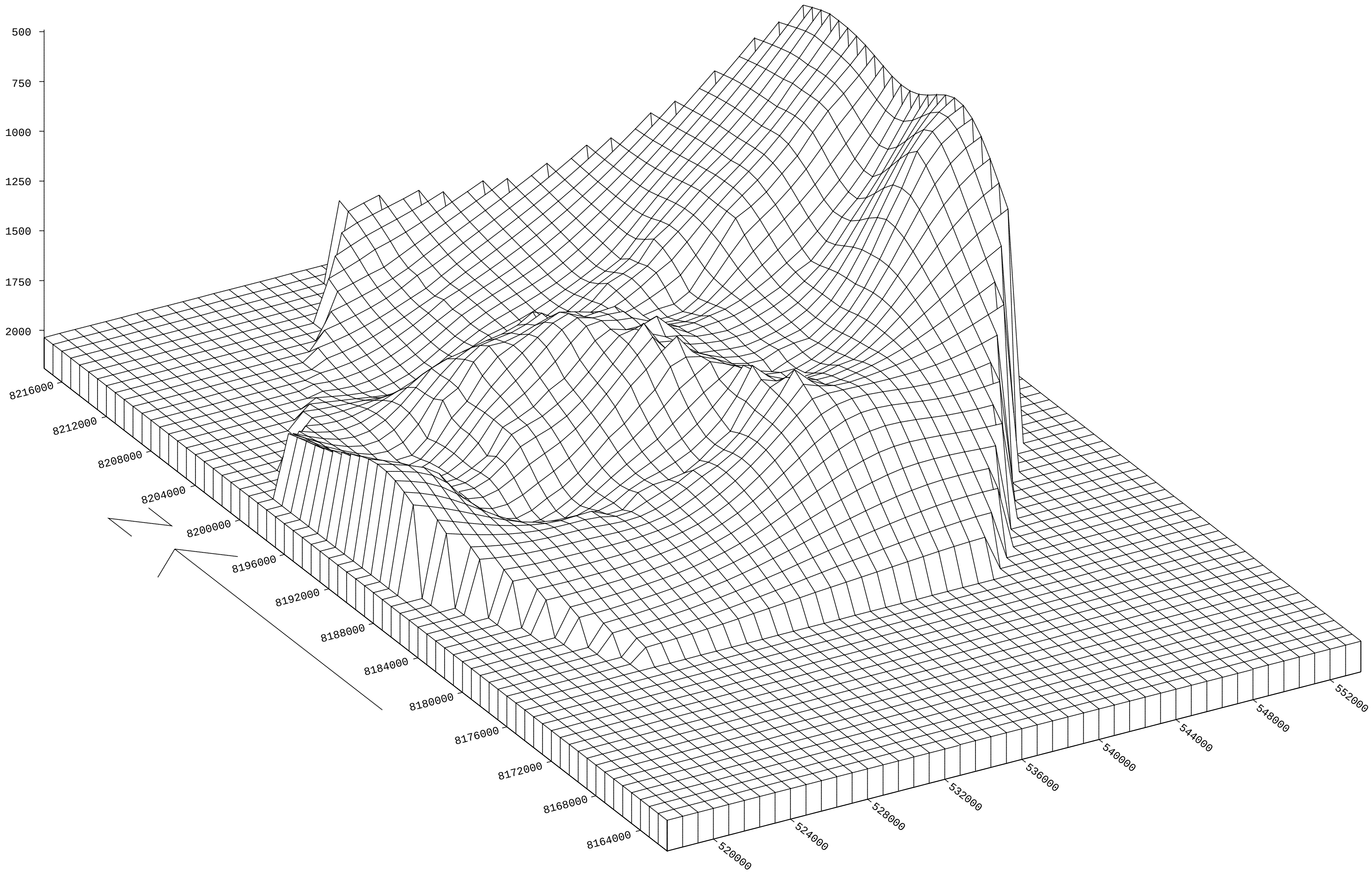
Fig 13 Perspective view of the erosion surface at the top of Megasequence M3 (c. 1615).



VIEWING ANGLE 30 DEGREES

VERTICAL EXAGGERATION 10.00

Fig 15   Perspective view of the erosion surface at the top of Megasequence M4 (c. 1575).



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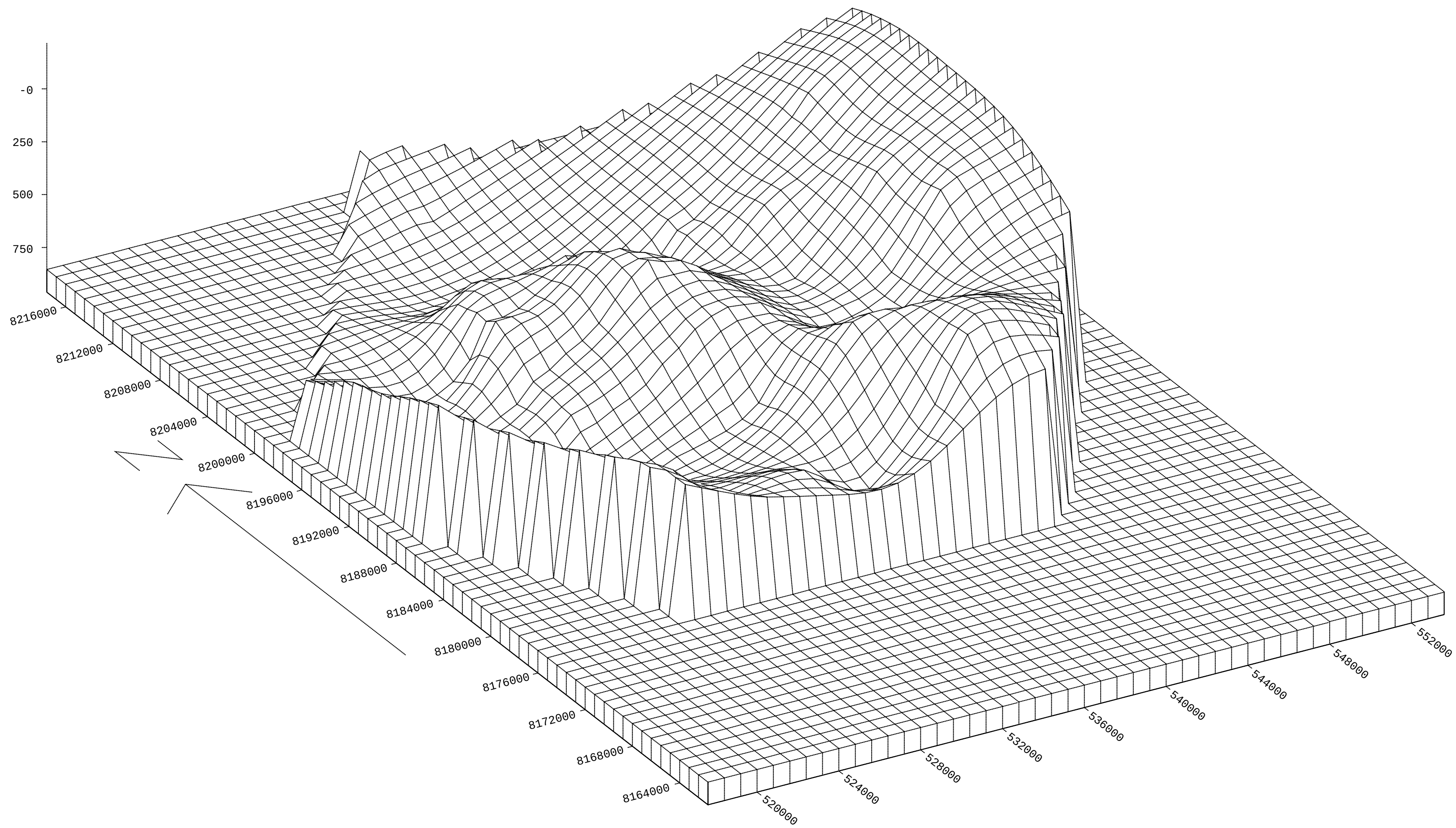
VERTICAL EXAGGERATION 10.00

Fig 18   Perspective view of the sequence boundary near the top of Bessie Creek Sandstone.



VIEWING ANGLE 30 DEGREES

VERTICAL EXAGGERATION 10.00

Table 1. Seismic Parameters

The Broadmere seismic survey was acquired by Amoco in 1983. It consists of 333 line kilometers of Sign-bit recorded Vibroseis data over the Broadmere (OP 191) area. Velocities are high throughout the area. The following recording parameters and processing sequences were followed. Processing was carried out by Interseis, New Orleans, La, USA in 1984.

Recording Parameters

Date Recorded	1983	Recorded by	GSC
Shot Point Interval	36 m	Group Interval	18 m
Configuration	Split Spread	Traces Recorded	512
Instruments	GEOCOR IV	Data Length	4 sec
Sample Rate	2 ms	Format	SEGY
Sweep Frequency	14-72 Hz	Sweeps/V.P.	6-12 composite
Energy Source	Vibroseis	Far Offset	4608 m
Near Offset	0 m	GEC/Group	6

Processing Sequence

Reformat	from a SEGY tape	
Resample	2-4 ms	
Geometry	Land	
Datum Correction	150 m using 3500m/sec	
Filters	Time-variant Bandpass	
	20-25-70-80 Hz	0-1500ms
	15-20-60-70 Hz	2000-4000 ms
CDP Gather	128 fold	
Velocity Analysis	Contour Velocity Analysis	
Mute	Surface Consistent	
Mute	Contour Velocity Analysis	
NMO		
Mute	Stretch Suppression	
Mute	Near Offsets	
Balance	Time-variant Scaling	
CDP Status	128 fold	
Deconvolution	(Time Variant) 180 ms Oper. .4 ms gap	
Client Requested Filters	Time Variant Bandpass	
	10-15-50-60 Hz	0-0 ms
	10-15-60-70 Hz	500-1000 ms
	12-17-55-65 Hz	2000-2000 ms
	15-20-45-55 Hz	2500-2500 ms
	17-22-35-45 Hz	3000-4000 ms
Filter	FK Spatially Variant (Noise Rejection)	
Migration	Wave Equation Algorithm	
Equalization	1000 ms Sliding Gate	
Composite	2 to 1	

Table 2. Summary of drillhole data for the Bauhinia Downs Map Sheet

DRILL HOLE:	OPERATOR:	LATITUDE:	LONGITUDE:	AMG E	AMG N	REPORT No:*
82/1	**Amoco**	16 10 00 S	135 18 00 E	532100	8213300	PR83/36
82/5	Amoco	15 23 00 S	135 58 00 E	603700	8206200	PR83/36
82/6	Amoco	16 44 17 S	136 14 08 E	631900	8151700	PR83/36
82/7	Amoco	16 46 48 S	135 59 56 E	606400	8144500	PR83/36
82/8	Amoco	16 41 31 S	135 49 51 E	588000	8154300	PR83/36
BJ1	Shell Company	16 25 20 S	135 57 30 E	600050	8183450	CR82/020
BJ2	Shell Company	16 25 20 S	135 57 30 E	600050	8184400	CR82/020
BJ3	Shell Company	16 26 00 S	135 56 20 E	599050	8183900	CR82/020
BJ4	Shell Company	16 26 12 S	135 58 39 E	601100	8183600	CR82/020
BJ5A	Shell Company	16 23 24 S	135 58 48 E	601250	8187000	CR82/269
BJ5B	Shell Company	16 23 24 S	135 58 48 E	601250	8187500	CR82/269
BJ6	Shell Company	16 24 55 S	135 51 31 E	593300	8186700	CR82/269
Broadmere #1	**Amoco**	16 19 48 S	135 19 17 E			PR85/15
DD82CA1	CRA	16 17 45 S	136 04 19 E	614500	8198100	CR83/022
DD83CA2	CRA	16 17 00 S	136 04 00E	614700	8198700	CR84/128
DD83CA3	CRA	16 18 00 S	136 04 00 E	614500	8198350	CR84/128
DD84CA4	CRA	16 18 00 S	136 04 00 E	614500	8198355	CR84/128
DD84TS7	CRA	16 58 18 S	135 47 00 E			CR85/181
DDH B1-G	T & W					No Report
DDH B2-G	T & W					No Report
DDH 1	Kratos	16 23 00 S	135 09 00 E			CR72/087
DDH 8	Kratos					CR72/087
DDH11	Kratos					CR72/087
FOE1	Norman Expl Ltd			657800	8131120	No Report
FOE2	Norman Expl Ltd			657800	8131120	No Report
FOE3	Norman Expl Ltd			657800	8131120	No Report
FOE4	Norman Expl Ltd			657850	8131480	No Report
FOE5	Norman Expl Ltd			657900	8131100	No Report
FOE6	Norman Expl Ltd			657880	8131210	No Report
FOE7	Norman Expl Ltd			657870	8131390	No Report
FOE8	Norman Expl Ltd			657850	8131480	No Report
GR 1	Shell Company	16 53 00 S	136 15 00 E			CR83/048
GR 2	Shell Company	16 56 00 S	136 17 00 E			CR83/048
GR 3	Shell Company	16 52 00 S	136 14 00 E			CR83/048
GR 4	Shell Company					CR83/048
GR 5	Shell Company	16 53 00 S	136 17 00 E			CR83/048
GR 6	Shell Company					CR83/048
GR 7	Shell Company	16 54 00 S	136 18 00 E			CR83/048
GR 8	Shell Company	16 59 00 S	136 20 00 E			CR83/048
GR 9	Shell Company	1658 00 S	136 19 00 E			CR83/048
GR10	Shell Company	16 56 00 S	136 18 00 E	639000	8127200	CR83/048
LY1	Shell Company	16 36 50 S	135 52 00 E	592500	8163000	CR82/020
MANT79-2	Amoco					CR80/064
McA 1	BHP	16 13 36 S	135 33 24 E	565100	8205700	CR83/068
McA 6	BHP	16 04 00 S	135 33 00 E			CR84/245
McA 7	BHP	16 30 34 S	135 56 33 E	600570	8174450	CR84/145
McA 8	BHP	16 30 19 S	135 56 39 E	600780	8174840	CR84/145
McA 9	BHP	15 28 58 S	135 55 43 E	599150	8177440	CR84/145
McA10	BHP	16 30 52 S	135 57 53 E	602950	8174300	CR84/145
McA11	BHP	16 30 39 S	135 58 44 E	604480	8174290	CR84/145
MY4	Shell Company	16 36 10 S	136 03 20 E	612000	8164000	CR82/020
MY5	Shell Company	16 35 30 S	136 02 40 E	610500	8165000	CR82/020
PD84 LC-2	CRA	17 06 24 S	136 07 54 E	620400	8108300	CR85/255
PD84 LC-3	CRA	17 08 26 S	136 00 11 E	606700	8104600	CR85/255

*Available through the Northern Territory Geological Survey