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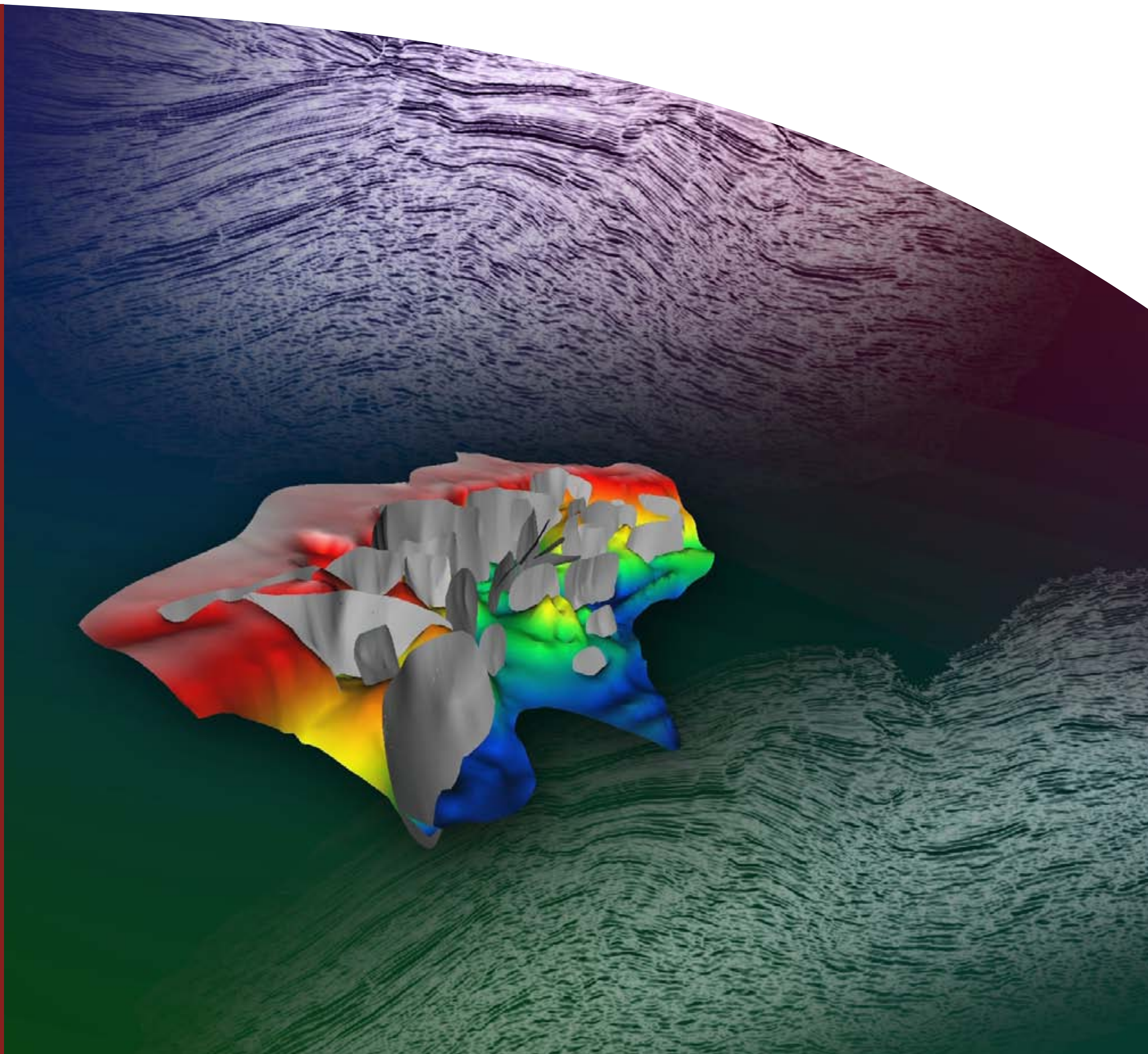
Australian Government
Geoscience Australia

Geology and Petroleum Potential of the Bremer Sub-basin,

Offshore Southwestern Australia

Compiled by: B.E. Bradshaw
With contributions by: B.E. Bradshaw, D.J. Ryan, C.J. Nicholson, R.P.D. O'Leary, C.J. Boreham, B.B. Hardy, R.W. Howe, F. Kroh, C. Mitchell, and E. Monteil.

Record
2005/21



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Australian Government
Geoscience Australia

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Minister for Industry, Tourism & Resources: The Hon. Ian Macfarlane, MP
Parliamentary Secretary: The Hon. Warren Entsch, MP
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ISSN 1448-2177
ISBN 1 920871 62 4

GeoCat # 63730

Bibliographic reference:

Bradshaw, B.E. (Compiler), 2005. Geology and Petroleum Potential of the Bremer Sub-basin, offshore southwestern Australia. Geoscience Australia, Record 2005/21.

O'Leary, R.P.D., Bradshaw., B.E. and Ryan, D.J., 2005. Stratigraphic framework. In: Bradshaw, B.E. (Compiler), 2005. Geology and Petroleum Potential of the Bremer Sub-basin, offshore southwestern Australia. Geoscience Australia, Record 2005/21.

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Executive Summary

The Bremer Sub-basin, which forms part of the Bight Basin off the southern coast of Western Australia, is a deep-water (100–4000 m water depth) frontier area for petroleum exploration. No wells have been drilled to test the sub-basin's petroleum potential, with company exploration limited to a regional seismic survey by Esso Australia Ltd in 1974. Early studies identified the Bremer Sub-basin as a series of Middle Jurassic–Early Cretaceous half graben, which contain potentially prospective structures for trapping hydrocarbons. However, a lack of sub-surface geological data, along with the deep-water setting, discouraged exploration of this area for over 30 years. In 2003, the Bremer Sub-basin was identified as a key frontier area in Geoscience Australia's New Oil Program where new exploration opportunities might occur. Subsequently, Geoscience Australia's Bremer Sub-basin Study commenced in 2004 with an aim to determine if the sub-basin formed under suitable geological conditions to generate and trap large volumes of hydrocarbons.

Acquisition of new data sets began during Geoscience Australia's Marine Survey 265 in February and March 2004, when several hundred sub-surface geological samples were collected by dredging the sub-marine canyons that incise up to 2 km into the basin succession. Geoscience Australia subsequently acquired 1300 km of new seismic data in the sub-basin, as part of its regional Southwest Frontiers Survey (S280) during October and November 2004. This survey provides the first regional seismic coverage across the complete extent of the Bremer Sub-basin.

Through integrating biostratigraphic and lithofacies data from dredge samples with seismic interpretations, this study has been able to compile the first detailed stratigraphic framework for the sub-basin. Six seismic stratigraphic units (Bremer 1–6) have been interpreted. Most of the basin succession consists of Middle Jurassic–Early Cretaceous fluvial and lacustrine sedimentary rocks from the Bremer 1, 2, 3 and 4 units. Mid–Late Cretaceous (Bremer 5 and Bremer 6 units) and Cainozoic marine sedimentary rocks are also present, but form only a thin overburden. Of particular importance to petroleum exploration is a series of three major cycles of lacustrine and fluvial sedimentation in the Tithonian–Valanginian, which provide key petroleum system elements of source, reservoir and seal rocks.

The structural architecture of the Bremer Sub-basin is characterised by a series of *en echelon* half graben that originated during rifting in the Middle–Late Jurassic. A large potential source kitchen area is formed in the central part of the sub-basin, where sediments are between 4–9.5 km thick. Here, the main exploration play is fault block traps in water depths of 1000 to over 2500 m that formed during the Valanginian–Aptian, and have the potential to trap ~250 million barrel of oil in place (P_{50} estimate; P_{10} estimate = ~500 million barrels). Trap preservation is the main exploration risk in the central Bremer Sub-basin, with many faults reactivated during Late Cretaceous break-up. Smaller depocentres containing 4–5 km of sediments occur in the western and eastern parts of the sub-basin. The main exploration play in these smaller depocentres is large anticlinal structures in water depths of 500–800 m, which have the potential to trap 500 million barrels of oil in place (P_{50} estimate; P_{10} estimate ~900 million barrels). Anticlinal structures formed in the hanging wall block of the main basin bounding fault systems during the Valanginian. Hydrocarbon charge is the main exploration risk in these smaller depocentres.

One dimensional burial history modelling using pseudo wells located in potential source kitchen areas has been undertaken to investigate the potential petroleum systems in the Bremer Sub-basin. Four source rock intervals have the potential to generate and expel hydrocarbons. Fluvial lacustrine mudstones from the Middle–Late Jurassic Bremer 1 unit are generally gas-prone, with their main

phase of expulsion modelled to occur during the Tithonian–Berriasian, before most structures formed in the sub-basin. Lacustrine mudstones at the base of the Bremer 2 and Bremer 3 units have good potential for oil and gas generation, with their main phase of expulsion modelled to occur during the Valanginian–Cenomanian, about the same time that most traps formed. Coaly source rocks at the top of Bremer 3 unit have potential in the thickest basin sections from the central sub-basin area to generate and expel hydrocarbons during the Barremian–Cenomanian, following trap formation. Evidence for hydrocarbon generation in the sub-basin includes several dredge samples with trace oil inclusions identified by fluid inclusion analysis, and fluorescing oil observed in the sedimentary matrix during vitrinite reflectance fluorescence analysis.

The Bremer Sub-basin Study has demonstrated that the geology and petroleum prospectivity of a frontier basin can be analysed without well data. In the case of the Bremer Sub-basin, dredge samples have provided key data on age, lithofacies and source potential of the basin succession. It has been possible to integrate dredge sample data with regional seismic interpretations to build a structural and stratigraphic framework for the Bremer Sub-basin, and assess the petroleum potential using conventional basin analysis techniques.

1. Introduction (B. E. Bradshaw)

AIMS OF THE BREMER SUB-BASIN STUDY

Australia's reserves of natural gas are at an all time high, however, oil production rates are estimated to decline by 50% from 2000 to 2010 (Powell, 2001). Most hydrocarbon exploration and production in offshore Australia has been from either Bass Strait off southeast Australia, or from the North West Shelf. Although continued exploration success in established offshore basins is essential, the best chance of reversing the decline in Australia's oil production rates is the discovery of a new oil province within one of the many frontier basins along the Australian continental margin. A key challenge lies in identifying new exploration opportunities and reducing exploration risks in frontier basins, particularly where our geological knowledge is limited through lack of sub-surface and other geological data. In May 2003, the Australian Government provided $A25 million to fund a four year program aimed at developing new exploration opportunities in offshore Australia, through an integrated program of seismic acquisition, geological sampling and natural hydrocarbon seep detection in key frontier basins.

The Bremer Sub-basin is a deep-water (100–4000 metres water depth), frontier area for petroleum exploration located off the southern coast of Western Australia (Figure 1.1). It forms part of the Bight Basin as defined by Bradshaw et al. (2003). A key question in assessing the potential of the Bremer Sub-basin as a new petroleum province is whether the sub-basin formed under suitable geological conditions to generate and trap large volumes (hundreds to billions of barrels) of hydrocarbons. Early studies identified the Bremer Sub-basin as consisting of a series of half graben, inferred to be of Middle Jurassic to Early Cretaceous age (Figure 1.2; Stagg and Willcox, 1991; Bradshaw et al., 2003; Totterdell and Bradshaw, 2004). However, a lack of well data and sparse seismic data, along with the deep-water setting, discouraged exploration since 1974.

Geoscience Australia's Bremer Sub-basin Study, which commenced in 2004, aimed to develop an understanding of the geological framework of the Bremer Sub-basin, and to provide an evaluation of the petroleum exploration potential of the sub-basin. A major challenge for the study was to assess the petroleum potential of a deep-water frontier basin where no wells have been drilled. The petroleum potential of such frontier basins is generally limited to theoretical assessments from seismic data and analogue models. However, a series of submarine canyons that incise parts of the Bremer Sub-basin allows geological sampling of the upper 2 km of the basin succession. As part of its Bremer Sub-basin study, Geoscience Australia undertook a marine geophysical and geological sampling survey (GA Survey 265) and a regional seismic survey (GA Survey 280) in 2004.

Blevin (2005) provides a geological framework report for the Bremer Sub-basin Study based on the geochemical, petrographic and palaeontological analysis of rock samples recovered from 45 dredge sites during GA Survey 265. Geochemical analysis of the dredge samples indicates that the Bremer Sub-basin may contain the necessary petroleum system elements to generate and trap hydrocarbons within Middle Jurassic–Early Cretaceous fluvial–lacustrine sedimentary rocks, and Early–Late Cretaceous marine sedimentary rocks. However, dredge sample data alone is unable to provide the structural and stratigraphic framework required to determine the petroleum exploration potential of the Bremer Sub-basin. The purpose of this report is to integrate results of the dredge sample analysis from Blevin (2005) with interpretations of new seismic data to develop a structural and stratigraphic framework of the sub-basin, and use this geological framework to assess petroleum exploration opportunities and risks.

REGIONAL GEOLOGY

The Bremer Sub-basin is one of a series of Mesozoic–Cainozoic depocentres that developed along Australia's southern margin during a period of passive margin formation that commenced in the Middle–Late Jurassic (Fraser and Tilbury, 1979; Bein and Taylor, 1981; Willcox and Stagg, 1990; Stagg et al., 1990; Hill, 1995; Totterdell et al., 2000; Norvick and Smith, 2001; Totterdell and Bradshaw, 2004). A recent reassessment of basin terminology along the southern Australian margin by Bradshaw et al. (2003) groups Mesozoic successions into the Bight Basin, and Cainozoic successions into the Eucla Basin. The Bremer Sub-basin is one of a series of six depocentres within the Bight Basin (Figure 1.1). The broad structural architecture of the Bight Basin is the product of northwest–southeast to north–south oriented crustal extension during the Middle–Late Jurassic to Early Cretaceous, superimposed on east-west and northwest–southeast orientated basement structures (Stagg et al., 1990; Stagg and Willcox, 1991; Bradshaw et al., 2003; Totterdell and Bradshaw, 2004). Collectively, the depocentres of the Bremer, Denmark and Recherche sub-basins comprise the western part of the Bight Basin, while the Madura Shelf, Ceduna, Eyre and the Recherche sub-basins form the eastern part of the Bight Basin (Figure 1.1). The deepwater Recherche Sub-basin appears to be continuous across the eastern and western regions of the Bight Basin.

The Bremer Sub-basin extends over an area of about 14,800 km^2 under the outer shelf and continental slope (100–4500 m water depth) in the western part of the Bight Basin, offshore of Albany and Esperance (Figure 1.2). Previously, the Bremer Sub-basin had variously been referred to as the Bremer Basin and the Albany Sub-basin (Middleton, 1991; Stagg and Willcox, 1991; Hocking, 1994). The Bremer Sub-basin contains a series of half graben that were initiated in the Jurassic (Stagg and Willcox, 1991; Bradshaw et al., 2003; Totterdell and Bradshaw, 2004). Previous estimates of total sediment thickness in the Bremer Sub-basin are highly variable, ranging from ~10 km by Cooney (1974), to ~ 5 km by Teasdale (2004). Rift structures from the Bremer Sub-basin appear to step-down to the south into the depocentres of the adjoining deepwater Recherche Sub-basin.

The Denmark Sub-basin was previously described by Stagg and Willcox (1991) as a small syncline within the Bremer Basin, which they referred to as the Denmark Trough. Bradshaw et al. (2003) have redefined this structure as a small rift basin and reclassified it as the Denmark Sub-basin. The Denmark Sub-basin appears to be structurally distinct and geographically separated from both the Bremer Sub-basin to the east and the deepwater Recherche Sub-basin (Figure 1.2). The Eucla Basin, on the other hand, extends landward from the northern margin of the Bremer Sub-basin as a thin veneer (~500 m) of Cainozoic cool-water carbonates and siliciclastics that overlie shallow basement from the Albany-Fraser Orogen and southern Yilgarn Craton (Hocking, 1994; Bradshaw et al., 2003; Clarke et al., 2003).

EXPLORATION HISTORY

The western Bight Basin (Bremer, Denmark and Recherche sub-basins) is a frontier region for petroleum exploration in which no wells have been drilled. Initial exploration in the western Bight Basin was undertaken by Esso Australia Limited between 1972 and 1974 (WA-50-P and WA-51-P). Exploration activities by Esso Australia Limited included a 2224 km marine seismic survey (Figure 1.3), and a 7025 line km aeromagnetic survey. Esso's analysis of this seismic data led to the identification of some large anticline structures. However, the prognosis was not sufficiently encouraging to follow up with a drilling program (Cooney, 1974; Cooney et al., 1975; Stagg and

Willcox, 1991). Between 1972 and 1973, Continental Oil Company held an adjacent exploration permit to the east (WA-47-P). Exploration of the permit area included a 595 km seismic survey conducted in the shallow waters (less than 200 m) of the Recherche Archipelago. The prospectivity of that area was regarded as poor, and the permit was relinquished in 1973 with no further work carried out. Other regional reconnaissance seismic data sets in the western Bight Basin include Shell's 1972 Petrel Survey, and BMR Surveys 17 and 18 in 1972 (Figure 1.3).

Previous drilling in the region has been limited to four wells in the onshore component of the Cainozoic Eucla Basin (Figure 1.3). Jonacoonack 1 is a stratigraphic well drilled in 1921. Kendenup 1, Sunday Swamp 1 and Ocumup 1 were drilled by Silfar Oil and Gas Search Limited and W.I. Robinson during 1974–1976. However, drilling results were not encouraging and hydrocarbon exploration onshore was subsequently suspended.

Prior to Geoscience Australia's New Oil Program, no exploration activity had occurred in the western Bight Basin for nearly 30 years. As an outcome of this study, the Australian Government released two designated frontier permits (W05-23 and W05-24) in the Bremer Sub-basin as part of its annual acreage release gazettal in April 2005 (applications close in April 2006). These permits cover the full extent of the Bremer Sub-basin (Figure 1.4). Logistically, established ports at Albany and Esperance can provide support for discoveries and ready access to the rest of Western Australia, particularly the major mining operations in the Eastern Goldfields.

DATA SETS

As noted above, prior studies of the Bremer Sub-basin were mainly limited to interpretations of the seismic data acquired by Esso Australia Limited in 1974 (R74a seismic data set). In 2001, Fugro Multi Client Services reprocessed the R74a seismic data. Geoscience Australia subsequently purchased the licensing rights to this reprocessed seismic data in 2004. However, seismic data quality for the R74a data varies, and is poor where seismic lines cross submarine canyons. Moreover, the R74a seismic data also provides only a partial coverage of the Bremer Sub-basin (Figure 1.4), and is a relatively shallow seismic data set acquired to depths of 5 seconds two-way-time (Figure 1.5). A higher quality seismic data set covering the full extent of the Bremer Sub-basin was required to undertake Geoscience Australia's geological framework and petroleum prospectivity study of the Bremer Sub-basin.

Geoscience Australia's study of the Bremer Sub-basin commenced in February through March 2004, with a geophysical and geological sampling survey (GA Survey 265) using the RV *Southern Surveyor*. A series of submarine canyons extend across the continental slope, and expose rocks of the Bremer Sub-basin along their walls. The Bremer Canyon is the largest of these, incising 1.5–2 km into the Bremer Sub-basin (Exon et al., 2005). During GA Survey 265, submarine canyons were mapped by collecting over 6200 km of high-resolution swath bathymetry data. Rock samples were then recovered by dredging the canyon walls. Several hundred rock samples were recovered from 45 dredge sites (Figure 1.4). Details regarding the operations and results from GA Survey 265 are documented in Blevin (2005).

In October and November 2004, Geoscience Australia's Geophysical Survey 280 acquired 2700 km of seismic data across the southwestern continental margin of Australia. Veritas DGC were contracted to undertake GA Survey 280 using the M/V Pacific Sword. 1300 km of industry-standard seismic reflection data, including nine dip lines and three strike lines, were acquired from the Bremer Sub-basin during the survey. Nineteen sonobuoys were also deployed to record refraction data from the seismic vessel's energy source. Seismic reflection data were acquired in a 25–30 km regional grid that covers the full extent of the Bremer Sub-basin, and extend 20–40 km into the Recherche Sub-basin (Figure 1.4). Most dip lines were orientated orthogonal to the general ENE–WSW strike of the Bremer Sub-basin, and positioned where possible on the spurs between submarine canyons. However, one dip line (280-18) was orientated NNE–SSW, orthogonal to the apparent trend of half graben in the western part of the Bremer Sub-basin as mapped by Bradshaw et al. (2003). Strike lines were orientated parallel to the ENE–WSW strike of the Bremer Sub-basin, and positioned to follow the approximate trend of the half graben. Seismic lines 280-27 and 280-28 were originally planned to be shot as one continuous line across the sub-basin. However, it was not possible to follow the trend of half graben using just one strike line due to their *en echelon* offset.

At the completion of the survey, seismic data were processed by Veritas DGC using a pre-stack time migration sequence (Appendix A). Processing of 2-D seismic data in the Bremer Sub-basin is complicated by the presence of sub-marine canyons and a rugose sea floor. The major effect from the canyons and rugose water bottom is to introduce severe noise and multiple artifacts into the seismic data. In order to reduce these noise artifacts, two passes of swell noise attenuation and despiking using F-X Decon were applied to the data. The multiple contaminations, from in and out of plane, were attenuated using an initial milder pass of Radon demultiple. Residual Multiple Scaling was then applied to reduce the high amplitude artifact generated by the rugose water bottom. A final more severe pass of radon demultiple was applied to the data after Pre Stack Time Migration when a more accurate velocity field could be determined. The acquisition and processing parameters used in GA Survey 280 provide a significant improvement in data quality from the reprocessed R74a data (Figure 1.5), including: higher frequency content, greater structural and stratigraphic resolution, better amplitude contrast, deeper sub-surface penetration, better definition and attenuation of multiples, and more stable velocities.

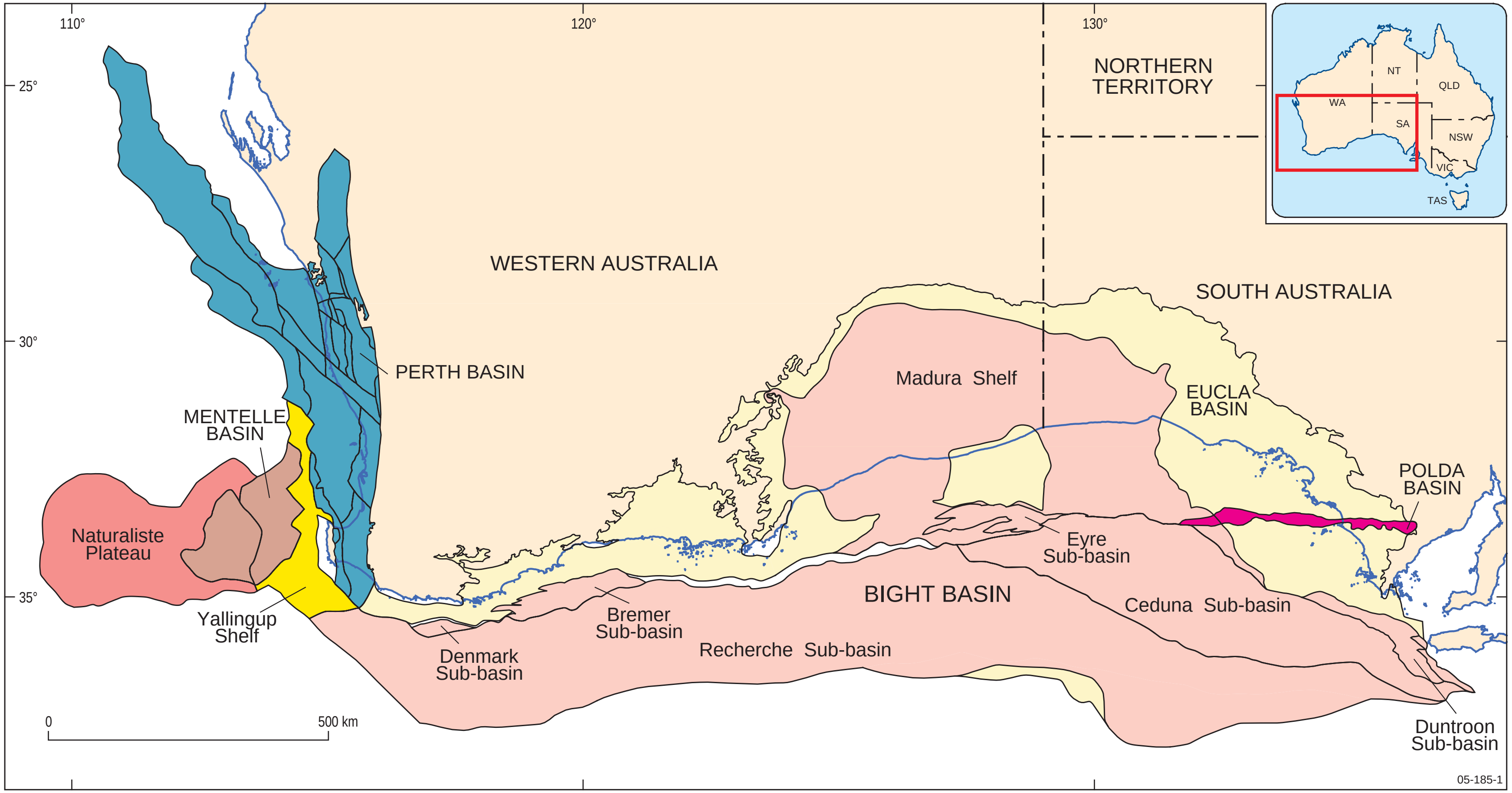


Figure 1.1: Location of the Bight Basin along the southern Australian margin, with component sub-basins (from Bradshaw et al., 2003).

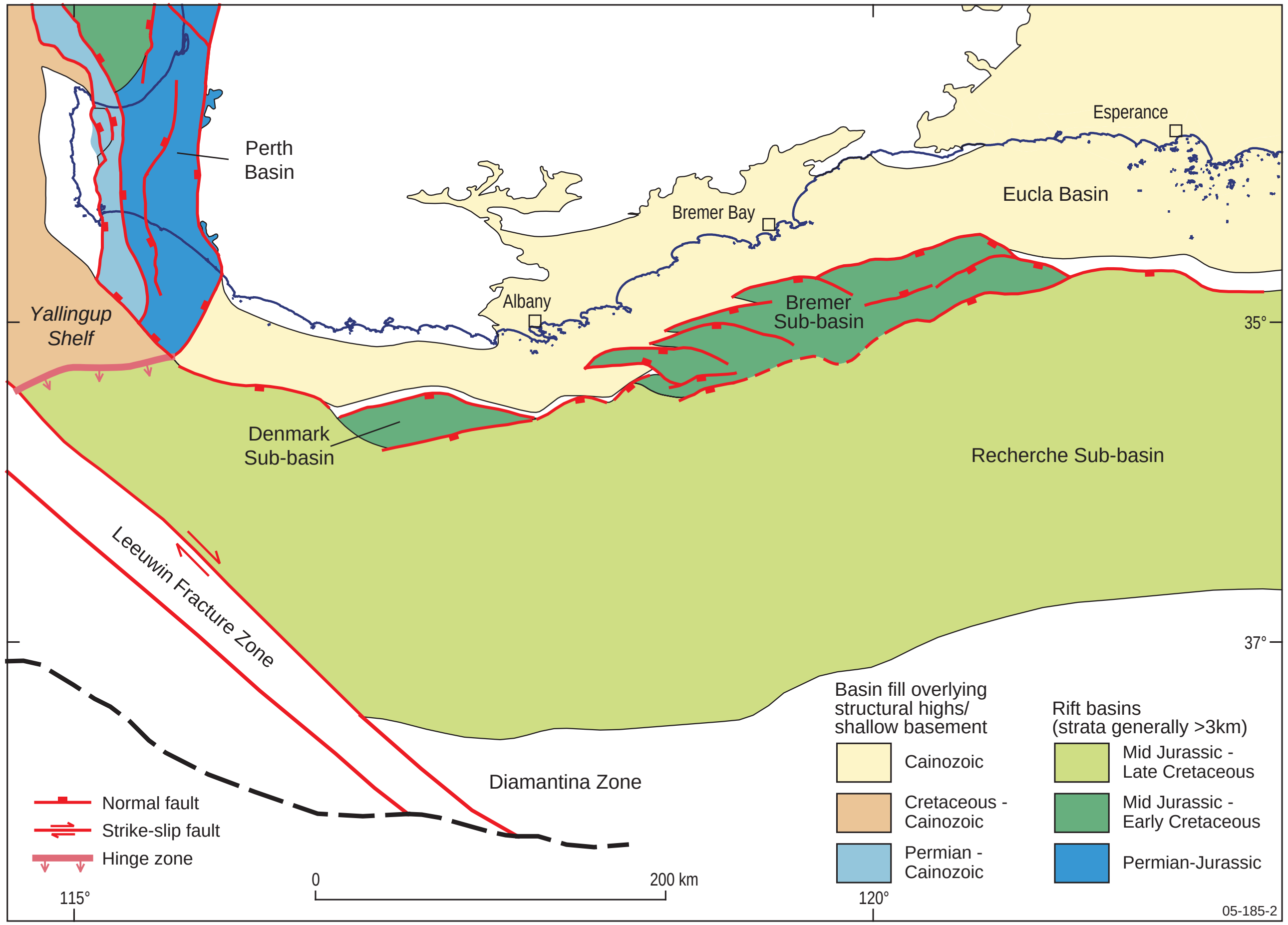


Figure 1.2: Structural elements map for the western Bight Basin (from Bradshaw et al., 2003).

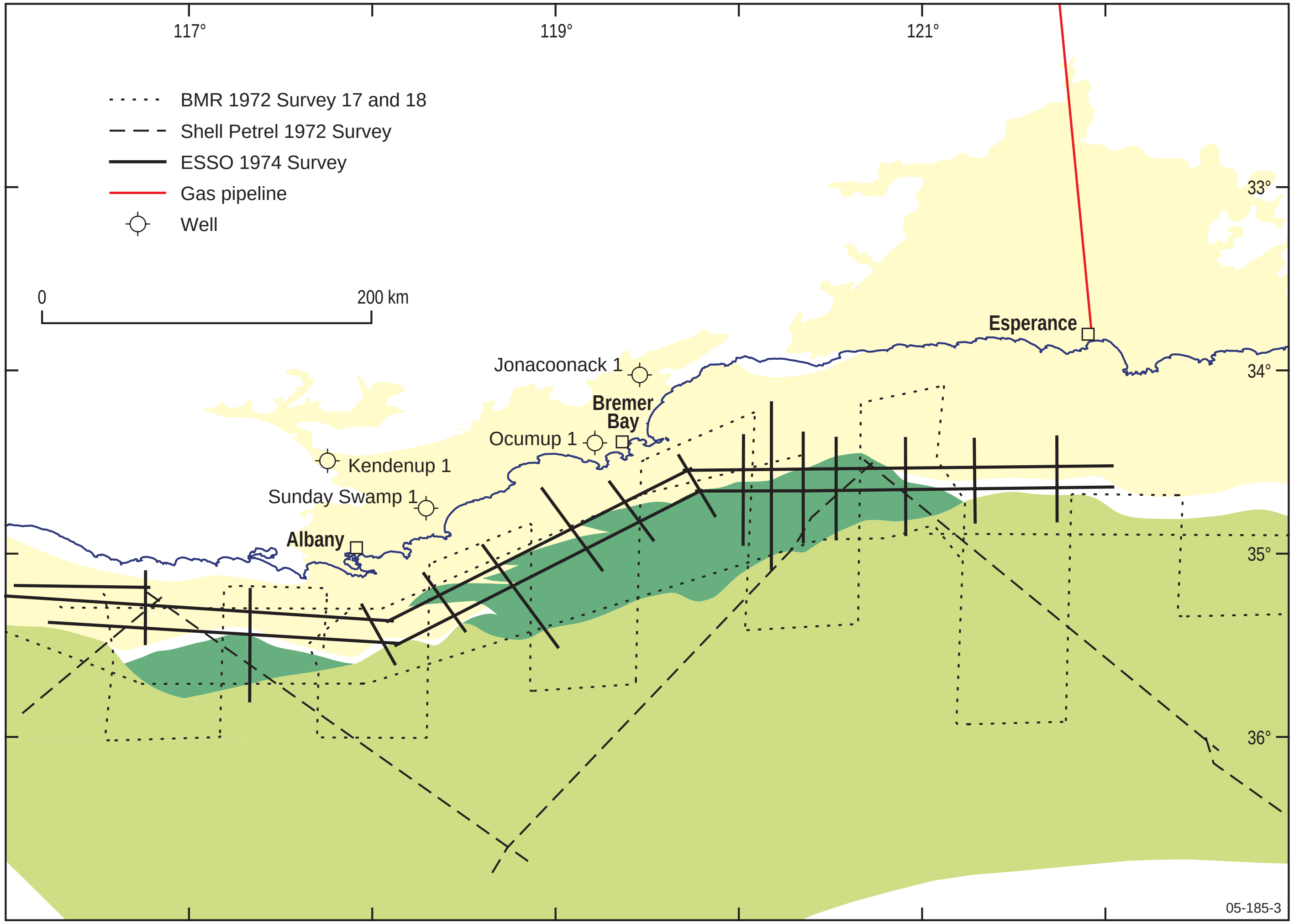


Figure 1.3: Petroleum datasets acquired in the western Bight Basin, prior to Geoscience Australia's Bremer Sub-basin Study (see Figure 1.2 for colour legend).

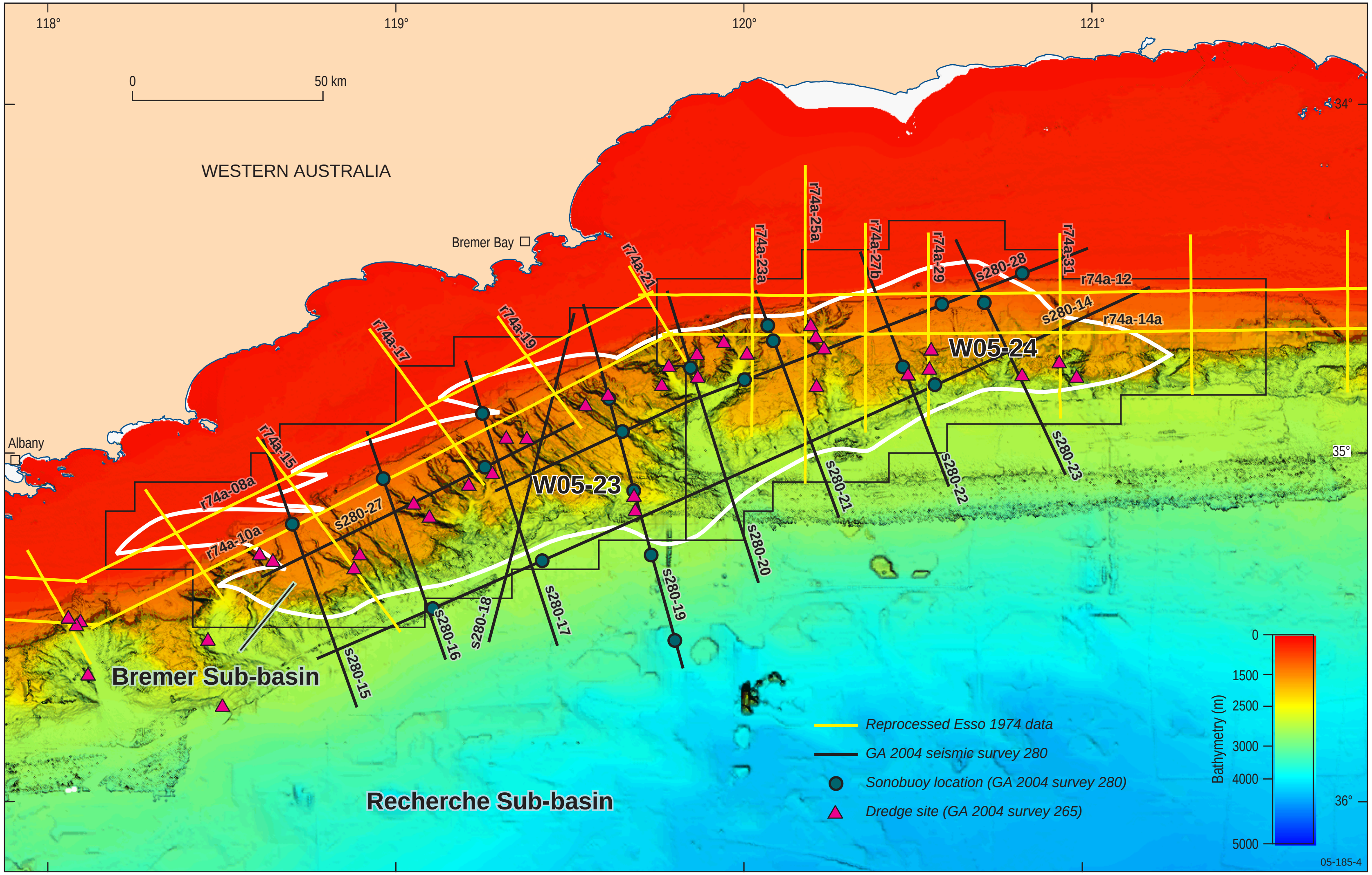


Figure 1.4: Data sets used in Geoscience Australia's Bremer Sub-basin Study. Also shown are 2005 acreage release areas, and the sub-basin's extent.

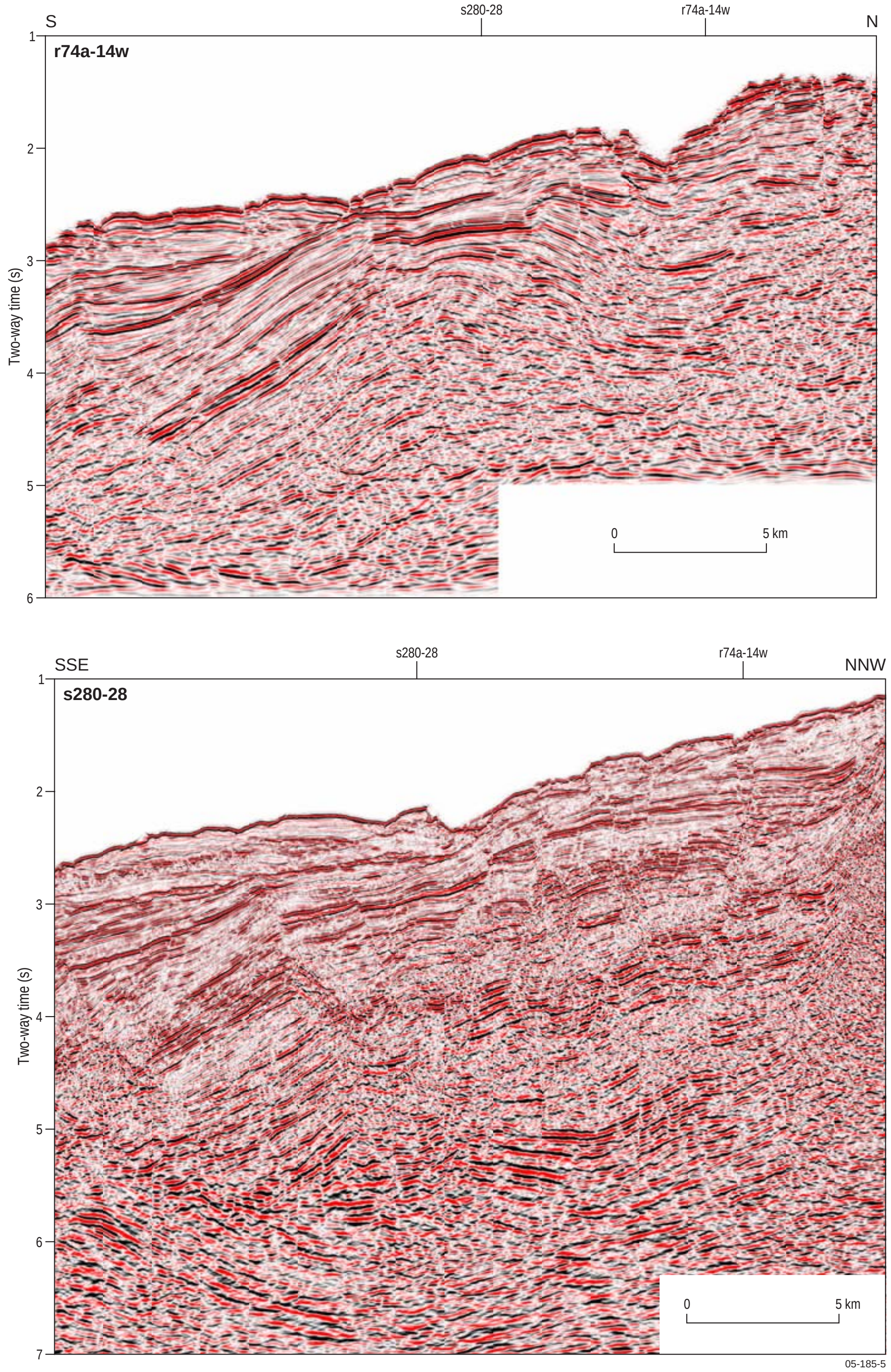


Figure 1.5: Example of improved seismic data quality in S280 survey compared to the reprocessed Esso R74a seismic data, using seismic lines across the same fault block structures in the central part of the Bremer Sub-basin.

2. Stratigraphic Framework (R.P.D. O'Leary, B. E. Bradshaw & D.J. Ryan)

KEY POINTS

- The Bremer Sub-basin is a frontier basin with no pre-existing stratigraphic framework. However, a series of submarine canyons have incised the Bremer Sub-basin, allowing geological sampling of the upper 2 km of the sub-basin succession.
- Through integrating biostratigraphic and lithofacies data from dredge samples with seismic interpretations, it has been possible to compile for the first time a stratigraphic framework for the Bremer Sub-basin.
- Six Mesozoic-age seismic stratigraphic units (Bremer 1–6) have been interpreted in the Bremer Sub-basin. Most of the basin succession consists of Middle Jurassic–Early Cretaceous fluvio-lacustrine sedimentary rocks (Bremer 1–4). Mid–Late Cretaceous (Bremer 5–6) and Cainozoic marine sedimentary rocks are also present, but form only a relatively thin cover.
- The Middle–Late Jurassic Bremer 1 unit consists of fluvio-lacustrine sandstones and claystones deposited during the main phase of crustal extension. Bremer 1 is a potential reservoir and source rock unit.
- Deposition of fluvial and lacustrine sandstones and mudstones continued during post-rift thermal subsidence in the Late Jurassic and Early Cretaceous (Bremer 2, Bremer 3 and Bremer 4 units). Of particular importance to petroleum exploration are 3 intervals of lacustrine mudstone deposition during the Tithonian, Berriasian and Valanginian. These lacustrine mudstones at the base of the Bremer 2, Bremer 3 and Bremer 4 units form potential source rocks and thick regional seals. Subsequent phases of fluvial sandstone sedimentation at the top of the Bremer 2 and Bremer 3 units provide potential reservoir intervals. An interval of thick coals in the Berriasian (upper Bremer 3 unit) may also represent a potential source rock unit.
- Marine conditions were established in the Bremer Sub-basin in the Late Aptian, during deposition of the Bremer 5 unit. This unit is generally thin (<500 m), and is absent in the sub-basin's western depocentres.
- A major unconformity associated with break-up of Australia and Antarctica formed in the Bremer Sub-basin during the Turonian. Subsequent passive margin sedimentation is limited to a thin cover of Late Cretaceous (Bremer 6) and Cainozoic (Eucla Basin) siliciclastic and carbonate sediments.

METHODOLOGY

Developing a stratigraphic framework for the Bremer Sub-basin has required innovative methods, given that no wells have been drilled to provide sub-surface geological data. A multidisciplinary approach has been used to construct a stratigraphic framework, drawing on lithological and biostratigraphic analyses of dredge samples, seismic interpretation and seismic facies analysis. The process has been iterative in both developing a regional seismic interpretation and stratigraphic framework for the sub-basin.

The Bremer Sub-basin consists of 5 major depocentres (Arpenteur, Colonna, Athena, Zephyr and Leata) bounded to the north by rift border faults (Figure 2.1; chapter 3 for details). A series of sub-marine canyons incise the sub-basin and expose parts of the sedimentary succession for dredge sampling. Biostratigraphic analysis was undertaken on 105 samples acquired from 27 dredge sites across the sub-basin to provide age control and environmental data (MacPhail and Monteil, 2005). However, there are sampling limitations with the seafloor dredging technique that need to be considered when using dredge data to construct a stratigraphic framework. There is intrinsically a bias in the dredge sampling process towards younger, shallower stratigraphic units, as older units are generally deeply buried and may not be exposed in canyons. Thus a dredge may not necessarily be sampling all the lithologies in a given stratigraphic interval. Biostratigraphic analysis also provides a bias when dating samples. For example, mudstones generally contain more fossils and are more easily dated than sandstones. This is evident in the Bremer Sub-basin where there are twice as many mudstones with age control relative to sandstones from samples recovered (Table 2.1).

A biozonation and dredge summary chart for the Bremer Sub-basin was constructed using biostratigraphic and lithological data from dredge samples (Appendix E). A summary version of this chart showing only the Middle Jurassic–Cretaceous dredge sample results is provided in Figure 2.2. Each of the dated samples is colour coded to represent a depositional environment, as determined from palynological analysis. Cretaceous-age samples have good age control, and show broad trends in depositional environments. Berriasian–Aptian age samples were deposited in brackish to fresh–brakish lacustrine environments, while Aptian–Maastrichtian age samples were deposited in inner–middle shelf marine environments. Middle–Late Jurassic age samples have limited age control, but appear to have been deposited in similar fresh–brackish lacustrine and fluvial depositional environments as Early Cretaceous rocks. The dredge summary data provide a broad sense of the stratigraphic succession in the sub-basin, but are simply the raw data obtained from individual dredge sites. In order to build a stratigraphic framework for the Bremer Sub-basin, these dredge data need to be analysed and integrated with seismic interpretations and seismic facies analysis.

Six seismic stratigraphic units, Bremer 1-6, have been interpreted in the Bremer Sub-basin (Figure 2.3). Interpretations for the S-280 seismic data are provided in Appendices C and D. Bremer 1, 2, 3 and 4 units comprise the majority of the basin fill, while the Bremer 5 and 6 units are generally thin across the sub-basin. Overlying the Bremer seismic stratigraphic succession is the Cainozoic-age Eucla Basin. Seismic stratigraphic units have been interpreted, rather than stratigraphic sequences, given the difficulty in picking sequence boundaries within a predominantly terrestrial succession without well data. The base of units Bremer 2, 3, 4 and 5 are interpreted as major flooding surfaces, while the base of units Bremer 1 and Bremer 6 are major unconformities. There are varying degrees of confidence in the absolute age of bounding horizons of seismic stratigraphic units due to the broad range of biostratigraphic zones such as the *Balmeiopsis limbata* and *Murospora florida* spore-pollen zones, together with the sparsity of dredge samples with good age control in Jurassic-age strata.

Seismic facies analysis has been used to provide insights into the paleoenvironments associated with each of the seismic stratigraphic units. Ten key seismic facies have been identified across the Bremer Sub-basin and are summarised in Table 2.2. Characteristics used to define seismic facies include seismic reflection amplitude, frequency and continuity, together with the internal reflection character. The method used is adapted from a similar study of the eastern Bight Basin by Krassay and Totterdell (2003), where depositional environments in a Late Cretaceous delta system were interpreted using seismic facies analysis and limited well data. Interpreted lithologies and depositional environments associated with each seismic facies in the Bremer Sub-basin are speculative, but are partly constrained by dredge sample data.

Many dredge sites can be confidently tied to a seismic line, and thus used to constrain the age, lithologies and depositional environments of seismic stratigraphic units (e.g. Figure 2.4). A dredge tie summary was created to document dredges that have been tied to seismic lines (Appendix F). In Figures 2.5 and 2.6, a number of dredges have been tied to seismic lines in the western and eastern parts of the Bremer Sub-basin. By repeating this process in all areas where dredge sites can be tied to seismic sections, it has been possible to refine our seismic interpretations and the dredge summary chart to determine the age of seismic stratigraphic units in the Bremer Sub-basin. Figure 2.7 shows the geographical distribution of seismic stratigraphic units that have been sampled at each dredge site across the sub-basin. Middle–Late Jurassic seismic stratigraphic units (Bremer 1 and 2) were dredged near basement highs and half-graben hinges in the eastern-most Bremer Sub-basin, and in dredges from the western part of the sub-basin. The central part of the Bremer Sub-basin contains the thickest sedimentary section. Here, canyons do not expose the older units, but instead incise into Early–Mid Cretaceous strata (Bremer 3, 4, and 5 units). The Late Cretaceous Bremer 6 unit was dredged south of the central depocentres and in the eastern part of the sub-basin.

A stratigraphic framework for the Bremer Sub-basin has been compiled through this iterative process of integrating seismic interpretations and dredge sample data (Figure 2.8). The interpreted age of each seismic stratigraphic unit is based on spore and pollen, dinoflagellate, foraminifera and nannofossil biozones, along with regional correlations to the eastern Bight Basin and the Perth Basin. The Middle Jurassic–Early Cretaceous Bremer 1, 2, 3 and 4 units represent the majority of the sedimentary fill in the sub-basin, and were deposited in fluvio-lacustrine environments during the Callovian–Late Aptian. The Bremer 5 and Bremer 6 units form only a thin cover, and were deposited in marine environments during the Late Aptian–Maastrichtian. The Eucla Basin forms a thin Cainozoic marine succession. Details of each seismic stratigraphic unit are discussed in the following sections.

BREMER 1 SEISMIC STRATIGRAPHIC UNIT

The oldest seismic stratigraphic unit in the Bremer Sub-basin is the Late Jurassic (Callovian–Kimmeridgian) Bremer 1 unit (Figure 2.8). Bremer 1 is only confidently interpreted on seismic lines from the western Arpenteur and Colonna depocentres, and the eastern Leata depocentres (Figures 2.1, 2.9, 2.10 and 2.11). The Bremer 1 unit is generally poorly imaged in the central Athena and Zephyr depocentres due to the reduced seismic resolution beneath thick overlying sediments. Strata from Bremer 1 are generally concordant with underlying high-amplitude basement reflections. The unit thickens landward towards the basin bounding faults, reaching a maximum thickness of ~2.7 s two-way time (~4.5 km) in the central Athena depocentre. Bremer 1 is at least 2 s two-way time (~4 km) thick across all major depocentres, and thins basinward as seismic reflections converge against the hinge of half-graben depocentres (Figure 2.10). This divergent wedge geometry indicates continuous growth on the basin bounding faults during deposition of the Bremer 1 unit in a phase of upper crustal extension.

Only a few dredge sites in the Bremer Sub-basin can be confidently tied to the Bremer 1 seismic stratigraphic unit (Figures 2.2 and 2.7). Dredge sites 19 and 20 sampled steeply-dipping strata from the base of Bremer 1 in the Colonna depocentre, adjacent to shallow granitic basement of the Penguin High (Figure 2.11). Bremer 1 may also have been sampled in dredges 40, 42 and 44 across the Cygnet High, a shallow basement area south of the Leata depocentre. However, it is unclear if these dredge sites are from either the Bremer 1 or Bremer 2 units, due to the poor resolution of the seismic data in this area (Figure 2.12). No samples were dredged from the Bremer 1 unit in the main half-graben depocentres. The Bremer 1 unit is interpreted to be at least Callovian–Kimmeridgian in age, based on a palynoflora from a rock sample from dredge 20, dated with moderate certainty as belonging to the *M. florida* spore-pollen zone (MacPhail and Monteil, 2005; Figures 2.2 and 2.8). The upper boundary of the Bremer 1 unit has been placed at the top of the Kimmeridgian, based on regional correlations of the Bremer 1 unit with the Sea Lion supersequence in the eastern Bight Basin (Totterdell et al., 2000).

Bremer 1 consists predominantly of fluvio-lacustrine sandstones and mudstones, with some evidence of local alluvial fan deposits. This interpretation is based largely on seismic facies and limited dredge sample data. Bremer 1 is characterised by two seismic facies that are interbedded (Figures 2.9 and 2.10): a high amplitude, low frequency facies interpreted as a sandstone-dominant amalgamated channel fill (seismic facies 2, Table 2.2); and a lower amplitude, and more variable reflection facies interpreted as mudstones and sandstones deposited in a floodplain to lacustrine environment (seismic facies 1, Table 2.2). Dredge samples recovered from the Bremer 1 unit are predominantly fluvial and lacustrine (fresh–brackish water) sandstones and mudstones (claystones, shales and siltstones), the two rock types often interbedded (Table 2.1). Sandstones include fine to very coarse grained quartz sandstones. Mudstones are generally carbonaceous (TOC 2–3%), and contain mica and coaly fragments. Conglomerates are also present in a dredge sample (19B1) adjacent to the Penguin High, which may be associated with alluvial fan deposits. Fluvial sandstones within Bremer 1 are potential reservoir intervals, while carbonaceous mudstones form potential source rocks.

Similar fluvio-lacustrine depositional systems extended along the southern and southwestern Australian continental margin during rifting of Australia, Antarctica and Greater India in the Middle–Late Jurassic. The Bremer 1 unit is an approximate time-equivalent unit to the Middle–Late Jurassic age Sea Lion supersequence in the eastern Bight Basin (Figure 2.8). This correlative supersequence in the eastern Bight Basin consists largely of fluvial-lacustrine sandstones and mudstones deposited in a series of half-graben depocentres, which formed during intracontinental extension between Australia and Antarctica (Totterdell et al., 2000). Bremer 1 is also an approximate time-equivalent unit to the fluvial-lacustrine sandstones, mudstones, and minor conglomerates and coals of the Yarragadee Formation in the Perth Basin (Figure 2.8). These were deposited in a northward flowing fluvial system in the Middle–Late Jurassic during a period of mechanical extension between Australia and Greater India (Marshall et al., 1993; Crostella and Backhouse, 2000; Norvick, 2003).

BREMER 2 SEISMIC STRATIGRAPHIC UNIT

The Bremer 2 seismic stratigraphic unit represents an extensive phase of lacustrine and fluvial deposition during initial post-rift sag and thermal subsidence in the Late Jurassic (Figure 2.8). Bremer 2 is well imaged on seismic sections from the Arpenteur (Figures 2.9 and 2.10) and Zephyr depocentres (Figure 2.1), but is generally poorly resolved elsewhere due to the loss of seismic resolution through thick overlying sediments. Seismic reflections in the Bremer 2 unit are concordant with the top of Bremer 1, however, the base of Bremer 2 is generally only well resolved in the Arpenteur depocentre. The Bremer 2 unit has a relatively consistent thickness of between 0.3–0.6 s two-way time (up to ~1 km) across the sub-basin, and reaches a maximum thickness of 1.1 s two-way time (~2.2 km) in the Zephyr depocentre. The geometry of the Bremer 2 unit is sub-parallel to parallel sheet-like fill, indicating deposition during a period of thermal subsidence following the initial phase of mechanical extension (Figure 2.10).

The Bremer 2 seismic stratigraphic unit is poorly constrained by dredge data. Bremer 2 may have been sampled amongst the 16 rocks (9 with age control) recovered from dredges 40, 42 and 44 across the Cygnet High, south of the Leata depocentre (Figure 2.12). However, it is unclear if these dredge sites are solely from the Bremer 2 and/or the Bremer 1 seismic stratigraphic units, due to poor seismic resolution at the dredge ties. Dredge 40 includes rocks dated to the latest Kimmeridgian to mid-Tithonian *Retitriletes watherooensis* spore-pollen zone (MacPhail and Monteil, 2005; Figures 2.2 and 2.8). The position of this spore-pollen zone is recorded within the Minke supersequence in the eastern Bight Basin. The upper boundary of the Bremer 2 unit is placed at the base of the

Berriasian *Biretisporites eneabbaensis* spore-pollen zone, and broadly equates to the top of the Yarragadee Formation in the Perth Basin and the top of the Minke supersequence in the eastern Bight Basin (Figure 2.8).

The Bremer 2 unit represents a major phase of lacustrine and fluvial sedimentation in the Bremer Sub-basin. This interpretation is based largely on seismic facies analysis. Figures 2.9 and 2.10 show that seismic facies at the base of the Bremer 2 unit are characterised by heterogenous fluvial deposits (seismic facies 6, Table 2.2), and low amplitude, relatively homogenous fill typical of lacustrine deposition (seismic facies 3, Table 2.2). This basal fluvio-lacustrine interval is overlain by high amplitude, continuous reflections (seismic facies 6, Table 2.2) interpreted as laterally extensive fluvial sediments. Rock samples recovered from dredges 40, 42 and 44 are predominantly fluvial and lacustrine (fresh and fresh–brackish water) sandstones and mudstones which are often interbedded (Table 2.1). However, it is uncertain if these rock samples are from the Bremer 2 or Bremer 1 units. Sandstones are very fine to coarse grained, and generally quartzose. Mudstones are generally carbonaceous (TOC 1.1–3.4%), and contain coaly fragments. Lacustrine mudstones from the base of Bremer 2 are potential source rocks and seals, while overlying fluvial sandstones are potential reservoir intervals.

Correlating Bremer 2 to stratigraphic units in the eastern Bight Basin or the Perth Basin is difficult due to uncertainty in constraining minimum and maximum ages for the unit. However, Bremer 2 probably correlates to the period of diminished growth observed on bounding faults in the eastern Bight Basin (Totterdell et al., 2000) during deposition of the Minke supersequence (Figure 2.8). Bremer 2 also appears to correlate to the upper part of the Yarragadee Formation in the Perth Basin (Figure 2.8), which was deposited during continued mechanical extension between Australia and Greater India (Marshall et al., 1993; Crostella and Backhouse, 2000; Norvick, 2003).

BREMER 3 SEISMIC STRATIGRAPHIC UNIT

The Bremer 3 seismic stratigraphic unit represents a second major phase of lacustrine and fluvial deposition during continued post-rift thermal subsidence in the Berriasian–Valanginian (Figure 2.8). The Bremer 3 unit is well imaged on seismic lines in the Arpenteur, Athena and Zephyr depocentres (Figures 2.1, 2.9 and 2.13). Strata from Bremer 3 unit are generally concordant with the underlying Bremer 2 unit, although seismic resolution at the base of the unit is often low. In the Arpenteur depocentre, strata at the base of Bremer 3 onlap the underlying Bremer 2 unit (Figure 2.9). Most of the Bremer 3 unit is characterised by sub-parallel to parallel, sheet-like concordant reflections. Sediment thickness ranges from 0.4–0.7 s two-way time (up to ~1 km) in the Arpenteur, Colonna and Leata depocentres, and ~ 1–1.3 s two-way time (~1.5–2 km) in the Athena (Figure 2.13) and Zephyr depocentres.

At least 17 rock samples from five dredge sites are confidently tied to the Bremer 3 seismic stratigraphic unit (dredge 16 A, B C; dredge 17 A, B, C, D; dredge 18 B, C, D; dredge 21 A, C, D, E; and dredge 22 A, B, C). Dredge site 17 extends across much of the Bremer 3 unit, and provides the most confident dredge tie (Figure 2.14). Dredge sites 16, 17, 18 and 21 all begin near the base of Bremer 3, and include rocks dated with high–moderate certainty in the Berriasian–Valanginian *B. eneabbaensis* spore-pollen zone, and/or *Fusiformacysta tumida–Gagiella mutabilis* dinoflagellate zone (MacPhail and Monteil, 2005; Figure 2.2 and 2.8). The maximum age for Bremer 3 is therefore broadly interpreted as occurring within the Berriasian. Dredge 22 extends over the upper part of Bremer 3, however, no confident dates were obtained from dredge samples at this site. Samples from the overlying Bremer 4 unit help to constrain the minimum age of Bremer 3 as occurring near the boundary between the *B. eneabbaensis* ane *B. limbata* spore-pollen zones.

The Bremer 3 unit represents a major phase of lacustrine (brackish to fresh-brackish) deposition followed by a coaly–fluvial/floodplain depositional phase. This interpretation is based on both seismic facies interpretations and dredge sample data. Bremer 3 begins with a distinct low amplitude seismic facies (Facies 3; Table 2.2; Figures 2.9 and 2.13), interpreted to represent thick, regionally extensive lacustrine deposits. Dredge samples correlating to this seismic facies are predominantly micaceous, carbonaceous claystones (TOC 1.5–3.4%) and micaceous, carbonaceous siltstones (TOC 0.7–2%), deposited in brackish and fresh–brackish lakes (Table 2.1). Coarser grained lacustrine sediments were also recovered from the Arpenteur depocentre, including a fine–medium grained calcareous (fossiliferous) sandstone from dredge 16, and a medium-grained glauconitic quartz sandstone from dredge 17. The lower part of Bremer 3 is therefore interpreted to consist of thick lacustrine mudstones and minor sandstones. These thick, extensive lacustrine deposits form a potential regional seal and source rock interval.

Lacustrine deposits are overlain by high amplitude, continuous and lenticular reflections (seismic facies 5, Table 2.2; Figure 2.13), which are interpreted as coals and floodplain deposits interbedded with sandstone-dominated channel fills. A coaly claystone recovered from the upper part of Bremer 3 at dredge 22 is interpreted to be associated with this coaly–fluvial/floodplain facies. In the Arpenteur depocentre, the geometry of the fluvial channel systems appears to be controlled by growth on the bounding fault, with fluvial units becoming thicker and more amalgamated towards the fault (seismic facies 4, Table 2.2; Figure 2.9). Thick interpreted coaly sections are often observed as very bright reflectors at the top of Bremer 3, which reduces the resolution of seismic reflections in the underlying lacustrine facies. In the Athena depocentre, seismic reflections with aggradational to complex asymmetric fill are locally observed. The asymmetric geometry of some reflections may represent the erosional surfaces of multilateral stacked incised valleys and associated fill. Fluvial sandstones from the upper part of Bremer 3 are potential reservoir rocks, while coaly sediments are potential source rock.

An igneous facies (seismic facies 7, Table 2.2) is observed near the base of Bremer 3 in the Colonna and Athena depocentres. This igneous facies is characterised by high amplitude seismic reflections associated with intrusive sills that cut across strata. An igneous rock sample recovered from Bremer 3 at dredge 21 is either a fine-grained feldspar-phryic basalt or a basaltic-andesite (Hocking and Jones, 2005). This igneous facies is possibly equivalent in age and composition to tholeitic volcanics in the southern Perth Basin, which include two extrusive flows of the Bunbury Basalt and underlying doleritic sills dated between approximately 123 Ma and 136 Ma (Frey et al., 1996). The igneous facies has intruded strata near the base of the Bremer 3, and produced locally overmature sediments (Ro = 4% in dredge sample 21E; Boreham et al., 2005a).

Correlating the Bremer 3 unit to stratigraphic units in the eastern Bight Basin and Perth Basin is difficult due to the uncertainty in constraining minimum and maximum ages for the unit. However, it probably corresponds to fluvial and lacustrine deposits in the Southern Right supersequence and lowermost Bronze Whaler supersequence in the eastern Bight Basin (Figure 2.8). The geometry and seismic facies of the Southern Right supersequence and the Bremer 3 unit show similarities with high amplitude reflections associated with coals also observed in the Southern Right supersequence (Totterdell et al., 2000). Bremer 3 broadly correlates to the Parmelia Group in the southern Perth Basin (Figure 2.8), which contains fluvial sandstones (Jervoise Sandstone and Charlotte Sandstone), and interbedded lacustrine shales, siltstones and sandstones (Otorowiri Formation and Carnac Formation; Crostella and Backhouse, 2000). The Parmelia Group was deposited during the final phase of mechanical extension between Australia and Greater India (Marshall et al., 1993; Crostella and Backhouse, 2000; Norvick, 2003).

BREMER 4 SEISMIC STRATIGRAPHIC UNIT

The Bremer 4 seismic stratigraphic unit represents the final phase of lacustrine and fluvio-lacustrine sedimentation, and initial restricted marine sedimentation in the Bremer Sub-basin during the Valanginian–Aptian (Figure 2.8). Bremer 4 is well imaged on seismic data across the sub-basin. The geometry of the unit is best represented in the Athena and Arpenteur depocentres (Figure 2.1). Seismic reflections at the base of Bremer 4 are concordant with underlying reflections from Bremer 3 (Figures 2.9 and 2.15). The upper boundary of Bremer 4 shows low angle truncation of seismic reflections below horizontal reflections in the Bremer 5 unit (Figures 2.13 and 2.15). Bremer 4 is generally characterised by a parallel, sheet-like fill (Figures 2.13 and 2.15). However, the upper part of Bremer 4 forms a divergent wedge geometry in the hanging wall blocks of the Arpenteur (Figure 2.9), Colonna and Leata depocentres. Bremer 4 was deposited during a second period of extension in the Bremer Sub-basin. Consequently, the unit shows variable thicknesses within each depocentre, and thickens across syn-depositional faults (Figure 2.6). The Bremer 4 unit reaches a maximum thickness of 1.4 s twt two-way time (~2.4 km) in the Athena and Zephyr depocentres.

Bremer 4 is the most sampled seismic stratigraphic unit in the Bremer Sub-basin, with at least 26 rock samples recovered from 8 dredge sites (dredge 15 B, C; dredge 23 B, D, F; dredge 27 A, B, D; dredge 28 A, B, C; dredge 34 A, B, C, D, E, F; dredge 36 B, D; dredge 37 A, B; dredge 39 A, B, C, D, E). Dredge site 28 provides the most confident dredge tie to Bremer 4 (Figure 2.16). Each dredge from the Bremer 4 unit recovered at least one rock sample dating from the late Valanginian–Aptian *B. limbata* spore-pollen zone (Figures 2.2 and 2.8). The maximum age of Bremer 4 is probably near the boundary between the *B. limbata* and *B. eneabbaensis* spore-pollen zones (Figure 2.8), as indicated by: several samples at the base of Bremer 4 interpreted with high–moderate certainty from the *B. eneabbaensis* spore-pollen zone and *F.tumida – G.mutabilis* dinoflagellate zone; one sample from the underlying Bremer 3 unit interpreted with moderate certainty from the *B. limbata* spore-pollen zone (MacPhail and Monteil, 2005). The minimum age of Bremer 4 is Late Aptian (Figure 2.8), based on: the presence of dinoflagellates from the lower *Odontochitina operculata* zone in one dredge sample (dredge sample 39A1); and several samples in the overlying Bremer 5 unit containing dinoflagellates from the *Diconodinium davidii* zone (MacPhail and Monteil, 2005).

Bremer 4 is largely characterised by lacustrine deposition followed by a coastal plain (fluvial–lacustrine and lagoonal) depositional phase. This interpretation is based on both seismic facies interpretations and dredge data. Dredge samples derived from the Bremer 4 unit are predominantly micaceous, carbonaceous–coaly mudstones (TOC 0.34–22.62%; Table 2.1). Sandstones, often interbedded with mudstones, were also recovered in several dredges. These include fine–medium grained quartzose sandstones that contain trace feldspar, lithic fragments, mica and coal fragments. Medium–coarse grained and coarse–very coarse grained quartz arenites are also present. Palynological analysis indicates that dredge samples recovered from Bremer 4 were mainly deposited in lacustrine (freshwater, fresh–brackish water and brackish water) environments (MacPhail and Monteil, 2005). However, Bremer 4 contains several sandstone samples from unknown depositional environments.

Seismic interpretations show a low amplitude, sheet-like seismic facies (seismic facies 3, Table 2.2; Figure 2.15) at the base of Bremer 4, which is interpreted as representing thick, regionally extensive lacustrine mudstones and minor sandstones. These lacustrine deposits form a potential regional seal and source rock interval. A high amplitude facies is occasionally observed at the base of Bremer 4, which is interpreted as representing isolated occurrences of the coaly–fluvial/floodplain facies seen at the top of Bremer 3 (Figure 2.15). Lacustrine deposits are overlain by two seismic facies that are generally interbedded (Figures 2.13 and 2.15): a high amplitude, low frequency facies interpreted as sandstone-dominant channel fills in a multilateral and multistorey amalgamated fluvial channel system (seismic facies 2, Table 2.2); a lower amplitude, and more variable reflection facies interpreted as mudstones and sandstones deposited in a floodplain to lacustrine environment (seismic facies 1, Table 2.2). Two dredge samples from Bremer 4 contain restricted marine dinoflagellate assemblages (MacPhail and Monteil, 2005): a Hauterivian–early Barremian coaly mudstone; and an Early Aptian fine grained sandstone (Figure 2.2). These restricted marine deposits indicate episodic coastal/lagoonal environments during deposition of Bremer 4. The upper part of Bremer 4 is therefore interpreted as containing coastal plain (fluvial–lacustrine and lagoonal) sandstones, mudstones and minor coals. These coastal plain deposits contain potential reservoir, seal and source rocks.

Bremer 4 correlates to much of the Bronze Whaler supersequence in the eastern Bight Basin (Figure 2.8). The Bronze Whaler supersequence contains similar fluvial, lacustrine and restricted marine sediments (Totterdell et al., 2000). Bremer 4 also broadly correlates to the Warnbro Group in the southern Perth Basin (Figure 2.8), which contains marine sediments deposited after the break-up of Australia and Greater India.

BREMER 5 SEISMIC STRATIGRAPHIC UNIT

The Bremer 5 seismic stratigraphic unit marks the onset of marine sedimentation in the western Bight Basin during continued thermal subsidence in the Late Aptian–Cenomanian (Figure 2.8). The Bremer 5 unit is generally thin across the Bremer Sub-basin (0.1–0.4 s two-way time; < 500 m), and is absent in the western Arpenteur and Colonna depocentres. Bremer 5 reaches a thickness of 0.8 s two-way time (~1 km) in the Athena depocentre (Figure 2.15), which may indicate higher subsidence rates in the central part of the Bremer Sub-basin relative to the eastern and western depocentres. In the Zephyr depocentre, Bremer 5 thickens across several faults that formed during the second phase of extension. Bremer 5 reaches a maximum thickness of 1 s two-way time (~1.3 km) in the outer-most parts of the Bremer Sub-basin. Here, Bremer 5 is characterised by non-tectonic polygonal faults. Polygonal faults are known to form in very fine grained sediments. There are several theories for their generation, including: gravity collapse, density inversion, syneresis and compactional loading (Goulty, 2001; Cartwright et al., 2003). Bremer 5 is comprised predominantly of sub-parallel seismic reflections, with an aggradational sheet-like fill. Strata from Bremer 5 are concordant with the underlying Bremer 4 unit. The lower boundary of Bremer 5 is characterised by a high amplitude, continuous seismic reflection across the sub-basin. The upper boundary is a major unconformity that truncates strata from Bremer 5 in many areas. This unconformity is interpreted to have formed during uplift and erosion associated with the break-up of Australia and Antarctica.

Twelve rock samples from 4 dredge sites are confidently tied to the Bremer 5 seismic stratigraphic unit (dredge 23 C, G, I; dredge 24 A, B, C, D, F; dredge 36 D; dredge 38 A, B and C). Dredge 24 is located within 1.5 km of line s280-27, and is the only dredge that extends from the base to the top of Bremer 5 (Figure 2.4). Rock samples from this dredge site range from late Aptian (*D. davidii* dinoflagellate zone) to Cenomanian (*Diconodinium multispinum* dinoflagellate zone; MacPhail and Monteil, 2005). Other dredge sites recovered samples of late Aptian (*D. davidii*) and Albian age (*Muderongia tetracantha–Endoceratium ludbrookiae* dinoflagellate zones; MacPhail and Monteil, 2005). The maximum age of Bremer 5 is confidently interpreted as late Aptian. This interpretation is based on dinoflagellates from the *D. davidii* zone in several dredge samples from Bremer 5, and a sample in the underlying Bremer 4 unit containing dinoflagellates from the lower *O. operculata* zone (Figures 2.2, 2.6 and 2.8). The minimum age of Bremer 5 is less precise, lying somewhere between the Cenomanian *D. multispinum* dinoflagellate zone observed in one dredge sample, and the

Coniacian *Conosphaeridium striatoconum* dinoflagellate zone observed in several dredge samples from the overlying Bremer 6 unit (Figures 2.2 and 2.8).

Seismic facies interpretations, together with dredge sample data, indicate that the Bremer 5 unit represents the onset of marine inner-shelf sedimentation in the Bremer Sub-basin. Dredge samples recovered from Bremer 5 are mainly claystones and siltstones, with some sandstones also present (Table 2.1). Claystones are generally micaceous and carbonaceous (TOC 0.36–3.4%). Siltstones are generally micaceous, and include a glauconitic siltstone and a silty claystone to greensand. Sandstone samples include a fine–medium grained, micaceous, glauconitic quartz arenite with carbonate needles, and a coarse grained calcarenite with numerous bioclastic fragments. The presence of glauconitic and carbonate sediments in Bremer 5 suggests a transgressive marine environment. This is further supported by palynological evidence for marine inner-shelf conditions in all samples from the Bremer 5 unit (Figure 2.2). Bremer 5 is characterised by two distinct seismic facies (Figure 2.15): a low amplitude, aggradational, homogenous marine facies (seismic facies 8, Table 2.2); and a moderate amplitude, interbedded and aggradational, heterogenous marine facies (seismic facies 9, Table 2.2). In the Athena depocentre, the upper part of the Bremer 5 unit is characterised by a progradational fill (seismic facies 10, Table 2.2; Figure 2.15), which is interpreted as a localised shoreface deltaic lobe. Marine sediments from Bremer 5 are generally too shallow to generate or trap hydrocarbons.

Bremer 5 correlates to the upper part of the Bronze Whaler supersequence, and to the Blue Whale and Tiger supersequences in the eastern Bight Basin (Figure 2.8). The late Aptian marine transgression evident in the Bremer 5 unit appears to have extended into the eastern Bight Basin, where marine conditions are first observed in the upper part of the Bronze Whaler supersequence, and continued during deposition of the Blue Whale and White Pointer supersequences (Totterdell et al., 2000).

BREMER 6 SEISMIC STRATIGRAPHIC UNIT

The Bremer 6 seismic stratigraphic unit was deposited during a period of post-break-up passive margin sedimentation in the Turonian–Maastrichtian (Figure 2.8). The Bremer 6 unit is generally thin and patchy across the sub-basin, and is often eroded by the base Cainozoic unconformity and submarine canyons of the Albany Canyon complex. The Bremer 6 unit is ~ 0.3 s two-way time (~300 m) thick, and has a maximum thickness of 0.6 s two-way time (~600 m) in the Athena depocentre.

At least 8 rock samples from 4 dredge sites are confidently tied to the Bremer 6 seismic stratigraphic unit (dredge 23 A; dredge 25 A, B and C; dredge 41 A dredge 43 A, B and C). Dredge 25 provides the most confident tie to Bremer 6 (Figure 2.17), and contains 3 samples dated with high certainty from the Coniacian *C. striatoconum* dinoflagellate zone (MacPhail and Monteil, 2005) — the oldest dated samples from Bremer 6 (Figures 2.2 and 2.8). Younger Santonian–early Maastrichtian (*Odontochitina porifera–Manumiella? cretacea*, lower *O. porifera* dinoflagellate zones; UC10-11, UC 17 nannofossil zone) samples were recovered from dredges 23, 41 and 43 (Howe, 2005; MacPhail and Monteil, 2005; Figure 2.2). An additional 4 dredges contain mixed Late Cretaceous and latest Paleocene–middle Eocene dinoflagellate assemblages (dredge 24 E, dredge 27 D, dredge 28 F, and dredge 36 A and C; MacPhail and Monteil, 2005). However, these are interpreted as younger deposits from the Eucla Basin that have incorporated reworked sediments from the Bremer 6 unit. Dredges 7 and 9 in the Denmark Sub-basin may also have recovered rock samples from the Bremer 6 unit. This interpretation is based on the presence of 6 rock samples with Santonian–Maastrichtian dinoflagellate and nannofossil assemblages. The minimum age for Bremer 6 is interpreted as late Maastrichtian, based on a sample from dredge 9 in the Denmark Sub-basin dated from the *Manumiella druggii* dinoflagellate zone.

Bremer 6 represents continued marine sedimentation in the Bremer Sub-basin. Dredge samples derived from Bremer 6 are mainly claystones, siltstones and minor sandstones (Table 2.1). Claystones and siltstones are often calcareous, and have low organic carbon contents (TOC 0.41–0.85%). Sandstones include a silty, very fine grained greensand, a very fine gained lithic sandstone and a medium–coarse grained quartz sandstone. Palynological analysis indicates that these sediments were deposited in inner–middle and outer-shelf environments. Seismic facies in Bremer 6 are difficult to resolve due to the thin and patchy nature of sediments. However, where the sedimentary fill is thickest in the Athena depocentre, Bremer 6 appears to contain a complex fill of aggradational and onlapping lenticular reflections, which is consistent with deposition in sub-marine canyons (Figures 2.13 and 2.15).

Bremer 6 correlates to the Tiger and Hammerhead supersequences in the eastern Bight Basin (Figure 2.8). However, post break-up passive margin sedimentation in the eastern Bight Basin is interpreted to have commenced in the late Santonian (Totterdell et al., 2000; Sayers et al., 2001; Totterdell and Bradshaw, 2004), about 5–7 million years later than in the Bremer Sub-basin. This suggests that sea-floor spreading commenced earlier in the western Bight Basin than in the eastern Bight Basin.

CAINOZOIC (EUCLA BASIN)

The Bremer Sub-basin is unconformably overlain by Cainozoic sediments that formed as part of a regional phase of carbonate platform deposition across the Southern Australian margin (Figure 2.8). Bradshaw et al. (2003) have previously defined all Cainozoic strata overlying Mesozoic rocks from the Bight Basin as forming the offshore component of the Eucla Basin. In the western part of the Bight Basin, the onshore Eucla Basin forms a discontinuous veneer (<1000 m) of Eocene marine and non-marine sediments overlying shallow basement rocks (Hocking, 1994; Clarke et al., 2003). Cainozoic strata continue offshore across the continental shelf, and extend over the basin bounding faults of the Bremer Sub-basin as a prominent sigmoidal progradational–aggradational carbonate wedge that forms the modern shelf break (see Chapter 3, Figure 3.18). On the continental slope, the Eucla Basin forms a thin (<500m thick), discontinuous sheet that is dissected by submarine canyons of the Albany Canyon complex (Exon et al., 2005). The base of the Eucla Basin is an erosional unconformity. Cainozoic strata generally either concordantly overlie or onlap Late Cretaceous strata from Bremer 6. In some areas, the basal Cainozoic unconformity has eroded into pre-break-up sediments (Figure 2.10). Seismic data show numerous incision surfaces, canyon-fills, chaotic reflections and relatively parallel continuous reflections within the Cainozoic strata, indicating deposition in a range of continental slope environments.

All of the dredge samples recovered from the offshore Eucla Basin are located on the continental slope, seaward of the modern-day shelf break. At least 36 samples were recovered from 21 dredge sites. Dredge 35 provides a confident tie to the Eucla Basin (Figure 2.18). Rocks dredged from the base of the Eucla Basin succession (dredge 7 A2; dredge 24 E, dredge 27 D, dredge 28 F, and dredge 36 A and C) contain mixed reworked Santonian–Maastrichtian and latest Paleocene–Middle Eocene dinoflagellate assemblages. These basal sediments are predominantly fine-grained, glauconitic, marine (inner–middle shelf) calcarenites, which are no younger than Middle Eocene. The basal "mixed assemblage" unit is interpreted to have been deposited in the Middle Eocene, during the main phase of accelerated continental margin subsidence and submarine canyon erosion described by Exon et al. (2005). These "mixed assemblage" sediments were probably derived from poorly consolidated post-break-up sediments that accumulated across a sediment-starved shelf, which were subsequently eroded and re-deposited in the Bremer Sub-basin.

Middle Eocene–Recent deep-marine carbonates (chalks, limestones, calcarenites, grainstones and calcareous mudstones–siltstones) were subsequently deposited as part of a regional phase of cool-water carbonate platform that developed across the Southern Australian margin (James and von der Borch, 1991; Feary and James, 1998; Clarke et al., 2003). This final phase of carbonate platform deposition occurred in rapidly increasing water depths related to accelerated subsidence at the onset of fast sea-floor spreading (Cande and Mutter, 1982; Totterdell et al., 2000; Norvick and Smith, 2001).

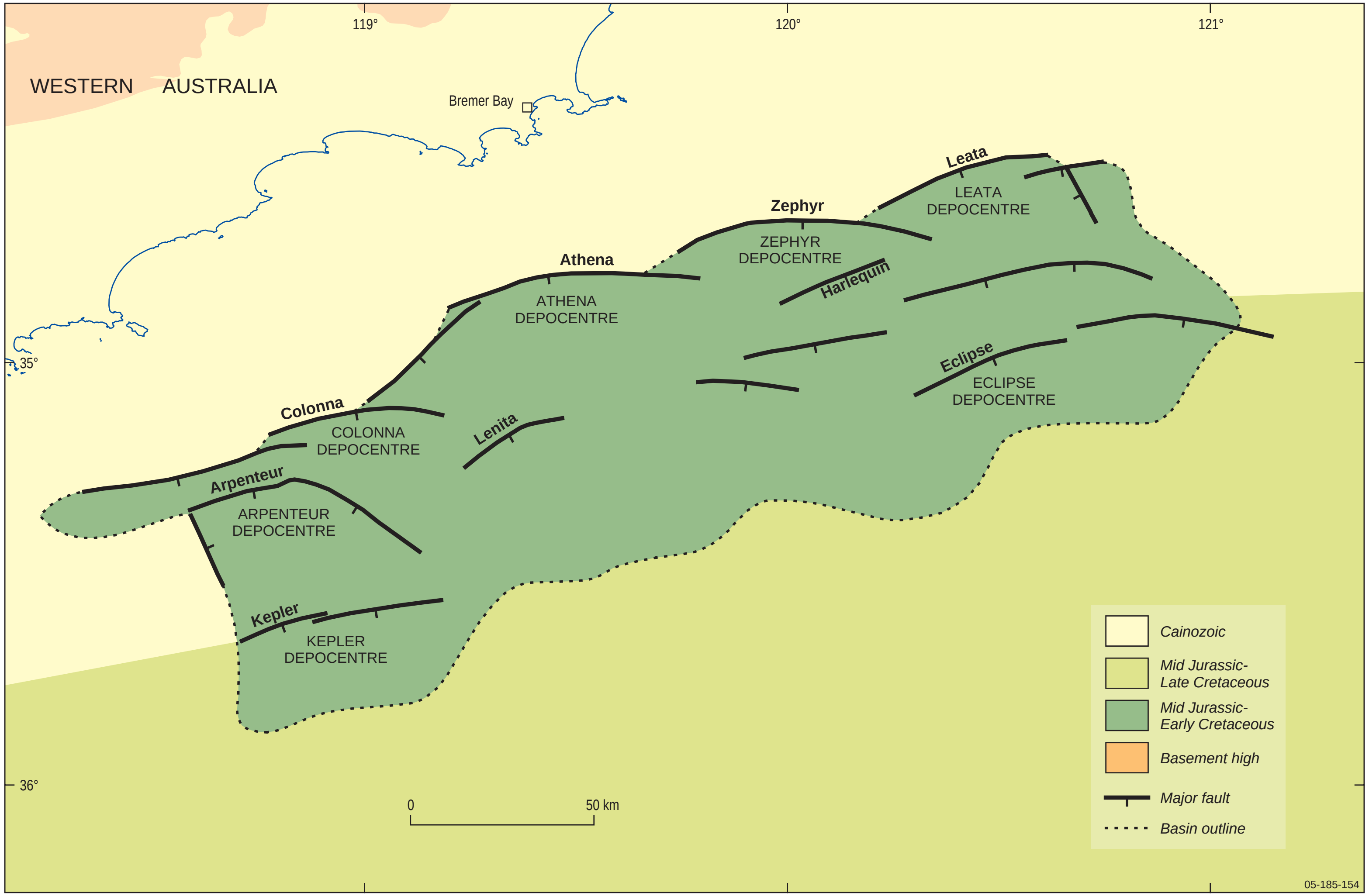


Figure 2.1: Major structural elements, basement highs and depocentres within the Bremer Sub-basin.

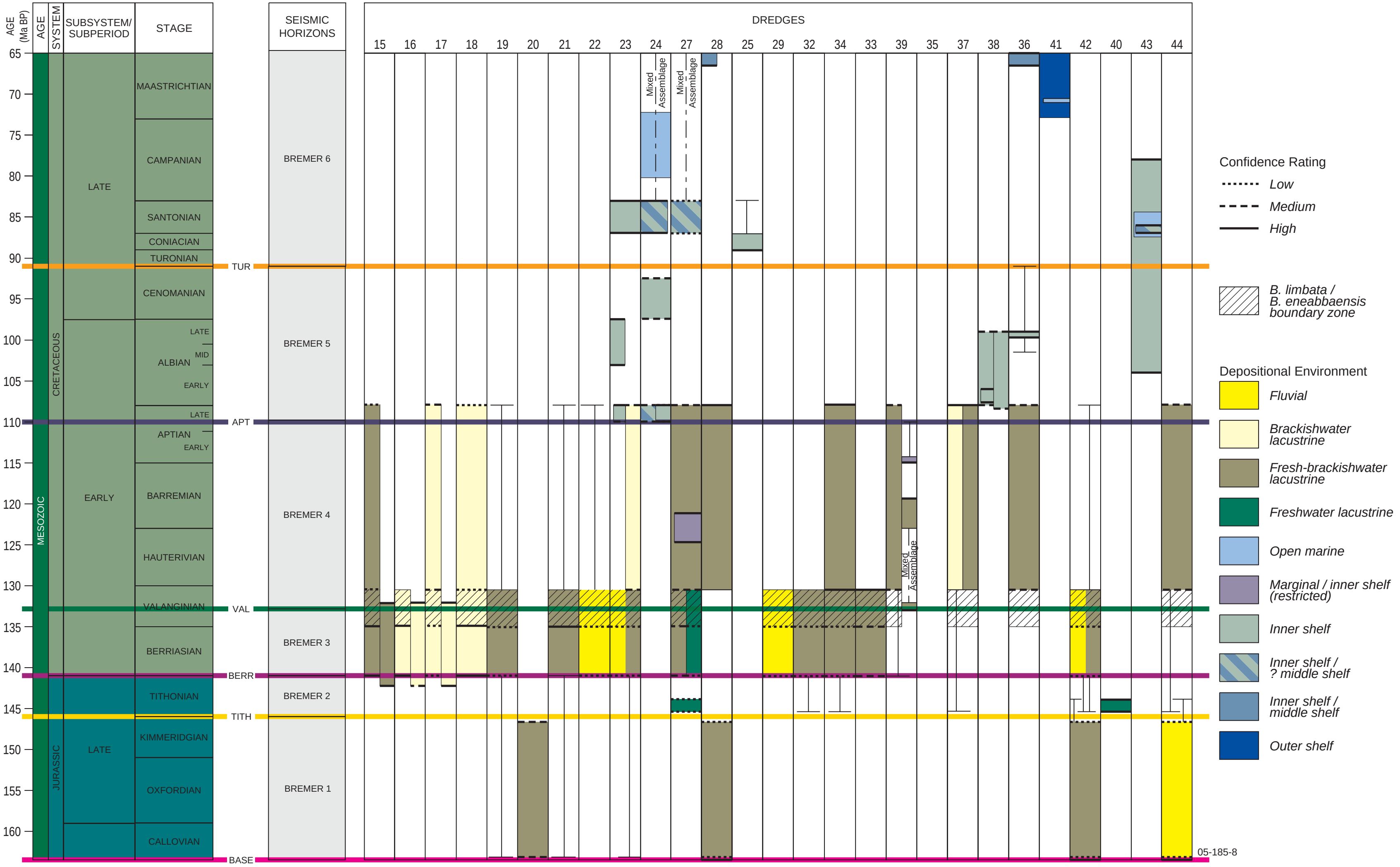


Figure 2.2: Bremer Sub-basin Mid Jurassic to Cretaceous biozonation and dredge summary chart (see Appendix E for detailed version).

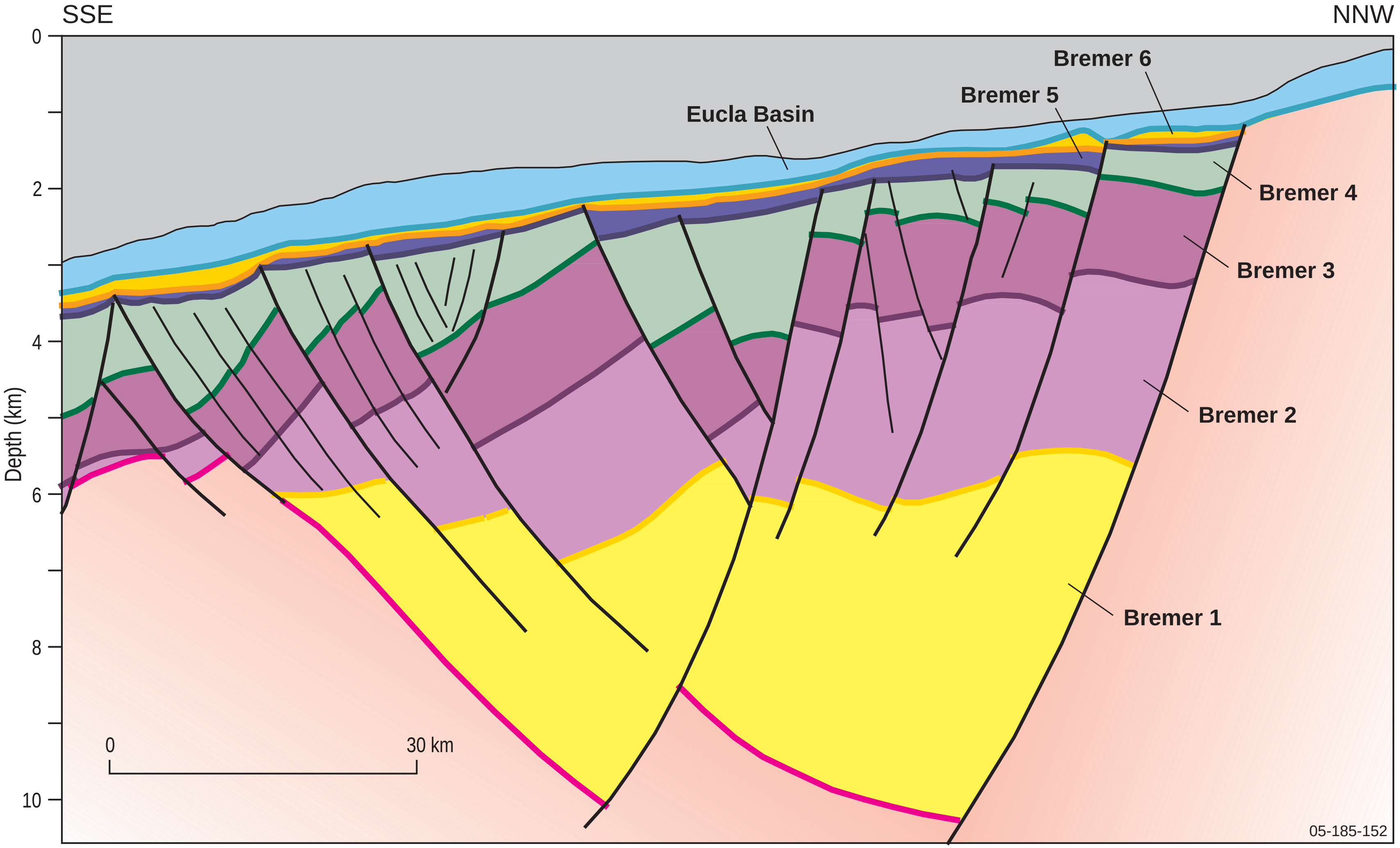


Figure 2.3: A schematic diagram of the Bremer seismic stratigraphic units based on seismic line s280-21 in the centre of the sub-basin.

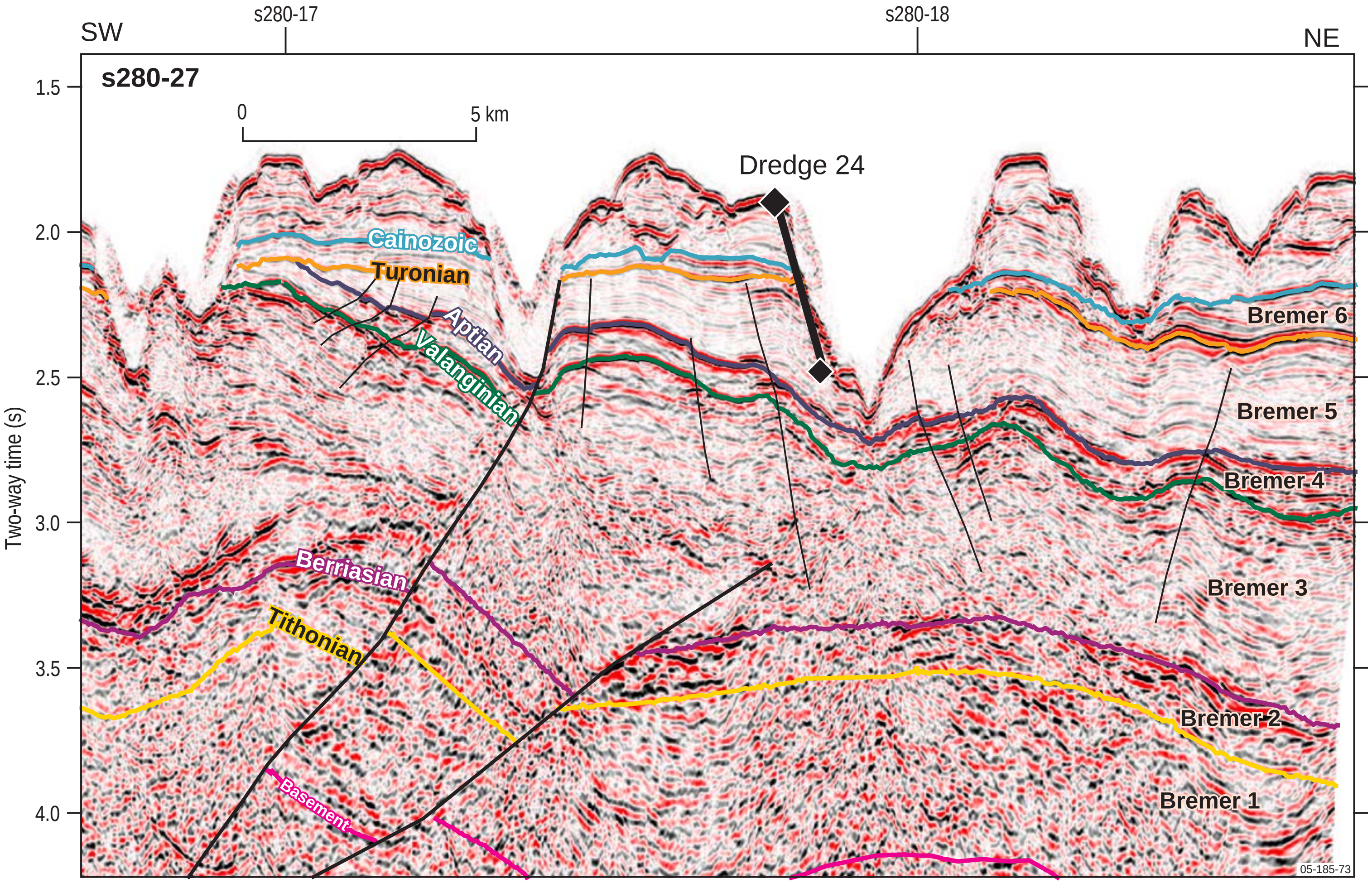


Figure 2.4: Example of a key dredge tied to seismic data. Here, dredge 24 is tied to seismic line s280-27 and extends across most of the Bremer 5 unit (see Appendix F for complete dredge tie summary).

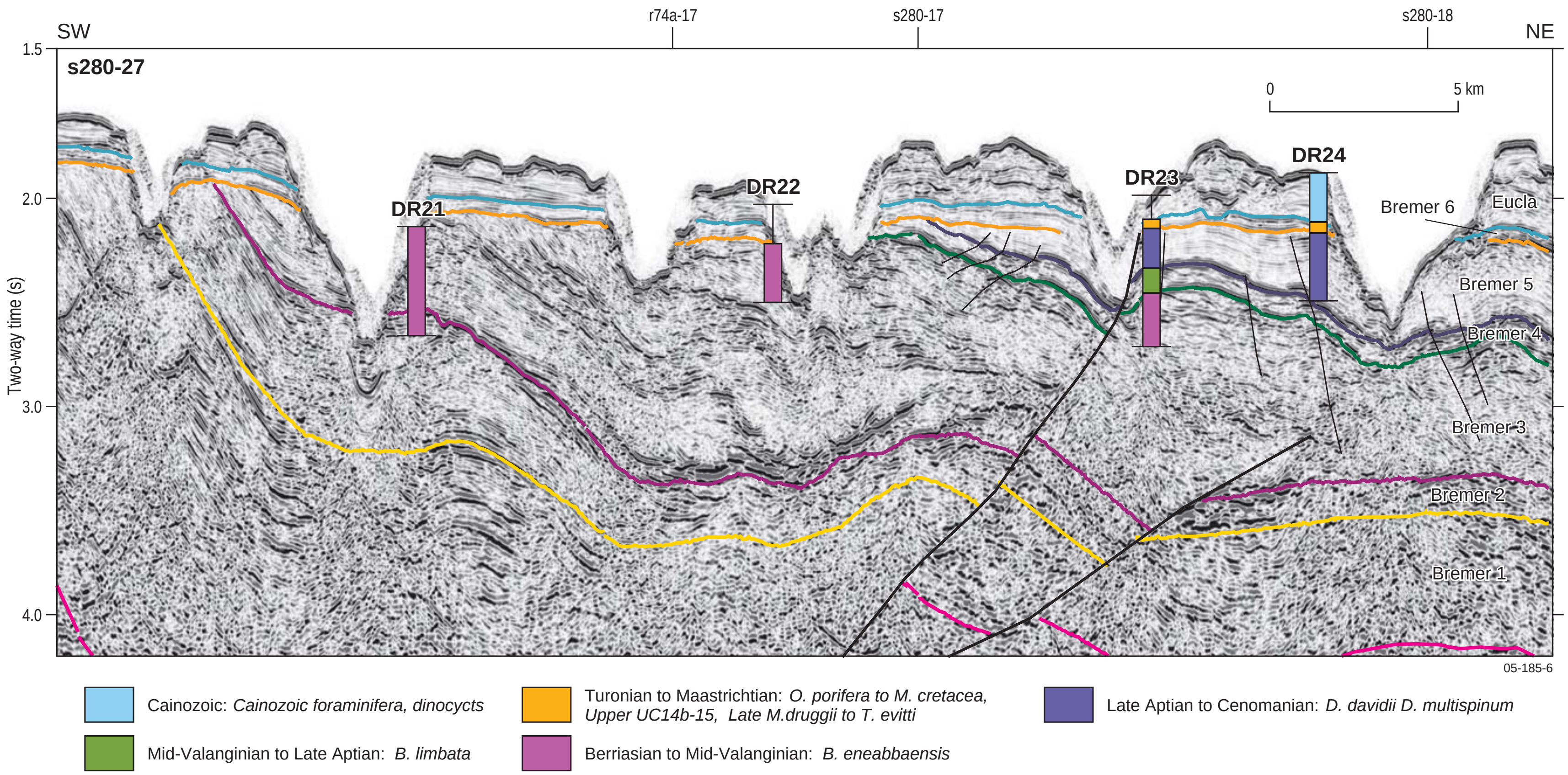


Figure 2.5: An example from the western Bremer Sub-basin where a number of dredges have been tied to seismic line s280-27. Each dredge has been coloured by age intervals derived from biostratigraphic analysis.

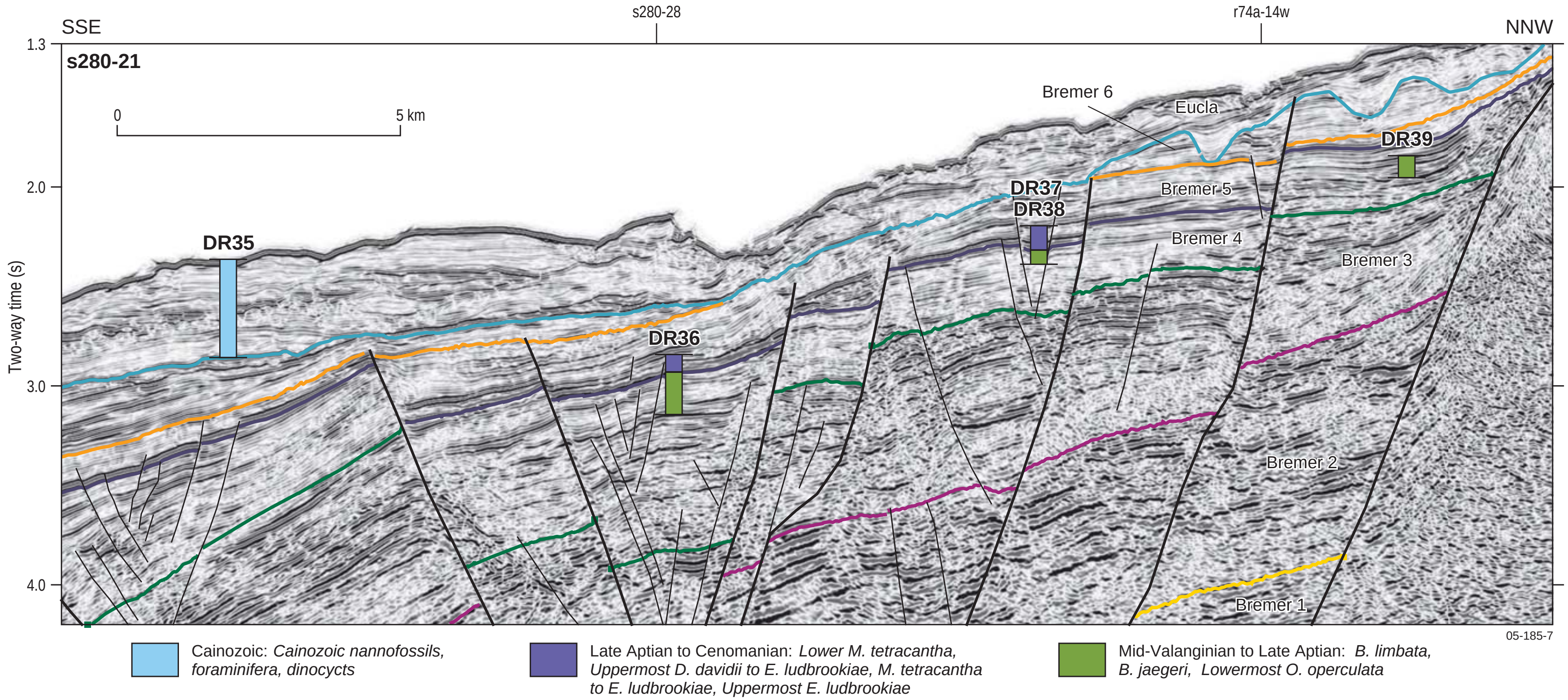


Figure 2.6: An example from the eastern Bremer Sub-basin where a number of dredges have been tied to seismic line s280-21. Each dredge has been coloured by age intervals derived from biostratigraphic analysis.

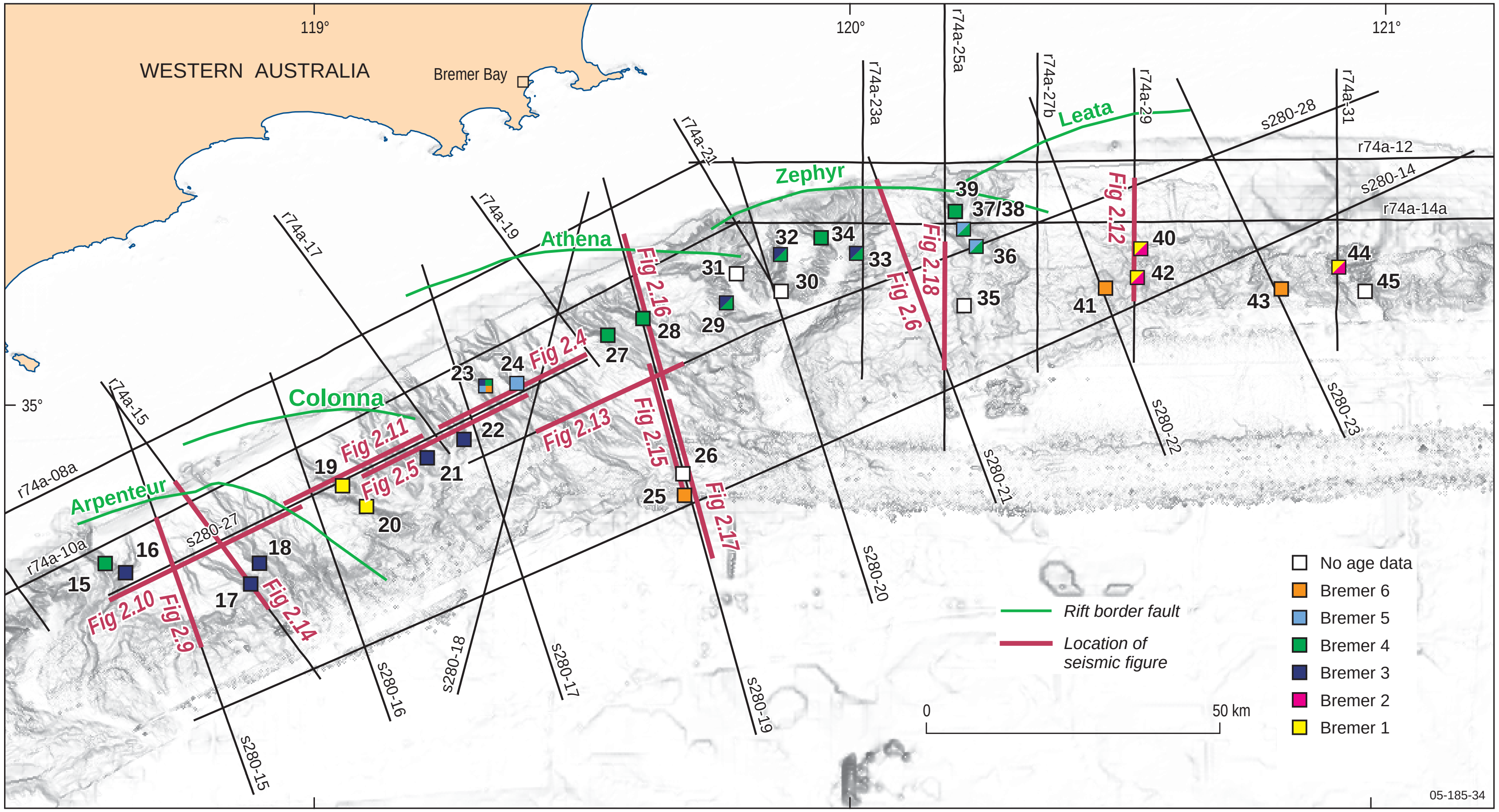


Figure 2.7: Summary of seismic stratigraphic units at dredge sites across the Bremer Sub-basin superimposed over bathymetry image. Also shown are locations of seismic figures.

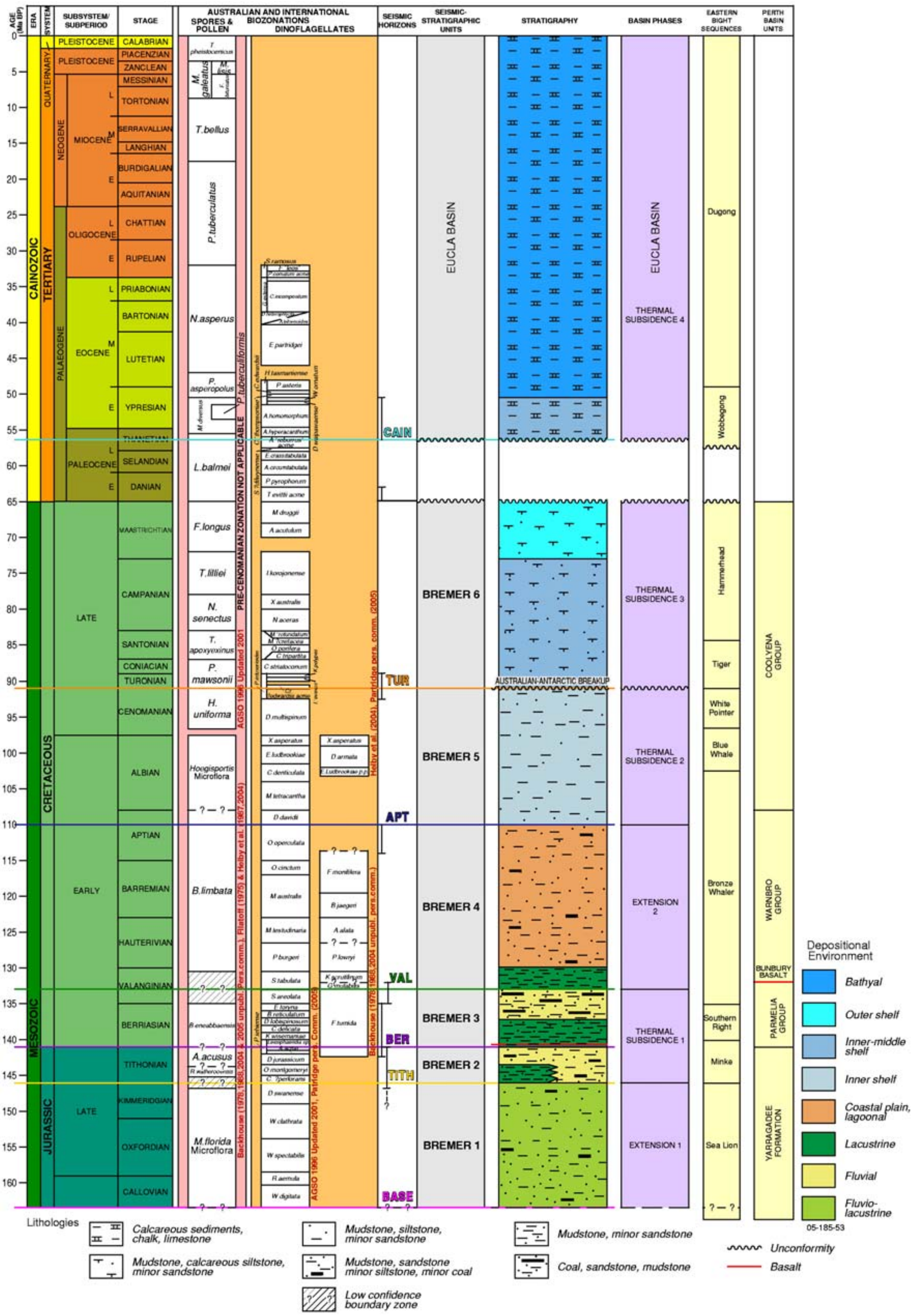


Figure 2.8: Bremer Sub-basin stratigraphic chart with correlations to the eastern Bight Basin and Perth Basin.

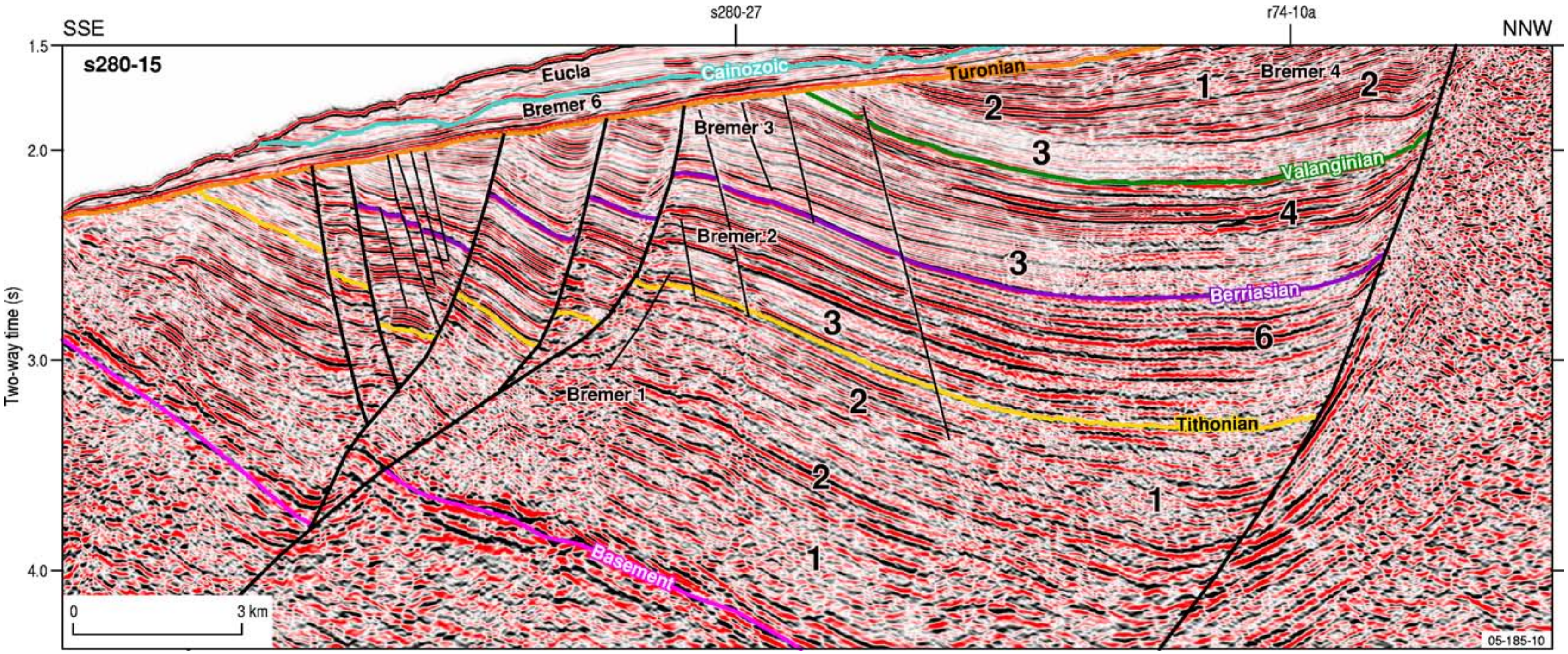


Figure 2.9: An example of seismic data from line s280-15 in the Arpenteur depocentre showing Bremer seismic stratigraphic units and numbered seismic facies (see Table 2.2 for details of seismic facies).

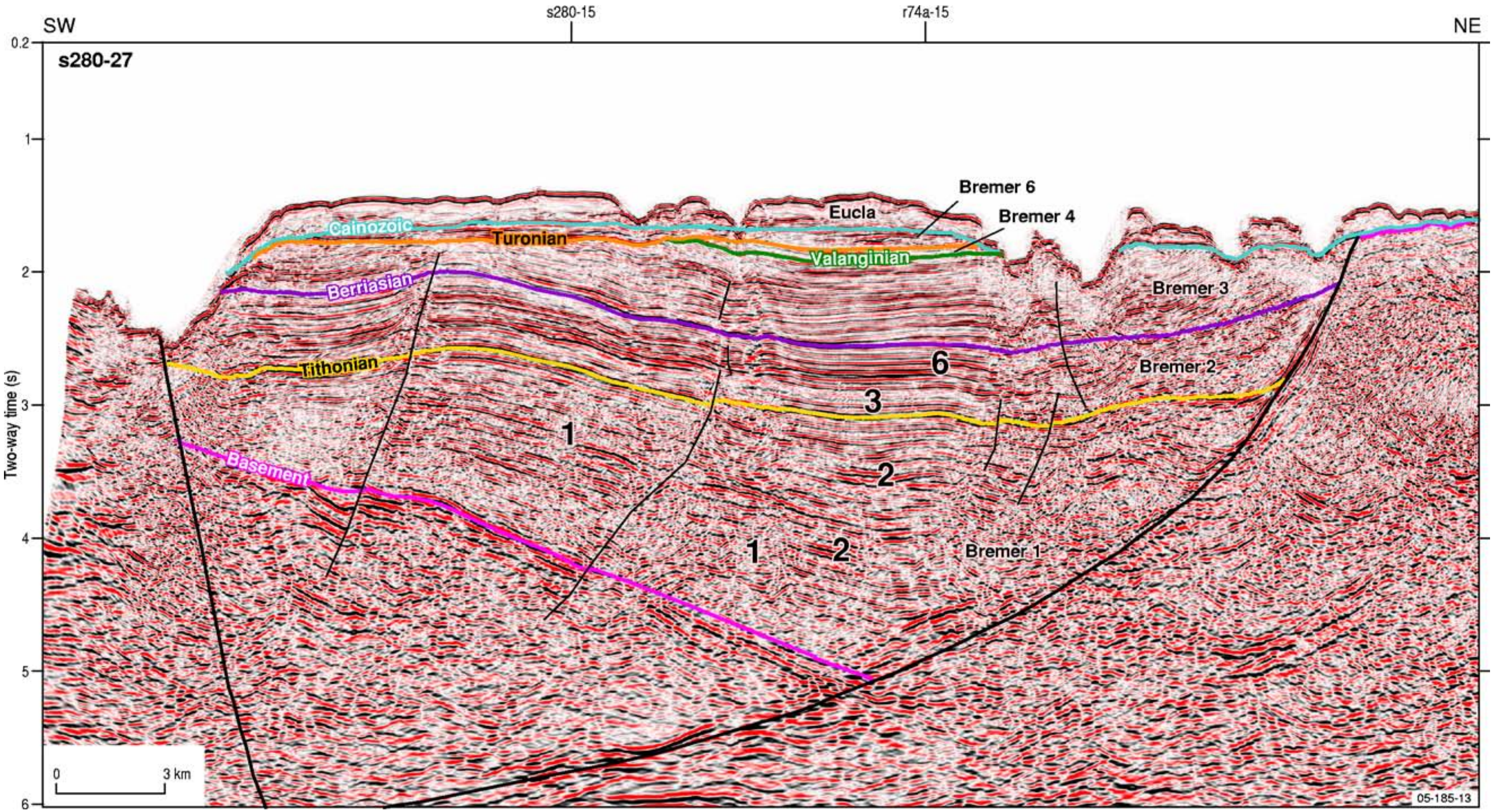


Figure 2.10: An example of seismic data from line s280-27 in the Arpenteur depocentre showing Bremer seismic stratigraphic units and numbered seismic facies (see Table 2.2 for details of seismic facies).

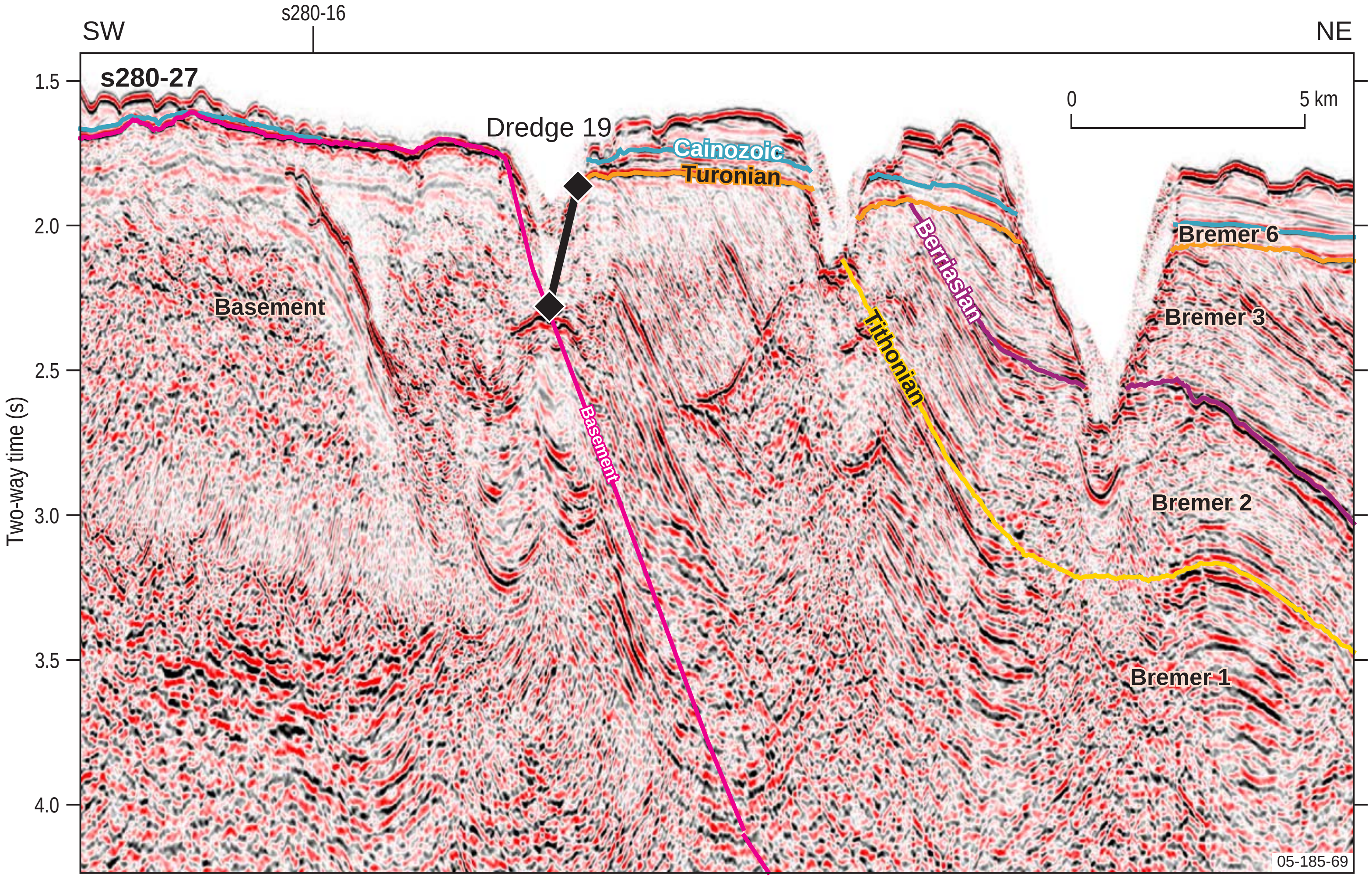


Figure 2.11: Dredge 19 tied to seismic line s280-27. This dredge sampled steeply-dipping strata from the base of Bremer 1 in the Colonna depocentre, adjacent to shallow granitic basement of the Penguin High (see Appendix F for dredge tie summary).

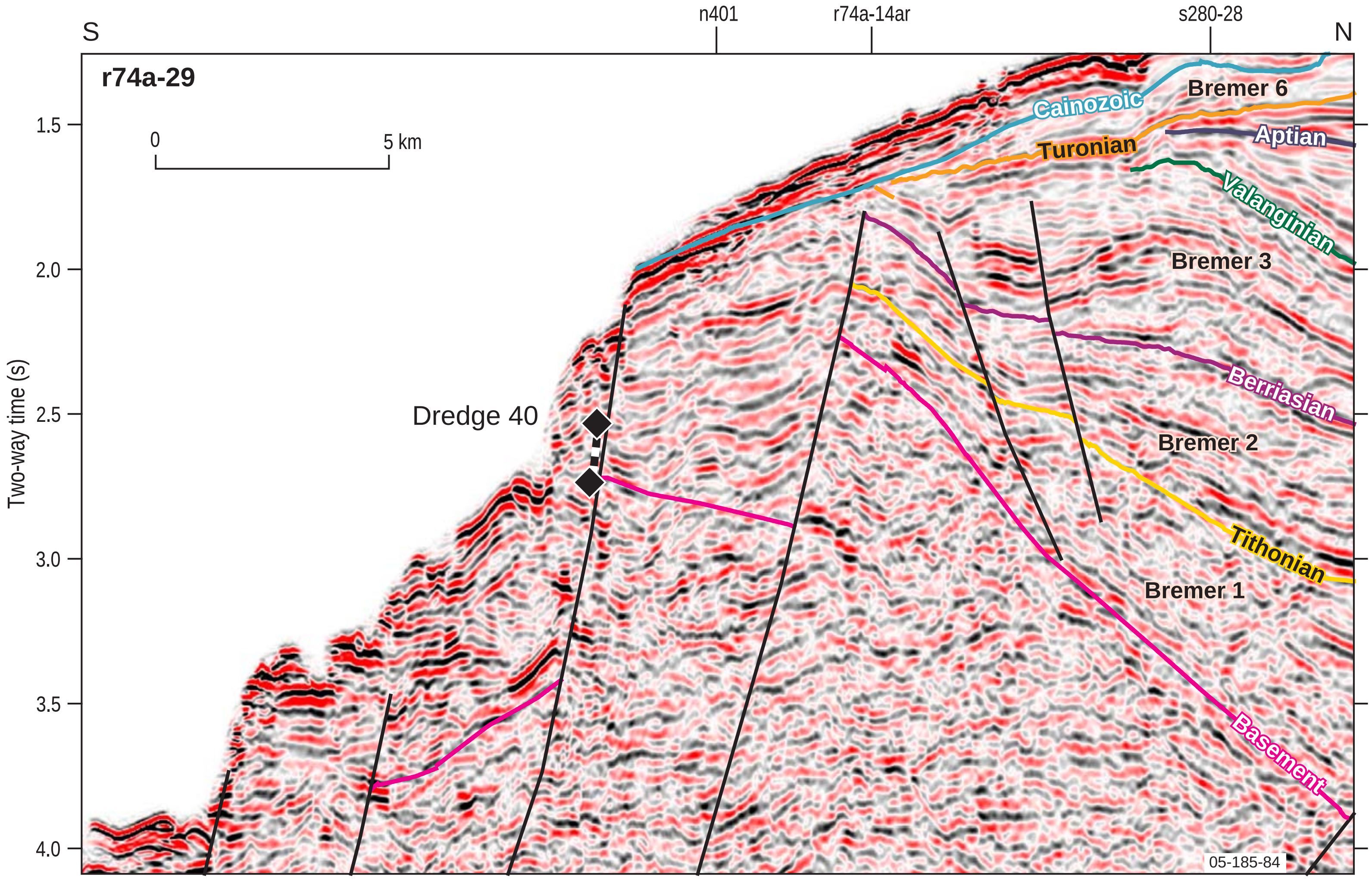


Figure 2.12: Dredge 40 tied to seismic line r74a-29. It is uncertain if this dredge site has sampled either the Bremer 2 and/or Bremer 1 units due to the poor seismic resolution (see Appendix F for dredge tie summary).

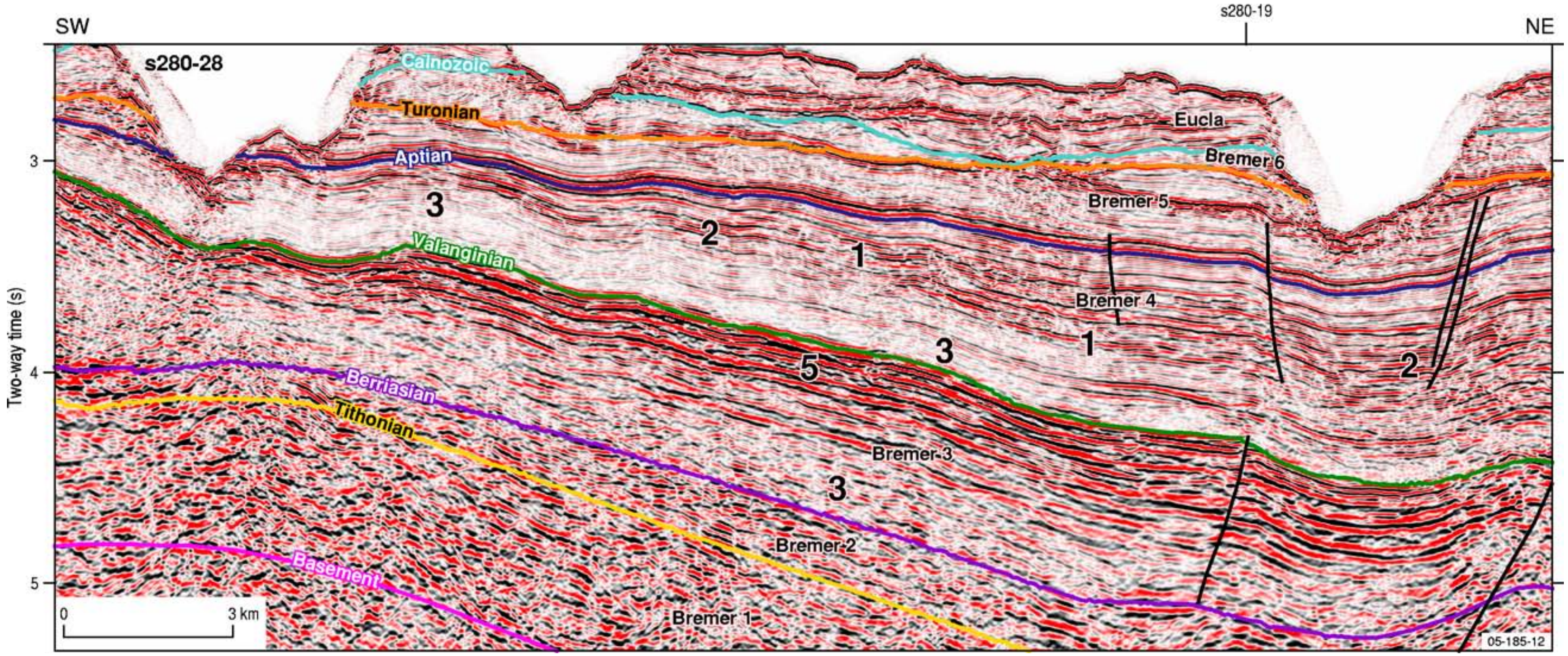


Figure 2.13: An example of seismic data from line s280-28 in the Athena depocentre showing Bremer seismic stratigraphic units and numbered seismic facies (see Table 2.2 for details of seismic facies).

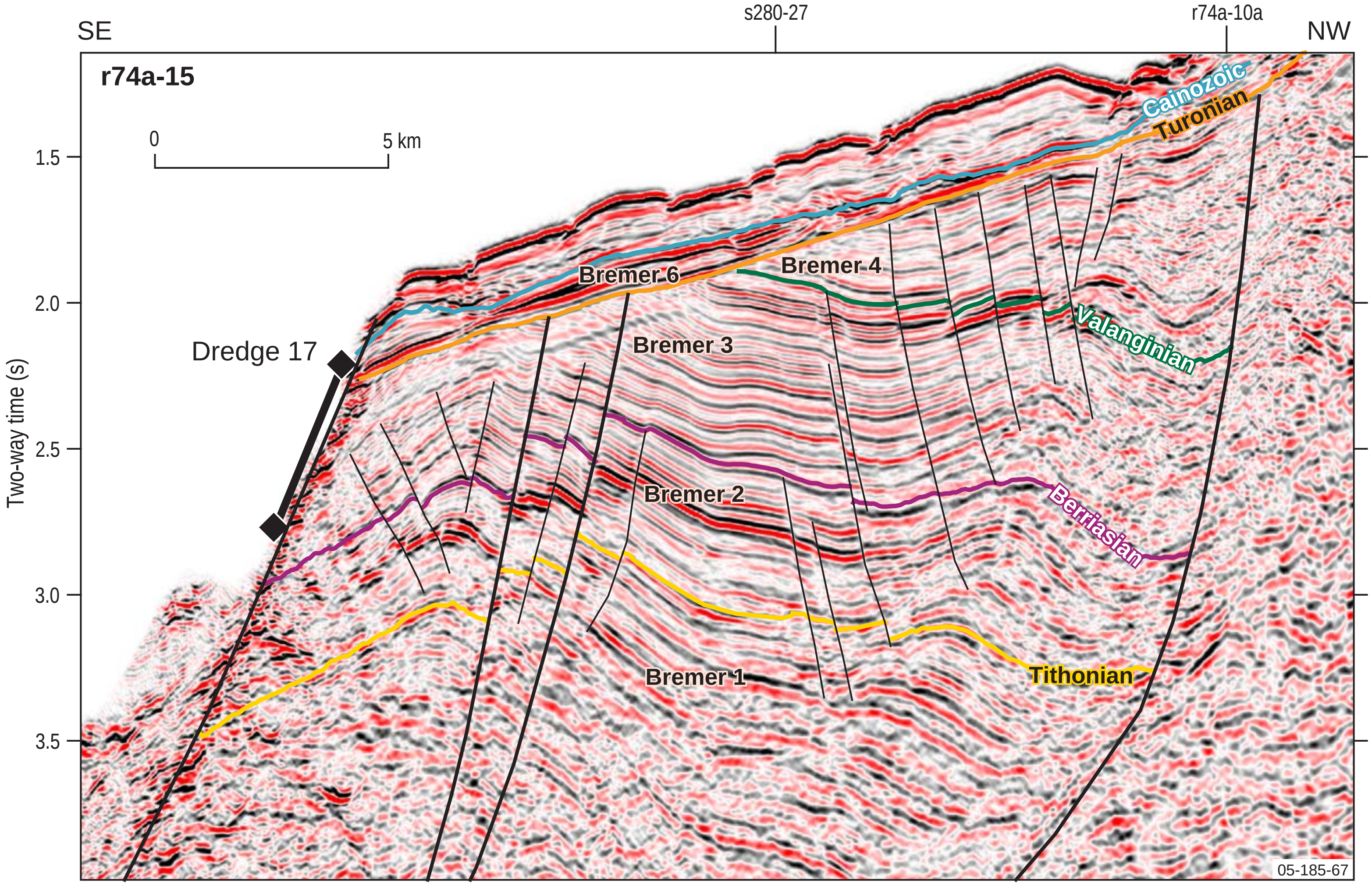


Figure 2.14: Dredge 17 tied to seismic line r74a-15. The Bremer 3 unit can be confidently tied to seismic data in the Arpenteur depocentre (see Appendix F for dredge tie summary).

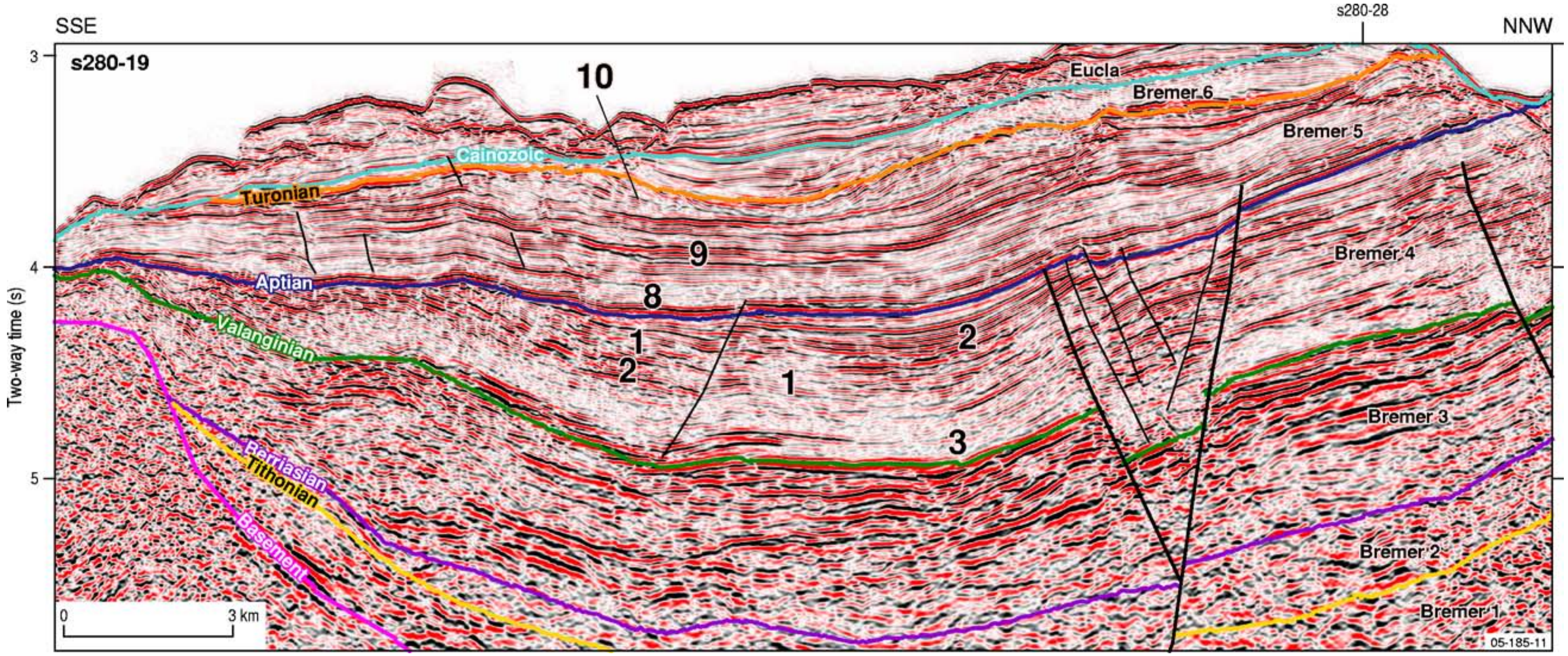


Figure 2.15: An example of seismic data from line s280-19 in the Athena depocentre showing Bremer seismic stratigraphic units and numbered seismic facies (see Table 2.2 for details of seismic facies).

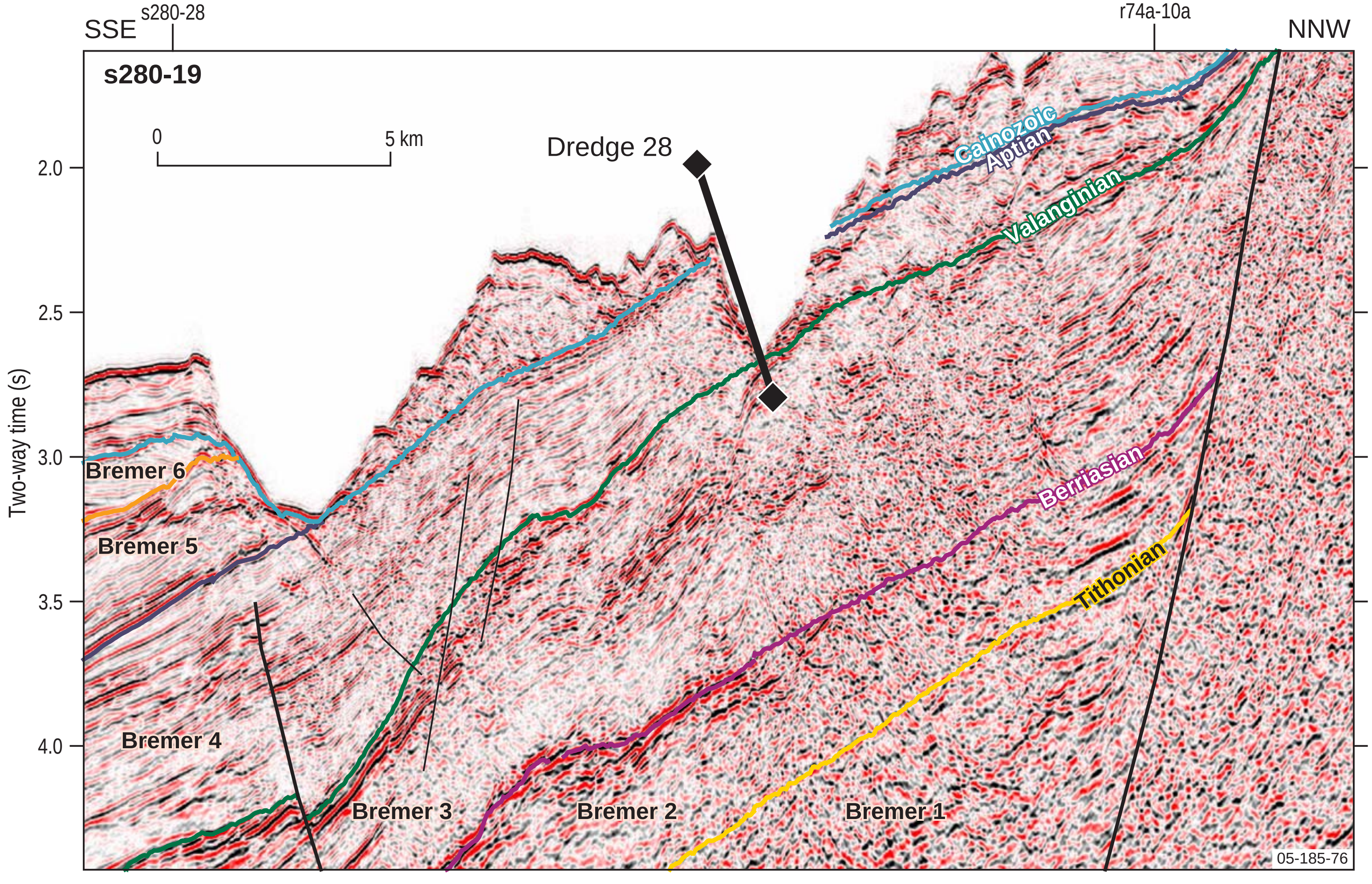


Figure 2.16: Dredge 28 tied to seismic line s280-19. The Bremer 4 unit can be confidently tied to seismic data at this dredge site in the Athena depocentre (see Appendix F for dredge tie summary).

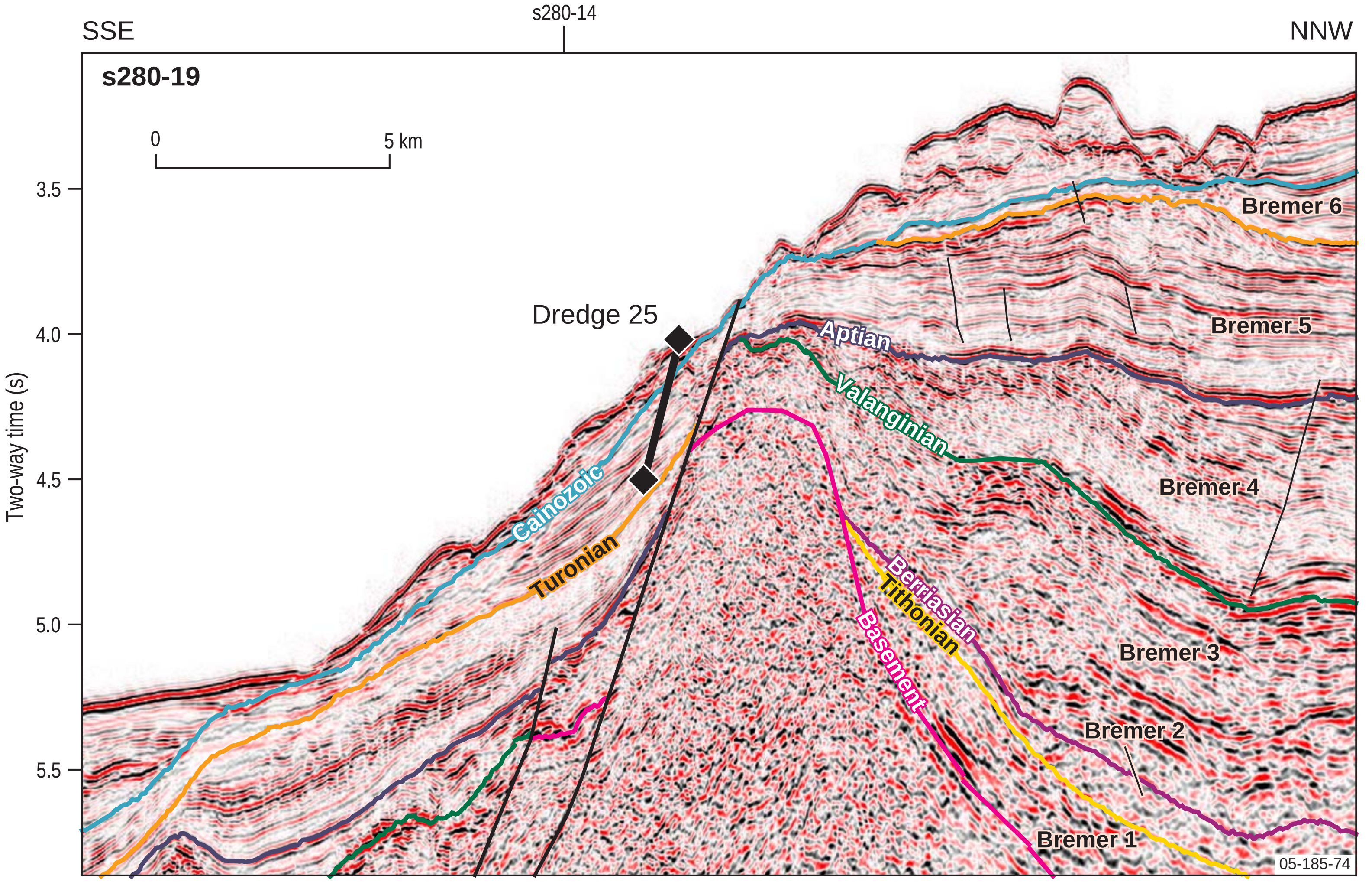


Figure 2.17: Dredge 25 tied to seismic line s280-19. This site provides the most confident tie to the Bremer 6 unit, extending from the base of unit to the sea floor in the Athena depocentre (see Appendix F for dredge tie summary).

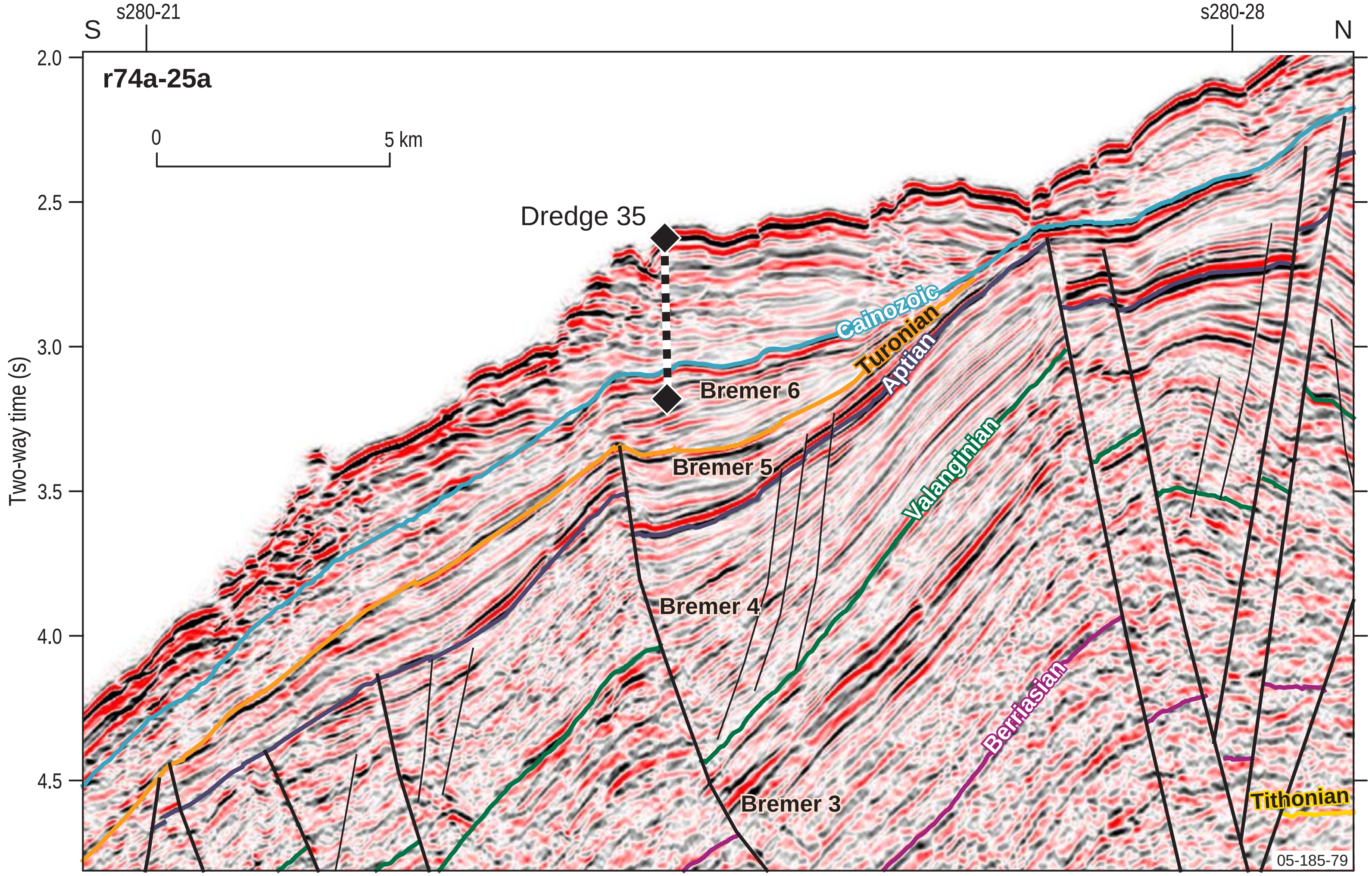


Figure 2.18: Dredge 35 tied to seismic line r74a-25a. This dredge site provides a confident tie to the Eucla Basin succession, extending through the entire seismic unit in the Zephyr depocentre (see Appendix F for dredge tie summary).

Table 2.1. Summary of dredge sample ages, environments and lithologies (* = inferred age; # = calcareous; ^ = glauconitic; © = coaly). Lithological data is sourced from Exon et al. (2005). Palaeoenvironmental data is sourced from Howe (2005); MacPhail and Monteil (2005); and Taylor and Haig (2005).

	Sandstone	Siltstone	Claystone/Shale	Calcarenite / Grainstone	Limestone/Chalk
Eucla Basin					
Marine (open)		15A4*#, 36A2^	10C*#, 12B*#	32C*, 39F*	14A2*, 15A3*, 18A1*, 18A2*, 18A3*, 18F*, 21B*, 21D2*, 21D3*, 22D1*, 22D2*, 26A*, 36E1*, 44G*
Marine (inner-middle shelf)	7A2, 36A1^		27D^#	24E^, 36C^	
Marine (bathyal)	1A	7B2#, 7D#, 10A#, 13G#, 16D#	24H#, 25E#, 24F#	24G^, 28D, 28F^, 28H, 35A1	5C, 5D1, 5D2, 7B1, 8A, 10D, 16D, 35A2, 39H
Bremer 6					
Marine (open)			43B1, 43B3*		
Marine (inner shelf)	23A		9B#, 25A, 25B^, 25C, 43A, 43B2		
Marine (inner-middle shelf)		7C#, 7D#			
Marine (outer shelf)	7A1^, 41A1#	9A#, 41A1#,	9C#		
Bremer 5					
Marine (inner shelf)		24C, 24D^	23C^, 23G, 23I, 36D2, 38A, 38B, 38C	24G	
Unknown	24A*, 24F*^	24B*			
Bremer 4					
Marginal Marine	39A		27B©		
Lacustrine (brackish)			37B1		
Lacustrine (fresh-brackish)	27A1, 28C	23D, 28B, 36B, 39B	15B, 15C, 27A3, 28B, 28C, 36D1, 37B2, 39C, 39D, 39E		
Lacustrine (fresh water)	27A4		27C1, 27C2		
Fluvial					
Unknown	28A*,	37A*	37B3*		
Bremer 3					
Lacustrine (brackish)	16A1*, 16A2#, 16A3*#, 17D^	16B, 18B	16C, 17A, 17B, 17C, 18C, 18D		
Lacustrine (fresh-brackish)	21D	21D	21C1, 21C2, 21C3, 21C4, 22C©		
Fluvial					
Unknown	22B*		21E*, 22A*		
Bremer 1					
Lacustrine (fresh-brackish)	19C	19C	20C		
Lacustrine (fresh water)					
Fluvial					
Unknown	19A, 19B*, 19D*, 20B1*, 20B2*,		19A		
Ambiguous Seismic Tie					
Bremer 3 or 4	29A1, 29A2*, 32A1*, 32A2*, 32A3*, 32A4*, 33A1*, 33A2*, 34A*, 34C*, 34D*		23B, 23D, 23F©, 32B, 33B1*, 33B2, 34B*, 34E, 34F,		
Bremer 1 or 2	40A, 40C, 42A*, 44A*, 44B*, 44C*, 44D*, 44I*, 44J*	42A*	40B, 40D, 42B1, 42B2, 42C, 44E, 44F		
Indeterminant Age					
	7A3, 13C, 23E, 27A2, 30A1, 30B1, 31A1, 31A2, 31A3,	13D, 36C	13E, 13F, 25D, 30C, 36D2, 41A2		

Table 2.2. Seismic facies identified in the Bremer Sub-basin.

Seismic Facies	Amplitude	Frequency	Continuity	Internal Reflections	Lithology	Depositional Environment
1	low to moderate	low to moderate	low	hummocky and wavy	interbedded sandstones, mudstones (claystones/shales and siltstones) and minor coal	Variable fluvial floodplain to lacustrine system
2	moderate to high	low to moderate	high	parallel	Sandstone bodies and minor coal	sandstone-dominant fill of an amalgamated channel system
3	low	moderate	moderate to high	parallel	interbedded claystones, shale, and fine sands	lacustrine system
4	high	variable	moderate to high	sub-parallel and lenticular (reflecting typical coal seam morphology)	coaly claystones interbedded with siltstone/sandstone and sandstone	laterally extensive coaly-fluvial floodplain system
5	high	variable	moderate to high	sub-parallel and in parts lenticular	coaly claystones interbedded with siltstone/sandstone and sandstone	fault controlled fluvial channel system
6	moderate to high	low to moderate	high	strongly parallel	thick sandstones, siltstones, claystones, shales units and minor coal (often interbedded)	laterally extensive fluvial system
7	high	low to moderate	low	disrupted to chaotic	feldspar-phryic basalt	igneous intrusive sill
8	low	moderate	moderate	parallel to wavy	homogenous claystones and siltstones	marine inner shelf
9	moderate to high	low to moderate	high	parallel to wavy	heterogenous claystones and siltstones with some sandstones	marine inner shelf
10	moderate	moderate to high	moderate	progradational	claystones and siltstones with some sandstones	deltaic

3. Structural Framework (C.J. Nicholson & D.J. Ryan)

KEY POINTS

- Interpretations of seismic reflection and refraction data, along with seafloor dredge data, have been used to increase our understanding of the Bremer Sub-basin's structural geology and tectonic evolution.
- The Bremer Sub-basin comprises a series of half graben perched on the continental slope in the western part of the Bight Basin.
- Proterozoic granites, gneisses and metasedimentary rocks of the Albany-Fraser Orogen are interpreted to form basement to the Bremer Sub-basin. Basement fabric has played a key role in the tectonic evolution and structural architecture of the Bremer Sub-basin.
- The sub-basin contains up to up to 9.5 km of sedimentary rocks, which is sufficient fill for hydrocarbon generation and expulsion. In particular, there is a potential large source kitchen area in the central part of the sub-basin (Athena and Zephyr depocentres). Smaller depocentres occur in the eastern and western parts of the sub-basin (Arpenteur, Leata, and Colonna depocentres).
- The Bremer Sub-basin formed during six basin phases:
    - Jurassic upper crustal extension;
    - Early Cretaceous post-rift thermal subsidence;
    - Valanginian–Aptian extension;
    - Aptian–Turonian thermal subsidence;
    - Turonian uplift and faulting;
    - Turonian–Recent post-break-up thermal subsidence.
- Anticlinal structures and rotated fault blocks formed during the Valanginia–Aptian extension phase, and have potential to trap large quantities of hydrocarbons. Anticlinal structures are located in the hanging wall blocks of rift border faults, while rotated fault blocks are mainly located along an intra-basin fault system in the Athena and Zephyr depocentres.

BASEMENT GEOLOGY AND REGIONAL STRUCTURAL FRAMEWORK

The Albany-Fraser Orogen, located onshore of the Bremer Sub-basin, comprises a series of Palaeoproterozoic–Mesoproterozoic rock belts that strike parallel to the Yilgarn Craton (Figure 3.1). These rock belts accreted during two phases of Mesoproterozoic tectonism as a collisional suture zone between the Yilgarn and Gawler Cratons (Myers et al., 1996). Granites and gneisses of the Albany-Fraser Orogen were dredged from several basement highs in the Bremer and Denmark sub-basins (Hocking and Jones, 2005). The Albany-Fraser Orogen is therefore interpreted to form basement beneath the Bremer Sub-basin (Figure 3.1). Plate reconstructions of the southern Australian margin by Fitzsimons (2003) also show that terranes from the Albany-Fraser Orogen extend beneath the Bremer Sub-basin and correlate with the Wilkes Orogen in Antarctica (Figure 3.2). The structural fabric within the Albany-Fraser Orogen is defined by ENE to NE striking, southerly-dipping thrust faults, which are cross-cut by dextral strike-slip shear zones in the west (Figure 3.1). When extrapolated offshore, the geology and structural trend of the Albany-Fraser Orogen broadly correlates with the ENE trend of the Bremer Sub-basin (Figure 3.1). This suggests that basement structures have influenced the overall structural architecture of the Bremer Sub-basin.

Basement beneath the Bremer Sub-basin can be interpreted and mapped using seismic reflection data. However, the confidence of basement interpretations varies significantly depending on the quality of seismic data, and thickness of overlying sedimentary rocks. To capture this, three levels of interpretation confidence were assigned to basement picks: high, medium and low confidence (Figure 3.3). High-confidence basement interpretations are possible where sedimentary rocks are relatively thin; whereas basement can only be inferred beneath thick sedimentary sections or where seismic data quality is poor.

Potential field data in the Bremer Sub-basin are generally of limited use for interpreting the nature of underlying basement terrain due to the limited quality and coverage of gravity and magnetic data, together with the steep, extensively incised seafloor topography. Therefore, P-wave velocity data were acquired from sonobuoys during Geoscience Australia Survey 280 to help interpret the nature of basement beneath the Bremer Sub-basin (Figure 1.4). One dimensional velocity models based on this sonobuoy data have been correlated with interpretations of basement in seismic reflection data. These correlations indicate that basement velocities vary between 5 and 6.2 km/s (Figure 3.4; Goncharov et al., 2005). Velocities of ~6 km/s are consistent with granitic and gneissic rocks from the Albany-Fraser Orogen. However, a number of models at or near interpreted basement show velocities of 5–5.7 km/s. These velocities are too low for granite and gneiss, but may indicate the presence of metasedimentary rocks (Goncharov et al., 2005). In parts of the Albany-Fraser Orogen, quartzose metasediments unconformably overlie crystalline basement (Fitzsimons, 2003). Therefore, basement beneath the Bremer Sub-basin is interpreted to be heterogenous, consisting of both crystalline granites and gneisses, and metasedimentary rocks from the Albany-Fraser Orogen.

Basement interpretations on seismic reflection data have been depth-converted using a time-depth function derived from S280 seismic stacking velocities. As stacking velocities are commonly unrealistically high compared to P-wave velocities, stacking velocity data were discarded if either interval velocities or RMS velocities exceeded 7km/s, excluding outliers beyond the maximum likely P-wave velocity within the sedimentary column (Goncharov et al., 2005). A comparison between stacking velocity data and sonobuoy data shows a relatively good correlation, and supports the reliability of the depth-conversion function used (Goncharov et al., 2005). Applying this depth-conversion function to seismic interpretations shows that basement reaches a maximum depth of ~11 km in the central part of the Bremer Sub-basin (Figure 3.5). Overlying sedimentary rocks in this central area reach thicknesses of up to 4.6 s two-way time (Figure 3.6), which equates to a maximum sediment thickness of ~9.5 km (Figure 3.7). This is sufficient basin fill for hydrocarbons to generate and expel from source rocks within the Bremer Sub-basin.

STRUCTURAL ELEMENTS

The Bremer Sub-basin is an ENE trending rift basin located on the continental slope in the western part of the Bight Basin. The sub-basin is composed of a series of *en echelon* half graben bounded to the north by rift border faults (Figure 3.8). These rift border faults have an arcuate geometry. At their western extents, the faults generally strike WSW–ENE, parallel to the structural trend of the adjoining Albany-Fraser Orogen. However, the eastern tips of the rift border faults generally strike E–W, oblique to the Albany-Fraser Orogen.

Similar structural styles have been observed in analogue models of extensional fault systems where basement structural trends are oblique to the extension direction (McClay et al., 2001; McClay et al., 2002). In these analogue models, *en echelon* fault sets form perpendicular to the extension direction, but are concordant with the basement fabric (Figure 3.9). The broad E–W trend of rift border faults in the Bremer Sub-basin suggests that they formed during N–S extension. This differs from the NNW extension direction interpreted in the eastern Bight Basin by Totterdell and Bradshaw (2004). Any difference in extension directions between the eastern and western parts of the Bight Basin may reflect changes in stresses that propagated along the western and southern margins of Australia during extension between Australia, Antarctica and Greater India. Both the western and eastern boundaries of the Bremer Sub-basin are defined by NNW striking, near-vertical faults that are hard-linked to basement and strike perpendicular to the basin axis (Figure 3.8). These structures are not aligned with the N–S extension direction that formed the sub-basin, and may have been controlled by underlying basement structures. Alternatively they may have formed as release faults accommodating variable strain across the hangingwall of basin bounding structures (Figure 3.10). The southern boundary of the Bremer Sub-basin is transitional in nature and characterised by a down-stepping series of fault blocks, which are onlapped by strata from the Recherche Sub-basin (Figure 3.11).

The Bremer Sub-basin comprises five main half graben bounded to the north by the Arpenteur, Colonna, Athena, Zephyr and Leata faults[1] (Figure 3.8). The Arpenteur and Colonna depocentres form the western part of the Bremer Sub-basin. These western depocentres are characterised by significant rift-flank uplift and truncation of northerly dipping strata beneath an angular Turonian unconformity (Figure 3.11). Maximum sediment thickness ranges from 5 km in the Arpenteur depocentre, to 4 km in the Colonna depocentre (Figure 3.7). The Arpenteur Fault has a particularly arcuate geometry, striking ENE in the west to SE on its eastern tip (Figure 3.8). Archaean shear zones present in the Yilgarn Craton and Albany-Fraser Orogen also strike SE (Figure 3.1), and show evidence of reactivation during Permian and Jurassic rifting in the Perth Basin (Dentith et al., 1994). It is possible that these Archaean shear zones reactivated as sinistral strike-slip faults during rifting in the Bremer Sub-basin, producing the very arcuate geometry of the Arpenteur Fault.

Anticline structures have developed in the hanging wall blocks of the Arpenteur and Colonna faults (Figures 3.12 and 3.13). Strata from Bremer 4 form a narrow divergent wedge over the anticlines that thicken towards the Arpenteur and Colonna faults. The anticlines appear to accommodate changes in the geometry of the rift border faults, and formed during a period of extension in the Valanginian–Aptian. The Kepler Fault System (Figure 3.11) is a major intra-basin fault system located basinward of the Arpenteur depocentre, which is characterised by a series of planar fault blocks. Previously, Stagg et al. (1990) have also referred to the Kepler Fault System as the “lower slope fault zone”.

Up to 9.5 km of strata were deposited in half graben bounded by the Athena and Zephyr faults (Figure 3.7). The Athena depocentre shows a divergent wedge geometry, with sediments thinning south and pinching-out against the Kingfisher basement high (Figures 3.8 and 3.14). A series of ENE striking, SSE dipping faults are located within the Athena depocentre (Figures 3.8 and 3.15). The Lenita Fault is the main structure within this intra-basin fault system. Strata from both the Bremer 1 unit and the Bremer 4 unit thicken across the Lenita Fault, indicating an origin during Jurassic extension, and subsequent fault reactivation during the Valanginian–Aptian (Figure 3.15). A large roll-over anticline structure formed in the hanging wall of the Lenita Fault during this Valanginian–Aptian extensional phase (Figure 3.16).

The Zephyr depocentre is characterised by an intra-basin graben structure, in which the Bremer 4 unit thickens across the southerly dipping Harlequin Fault, and a series of ESE striking antithetic faults (Figure 3.17). Previously, Stagg and Willcox (1991) interpreted this structure as a wrench anticline. However, we interpret this as part of a more regional structral trend, the Lenita-Harlequin trend, which originated during extension in the Valanginian–Aptian. South of the Zephyr depocentre is a series of ENE and E striking intra-basin fault blocks that step down toward the Recherche Sub-basin (Figure 3.17).

[1] Structural elements are named after historic shipwrecks in the region.

The Leata depocentre in the eastern Bremer Sub-basin (Figure 3.8) shows a similar structural architecture as the Arpenteur and Colonna depocentres. Strata within the Leata depocentre dip to the north, and are truncated on the half-graben hinge by a Turonian unconformity (Figure 3.18). This is a relatively small depocentre, containing a maximum sediment thickness of ~4 km (Figure 3.7). However, strata also dip west towards the deeper Zephyr depocentre, providing potential hydrocarbon migration pathways from this adjacent source kitchen area. A large ramp-flat anticline structure is located in the hanging wall block of the Leata Fault, which formed during the Valanginian–Aptian extensional phase (Figure 3.19). The Eclipse Fault System is a major ENE trending intra-basin fault system located basinward of the Leata depocentre, which is characterised by a series of planar south and north dipping fault blocks that step down toward the Recherche Sub-basin.

STRUCTURAL EVOLUTION

Jurassic Extension

The Bremer Sub-basin was initiated in the Middle–Late Jurassic during rifting between Australia and Antarctica. This phase of upper crustal extension produced at least 5 half graben bounded by southerly dipping, arcuate, *en echelon* normal faults (Figure 3.20). These bounding faults are soft-linked by relay ramps that deepen to the east, and were probably pathways for sediment transport into the half graben (Figure 3.21). Sediment fill from this Jurassic phase of extension is equivalent to the Bremer 1 unit. These syn-rift strata diverge into the rift border faults where the bulk of sedimentation was accommodated, and converge against the hinge side of the half graben (Figure 3.22). Syn-rift strata reach a maximum thickness of 2.7 s two-way time (~ 4.5 km) in half graben adjacent to the Athena and Zephyr faults.

Late Jurassic–Early Cretaceous Thermal Subsidence

A period of post-rift thermal subsidence occurred during the Tithonian–early Valanginian, and was characterised by diminished faulting and relatively uniform sedimentation across the sub-basin (Figures 3.18 and 3.23). This phase of thermal subsidence is represented by the Bremer 2 and Bremer 3 units. These post-rift strata generally form a relatively continuous sheet-like fill across the sub-basin. However, sedimentation was locally concentrated over previous rift depocentres adjacent to the Athena and Zephyr faults, where post-rift strata reach a combined maximum thickness of up to 2.4 s two-way time (~ 4.4 km; Figure 3.23).

The northerly extent of post-rift deposition is constrained by the rift border faults. However, post-rift strata do not thicken into these faults, indicating that little or no upper crustal extension occurred at this time. Easterly dipping relay ramps are located between the *en echelon* rift border faults, and probably continued to form sediment transport pathways into the sub-basin.

Valanginian – Aptian Extension

A phase of renewed extension occurred in the Bremer Sub-basin from the Valanginian–Aptian. The initiation of this basin phase correlates with the onset of seafloor-spreading and continental break-up in the Perth Basin on the south-western margin (Veevers et al., 1991). This second phase of extension produced a major intra-basin fault system and depocentre south of the Lenita and Harlequin faults (Figures 3.15, 3.24 and 3.25), and generated large anticlines in the eastern and western parts of the sub-basin (Figures 3.12 and 3.19). A sag-fill geometry formed in some parts of the Athena depocentre (Figure 3.14).

Sedimentation during this extension phase is represented by the Bremer 4 unit, which reaches a maximum thickness of 1.4 seconds two-way time (~2.4 km) in the main intra-basin depocentre located over the Lenita-Harlequin trend (Figure 3.24). Active faulting within the intra-basin fault system produced significant growth of Bremer 4 strata, particularly within the intra-basin graben structure associated with the Harlequin Fault (Figure 3.17). Rotated fault blocks from this Valanginian–Aptian intra-basin fault system are potential hydrocarbon traps in the central part of the sub-basin. Rift border faults generally show diminished activity during this second extension phase. However, the Leata and Arpenteur faults show evidence of some continued extension, with strata from Bremer 4 forming narrow divergent wedges that thin over the crests of anticlinal structures (Figures 3.12, 3.13 and 3.19). Growth of the anticlines was also accompanied by minor uplift. These large anticlinal structures form potential hydrocarbon traps in the western and eastern parts of the sub-basin.

Aptian–Turonian Thermal Subsidence

A period of thermal subsidence and uplift preceding continental break-up occurred from the Aptian–Turonian. This thermal subsidence phase is represented by the Bremer 5 unit. Although some faults in the Zephyr depocentre continued to be active, this thermal subsidence phase is generally characterised by diminished fault activity and a sag-fill sediment geometry across the sub-basin (Figure 3.14). Strata from this basin phase reach a maximum thickness of 0.8 s two-way time (~1 km) in the Athena depocentre (Figure 3.14), which may indicate higher subsidence rates in the central part of the Bremer Sub-basin relative to the eastern and western depocentres.

Turonian Faulting and Uplift

A period of faulting, uplift and erosion occurred in the Bremer Sub-basin during the Turonian. Many faults in the sub-basin were either generated or reactivated during this basin phase (Figures 3.11, 3.16, 3.17 and 3.18). Significant rift-flank uplift also occurred in the western and eastern parts of the sub-basin, producing an angular unconformity that truncates much of the basin fill over the hinge side of half graben (Figures 3.11, 3.13 and 3.18). Elsewhere, the correlative Turonian sequence boundary varies from an erosional unconformity, to a conformable surface (Figures 3.14, 3.17 and 3.25). This period of uplift, erosion and faulting was probably associated with break-up. Continental break-up and emplacement of oceanic crust occurred in the eastern part of the Bight Basin during the Santonian (Sayers et al., 2001; Totterdell and Bradshaw, 2004), about 5 million years after the period of Turonian faulting and uplift in the Bremer Sub-basin.

Post Break-up Thermal Subsidence

Break-up was followed by a phase of passive margin thermal subsidence from the Turonian to present day. During this passive margin phase, a thin carbonate platform was deposited over the Bremer Sub-basin, and extended north of the rift border faults to overlie shallow basement across the modern continental shelf and onshore region (Figure 3.26). This was generally a tectonically inactive period in the sub-basin's evolution. However, the onset of rapid sea-floor spreading in the Middle Eocene resulted in accelerated subsidence and collapse of the shelf margin, producing the present day southerly sloping geometry of the sub-basin (Stagg and Willcox, 1991). In some parts of the Bight Basin, the shelf margin subsided to between 1000 and 2000 m water depth (Norvick and

Smith, 2001). Rapid subsidence and collapse of the continental margin in the Middle Eocene also initiated the formation of sub-marine canyons that incise up to 2 km into the Bremer Sub-basin (Figure 3.27; Exon et al., 2005).

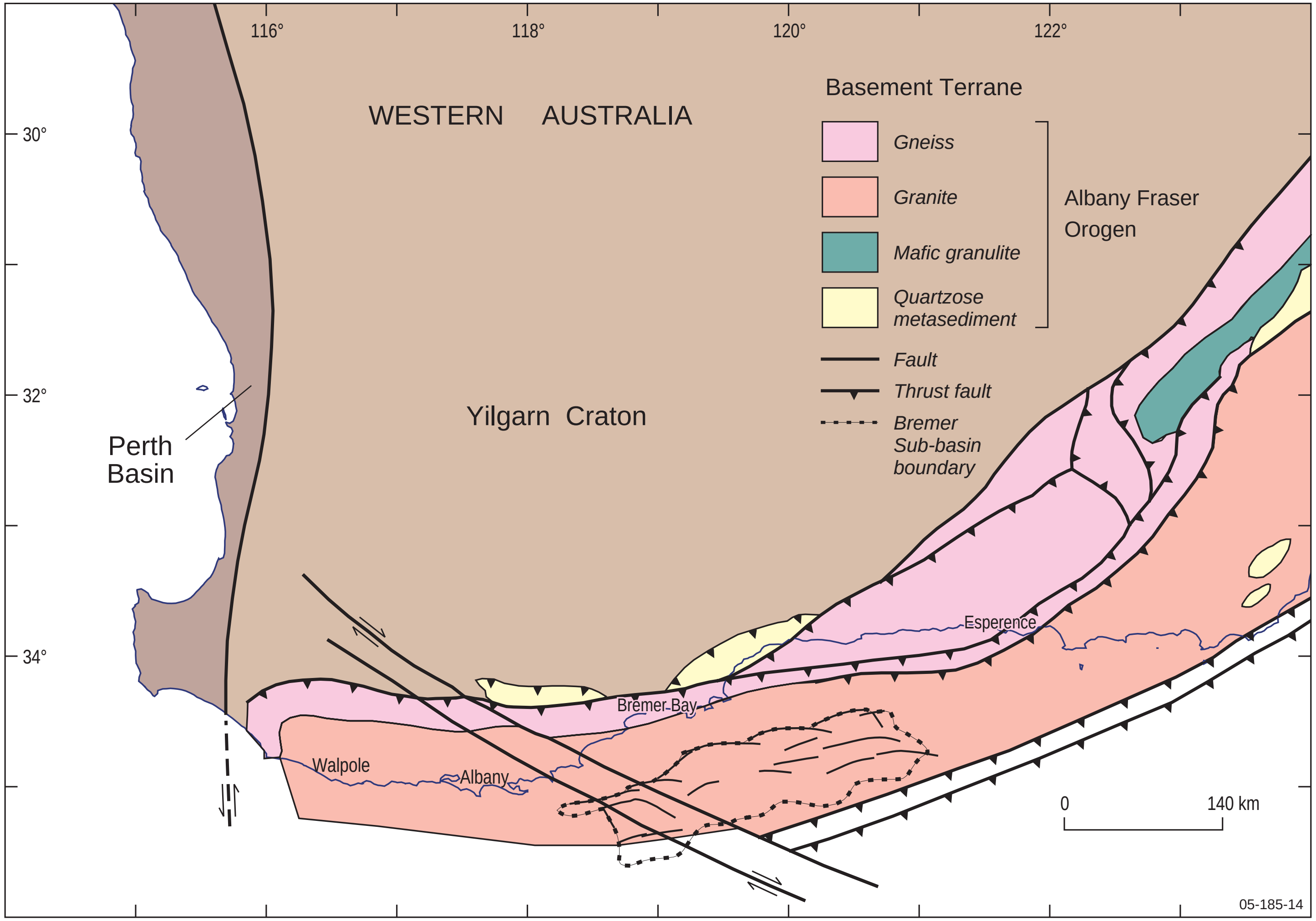


Figure 3.1: Structural terrane map of the Albany-Fraser Orogen (modified after Fitzsimons, 2003). Structures and geology have been extrapolated offshore.

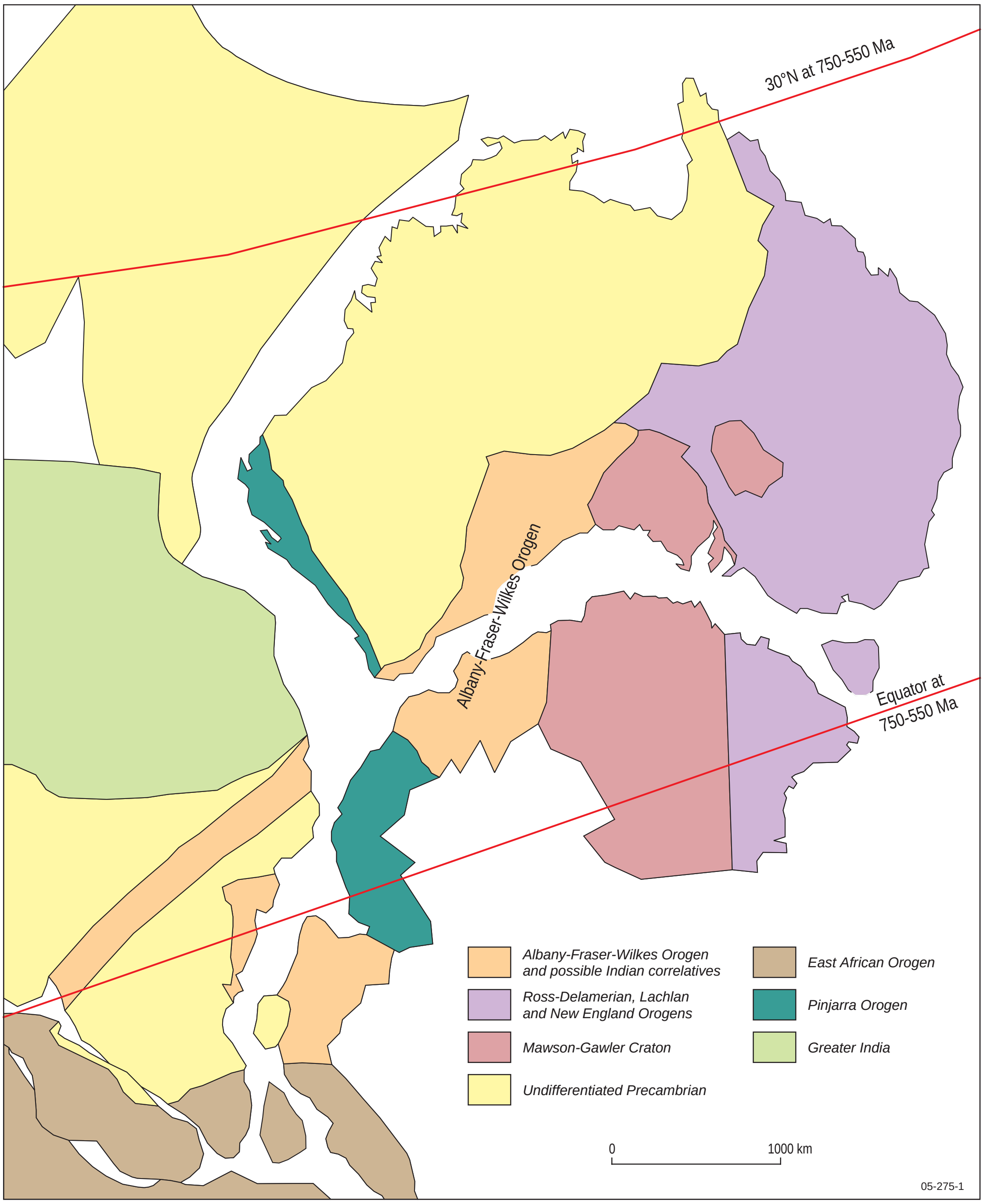


Figure 3.2: Gondwana reconstruction showing late Mesoproterozoic belts (Albany-Fraser-Wilkes Orogen) in Austro-Antarctica (modified after Fitzsimons, 2003).

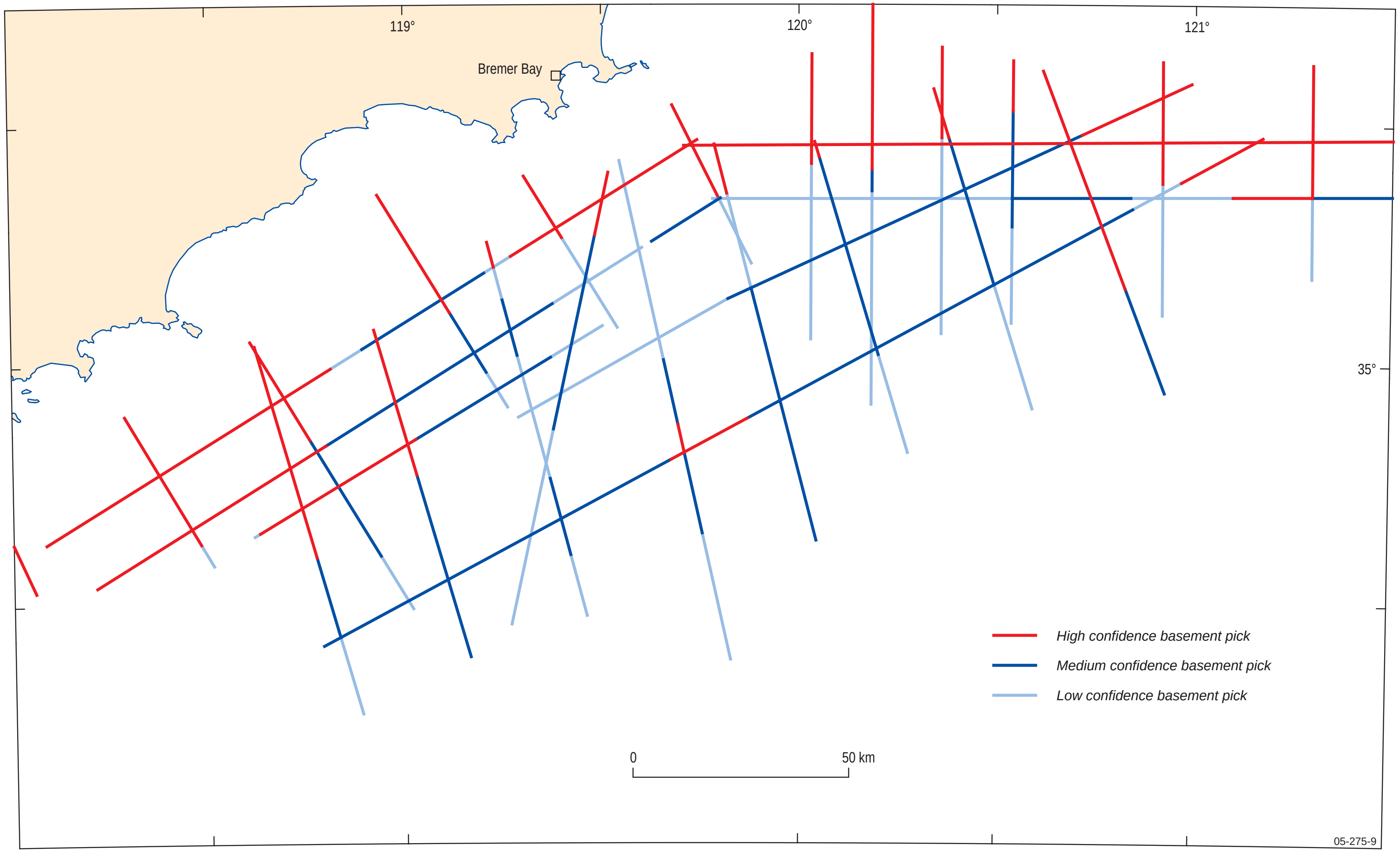


Figure 3.3: Map displaying the confidence of basement interpretations across the sub-basin, from high to low.

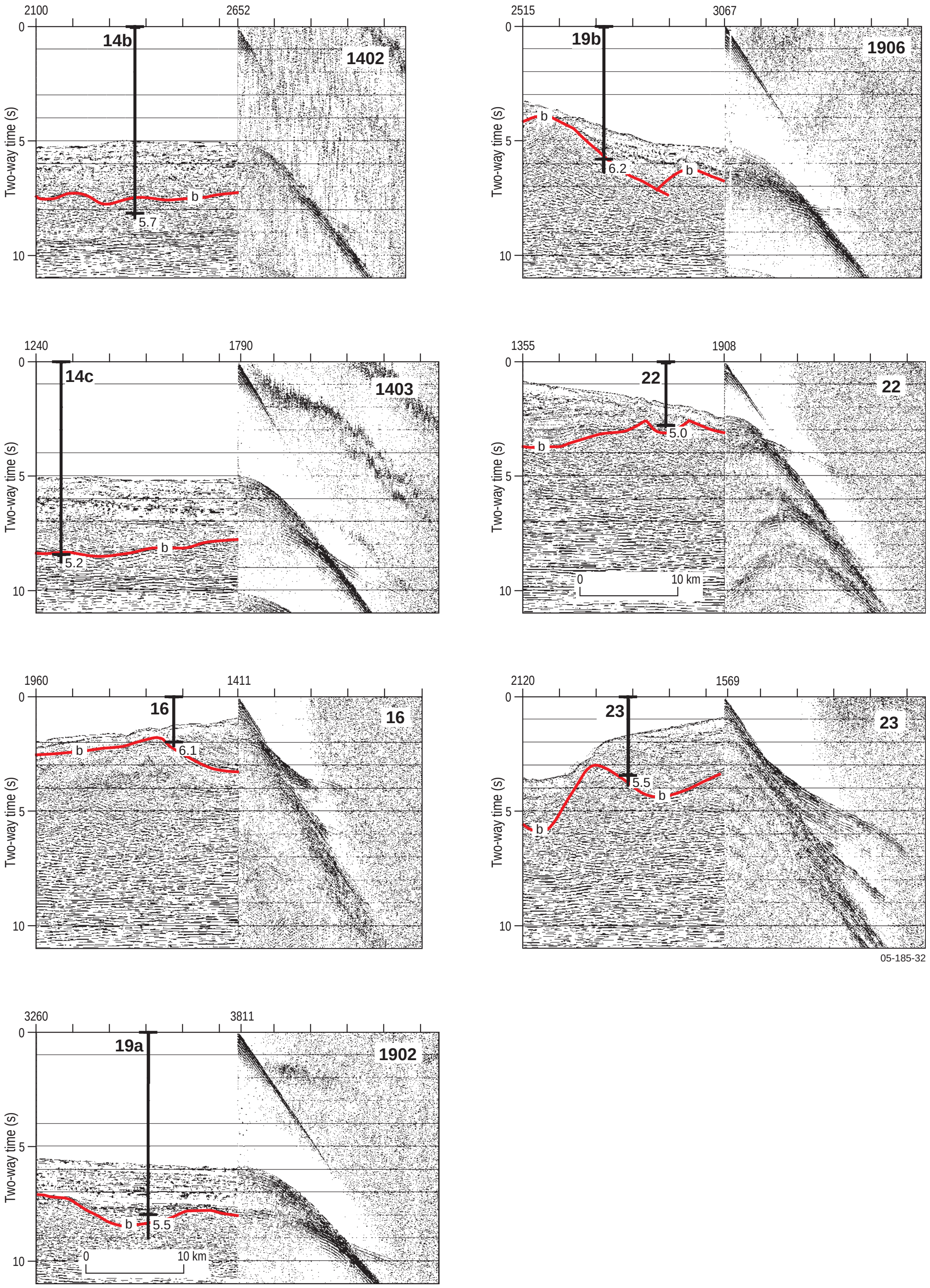


Figure 3.4: One dimensional velocity models depicting rock velocities within or near basement derived from sonobuoy data (right panel), and correlated with basement interpretations on reflection seismic data (left panel; from Goncharov et al., 2005).

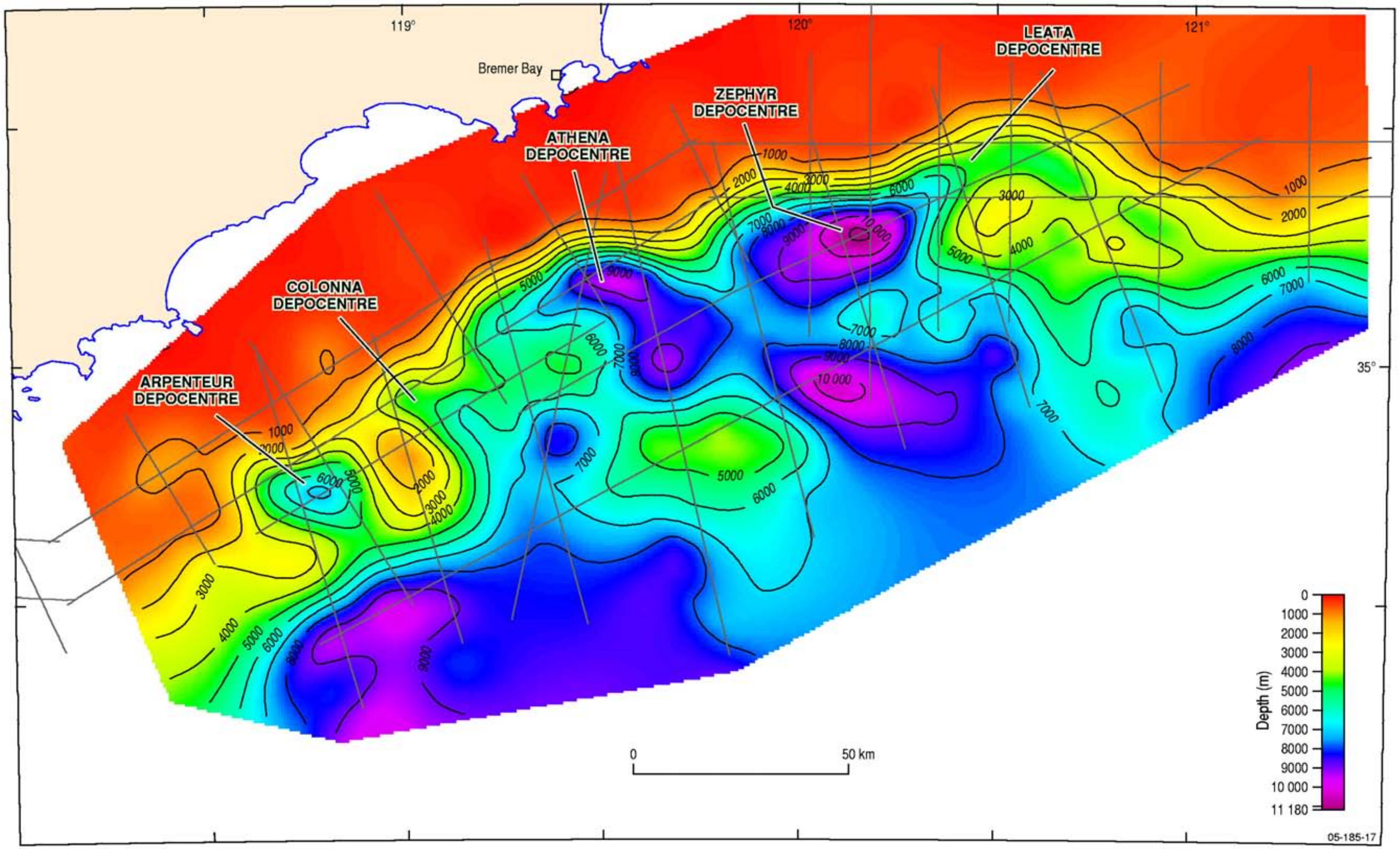


Figure 3.5: Depth to basement map of the Bremer Sub-basin in metres, showing a maximum basement depth of just over 11,000 metres.

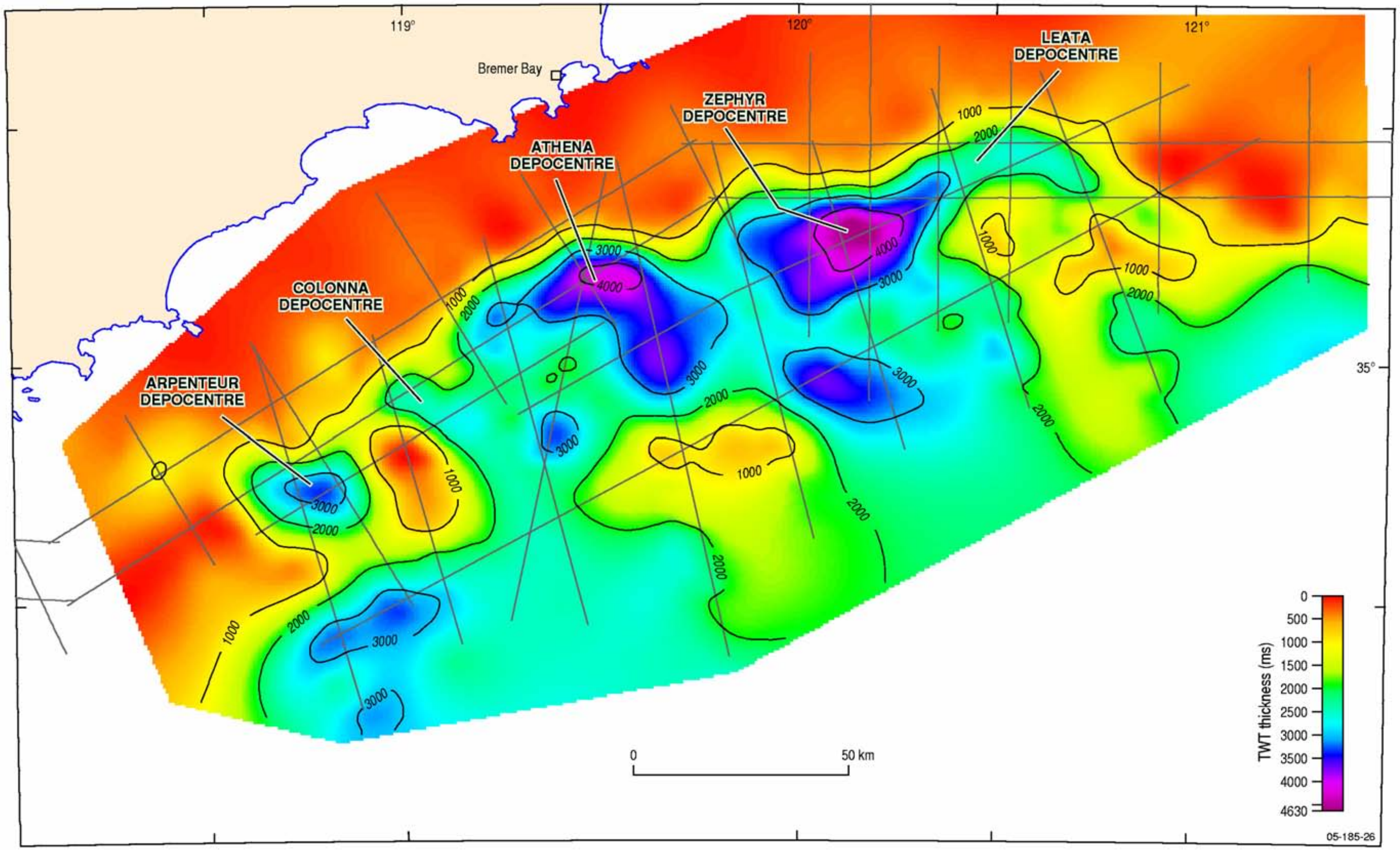


Figure 3.6: Total sediment thickness in two-way time (TWT), showing a maximum thickness of approximately 4.6 seconds.

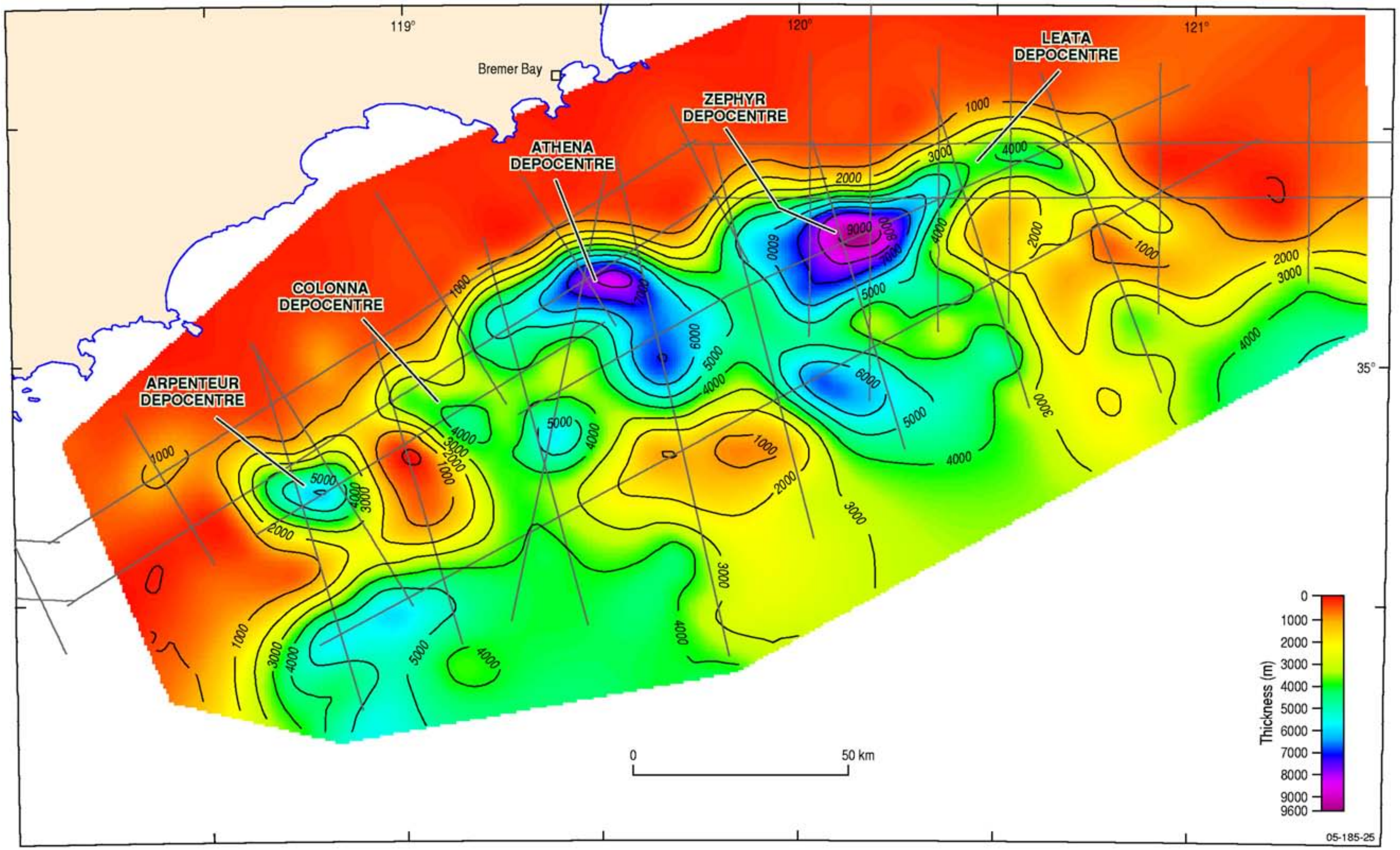


Figure 3.7: Total sediment thickness map in metres, showing a maximum thickness of about 9600 metres.

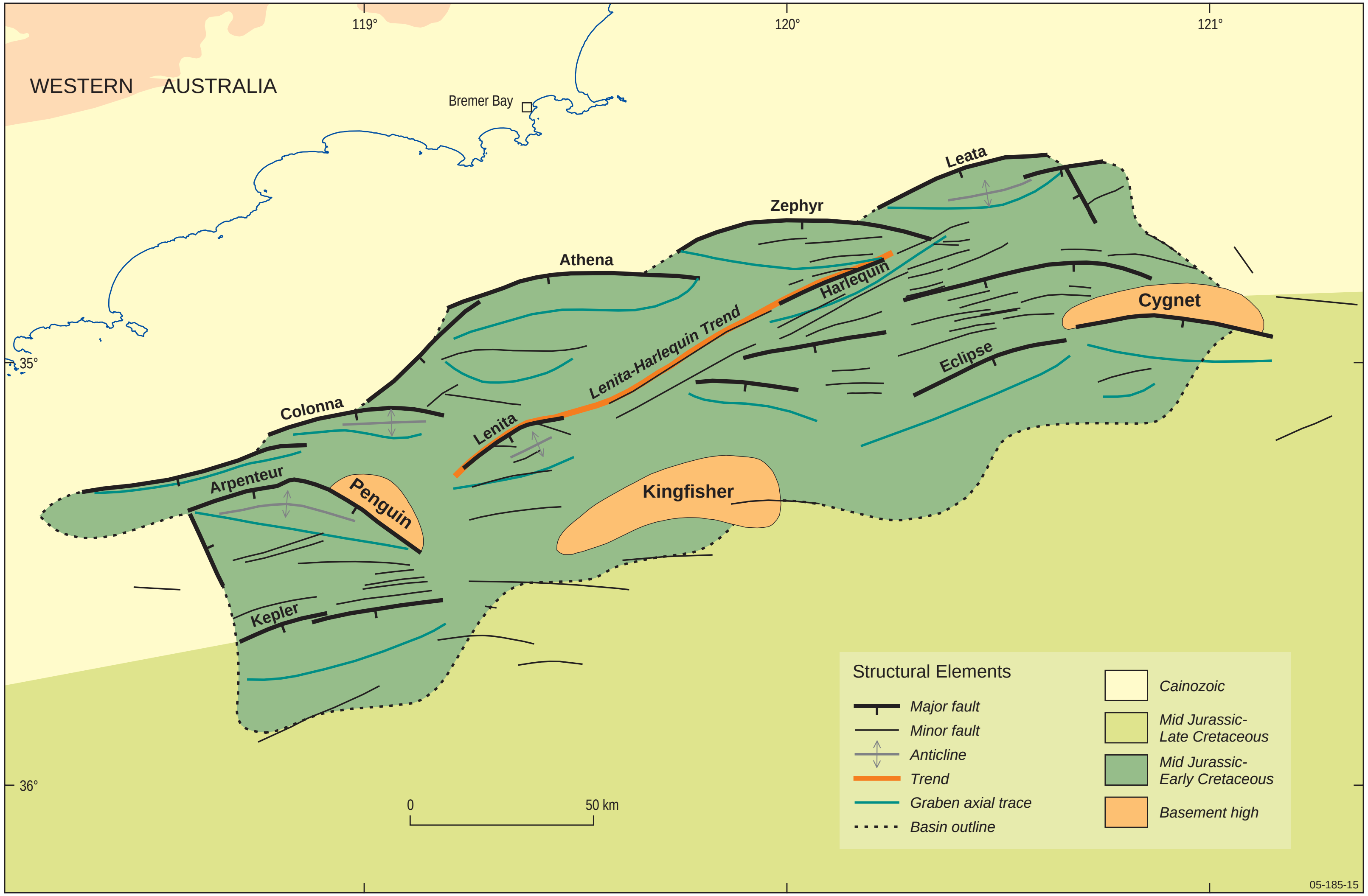


Figure 3.8: Structural elements map for the Bremer Sub-basin.

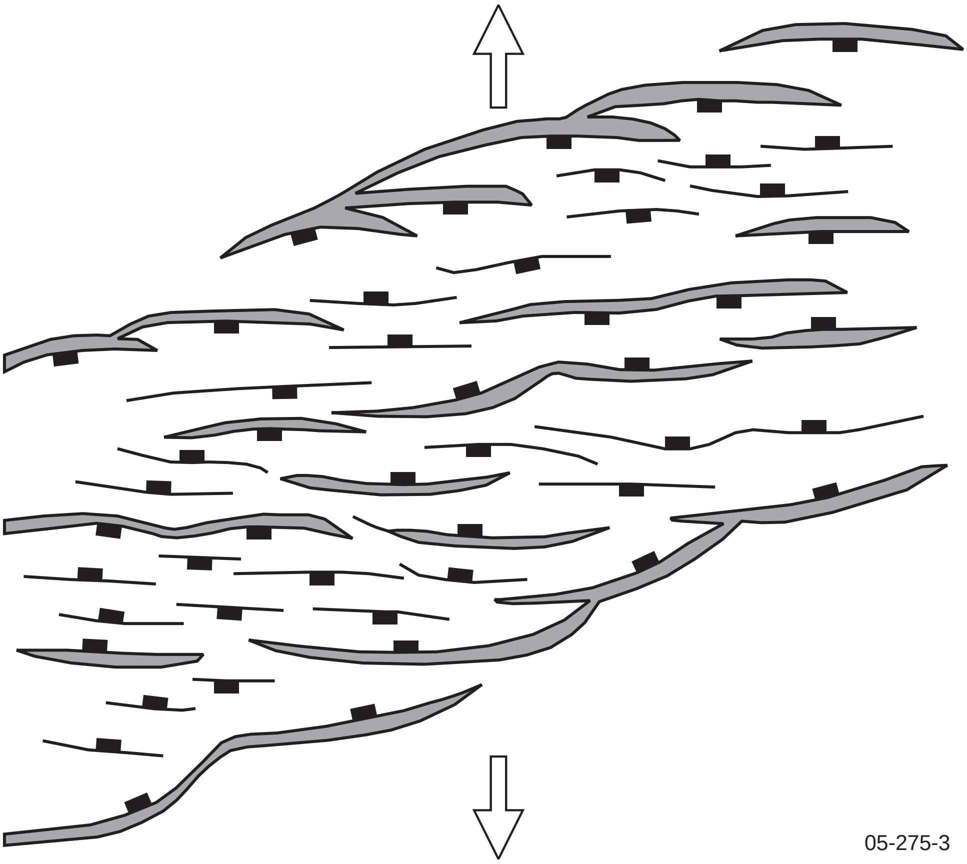


Figure 3.9: Analogue model illustrating an extensional fault system oblique to basement structural trends. Note individual faults have generally formed perpendicular to the extension direction, while the *en echelon* fault sets follow the oblique trend of underlying basement fabric (from McClay et al., 2001).

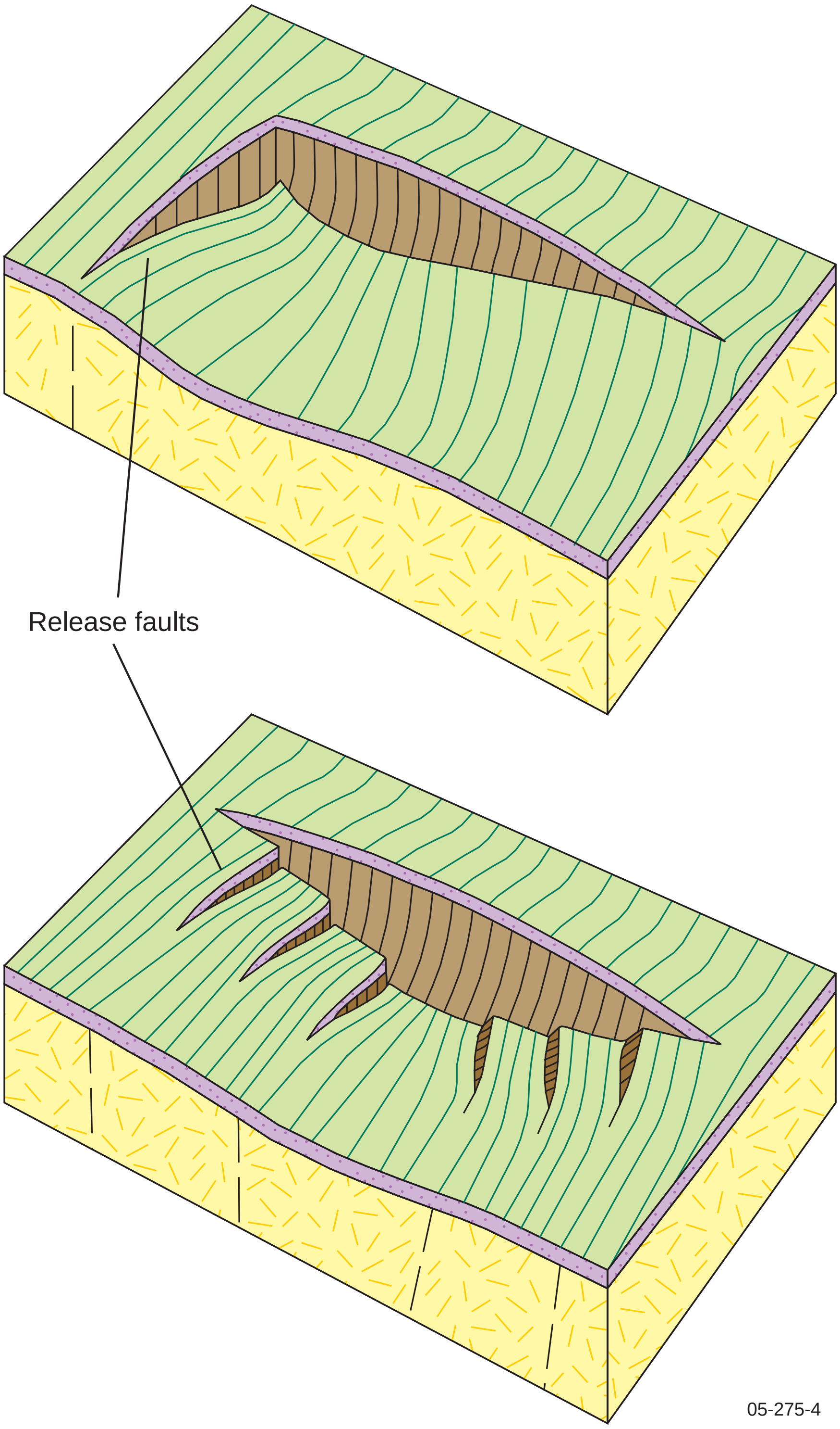


Figure 3.10: Block diagrams of release faults accommodating variable strain across the hanging wall of normal faults (from Destro et al., 2003).

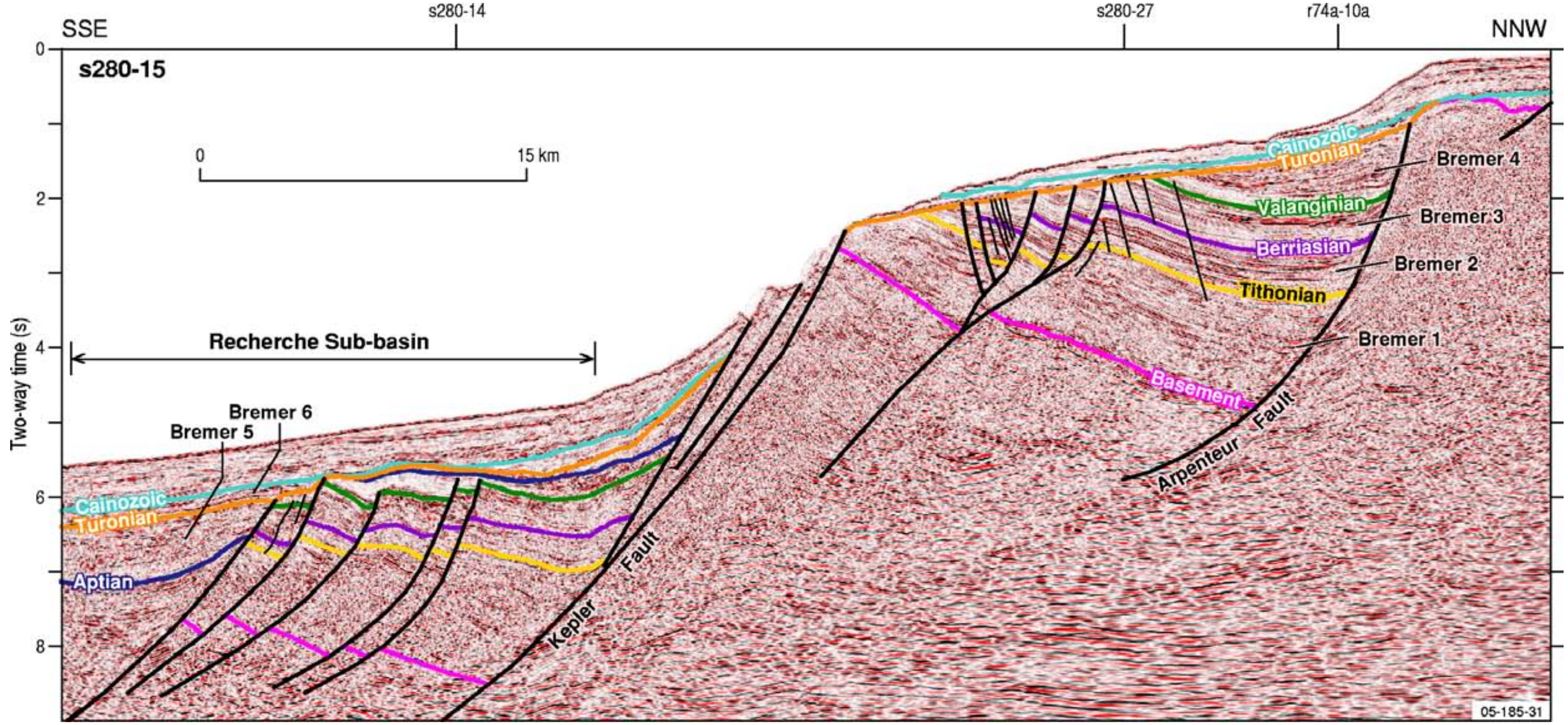


Figure 3.11: Seismic line s280-15 through the Arpenteur depocentre in the west of the sub-basin, showing rift-flank uplift and truncation of steeply-dipping strata beneath a Turonian unconformity.

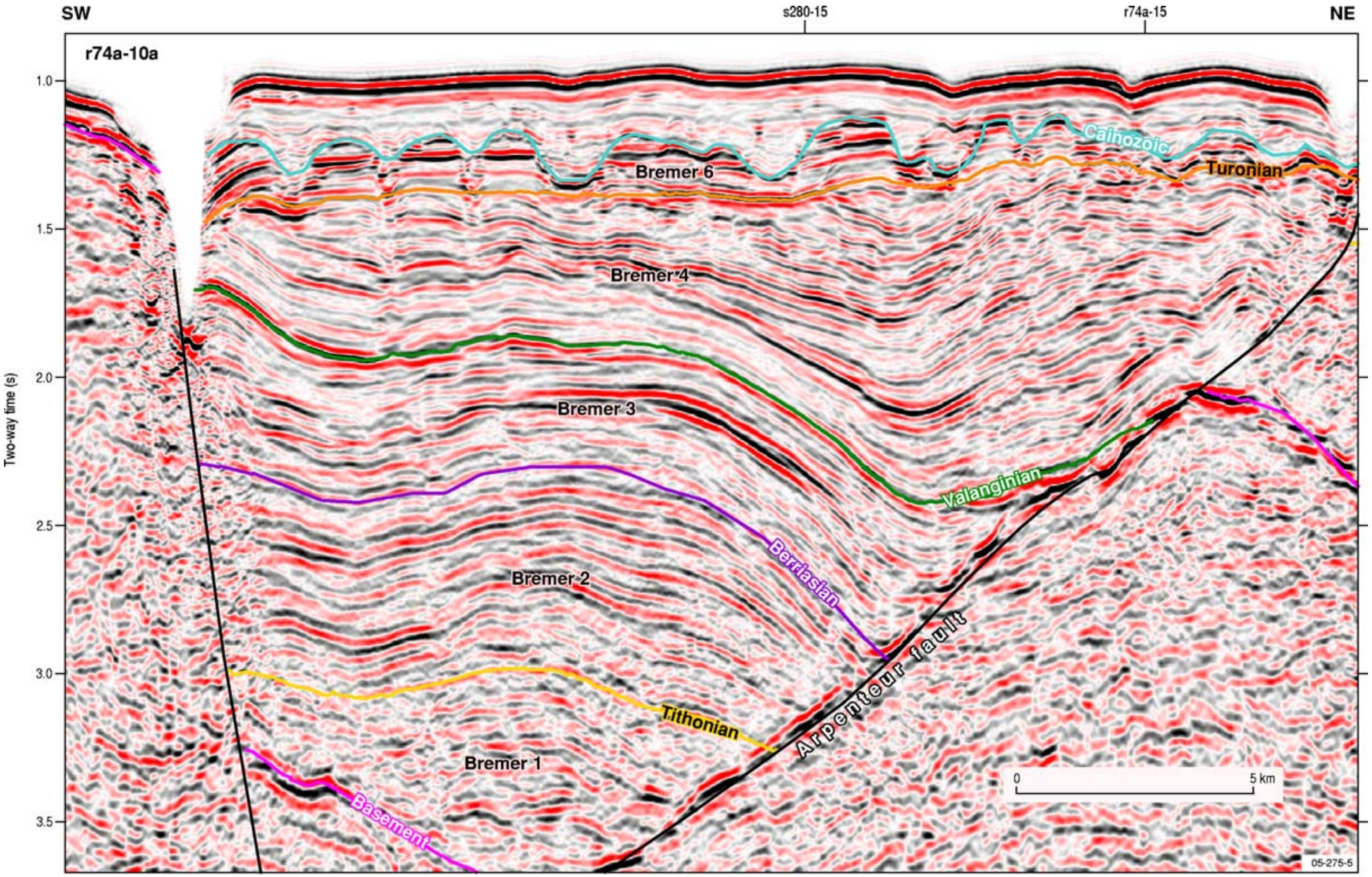


Figure 3.12: Anticline structure in the hanging wall of the Arpenteur Fault, western Bremer Sub-basin.

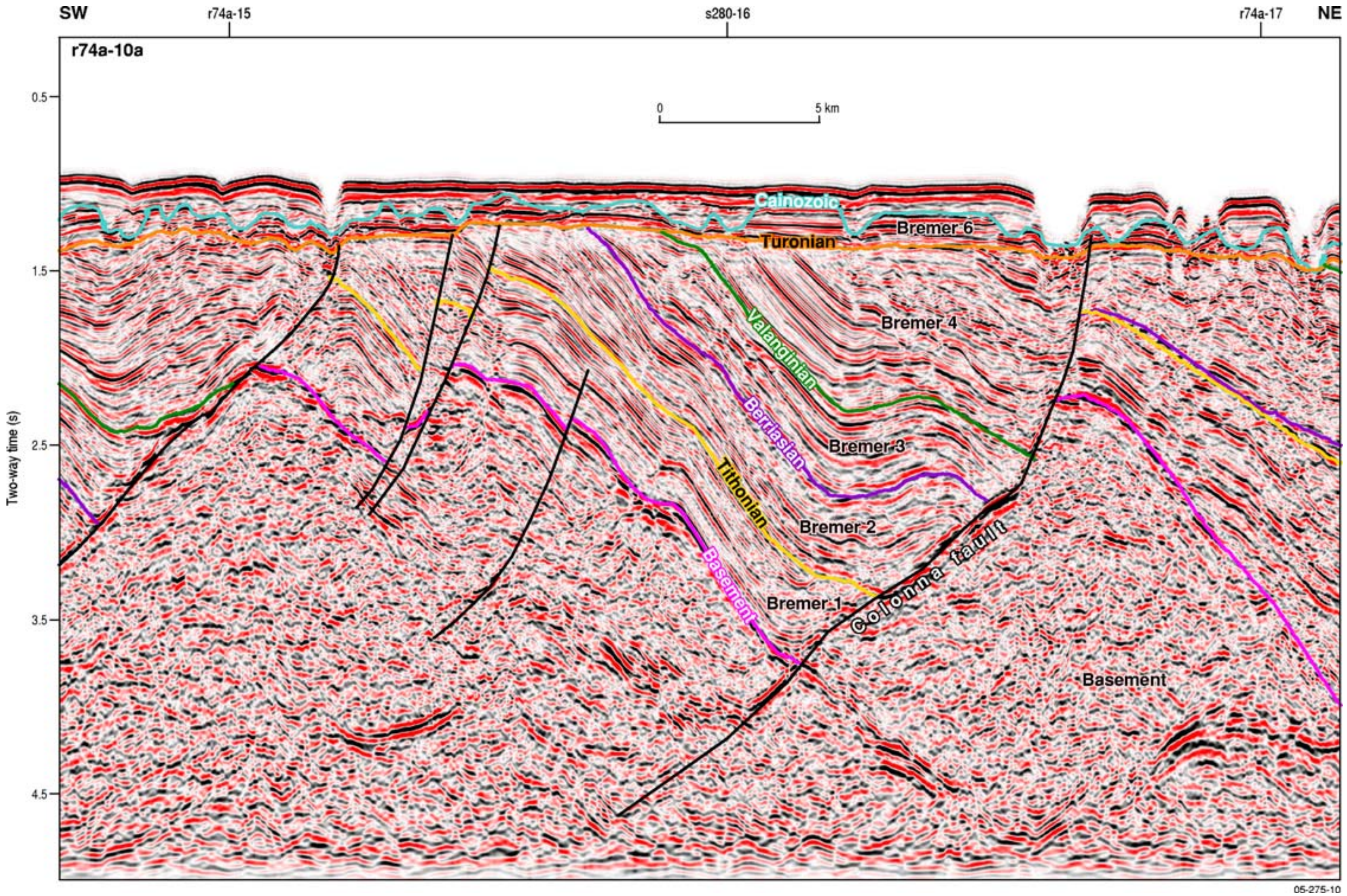


Figure 3.13: Anticline structure in the hanging wall of the Colonna Fault, western Bremer Sub-basin.

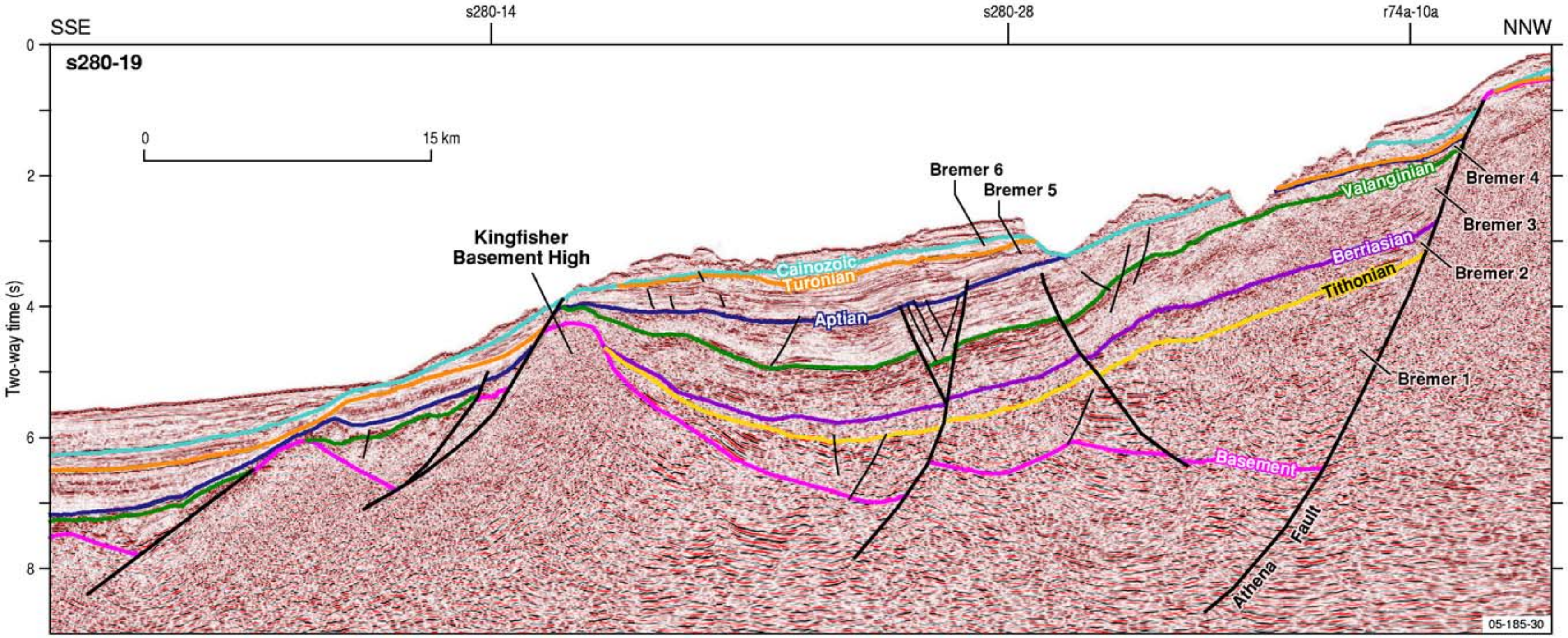


Figure 3.14: Seismic line s280-19, showing an example from the Athena depocentre of divergent wedge geometry in the Jurassic Bremer 1 unit.

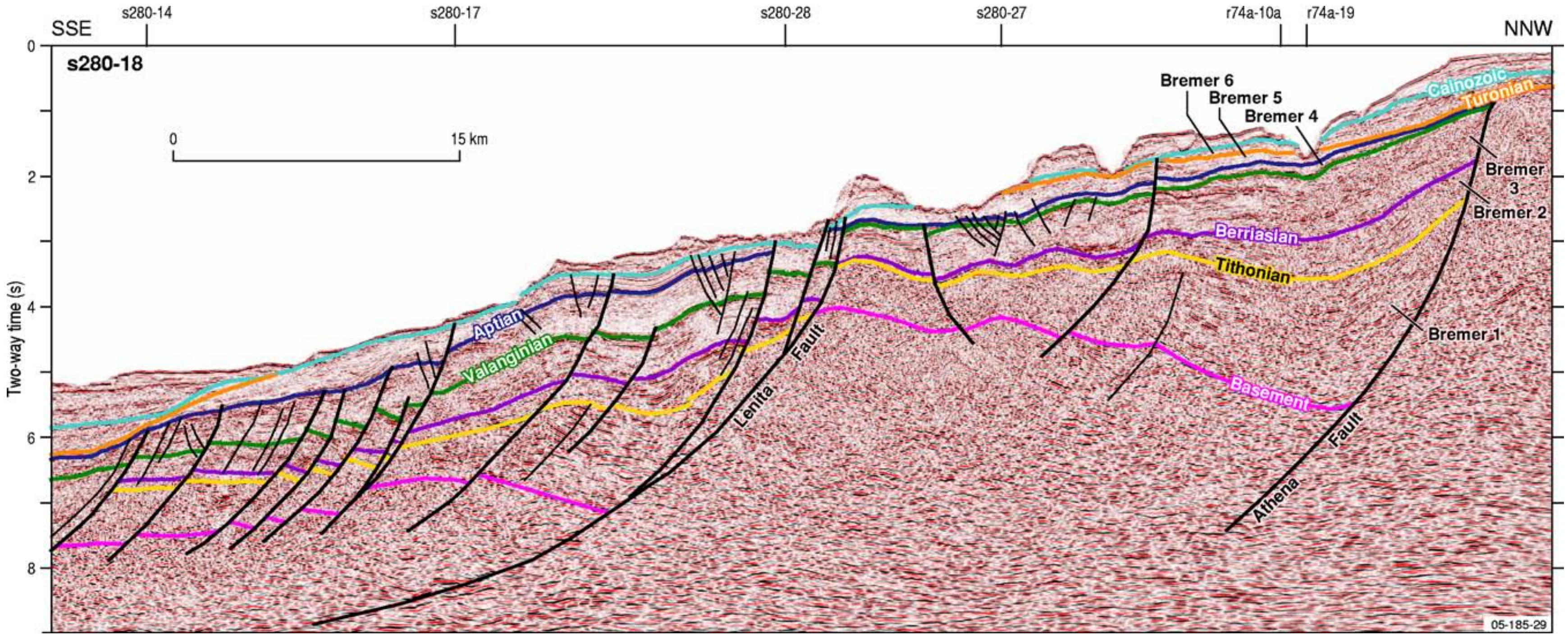


Figure 3.15: Seismic line s280-18 showing the Athena and Lenita faults, and a southerly dipping, down-stepping intra-basin fault system.

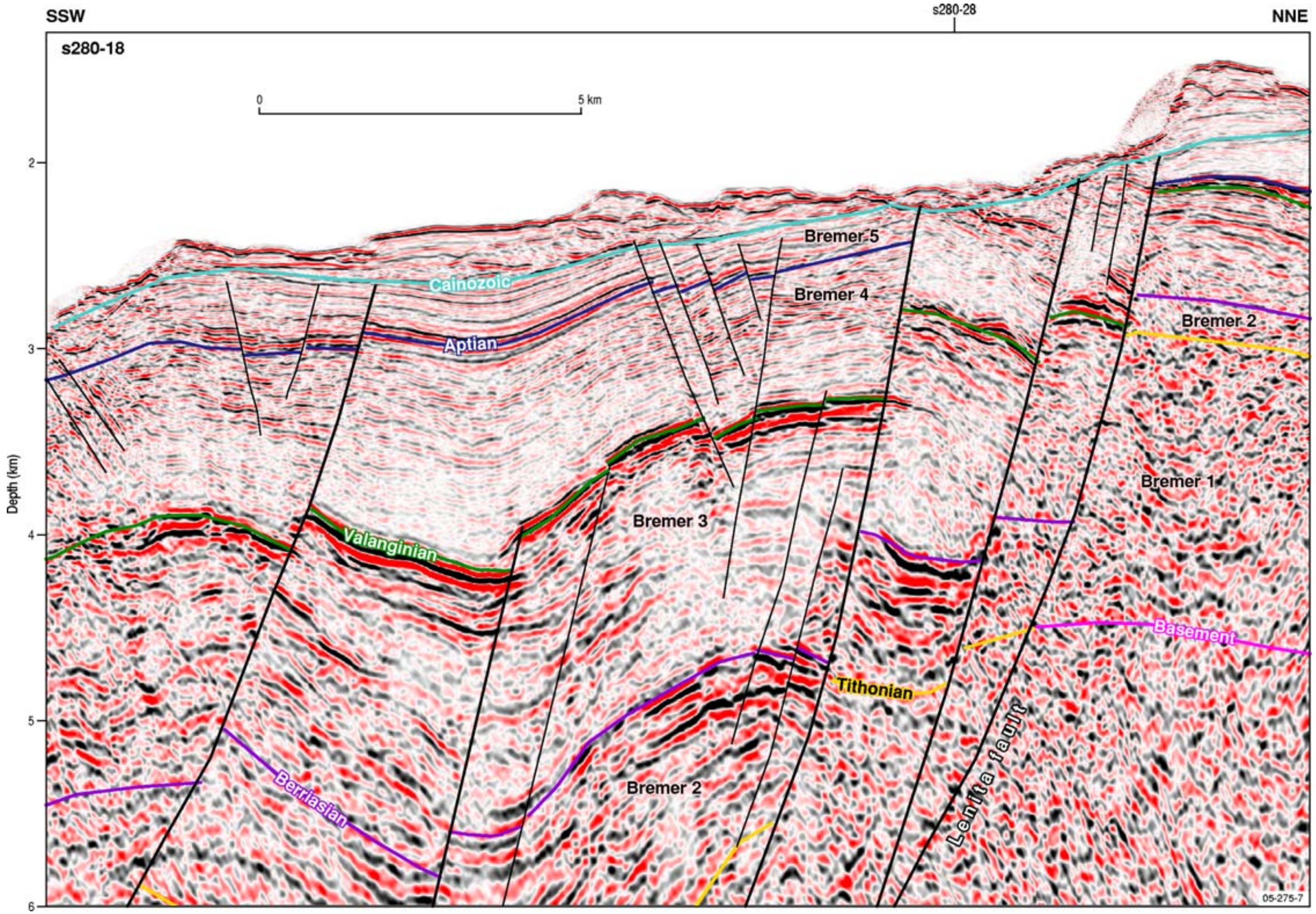


Figure 3.16: Roll-over anticline formed against the Lenita Fault, in the Athena depocentre.

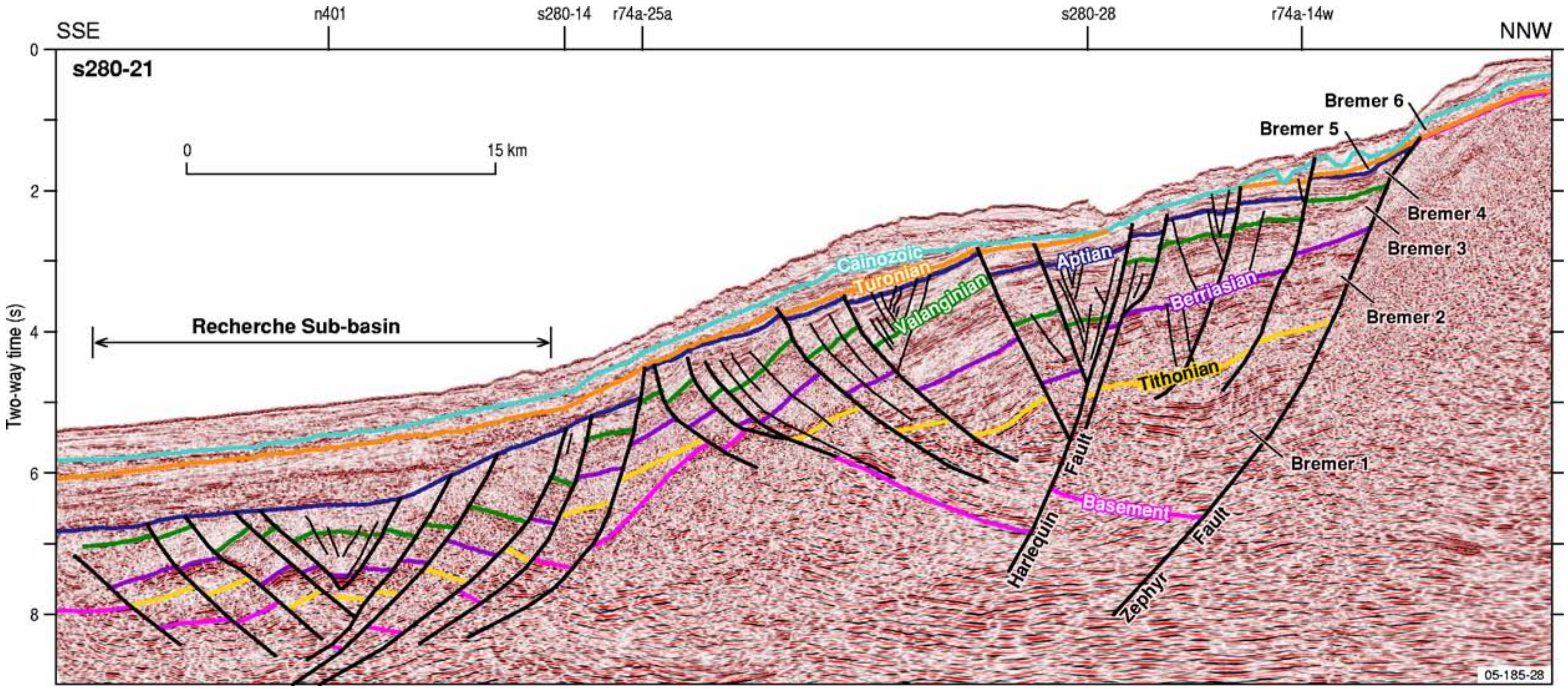


Figure 3.17: Seismic line s280-21 through the Zephyr depocentre showing the intra-basin Harlequin Fault and associated antithetic faults. Growth across these faults in the Valanginian has formed an intra-basin graben structure.

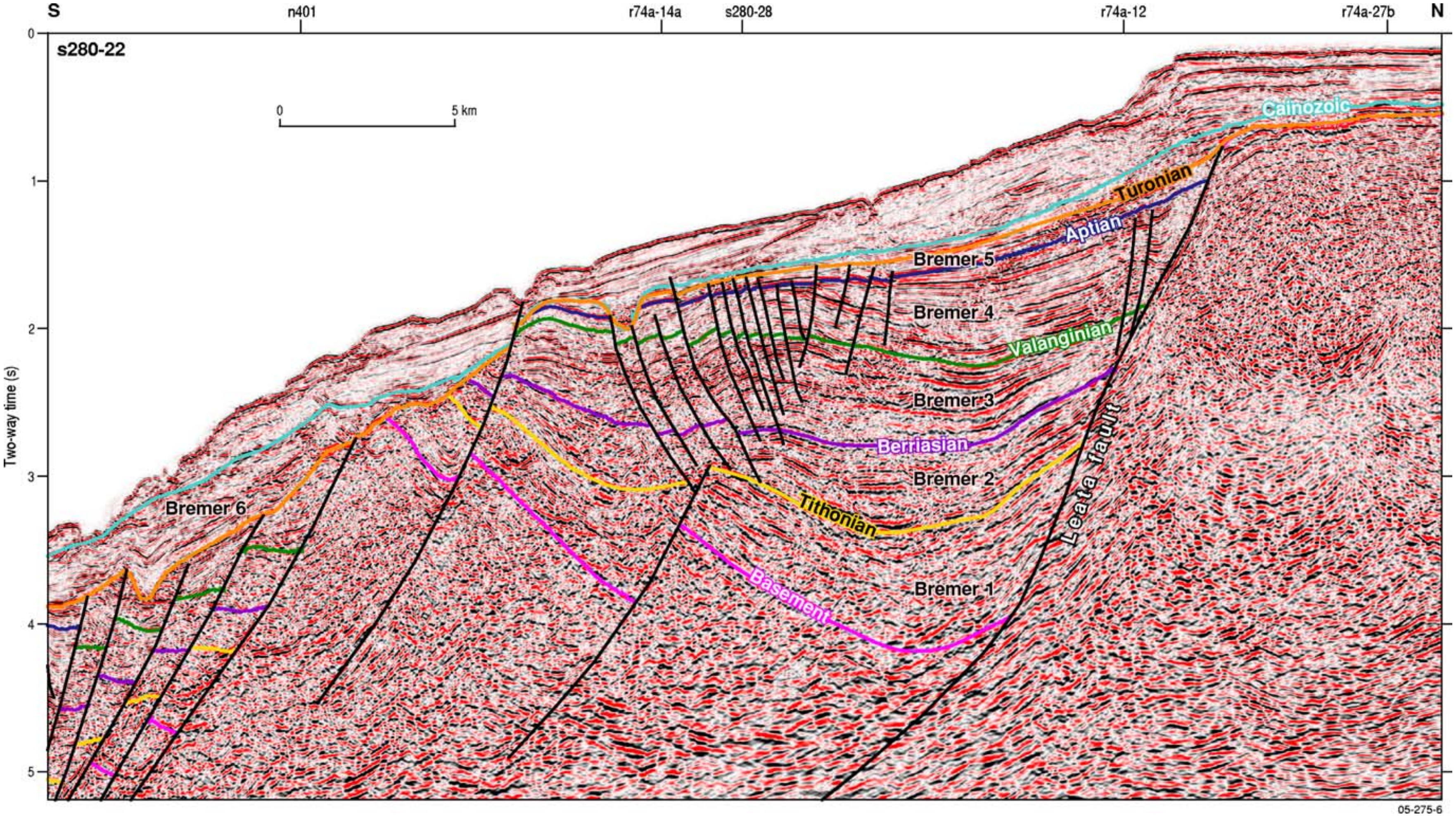


Figure 3.18: Seismic line s280-22 illustrating the sag-fill geometry of the Early Cretaceous post-rift thermal subsidence in the Leata depocentre.

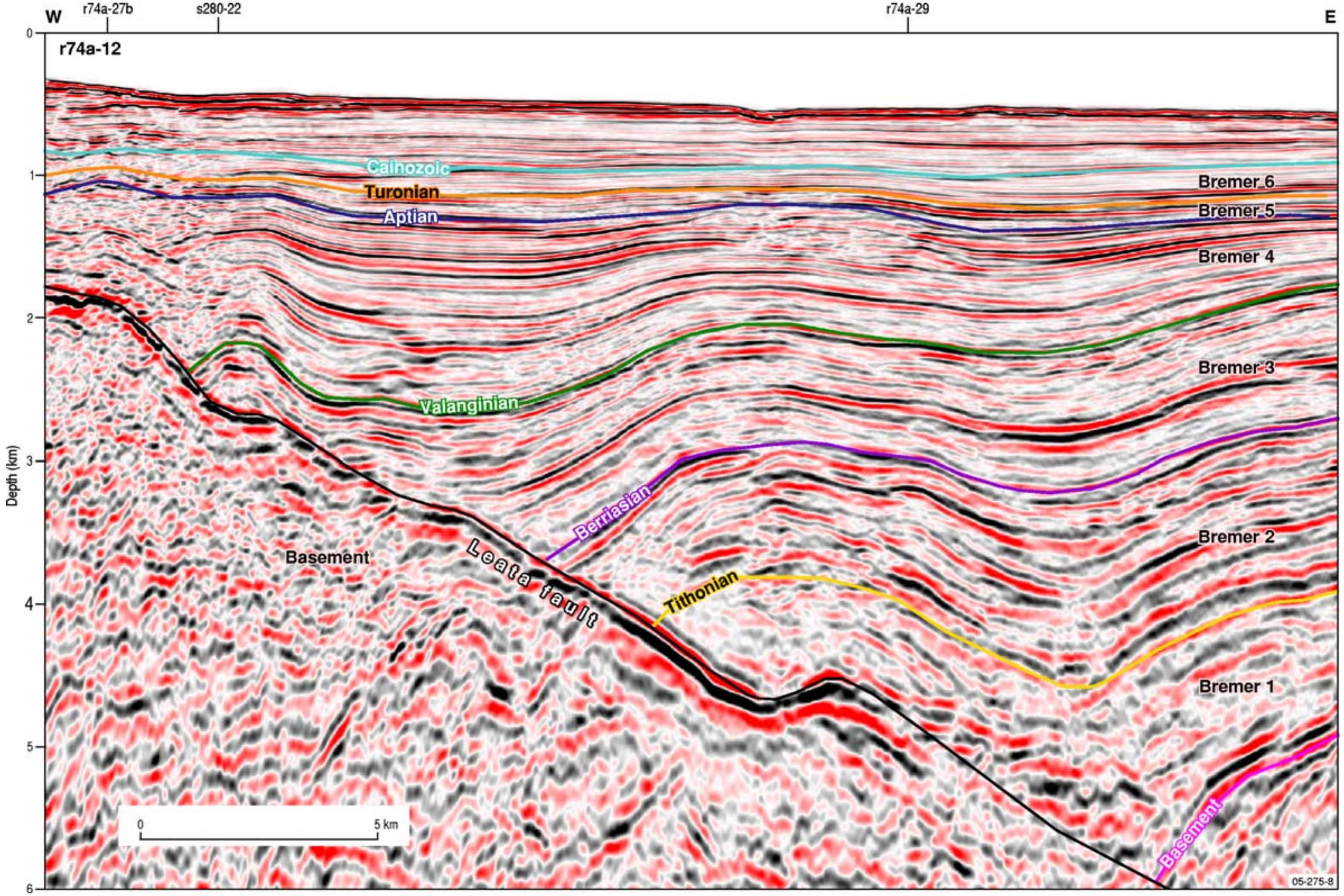


Figure 3.19: Ramp-flat anticline formed against the Leata Fault, eastern Bremer Sub-basin.

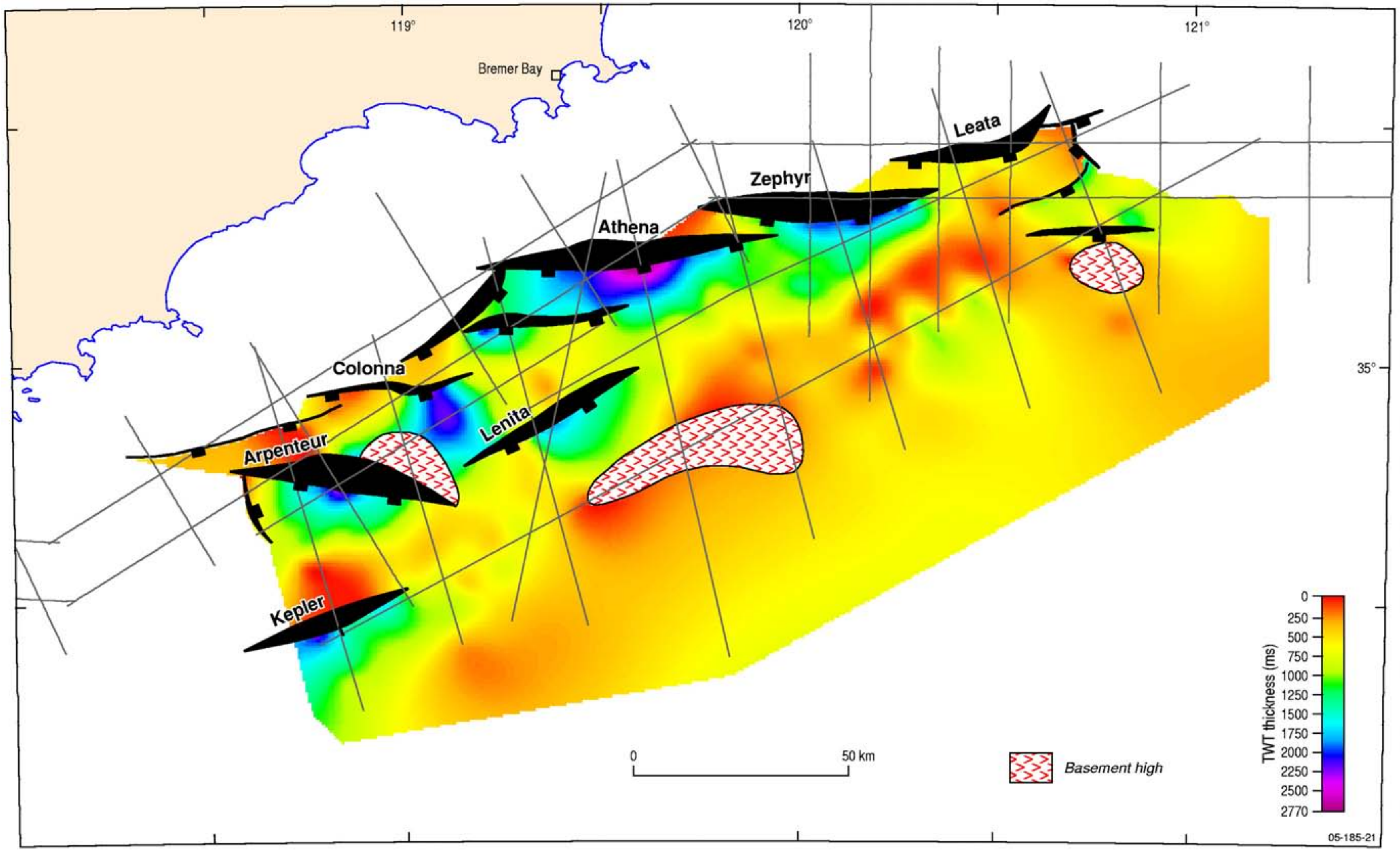


Figure 3.20: Middle-Late Jurassic syn-rift isopach showing a series of depocentres with an ENE trend.

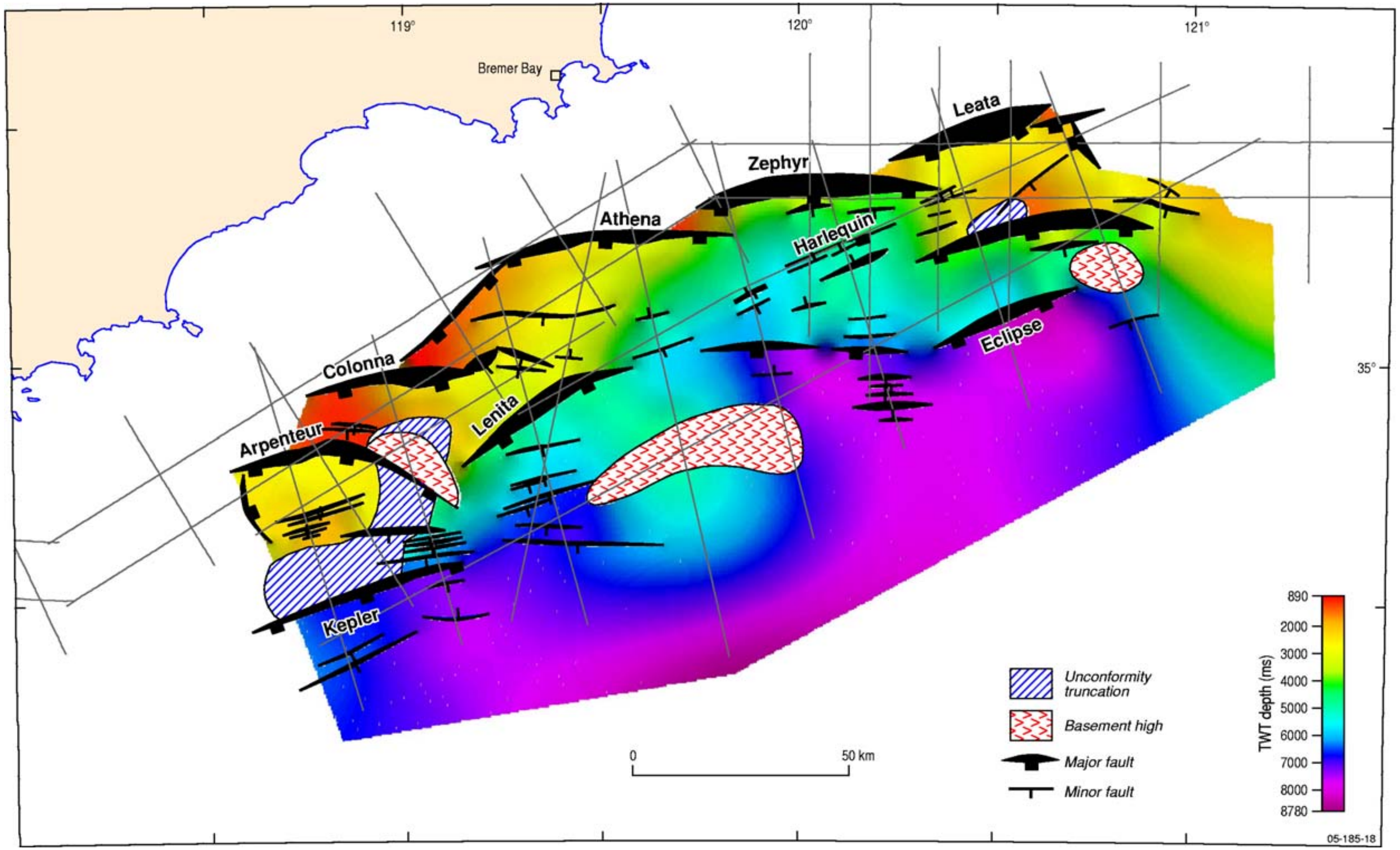


Figure 3.21: Time-structure map of the Tithonian post-rift surface illustrating its present day southerly sloping geometry, and easterly dipping relay ramps soft linking *en echelon* rift border faults.

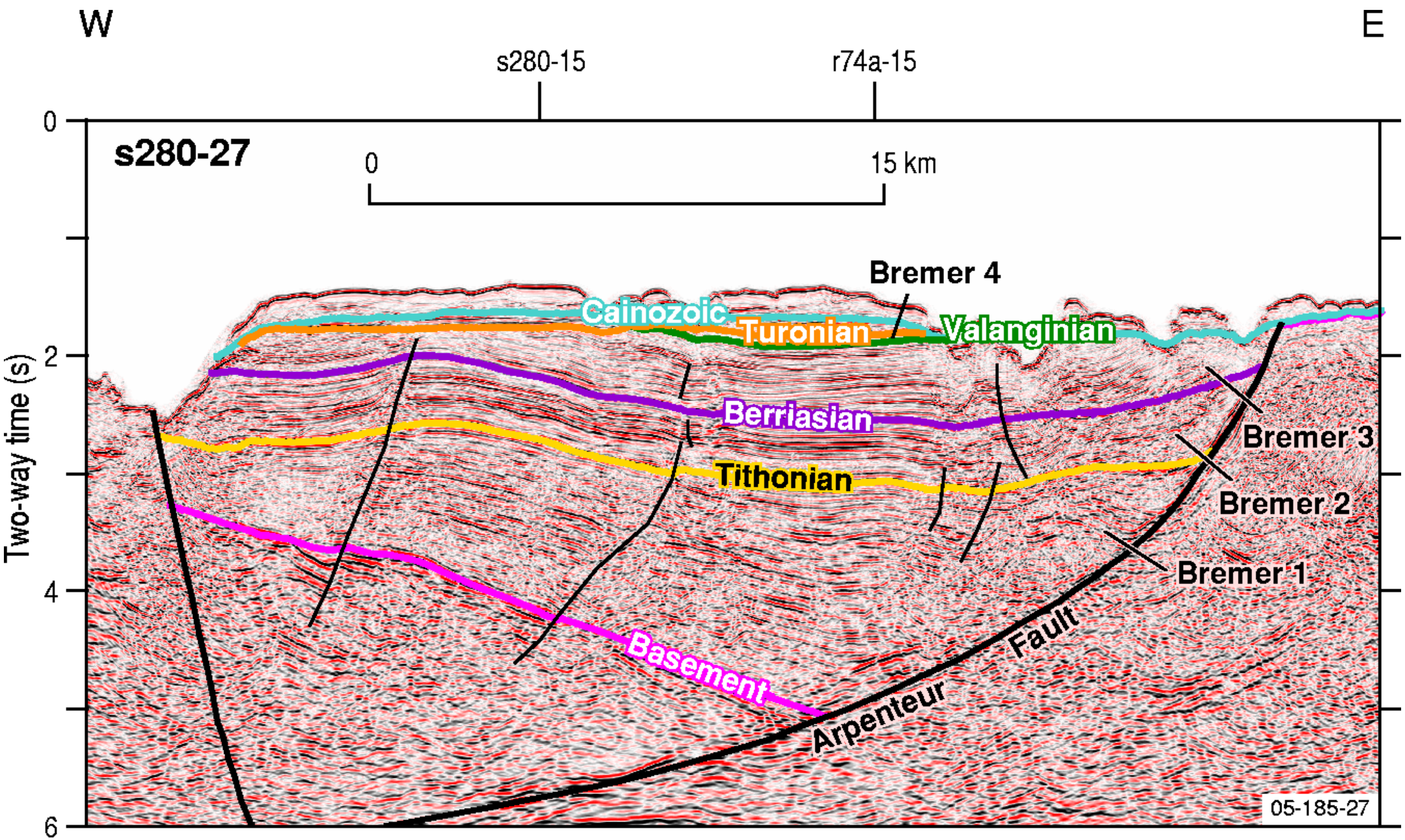


Figure 3.22: Seismic line s280-27 through the Arpenteur depocentre, illustrating the divergent wedge geometry of Middle–Late Jurassic syn-rift sediment fill (Bremer 1).

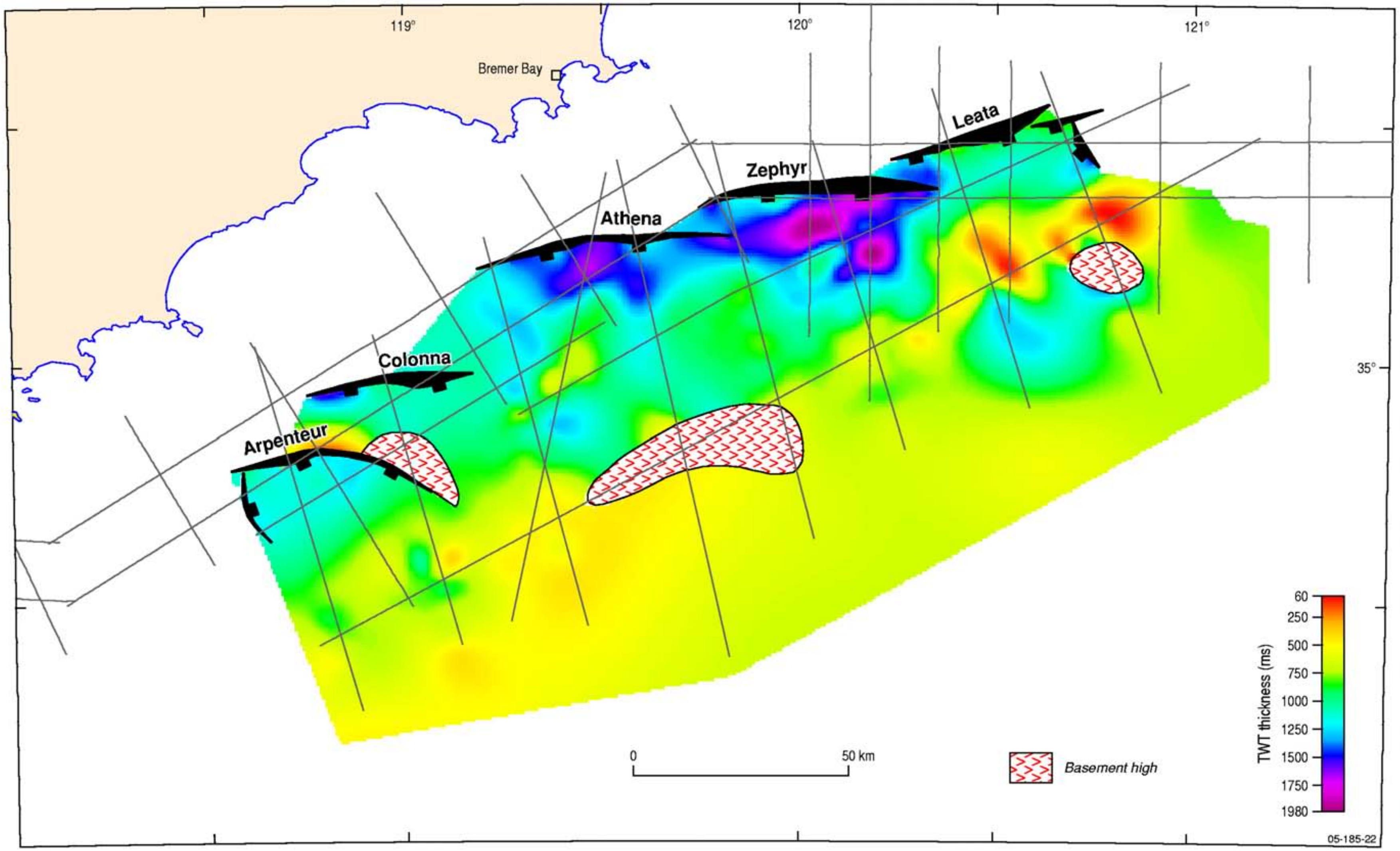


Figure 3.23: Early Cretaceous post-rift isopach. Note the more laterally continuous veneer of sediment fill compared to the syn-rift isopach (figure 3.20).

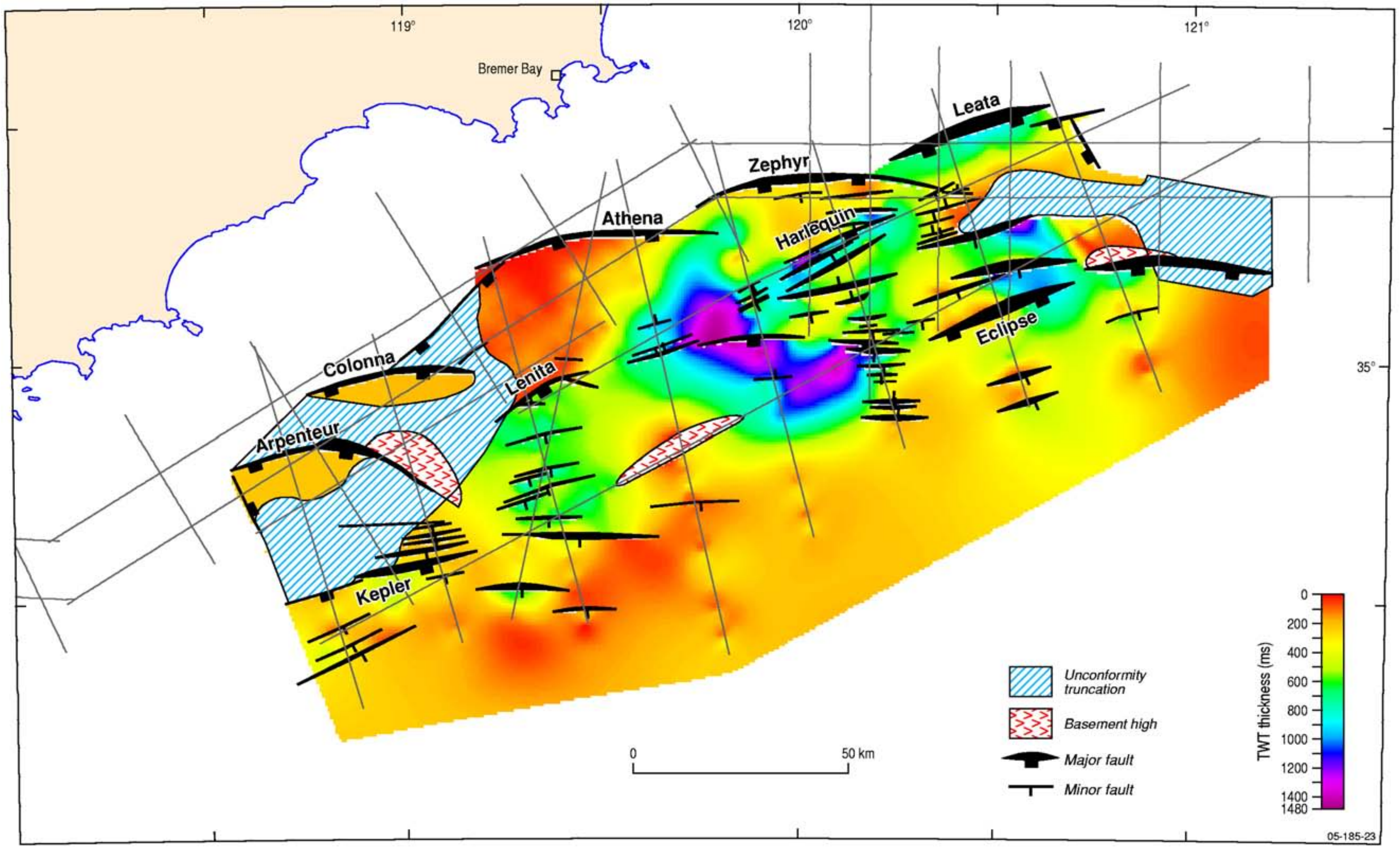


Figure 3.24: Isopach map for the Valanginian–Aptian extension phase. Note the intra-basin depocentre with the bulk of sediment thickening occurring basinward of the rift border faults.

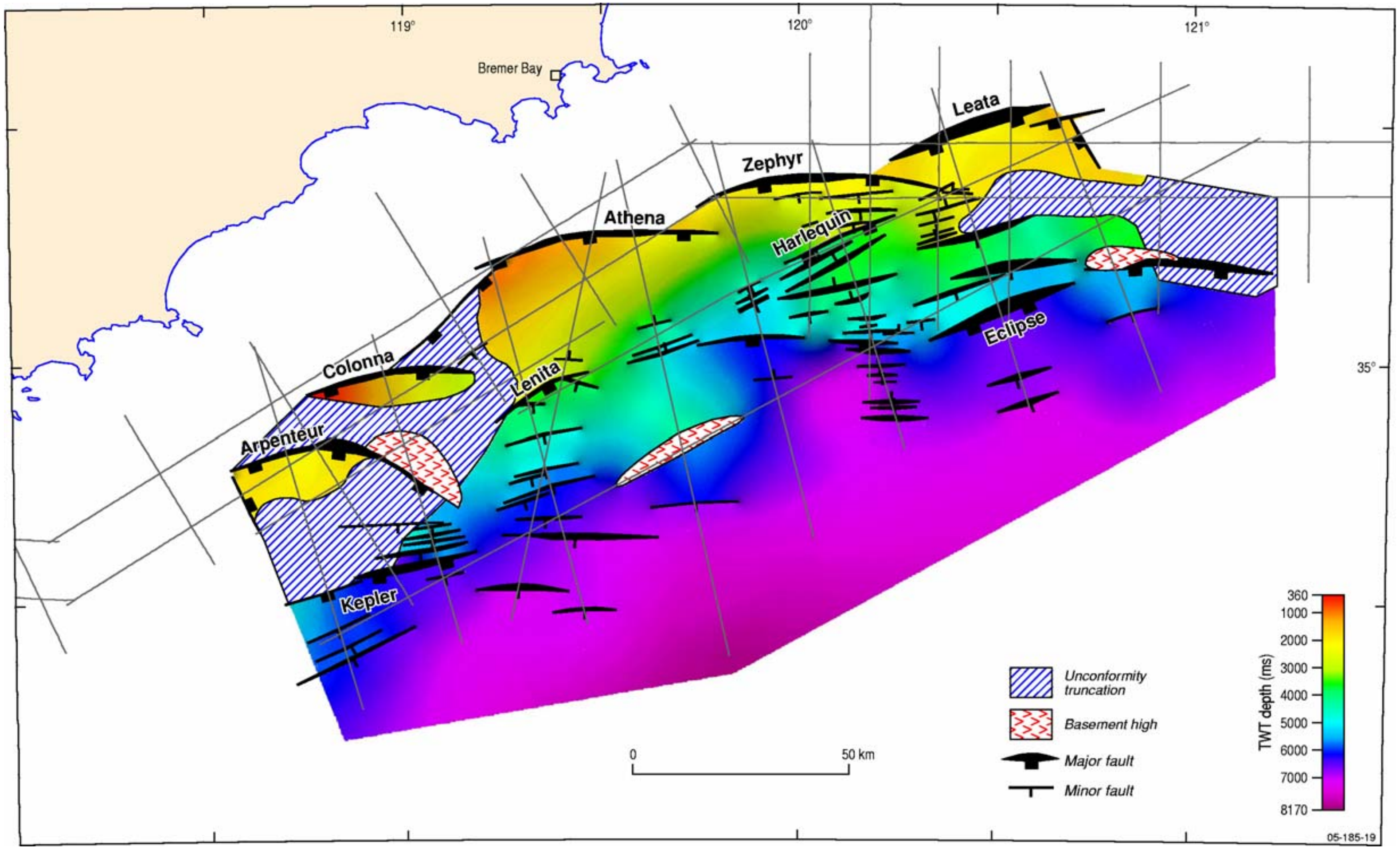


Figure 3.25: Time-structure map of the Valanginian surface illustrating its southerly-sloping geometry, and a significant intra-basin fault system.

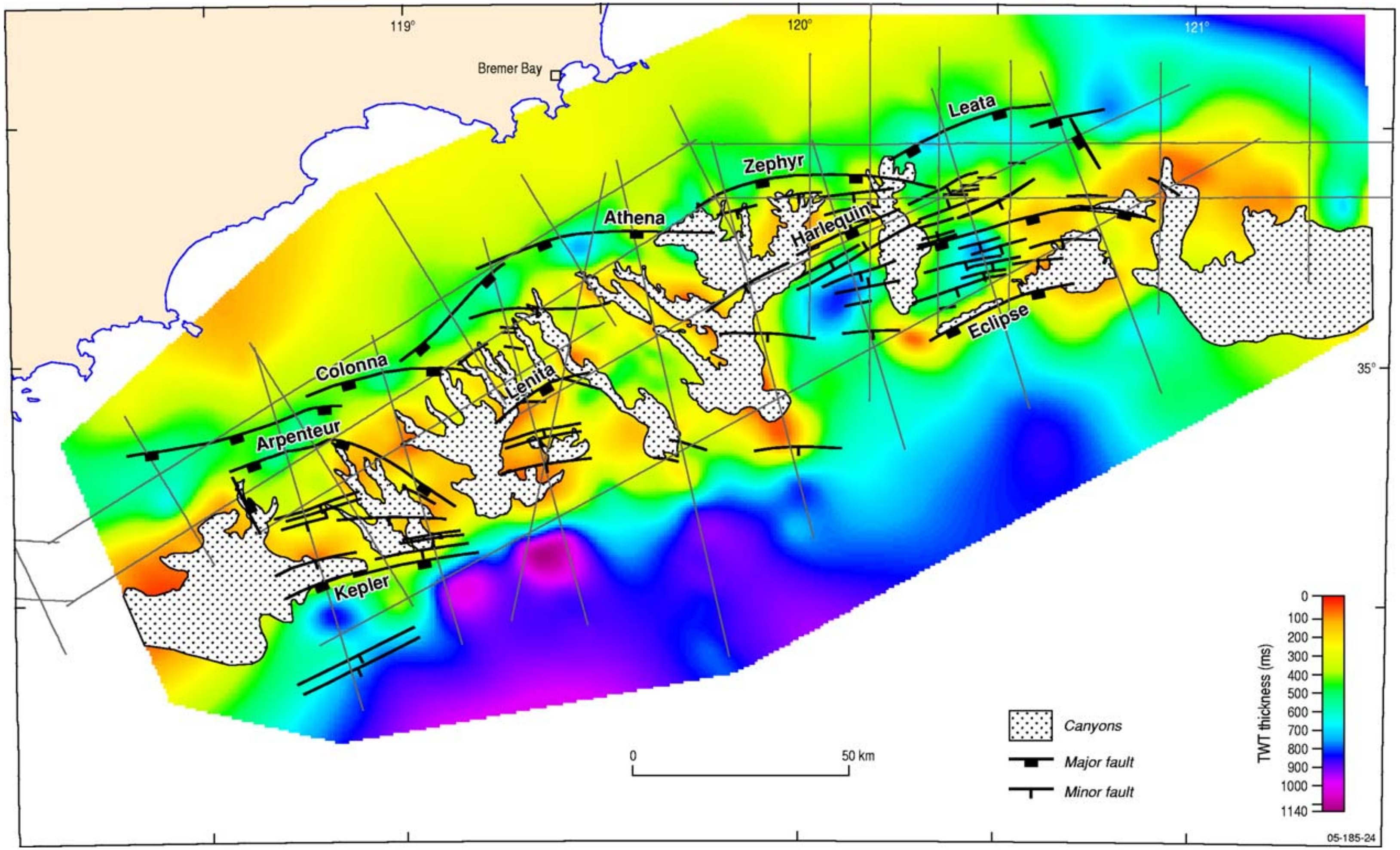


Figure 3.26: Isopach map for post-break-up strata (base Turonian) showing a veneer of unstructured sediment fill extending north of the rift border faults and thickening southwards.

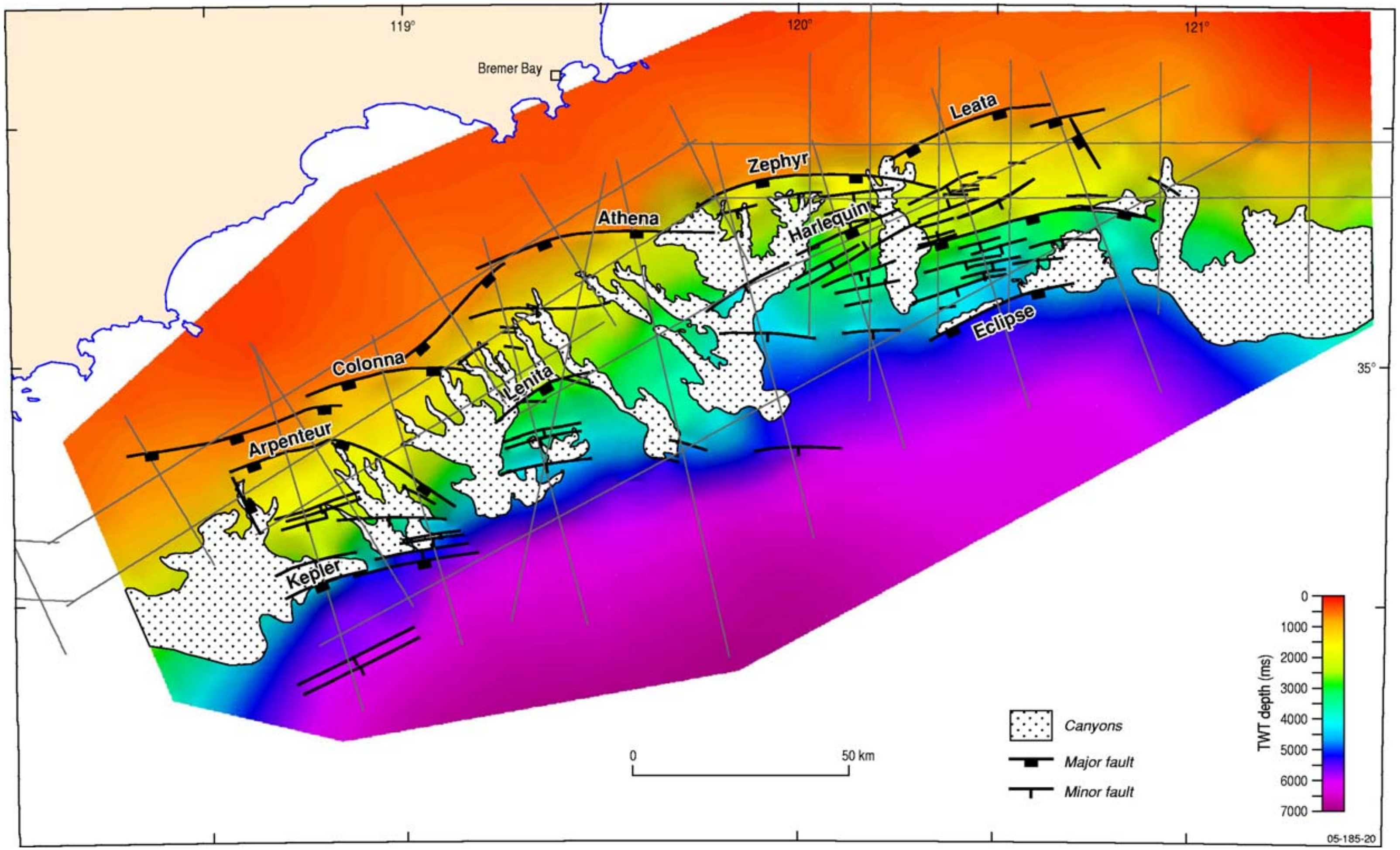


Figure 3.27: Time-structure map of the Turonian surface illustrating the southerly dip of the sub-basin that formed as the rate of sea-floor spreading accelerated during the Eocene. The associated collapse of the shelf triggered widespread canyon incision.

4. Petroleum Prospectivity (D.J. Ryan, B. E. Bradshaw & C.J. Boreham)

KEY POINTS

- Although no wells have been drilled in the Bremer Sub-basin, dredge samples and seismic data have been used to evaluate the sub-basin's petroleum prospectivity and develop a petroleum systems model. Results show that all of the key elements of a potential petroleum system are present within the Bremer Sub-basin.
- Additional specialist analyses and techniques are used to further assess the hydrocarbon generation and accumulation potential of the Bremer Sub-basin including: source rock geochemistry (Rock-Eval pyrolysis, gas chromatography, kerogen kinetics, molecular and isotopic analysis); fluid inclusion analysis using the Grains with Oil Inclusion (GOI™) and Quantitative Grain Fluorescence-Extract (QGF-E) techniques; Mercury Injection Capillary Pressure (MICP) analysis; and Vitrinite Reflectance (VR) and Vitrinite-inertinite reflectance and fluorescence (VRF®) analyses.
- The cyclic fluvial and lacustrine depositional history of the Bremer Sub-basin is favourable for deposition of distinct reservoir and seal pairs. In particular, thick Berriasian and Valanginian lacustrine mudstones occur at the base of the Bremer 3 and 4 units, and directly overlie fluvial sandstones at the top of the Bremer 2 and Bremer 3 units.
- Integration of geochemical and seismic facies data has identified potential source rock intervals at several stratigraphic levels. The thick syn-rift Bremer 1 unit is largely overmature and gas-prone. Two Tithonian–Valanginian lacustrine units at the base of the Bremer 2 and Bremer 3 units have good potential for oil and gas generation. A thick coal succession at the top of the Bremer 3 unit may have good potential for oil generation in the centre of the sub-basin.
- Geohistory models based on pseudo-wells have been used to model the maturity and hydrocarbon generation potential of source kitchen areas. Source rocks at the base of the Bremer 1 unit are overmature in all of the major depocentres, whereas lacustrine source rocks from the Bremer 2 and Bremer 3 units are within the oil and wet gas windows. Generation and expulsion of oil and gas is predicted to have occurred from several source rock intervals, with favourable post-trap expulsion from a central source kitchen area corresponding to the Athena and Zephyr depocentres.
- The Bremer Sub-basin contains a range of fault block, anticline and stratigraphic plays that formed during the Valanginian–Aptian. Large anticlinal structures with the potential to trap ~500 million barrels of oil in place are the main exploration plays in the western Arpenteur and Colonna, and the eastern Leata depocentres. Hydrocarbon charge is the key exploration risk in these western and eastern depocentres. Fault block traps with the potential to trap ~250 million barrels of oil in place are the main exploration play in the central Athena and Zephyr depocentres. Trap preservation is the main exploration risk in this main source kitchen area.

SOURCE ROCKS

The distribution and hydrocarbon generation potential of source rocks within the Bremer Sub-basin has been assessed through the analysis and integration of geochemical and biostratigraphic data, seismic mapping and facies analysis, regional analogs, and geohistory and hydrocarbon expulsion modelling. Geochemical analysis of 59 rock samples from 25 dredge sites has identified three diverse source rock facies with the potential to generate oil and gas (Boreham et al., 2005a, 2005b). The results of the geochemical analysis have been integrated with seismic and stratigraphic data to identify potential source rocks at several stratigraphic levels including:

- Late Jurassic syn-rift fluvio-lacustrine mudstones (Bremer 1 unit),
- Late Jurassic–Early Cretaceous lacustrine mudstones (Bremer 2 and Bremer 3 units),
- Valanginian coals (Bremer 3 unit), and
- Valanginian lacustrine–marginal marine mudstones (Bremer 4 unit).

Distribution and Quality of Potential Source Rocks

Late Jurassic syn-rift fluvio-lacustrine mudstones (Bremer 1 unit)

The Late Jurassic syn-rift Bremer 1 unit contains potential fluvio-lacustrine source rocks that were deposited during a period of mechanical extension (Figure 4.1). The Bremer 1 unit exhibits a half-graben wedge geometry that thickens northwards towards the basin bounding faults (Figure 3.22). The unit is at least 2000 m thick in all of the major half graben, and reaches a maximum thickness of ~2.5 s two-way time (~ 4.5 km) in the central Athena and Zephyr depocentres.

Potential source rocks from the Bremer 1 unit were sampled from a maximum of 5 dredge sites. Samples from this unit comprise mudstones and fine–very course grained quartz sandstones. Mudstones from Bremer 1 are generally carbonaceous and contain mica and coaly fragments. Geochemical analyses of 10 samples indicate that the organic content of these mudstones ranges from 1–4 % total organic carbon (TOC; Figure 4.2), with Hydrogen Index (HI) values of 25–90 mg HC/g TOC. Importantly, the S_2-peak and estimated HI values for organic matter can be artificially suppressed by the ‘mineral matrix effect’, giving rise to a lowered HI for the whole rock (Boreham and Powell, 1997). A more realistic measure of hydrocarbon potential is gained by removing mineral matter with strong acids and performing Rock Eval analysis on the organic kerogen concentrate (Boreham et al., 2005a). Pyrolysis of the kerogens shows that HI_{Ker} values range from 50–170 mg C/g TOC, indicating a Type III gas-prone source (Figures 4.2 and 4.3). It is worth noting that these Bremer 1 samples were dredged on the thin outer hinge of the half graben where terrestrial organic input would be relatively high, and may not be representative of more organic-rich sediments in the main depocentres.

Generation of hydrocarbons from Jurassic syn-rift successions along the southern and southwestern margins of Australia has been demonstrated in the Bight, Otway and Perth basins. A palaeo-oil column has been identified in the Jerboa-1 well from the Eyre Sub-basin, which has been typed to Late Jurassic lacustrine source rocks from the Sea Lion supersequence (Ruble et al., 2001). Late Jurassic–Early Cretaceous fluvio-lacustrine rocks from the Crayfish supersequence have sourced oil and gas fields in the western and central Otway Basin (Boreham et al., 2004; Ryan et al., 2005). In the Vlaming Sub-basin (Perth Basin), fluvio-lacustrine mudstones from the Middle–Late Jurassic Yarragadee Formation have been interpreted as the source for oils recovered from the Gage Roads 1 and Auracaria 1 wells (Miyazaki et al., 1996; Summons et al., 1995).

Late Jurassic and Early Cretaceous lacustrine mudstones (Bremer 2 and 3 units)

Two distinct lacustrine units were deposited in the Bremer Sub-basin during a period of thermal subsidence in the Tithonian and Berriasian (Figures 2.8 and 4.1). These lacustrine units form the lower parts of the Bremer 2 and Bremer 3 units, and are mainly composed of claystones, siltstones and shales. The Bremer 2 and Bremer 3 lacustrine units are thickest above the axis of the syn-rift half graben, and reach a maximum thickness of approximately 1 km in the central Athena and Zephyr depocentres.

No dredge samples can be confidently tied to the Bremer 2 unit. However, at least 17 samples are known to have been dredged from the Bremer 3 unit. Fifteen micaceous and carbonaceous mudstone samples from Bremer 3 were geochemically analysed; TOC values range from 1.0–3.5 %; the median HI_{Ker} value is 150 mgHC/g TOC (Figures 4.2 and 4.3). Three samples have HI_{Ker} values of 230–300 mgHC/g TOC, suggesting that some source rocks are present with very good potential for the generation of oil and gas.

Lacustrine mudstones from the Bremer 2 and Bremer 3 units were deposited during a more regional period of lacustrine deposition in the Perth and Bight basins during the Late Jurassic and Early Cretaceous. The Parmelia Group in the Vlaming Sub-basin correlates to the Bremer 3 unit, and includes lacustrine mudstones in the Otorowiri and Carnac formations (Crostella and Backhouse, 2000). The Parmelia Group mudstones are often organic rich (TOC >3%), and generally have HI values >300 (Marshall et al., 1993). The Minke and Southern Right supersequences in the Bight Basin include similar age fluvio-lacustrine claystones, siltstones and sandstones as the Bremer 2 and Bremer 3 units. Geochemical analysis from a limited number of well samples in the eastern Bight Basin suggest that the Southern Right supersequence has minor potential for the generation of waxy oil, and significant potential for gas generation (TOC 0.8–1%, HI 16–173; Struckmeyer et al., 2001).

Valanginian coals (Bremer 3 unit)

A major coaly-fluvial floodplain succession with potential coal source rocks was deposited during waning thermal subsidence in the Berriasian–Valanginian (Figure 4.1). The succession is characterised by high-amplitude and continuous seismic reflections interpreted as coal seams and fluvial floodplain deposits (Figure 2.13). The coaly interval is best developed in the central Bremer Sub-basin within the Athena and Zephyr depocentres. In the western and eastern ends of the sub-basin, the coaly facies grades into a fluvio-lacustrine facies. The coaly facies reaches a maximum thickness of ~1 km in the Athena depocentre, however, the thickness and nature of the individual coal seams is unknown. Based on regional analogs to the Bight and Otway basins, it is likely that the coal seams are at least 1–3 m thick, and interbedded with fluvio-lacustrine sediments.

No coal samples from the Bremer 3 seismic-stratigraphic unit were recovered from dredging. However, the hydrocarbon generative potential of coals from other basins along the southern margin is considered as excellent (Struckmeyer et al., 2001; Boreham et al., 2003, 2004). Coals in the upper part of the Bremer 3 seismic stratigraphic unit are regional equivalents to coals that have been interpreted from seismic data in the Southern Right supersequence in the Eyre Sub-basin. Although no coals have been sampled from the Southern Right supersequence, coals with excellent potential for both oil and gas generation have been widely sampled from the Aptian–Albian section of Bronze Whaler supersequence in the Bight Sub-basin (Struckmeyer et al., 2001).

Valanginian–Hauterivian lacustrine-restricted marine mudstones (Bremer 4 unit)

Lacustrine and restricted-marine source rock facies were deposited in the central Bremer Sub-basin during the Valanginian and Hauterivian (Figure 4.1). Two source rock facies occur in the Bremer 4 unit: a lacustrine facies at the base of Bremer 4; and a lacustrine to restricted-marine facies in the upper part of Bremer 4 (Figures 2.13 and 2.15). Only rocks at the base of the Bremer 4 unit have sufficient depth of burial to locally source hydrocarbons.

A total of 8 dredges comprising mudstones and sandstones can be confidently tied to the Bremer 4 unit. Potential source rock samples recovered from this unit are predominately mudstones, which are generally micaceous, carbonaceous–coaly, and often silty. Geochemical analysis was performed on

14 samples from lacustrine facies. Four samples have TOC values between 5 and 22%, and HI_{Ker} values of 135–340, indicating very good potential for the generation of oil and gas (Figures 4.2 and 4.3).

Maturity of Potential Source Rocks

With no wells drilled in the Bremer Sub-basin, and only a limited number of dredge samples, assessments of source rock maturity is largely based on the results of geohistory modelling and seismic structural mapping. Eight 1-D pseudo-well geohistory models were generated using Fobos Pro™ and Winbury™ modelling software in order to help understand the thermal history of the sub-basin.

Analysis of vitrinite reflectance data from dredge samples indicates that the shallow stratigraphy exposed in the sub-marine canyons is immature for oil generation, as would be expected. VR analysis was performed on 59 dredge samples by Keiraville Konsultants, while 13 samples underwent VRF analysis at Newman Energy Research Ltd. All but two samples analysed are immature with vitrinite reflectance values of < 0.64% Ro. However, two samples are overmature as a result of local igneous activity (Cook, 2005; Newman, 2005). Dredge sample 21E1 has an extremely high vitrinite reflectance of approximately 4.0% Ro, and exhibits microscopic textures indicative of intrusive igneous rocks explosively mixing with sedimentary rocks (Newman, 2005). A coaly claystone sample from Dredge 22C1 has two populations of Ro values that range from 0.41–2.33%, suggesting varying degrees of thermal alteration as a result of local igneous activity. Both of these samples can be correlated to a high amplitude and chaotic seismic facies characteristic of igneous intrusions and flows.

Geohistory Modelling Methodology

To assess the maturity of potential source rocks within the major depocentres, geohistory models were generated at eight pseudo-well locations (Figure 4.4). Burial and thermal modelling was carried out using Fobos Pro™, a 1-D basin modelling package. This software uses lithospheric parameters (initial thickness, density and radioactive heat productivity), sediment parameters (compaction, density and radioactive heat productivity), and changes to the lithosphere and sediment package (predicted from crustal and mantle lithosphere stretching) to predict heatflow and sediment palaeo-temperatures. The model was calculated using a finite element manipulation of the transient heatflow equation, and was then calibrated against observed subsidence using a geohistory model of basement, including palaeo-waterdepths (e.g. Figure 4.5a). Stratigraphic control for the geohistory models is based on depth-conversion of seismic interpretations using the stacking-velocity based time-depth function in Goncharov et al. (2005). The basement and crustal parameters used for the modelling draw on a number of sources, including the results of the Bremer Sub-basin seismic refraction study (Goncharov et al., 2005), data obtained from onshore samples within the Albany-Fraser Orogen (Geoscience Australia's OZCHEM database, Sandra McClaren, Australian National University, pers. comm. 2005), and published literature (Cull, 1982; Denith et al., 2003).

The predicted maturity versus depth profiles generated by the 1-D geohistory models were integrated with regional structure grids to help understand the maturity and locations of potential source rock kitchens. A polynomial equation was calculated from the predicted maturity versus depth functions generated by the pseudo-well models (Figure 4.6). Depth below seafloor grids were then generated for seismic horizons at potential source rock levels. The calculated maturity versus depth function was then applied to the seismic structural grids to generate maps of the maturity and location of the source kitchens. A limitation of this maturity mapping method is that subsidence and uplift history of any particular part of the basin is essentially ignored, so that an area that was buried and subsequently uplifted will have a lower predicted maturity than actual maturity. However, given the frontier nature of the Bremer Sub-basin, this method allows the overall maturity trends and main source kitchen areas to be easily identified. Without any well control, it must be remembered that any assessment of source rock maturity and timing of generation and expulsion is somewhat speculative and based on a number of assumptions.

Geohistory Modelling Results

The predicted maturity versus depth profiles generated by the geohistory models suggest that the oil window (~0.7% Ro) is reached at depths between 2150–3500 m, and the gas window is reached at depths ranging from 3000–5000 m below the seafloor (Figure 4.6). These predicted depths to the oil and gas windows are similar to observed trends in the Bight and Otway basins. Vitrinite reflectance data from the eastern Bight Basin indicates the oil window is reached at depths between 1800–3600 m (Struckmeyer et al., 2001), whereas in the Otway Basin, the oil window depth is between 2000 and 3500 metres below the sea floor (Ryan et al., 2005).

Maturity mapping of source rocks within the Bremer 1 syn-rift succession suggest that the Mid–Late Jurassic source rocks are mature to over mature throughout the entire basin (Figures 4.7 and 4.8). Source rocks at the base of the Bremer 1 syn-rift unit are within or have passed through the gas window, and are over mature in the deepest half graben (Figure 4.7). In the central Athena and Zephyr depocentres, the base of the Bremer 1 reaches depths of over 7000 m and has passed through the dry gas window, with predicted vitrinite reflectance of > 2.5 % Ro. The base of the Bremer 1 unit is also within the dry gas window in the western Arpenteur depocentre. However, the maturity in the shallower Leata depocentre in the west and Colonna depocentre in the east is predicted to range from within the oil window at ~ 0.7 % Ro, to within the wet gas windows at ~ 1.2 % Ro. A predicted maturity map generated for source rocks at the top of the Bremer 1 unit suggests that this unit is mature to over mature in most of the sub-basin (Figure 4.8), with predicted vitrinite reflectance values of between ~ 0.7–1.4 % Ro in all of the major half graben.

The maturity of two lacustrine units at the base of the Bremer 2 and Bremer 3 units, and the location of source kitchen areas are critical data for assessing the petroleum prospectivity of the Bremer Sub-basin. The predicted maturity map of the 'Tith' seismic horizon (base of Bremer 2) highlights that the lacustrine source rocks at the base of Bremer 2 are within the oil window in the inner Athena depocentre, and within the wet gas window in the Zephyr and outer Athena depocentres (Figure 4.8). Although a maturity map equivalent to the lacustrine mudstones at the base of the Bremer 3 unit has not been created, modelling suggests that this source unit would have predicted maturity values of ~ 0.8–1.2 % Ro in the central Zephyr and Arpenteur depocentres, and is mature for the generation of oil and wet gas.

A predicted maturity map generated for the 'Val' seismic horizon indicates that the top of the Bremer 3 coaly interval and the base of the Bremer 4 lacustrine unit are largely immature for oil generation (Figure 4.9). In the central Athena and Zephyr depocentres, maturity at the 'Val' seismic horizon level ranges from ~ 0.5–0.6 % Ro. Farther basinwards in an outer Valanginian depocentre, predicted maturity reaches > 1.4 % Ro. The coaly interval at the top of Bremer 3 is up to 1400 m thick in the Athena and Zephyr depocentres. Here, coals from the base of this interval would be within the oil window with predicted maturity values up to ~ 0.9 % Ro. As previously mentioned, the lacustrine mudstones at the base of Bremer 4 reach a maximum predicted maturity of ~ 0.6 % Ro, and are largely immature for oil generation throughout the sub-basin.

Generation and Expulsion

The hydrocarbon generation and expulsion history of the Bremer Sub-basin has been assessed through integration of geochemical analysis and source rock modelling in the Winbury™ software package. Source rock intervals were defined in each pseudo-well model based on seismic facies analysis (Figure 4.5b). Potential source rocks from within the thick Bremer 1 syn-rift section were generally modelled as one source rock interval. However, where the thickness of the modelled source rock unit exceeded 3000 m, an upper Bremer 1 unit was also included in the model. Although this method may over exaggerate the volumes generated from the Bremer 1 unit, it was adopted to help understand the major generation and expulsion events relative to trap formation. The thickness and depth of source rocks from the thinner Bremer 2, Bremer 3 and Bremer 4 units were simply based on seismic facies analysis at the pseudo-well locations. Source rock parameters used for the modelling are based on the geochemical analysis of the dredge samples. As only a limited number of source rock samples were recovered from dredges, the highest TOC and HI data points presented in Figure 4.2 were used. As well as basic RockEval data such as TOC and HI, data acquired from new kerogen kinetics analysis were also used in the modelling. Kerogen kinetic analysis was performed on one lacustrine and one coaly sample to determine the temperatures at which the kerogens transform to hydrocarbons. Results from the kerogen analysis suggest that kerogens in the Bremer Sub-basin source rock intervals are quite labile, and begin transforming to hydrocarbons ~ 10–30° C lower than the standard Type I, II and III kinetics. Bulk geochemical parameters, kerogen kinetics and thermal history are then used by the software to predict the rate and volume of hydrocarbons generated and expelled during time for each source rock (Figure 4.5b).

The expulsion models for the fluvio-lacustrine source rocks in the Middle–Late Jurassic Bremer 1 unit predict a major phase of oil and gas expulsion during rapid burial in the Tithonian–Valanginian (Figure 4.10). This phase of expulsion is sourced from the deeper half-graben troughs during deposition of the Bremer 2 and Bremer 3 units. Subsequent expulsion from the upper section of Bremer 1 during the Valanginian–Barremian is also modelled (Figures 4.10, 4.11).

Hydrocarbon generation and expulsion models developed for the Bremer 2 and Bremer 3 lacustrine units suggest that significant generation and expulsion of oil has occurred in the centre of the sub-basin in the vicinity of the Athena and Zephyr depocentres (Figures 4.5b, 4.11 and 4.12). The main phase of in-situ oil generation began in the Berriasian and continued until the Aptian (Figure 4.12a), whereas expulsion of oil from these source intervals is modelled as occurring slightly later from the Valanginian–Turonian (Figure 4.12b). The modelling also suggests that in some areas oils were generated within these source rocks, but there was insufficient volumes generated to expel hydrocarbons (e.g. in the eastern Leata depocentre). The generation and expulsion of hydrocarbons during the Valanginian–Turonian is important for the petroleum prospectivity in the Bremer Sub-basin, as it provides favourable timing to charge structures that formed during the second extension event in the Valanginian–Aptian. The distribution of this later expulsion event is controlled by the burial from the overlying Bremer 4 unit. An isopach map of the Bremer 4 unit (Figure 3.24) was therefore used to determine where this favourable hydrocarbon charge may have occurred in the Bremer Sub-basin. Results suggest favourable conditions for this late expulsion event in the central sub-basin, adjacent to the Lenita-Harlequin trend, and possibly within the Leata depocentre.

Modelling of the upper Bremer 3 coaly source rock intervals predicts only minor generation and expulsion of hydrocarbons. Modelled generation and expulsion from these source rocks occurred from the Aptian–Turonian in the centre of the sub-basin where post-Valanginian sedimentation was greatest (Figures 4.5b and 4.11). Although this coal interval is marginally mature in the centre of the sub-basin, kerogen kinetic analysis suggests that these coals are quite labile and begin transforming to oil at maturity levels of 0.5–0.7 % Ro.

The lacustrine mudstones at the base of the Bremer 4 unit are largely immature throughout the Bremer Sub-basin. No significant generation and expulsion of hydrocarbons has been modelled in Bremer 4, or any overlying stratigraphic units (Figures 4.5b, 4.9 and 4.11).

Evidence of Hydrocarbon Generation

The petrographical techniques of GOI™ (Grains with Oil Inclusions) and VRF® (Vitrinite-inertinite Reflectance Fluorescence) have both provided evidence for hydrocarbon generation in the Bremer Sub-basin. GOI analysis was carried out on ten dredge samples, and identified trace oil inclusions in five samples (Kempton, 2005). In addition to grain oil inclusions, other oil-bearing aqueous inclusions also provide evidence for the presence of oil (Kempton, 2005). When these are also taken into account, eight of the ten samples analysed for GOI show evidence for the presence of oil. If these oil inclusions formed during the current burial cycle, then they provide supporting evidence for the presence of mature source rocks in the Bremer Sub-basin. Furthermore, given the low maturity of the dredge samples (Ro <0.6%), it is likely that oils within these inclusions have migrated from a deeper, mature source.

A number of potential indications of migrated hydrocarbon were also found during VRF analysis (Newman, 2005). Five samples from the western and central areas of the sub-basin emitted greenish-yellow fluorescing oil from the sedimentary matrix under a hot ultra-violet (UV) beam. The low maturity of the samples suggests this may be migrated oil that was generated deeper in the sub-basin. Other observations noted during VRF analysis highlight the inherent hydrocarbon generative potential of some source rocks. Diffuse emissions of hydrocarbons were observed in a few Tithonian–Valanginian samples (Bremer 2 and Bremer 3 units) coming directly from the vitrinite material, but only under a very hot UV beam. This highlights the capacity for these source rocks to generate oil when maturity is reached. Furthermore, a sample recovered from dredge 42 contains asphalt occurring locally as a matrix within siltstone, and melted vigorously under a hot UV beam. The location of this dredge site on the thin outer hinge of a half graben may indicate the hydrocarbon generative potential of syn-rift source rocks within the Bremer 1 unit.

SEAL ROCKS

Given the cyclic fluvial and lacustrine depositional history of the Bremer Sub-basin, potential regional and intraformational seals are present at several stratigraphic levels. In particular, three widespread Tithonian–Valanginian lacustrine units have the potential to seal hydrocarbons across the sub-basin (Figure 4.1). Seal lithologies include micaceous and carbonaceous mudstones deposited in floodplain and lacustrine environments. Mercury Injection Capillary Pressure (MICP) analysis was undertaken on 10 dredge samples to gather quantitative data on the seal and reservoir potential of different stratigraphic units (Table 4.1). Dredge samples show varying degrees of weathering, and have probably been affected by dissolution, decompaction or clay modification through prolonged exposure at the seafloor (Daniel, 2005). It is therefore necessary to use MICP measurements cautiously, with seal capacity measurements likely to represent minimum values, while porosity measurements are probably maximum values.

Late Jurassic syn-rift mudstones (Bremer 1 unit)

The Bremer 1 seismic-stratigraphic unit comprises an interbedded succession of fluvio-lacustrine sediments deposited in a range of fluvial channel, floodplain and lacustrine (fresh–brackish water) environments. Intraformational lacustrine–fluvial floodplain mudstones may have sealing potential where they are well developed above fluvial channel systems. MICP analysis on a mudstone sample from the Bremer 1 unit (sample 19A1) shows a capacity to seal a minimum oil column of 36.3–60 m (Table 4.1; Daniel, 2005).

Tithonian–Valanginian lacustrine mudstones (Bremer 2, Bremer 3 and Bremer 4 units)

Three thick, regionally extensive lacustrine units were deposited in the Bremer Sub-basin during the Tithonian–Valanginian. A lacustrine facies at the base of the Bremer 2 unit (seismic facies ‘3’ on Figures 2.9 and 2.10) has potential to seal fluvial sandstone reservoirs at the top of the underlying Bremer 1 unit. However, a fluvial facies (seismic facies ‘6’ on Figures 2.9 and 2.10) is also observed at the base of Bremer 2 in some areas (Figure 4.1). A widespread lacustrine facies is observed at the base of the Bremer 3 seismic-stratigraphic unit (Figure 4.1; seismic facies ‘3’ on Figures 2.9 and 2.13), which has potential to form a regional seal to underlying fluvial sandstones from Bremer 2. Dredge samples tied to this lacustrine facies are predominantly micaceous, carbonaceous mudstones. A third widespread lacustrine unit was deposited at the base of the Bremer 4 unit during a period of renewed extension in the Valanginian (Figure 4.1). MICP analysis of a lacustrine mudstone dredged from the base of Bremer 4 (sample 15C1) indicates that it can seal a minimum oil column of 42–71 m (Table 4.1). Lacustrine mudstones at the base of Bremer 4 have the potential to provide a top and cross-fault seal to the underlying coaly-fluvial sediments of Bremer 3 (Figure 2.13).

Hauterivian–Aptian lacustrine to restricted-marine mudstones (Bremer 4 unit)

Locally developed lacustrine and restricted-marine seal lithologies may also be present in the Hauterivian–Aptian section of the Bremer 4 unit (Figure 4.1). The Hauterivian–Aptian section in the Bremer Sub-basin is characterised by a thick aggradational succession of non-marine to restricted-marine sediments (Figure 2.15). Regionally extensive lacustrine or restricted marine seismic facies have not been identified in sediments of this age. However, fluvial to coastal plain reservoir sandstones units may be sealed locally by intraformational lagoonal to lacustrine mudstones.

Potential sealing lithologies may occur in Aptian–Maastrichtian age marine mudstones from the Bremer 5 and Bremer 6 units. MICP analysis of two dredge samples shows that Late Cretaceous marine mudstones have potential to seal minimum oil column heights of 51–85 m and 88–146 m (Table 4.1; Daniel, 2005). However, marine mudstones from Bremer 5 and Bremer 6 probably have limited seal potential in the Bremer Sub-basin due to the thin and patchy nature of these sediments, together with their deposition after the main phases of hydrocarbon expulsion.

RESERVOIR ROCKS

Fluvial sandstones with the potential to reservoir hydrocarbons exist at several stratigraphic levels in the Bremer Sub-basin. In particular, two distinct fluvial cycles that are Tithonian and Berriasian in age occur at the top of the Bremer 2 and Bremer 3 units, respectively, and are overlain by regional lacustrine seals (Figure 4.1). Other potential reservoir rocks also occur in the Late Jurassic Bremer 1 syn-rift succession, and the fluvial-coastal plain facies of the Valanginian–Aptian Bremer 4 unit.

Dredge sample descriptions, seismic facies analysis, and specialised analysis techniques were used to assess the reservoir potential at several stratigraphic levels. MICP analysis was undertaken on 10 dredge samples to obtain quantitative data on reservoir quality for different stratigraphic units in the Bremer Sub-basin (Table 4.1; Daniel, 2005). Furthermore, petrographic analysis was performed during GOI™ analysis, which provides further insight into the properties of potential reservoir rocks (Kempton, 2005).

Late Jurassic syn-rift sandstones (Bremer 1 unit)

Potential reservoir rocks from the Late Jurassic Bremer 1 seismic-stratigraphic unit occur within fluvio-lacustrine, fine to very coarse grained quartz sandstones. Seismic facies analysis suggests the sandstones were deposited in meandering channel systems, and also in floodplain settings where they are interbedded with mudstones (seismic facies '1' and '2' in Figure 2.10). MICP analysis on a dredge sample interpreted to be from the Bremer 1 unit (19B1) indicates a maximum porosity of 24% (Table 4.1; Daniel, 2005). This is supported by petrographic analysis which reports very good visual porosity of more than 20 %, as well as evidence of secondary dissolution porosoity (Kempton, 2005). Detrital grains in the sample are sub-rounded to rounded and well-sorted.

Tithonian–Valanginian fluvial sandstones (Bremer 2 and Bremer 3 units)

Tithonian–Valanginian aged strata are characterised by two distinct lacustrine and fluvial cycles in the Bremer 2 and Bremer 3 units (Figure 4.1). Both fluvial units can be identified by their distinct, high-amplitude seismic facies, interpreted to be an interbedded channel sandstone and coaly-floodplain succession (seismic facies '4' and '5' in Figures 2.9 and 2.13). The fluvial unit in the Tithonian Bremer 2 unit reaches a maximum thickness of ~ 1500 m in the Zephyr depocentre, whereas the coaly-fluvial unit in the Early Cretaceous Bremer 3 unit is up to 1000 m thick.

Variations in seismic facies are observed within each unit, indicating local changes in depositional environments across the sub-basin. In the central sub-basin area, the Bremer 3 fluvial unit is characterised by high-amplitude and continuous reflections, interpreted as a coaly-fluvial floodplain succession (seismic facies '5' on Figure 2.13). In the Arpenteur depocentre, the geometry of fluvial channel systems appears to be controlled by growth on the bounding fault, with fluvial channels becoming thicker and more amalgamated towards the Arpenteur Fault (seismic facies '4' on Figure 2.9). In the eastern part of the sub-basin, the Bremer 3 unit appears to grade into a more interbedded succession of fluvial and floodplain sediments.

Although no samples can be confidently tied to the Bremer 2 seismic-stratigraphic unit, 17 dredge samples have been tied to the Bremer 3 unit. These Bremer 3 sandstone samples are quartoze to sub-arkosic, and contain variable amounts of feldspar, mica, lithics and coaly fragments. Some glauconitic and calcareous lacustrine sandstones also occur at the base of Bremer 3. MICP analysis on sandstone samples possibly dredged from Bremer 2 (sample 44A1) and Bremer 3 (sample 34D1) indicate maximum porosities of 31% and 34% (Table 4.1; Daniel, 2005). Petrographic analysis reports fair–poor visual porosity, with primary intergranular porosity occluded by trace amounts of quartz overgrowths (Kempton, 2005).

Valanginian–Aptian fluvial to coastal plain sandstones (Bremer 4 unit)

Valanginian–Aptian sandstones have the potential to reservoir hydrocarbons where local seals are well developed. In the central Bremer Sub-basin, the Hauterivian–Aptian section is characterised by a thick aggradational succession of non-marine to restricted-marine sediments. The unit is largely absent in the western end of the sub-basin, and thins to the east. Potential Bremer 4 exploration targets may occur in the centre of the sub-basin where fluvial to coastal plain sandstones are locally sealed by intraformational lagoonal to lacustrine mudstones. MICP analysis of a sandstone dredged from Bremer 4 (sample 27A1) shows a maximum porosity of 30% (Daniel, 2005). This is supported by petrographic analysis which reports very good visual porosity (Kempton, 2005). Detrital grains in the sample are sub-rounded to well-rounded, and well-sorted.

EXPLORATION PLAYS AND RISKS

Three main play types are evident in the Bremer Sub-basin: anticlinal plays, combined structural/stratigraphic plays, and fault block plays (Figures 4.13 and 4.14). The steeply-dipping seafloor topography over the sub-basin can make identification of potential traps difficult on seismic data in two-way time. Therefore, selected seismic lines were depth-converted using a time-depth algorithm based on pre-stack time-migrated stacking velocities (F. Kroh, pers. comm. 2005). Potential trap sizes on depth-converted sections range from: 500 million barrels for anticlinal traps (P_{50} estimate; P_{10} estimate = 900 million barrels; P_{90} estimate = 200 million barrels); to 250 million barrels for fault block traps (P_{50} estimate; P_{10} estimate = 500 million barrels; P_{90} estimate = 100 million barrels); and 200 million barrels for structural/stratigraphic traps (P_{50} estimate; P_{10} estimate = 400 million barrels; P_{90} estimate = 100 million barrels). Anticlinal structures are observed adjacent to the basin bounding fault systems. Combined structural/stratigraphic plays are common in most seismic stratigraphic units throughout the sub-basin. Potential structural/ stratigraphic traps occur in up-dip stratigraphic pinch-outs associated with fluvial-lacustrine deltas, fluvial channel complexes, and transgressive lacustrine sandstones. Fault block plays are mainly associated with the Lenita-Harlequin fault trend.

Anticlinal plays and combined structural/stratigraphic plays present the main exploration opportunities for the Arpenteur, Colonna and Leata depocentres at the eastern and western ends of the sub-basin (Figures 4.13 and 4.15). As these areas represent the smallest depocentres in the sub-basin, hydrocarbon charge is the main exploration risk. Fault block plays along the Lenita-Harlequin trend represent the main exploration opportunity in the central Athena and Zephyr depocentres (Figures 4.14 and 4.15). Any valid traps present in this central part of the sub-basin will have good exploration potential due to their location in a potentially large source kitchen area. The key risk for exploration along the Lenita-Harlequin trend will be trap preservation, with many faults reactivating during break-up in the Turonian, and some large sub-marine canyons locally eroding up to 2 km into the central part of the Bremer Sub-basin.

Arpenteur, Colonna and Leata Depocentres

The western and eastern parts of the Bremer Sub-basin are characterised by a series of small half graben, the Arpenteur, Colona, and Leata depocentres (Figure 3.7). Each has a similar structural architecture, with strata from Bremer 1, Bremer 2 and Bremer 3 dipping steeply to the north–northeast, and Bremer 4 forming a narrow syn-tectonic wedge in the hanging wall of the Arpenteur, Colonna, and Leata faults. Anticlinal traps and combined structural/stratigraphic traps are the dominant play types, while fault block plays are limited to the Arpenteur Depocentre (Figure 4.13). Burial history modelling indicates that thermally mature source rocks would occur within Bremer 1, provided suitable quality source rocks are present, with peak generation during the Berriasian. Generation from potential source rocks in Bremer 2 may also have occurred during the Valanginian–Barremian. Source kitchen areas would be restricted to the main syn-rift wedge adjacent to the Arpenteur, Colonna, and Leata faults. Any hydrocarbons generated in these source kitchens will migrate towards the south–southwest, away from the basin bounding faults. The main exploration risk in these depocentres will therefore be the volume of hydrocarbon charge from these smaller source kitchen areas, and the timing of hydrocarbon expulsion versus trap formation. Trace oil inclusions in sandstones from Bremer 1 adjacent to the Penguin and Cygnet highs provide some supporting evidence that hydrocarbons were generated in the Arpenteur and Leata depocentres (Kempton, 2005).

Anticlinal structures formed adjacent to the Arpenteur, Colona, and Leata faults during the Valanginian–Aptian period of extension. These are potentially the largest, shallowest water (500–750 m water depth) traps in the Bremer Sub-basin. The main exploration target in these anticlinal structures is fluvial sandstones at the top of Bremer 2 (~2000–2500 m sub-surface), with top seal provided by lacustrine mudstones at the base of Bremer 3 (Figure 4.16). An anticlinal structure in the Leata depocentre has a potential closure area of 20 km^2, and ~300 m of vertical closure at the top of Bremer 2. In addition, there is potential for stacked plays in other stratigraphic intervals from Bremer 1 and Bremer 3. Anticlinal structures are located within the potential source kitchen areas of each of the three depocentres, but down-dip of the main hydrocarbon migration pathway. The timing of trap formation during the Valanginian–Aptian post-dates hydrocarbon generation from potential source rocks in Bremer 1, but is favourable for generation from potential source rocks within Bremer 2. Hydrocarbon charge will therefore depend on vertical migration from lacustrine mudstones at the base of Bremer 2 into overlying fluvial sandstones. Anticlinal structures have good preservation potential, with no sub-marine canyon erosion or fault breaches evident.

Combined structural/stratigraphic traps may be present in the Arpenteur, Colona, and Leata depocentres where sandstones in Bremer 1, Bremer 2, Bremer 3 and Bremer 4 pinch-out up-dip, and are sealed vertically and laterally by lacustrine or floodplain mudstones. A potential structural/stratigraphic trap is present in the Arpenteur depocentre where a fluvial channel system in Bremer 3 thins to the south and pinches-out up-dip (Figure 4.17). This is a relatively large feature, extending ~8 km up-dip from the Arpenteur Fault, and reaching a maximum thickness of ~250 m. The fluvial system also extends ~ 8 km along-strike over the crest of an anticlinal structure, where it is ~100 m thick. The up-dip pinch-out of the fluvial system occurs in 1000 m water depth, and ~2000 m sub-surface. This potential combined structural-stratigraphic trap is located within the source kitchen area of the Arpenteur depocentre. Trap formation was probably initiated during Valanginian–Aptian extension; however, most of the tilting associated with this trap occurred during break-up in the Turonian. Key risks for this play are whether a structural/stratigraphic trap was present during the Valanginian–Aptian, and if hydrocarbons generated from Bremer 2 during the Valanginian–Barremian subsequently migrated vertically along the Arpenteur Fault into the trap. A potential structural/stratigraphic trap at this same stratigraphic interval is also evident in seismic data from the Leata depocentre (Figure 4.18).

Major faults are limited to the uplifted rift flank of the Arpenteur depocentre. These faults form potential high-side fault block traps in 1100 m water depth (Figures 3.11 and 4.13). The main reservoir intervals will be fluvial sandstones at the top of Bremer 1 (~1400 m sub-surface) sealed vertically and across faults by lacustrine mudstones from the base of Bremer 2, and fluvial sandstones at the top of Bremer 2 (~800 m sub-surface) sealed vertically and across faults by lacustrine mudstones from Bremer 3. At the Bremer 1 stratigraphic level, the potential trap area is ~30 km^2, and vertical closure ~250 m. At the Bremer 2 stratigraphic level, the potential trap size appears smaller with an area of ~10 km^2, and vertical closure of ~250 m. The up-dip location of the fault block would be on the migration pathway for any hydrocarbons generated from the main source kitchen area. The key risk for this play is the timing of fault generation versus hydrocarbon charge, and trap preservation. If the faults formed during the Valanginian–Aptian period of extension, then the fault blocks could be charged by any hydrocarbons generated from Bremer 2 that migrated up-dip. This would limit the potential reservoir interval to fluvial sandstones at the top of Bremer 2. However, if the faults were generated during the Turonian, then trap formation will post-date hydrocarbon charge.

Athena and Zephyr Depocentres

The Athena and Zephyr depocenters are the main potential source kitchen areas in the Bremer Sub-basin (Figure 3.7). Hydrocarbon generation and expulsion is possible from source rocks in Bremer 1 and Bremer 2 throughout the main half-graben depocentres. Potential source rocks in Bremer 3 may also have generated and expelled hydrocarbons in the thickest sedimentary successions. Strata in the Athena and Zephyr depocentres dip to the north, focussing any migrating hydrocarbons towards the main bounding faults. Any valid traps will therefore be potentially prospective for hydrocarbon exploration. The Lenita-Harlequin Fault trend is the dominant structural system within the Athena and Zephyr depocentres. Fault block plays associated with this structural trend are the dominant play type (Figure 4.14). Anticlinal and structural/stratigraphic plays are less common. The main exploration risk in the Athena and Zephyr depocentres is trap preservation, with many faults reactivating during the Turonian, and some large sub-marine canyons present in the Zephyr Depocentre.

The Lenita Fault in the Athena depocentre contains potential fault block traps in water depths of 2000–2500 m (Figure 4.19). This major growth fault and associated series of rollover anticlines formed during a period of extension in the Valanginian–Aptian. A younger series of faults formed during the Turonian. The first and largest rollover structure is offset near the anticline crest by a major Turonian-age fault, and may therefore represent a low-side fault block trap with fault-dependant closure (Figure 4.19). Fluvial sandstones at the top of Bremer 3 are the main reservoir interval (~1000 m sub-surface), with top seal provided by lacustrine mudstones in Bremer 4, and potential cross-fault seal provided by lacustrine mudstones at the base of Bremer 3. At this reservoir level, the rollover structure is about ~5 km wide, and has a vertical closure of up to 750 m. A smaller rollover structure located farther basinward may have fault independent closure at the top of Bremer 3 (Figure 4.19). High-side fault block traps are also present adjacent to the Lenita Fault. Potential reservoir intervals include fluvial sandstones at the top of Bremer 3 (~750–1500 m sub-surface) sealed vertically and across faults by lacustrine mudstones at the base of Bremer 4, and fluvial sandstones at the top of Bremer 2 (~1750–2500 m sub-surface) sealed vertically and across faults by lacustrine mudstones from Bremer 3 (Figure 4.19). High-side fault block traps are ~ 2.5 km wide with ~ 200 m of closure. The Lenita Fault zone is located within a possible source kitchen area, with potential for hydrocarbon generation from Bremer 1 in the Berriasian–Valanginian, and Bremer 2 during the Valanginian–Aptian. The Lenita Fault zone therefore has potentially favourable timing for trap formation versus hydrocarbon charge from source rocks within Bremer 2, and late generation from source rocks in Bremer 1. The main exploration risk is that Turonian faulting may have breached traps. However, an AVO anomaly is present in a high-side fault block (Figure 4.19), providing a possible indication of trapped hydrocarbons (Kroh and Williamson, 2005). Large rollover structures with fault independent closure may occur farther along the Lenita-Harlequin trend.

The Zephyr depocentre contains a series of potential high-side fault traps (Figure 4.20). Fluvial sandstones at the top of Bremer 2 and Bremer 3 are the main reservoir units. Lacustrine mudstones at the base of overlying units provide both top seal and cross-fault seals. The largest fault block traps in the Zephyr depocentre are ~3 km wide and have ~400 m of closure. Two different age fault systems are present. A series of Turonian-age break-up faults occur between the Zephyr and Harlequin faults in water depths of 1000–1750 m. Potential traps occur at the top of Bremer 3 (~1000 m sub-surface), and the top of Bremer 2 (~2000 m sub-surface). The Harlequin Fault is a major growth fault that formed during the Valanginian–Aptian period of extension. Potential high-side fault traps are associated with a series of antithetic growth faults in 1750–3000 m water depth. Most of these faults had minor reactivation during the Turonian. Potential traps occur at both the top of Bremer 3 (1500–2000 m sub-surface), and the top of Bremer 2 (~3000 m sub-surface). Traps associated with the Harlequin Fault have potentially favourable timing to be charged by hydrocarbons generated from the Bremer 2 and Bremer 3 lacustrine units in the Hauterivian–Turonian. Turonian-age faults between the Zephyr and Harlequin faults are unlikely to have favourable timing for hydrocarbon charge from any potential source rock intervals. The main risk for fault block plays associated with the Harlequin Fault is breaching of traps during fault reactivation in the Turonian. The Bremer Canyon extends into the Zephyr depocentre and erodes up to 2000 m sub-surface to the top of Bremer 3. This presents an additional, though fairly localised preservation risk for exploration at this stratigraphic level.

At least one anticlinal structure is evident in the Athena depocentre, while none have been observed in the Zephyr depocentre. The anticlinal structure in the Athena depocentre is located within the main half graben, in 1000 m of water (Figure 4.21). The potential reservoir unit is fluvial sandstones at the top of Bremer 2 (~2200 m sub-surface), sealed by lacustrine mudstones from the base of Bremer 3. At this reservoir interval, the anticline is ~7 km wide, with vertical closure of ~300 m. The southeastern flank of the structure appears to be extensively intruded by igneous sills, and has minor offset across a Turonian-age fault (Figure 4.21). The anticline appears to have formed during deposition of Bremer 3 in the Berriasian–Valanginian. Potential hydrocarbon expulsion in the main Athena source kitchen area was from source rocks in Bremer 1 during the Berriasian, Bremer 2 in the Hauterivian–Albian, and Bremer 3 during the Aptian–Santonian. Timing of trap formation versus hydrocarbon expulsion is thus potentially favourable for all potential source rock intervals. The main uncertainty is whether a valid trap is present, as the southern flank of the anticline is difficult to interpret due to the presence of igneous intrusions, and there is insufficient seismic data to determine if the structure has along-strike closure. An AVO anomaly is present at the top of the anticline, which may be associated with hydrocarbons trapped within the structure (Kroh and Williamson, 2005).

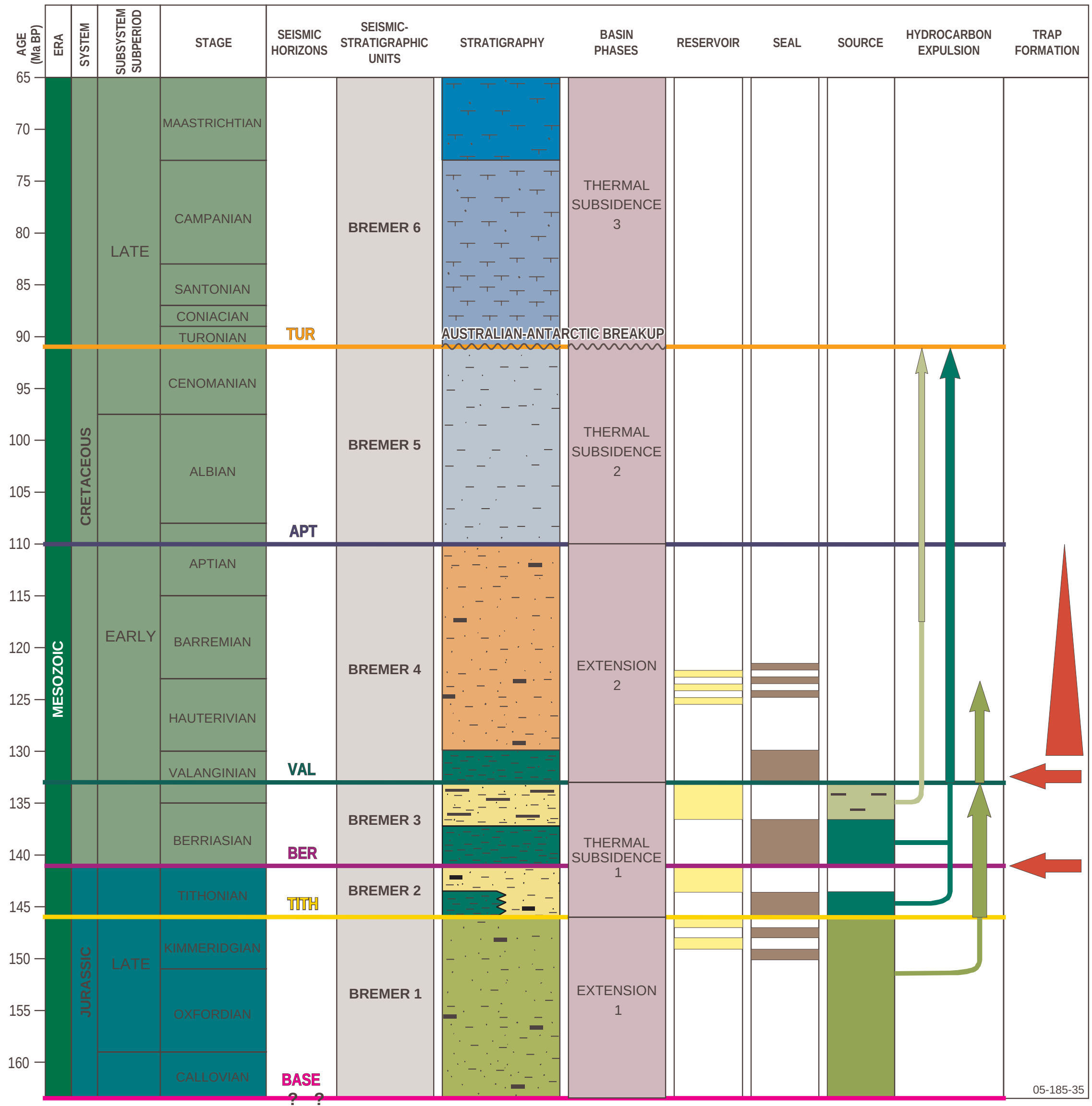


Figure 4.1: Stratigraphy and petroleum system elements of the Bremer Sub-basin.

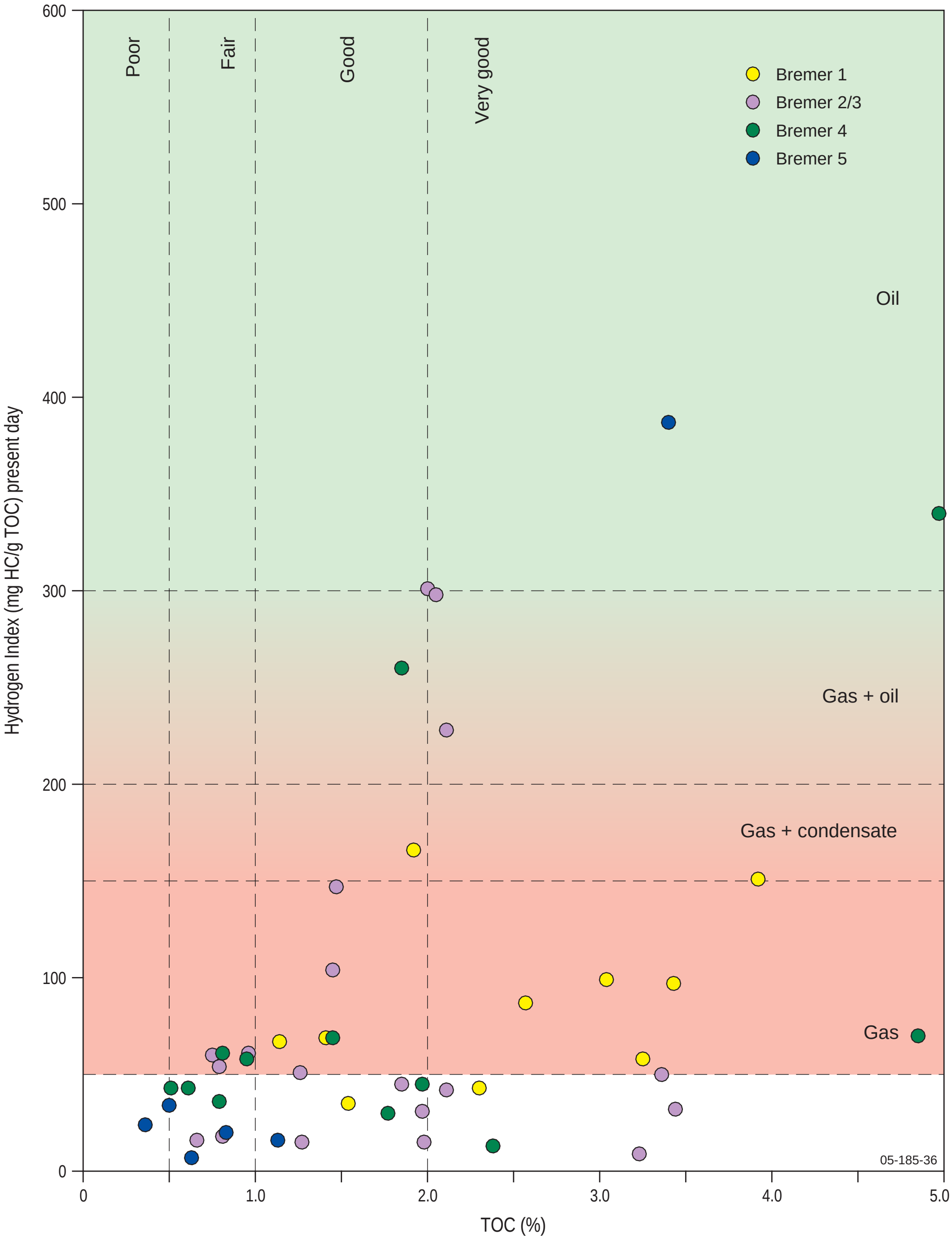


Figure 4.2: Source quality-maturity plot of kerogen Hydrogen Index versus TOC.

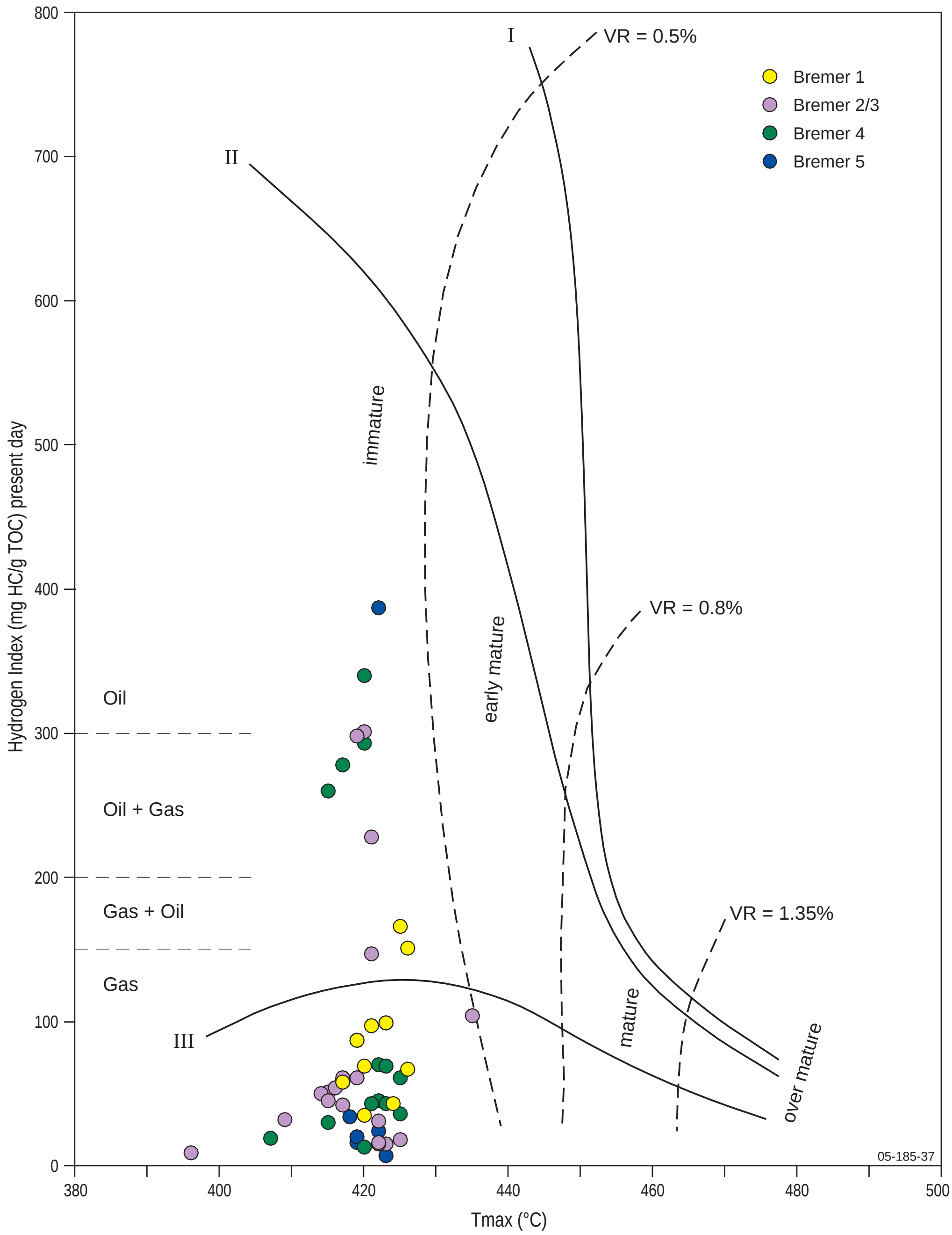


Figure 4.3: Source quality-maturity plot of kerogen Hydrogen Index versus Tmax.

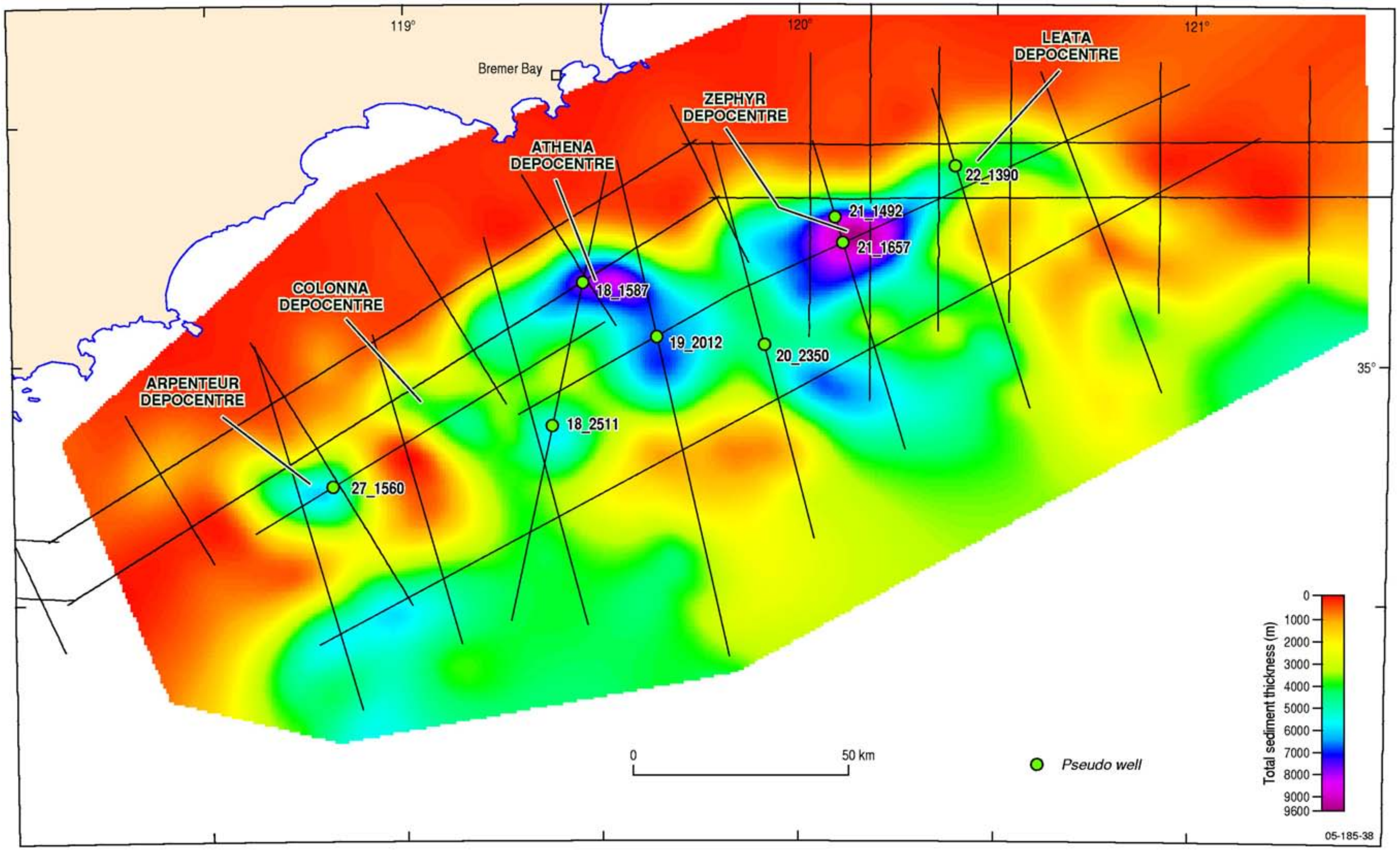


Figure 4.4: Location of 1-D pseudo-well geohistory models.

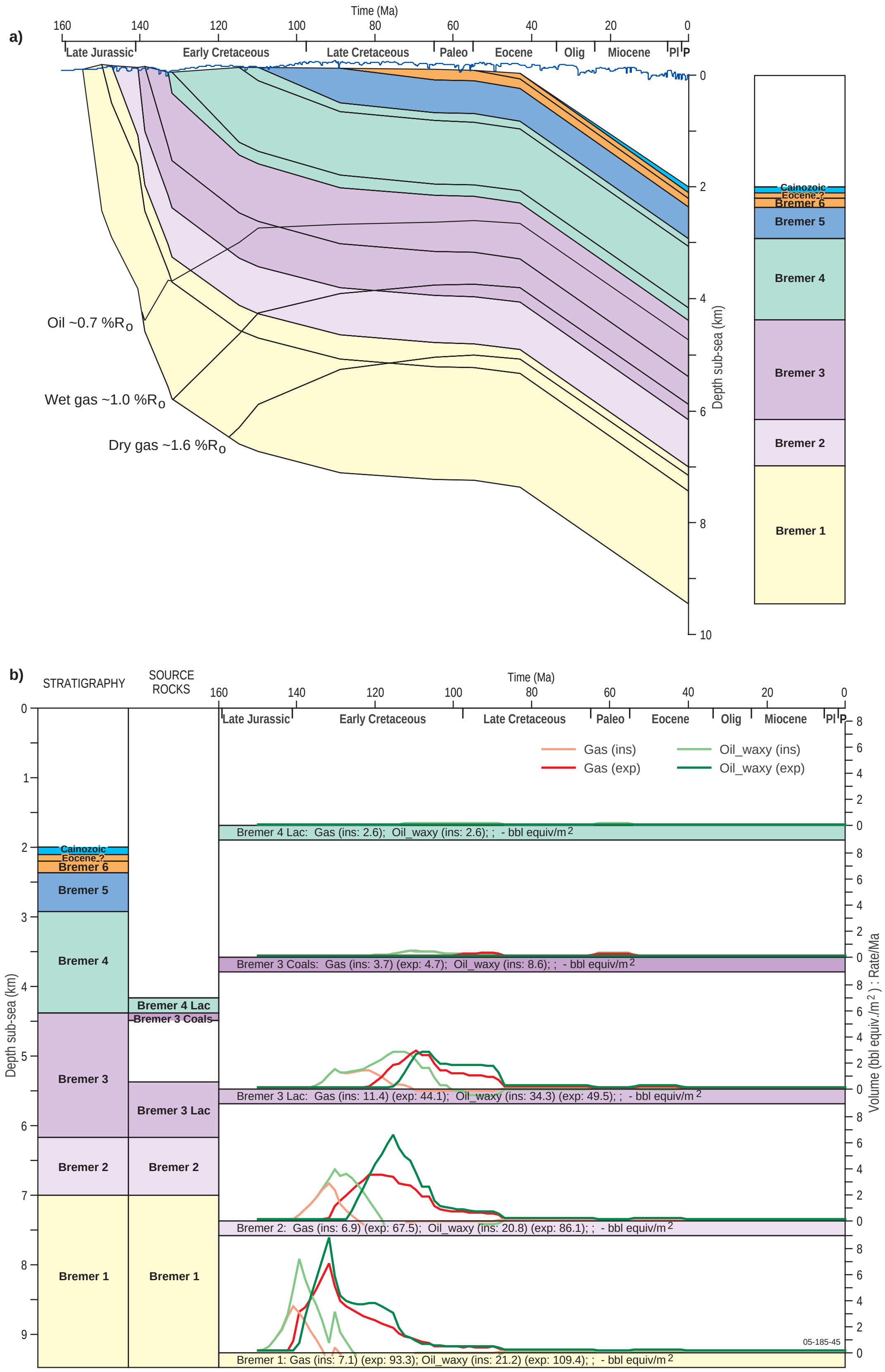


Figure 4.5: Summary of geohistory modelling for pseudo-well 19_2012; a) geohistory and subsidence model, b) source rock expulsion models.

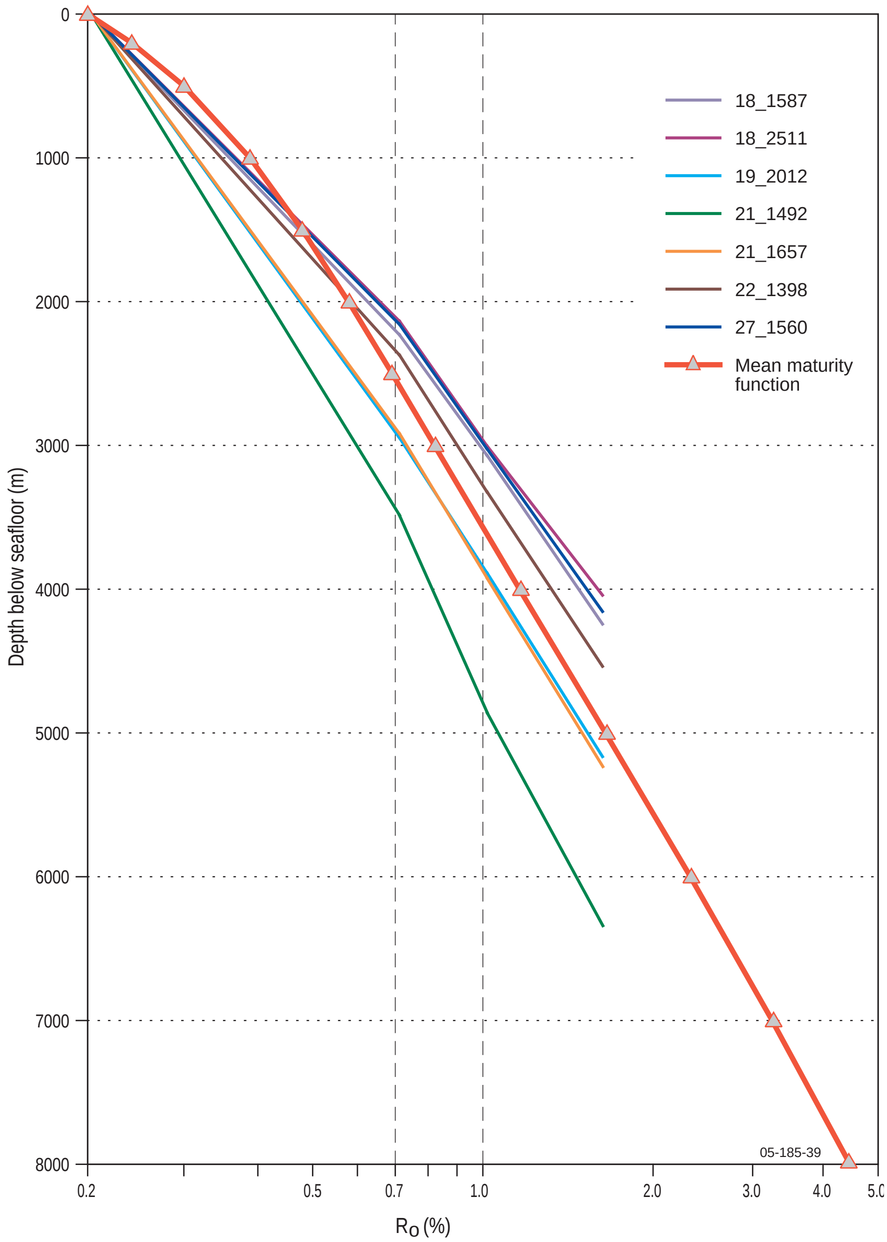


Figure 4.6: Predicted maturity-versus-depth profiles generated by the 1-D geohistory models and polynomial function used to generate maturity maps.

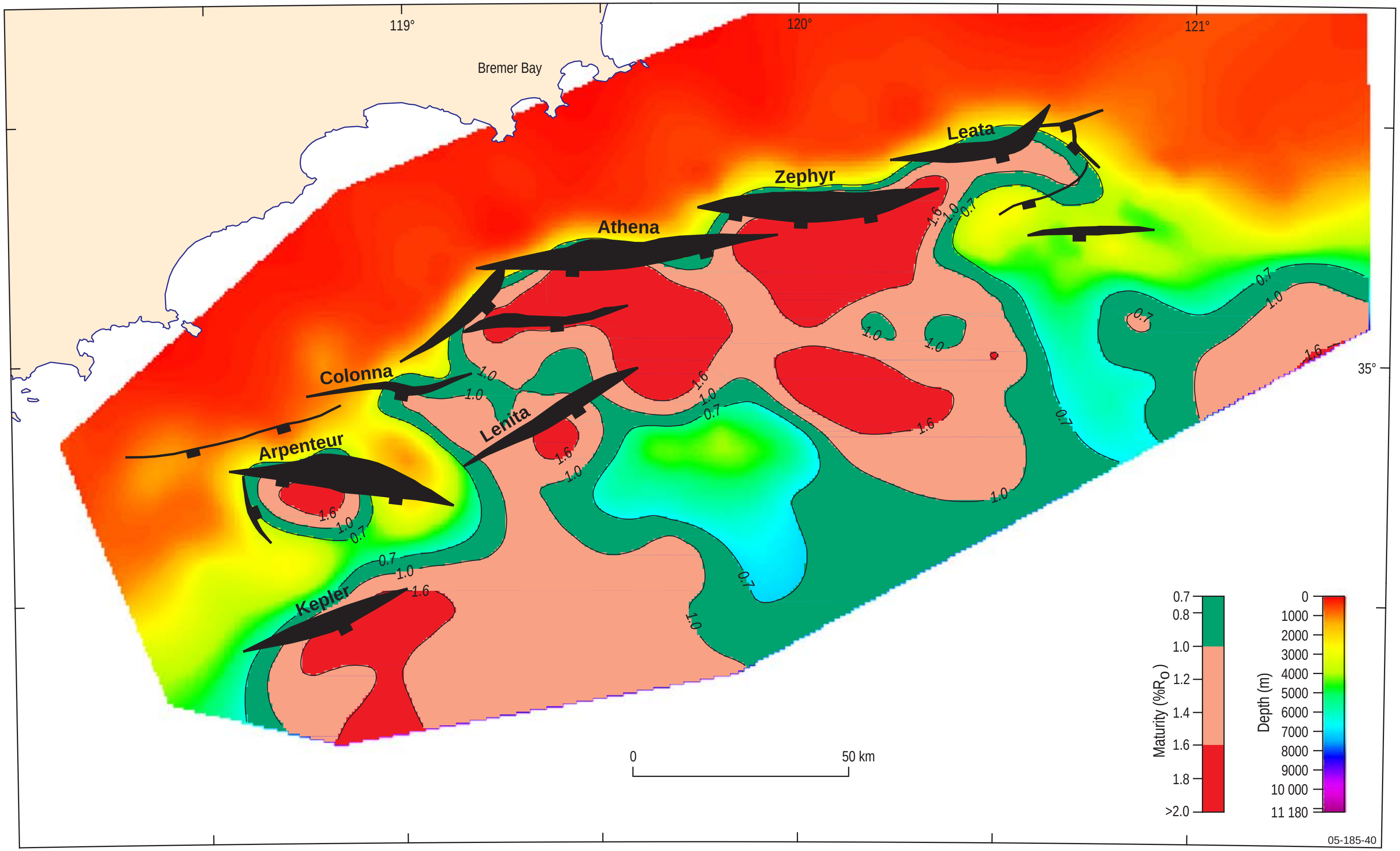


Figure 4.7: Predicted maturity map superimposed over a depth-structure map of the 'Base' seismic horizon, highlighting the over mature source rocks overlying basement.

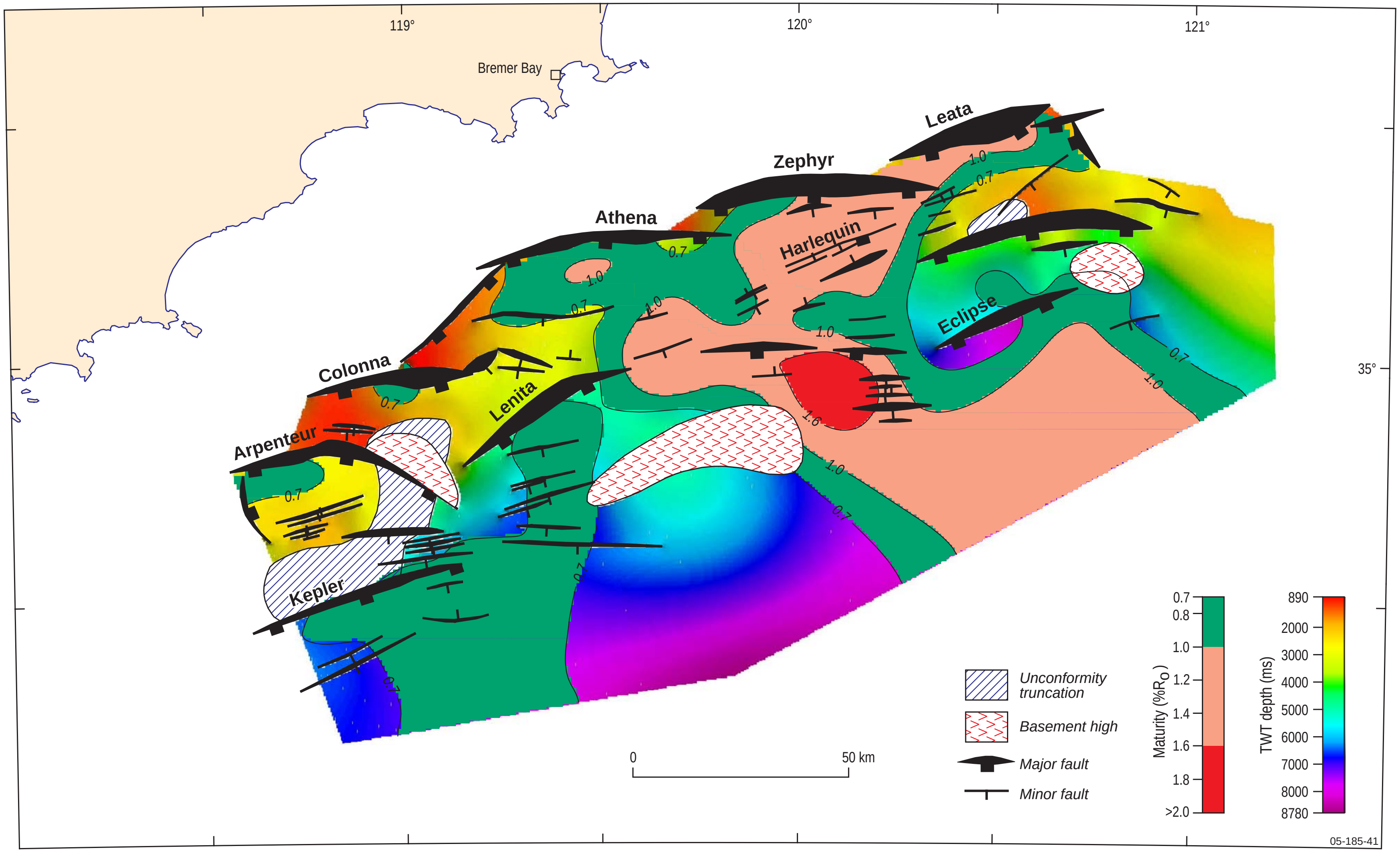


Figure 4.8: Predicted maturity map superimposed over a time-structure map of the 'Tith' seismic horizon, highlighting potential kitchen areas for the Bremer 2 lacustrine source rock and for source rocks at the top of Bremer 1.

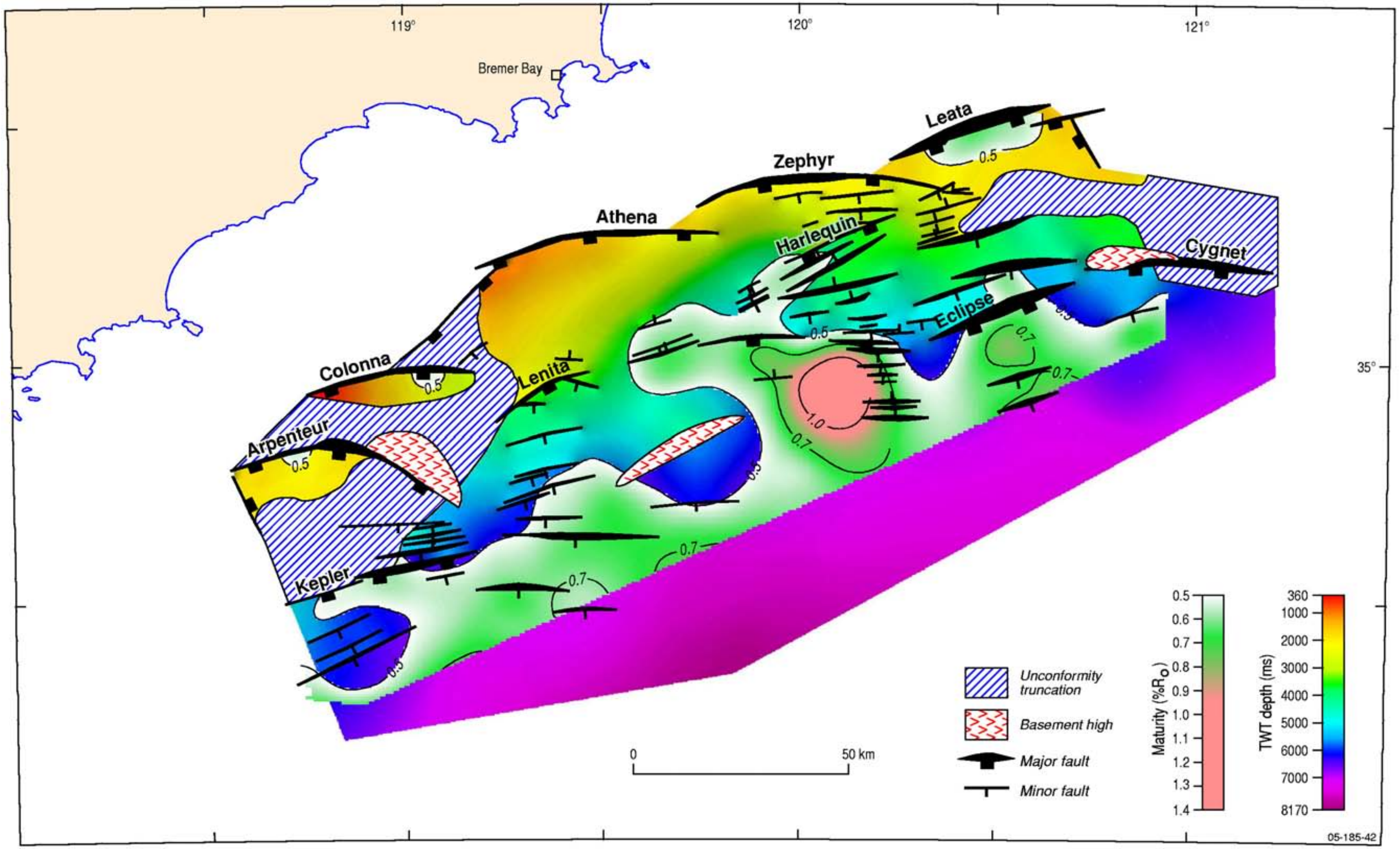


Figure 4.9: Predicted maturity map superimposed over a time-structure map of the 'Val' seismic horizon, highlighting potential source kitchen areas of the Bremer 3 coaly-facies source rock.

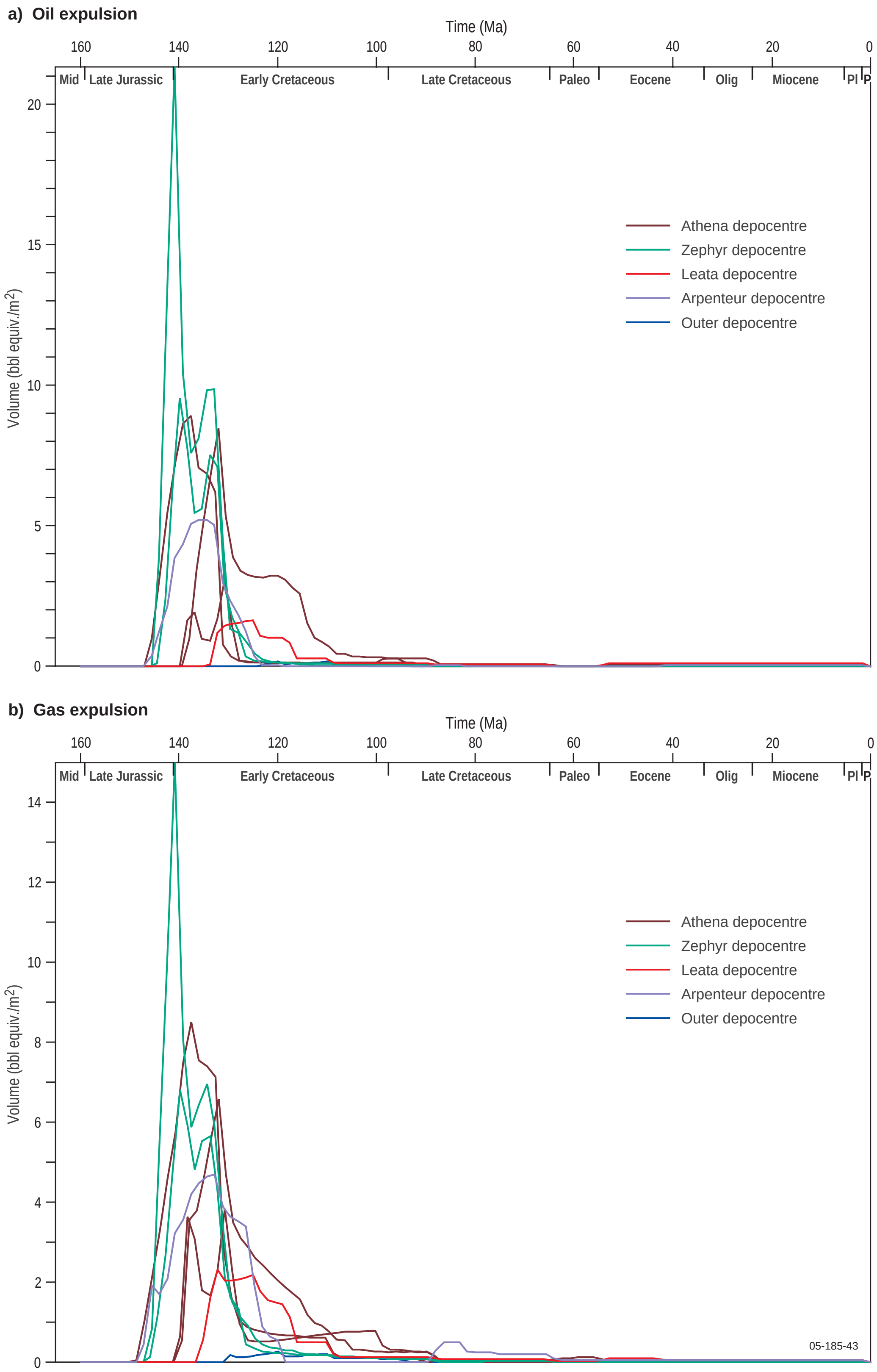


Figure 4.10: Modelled hydrocarbon expulsion from the Bremer 1 seismic-stratigraphic unit; a) modelled oil expulsion, b) modelled gas expulsion.

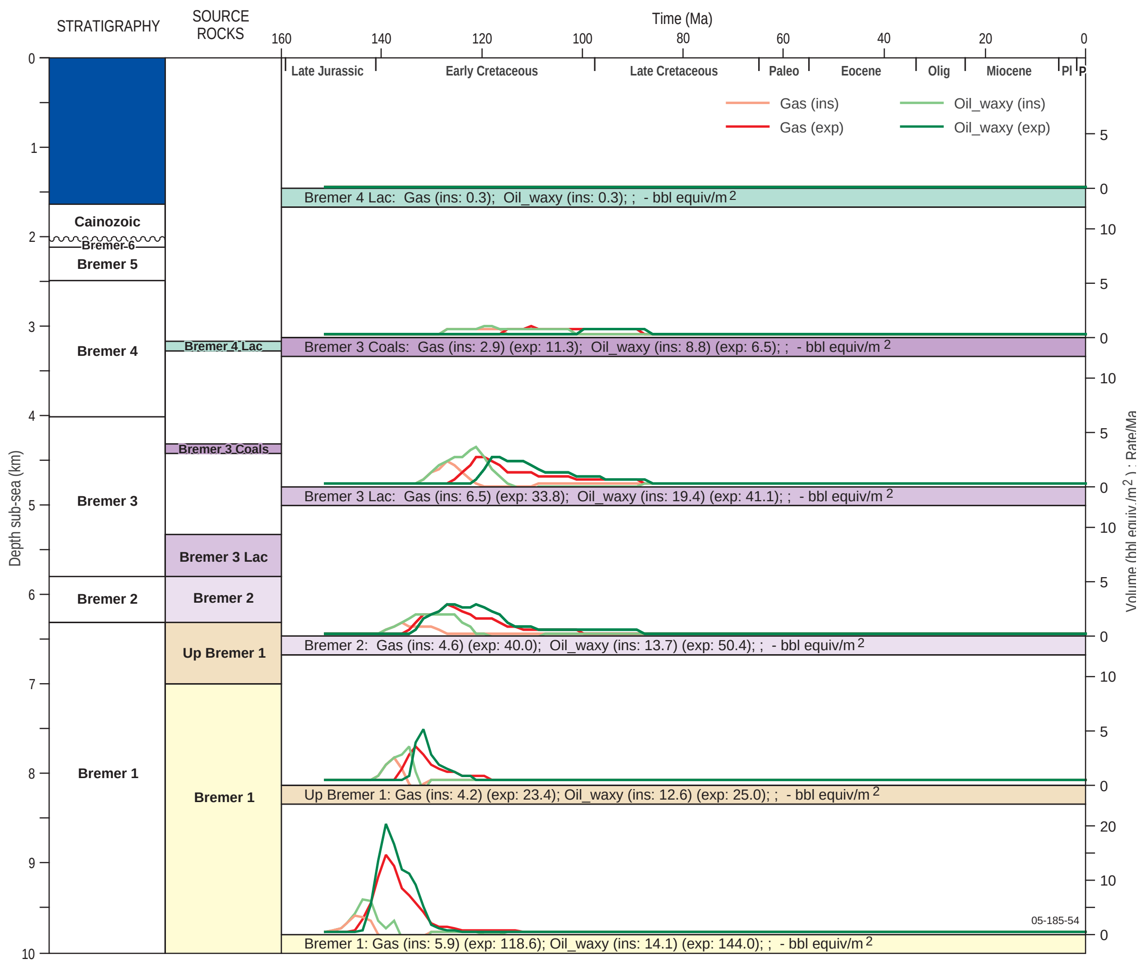
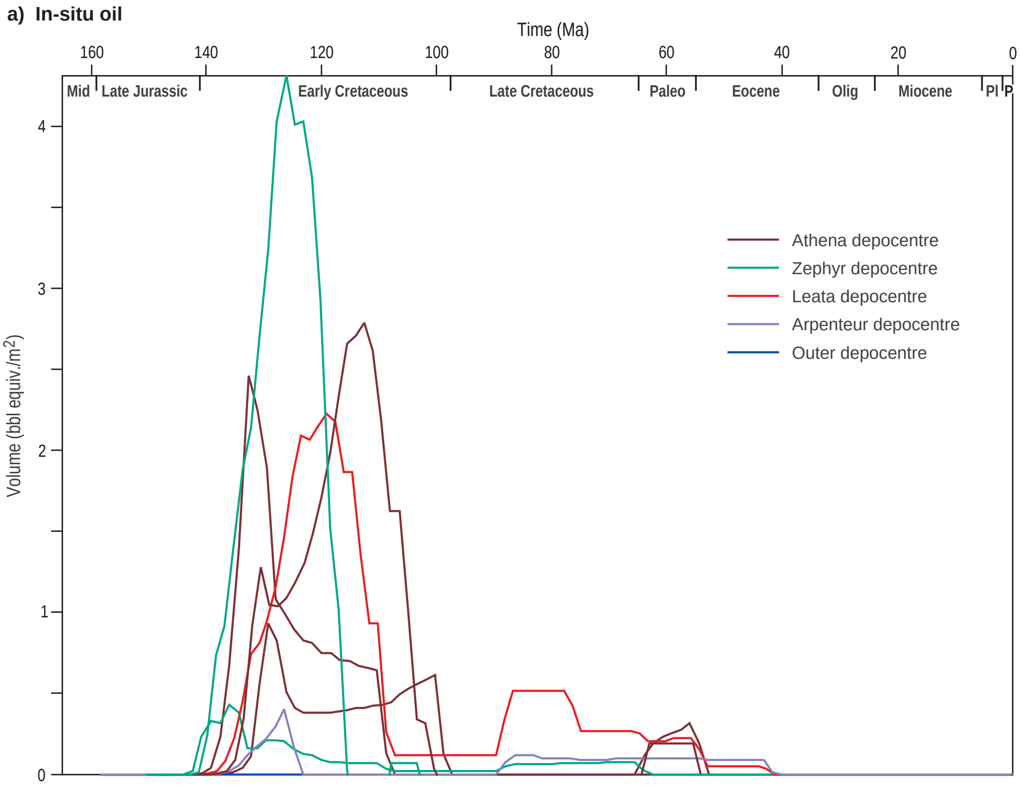


Figure 4.11: Hydrocarbon generation and expulsion models for pseudo well 21_1657.



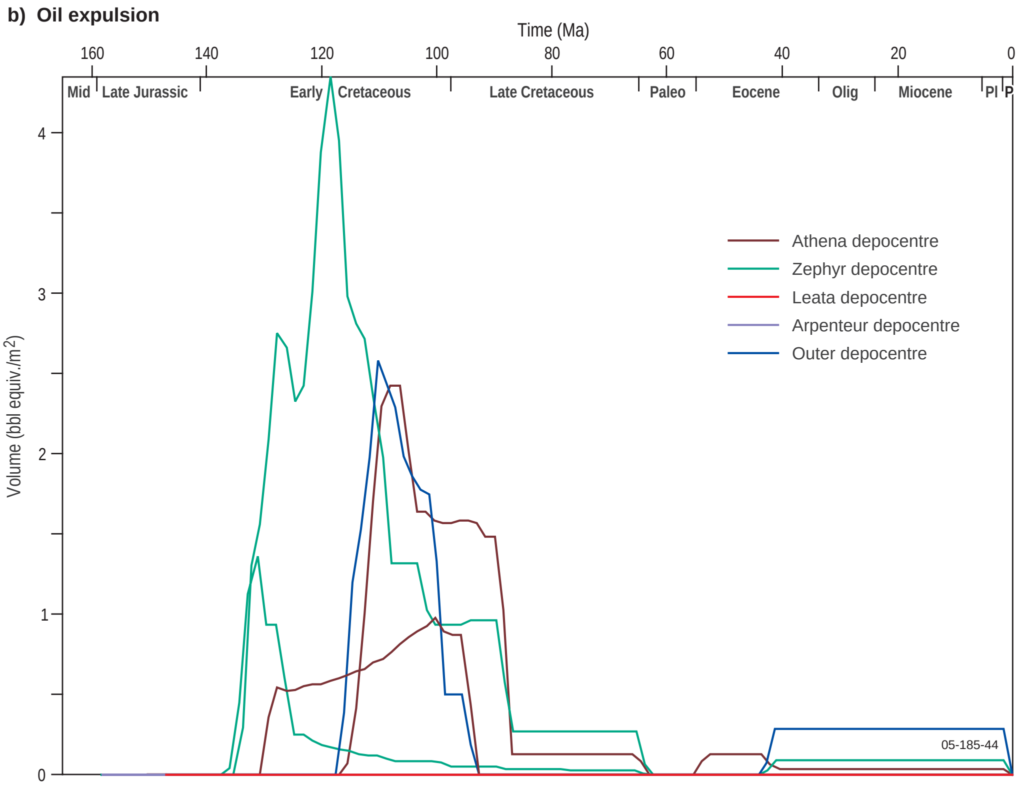


Figure 4.12: Modelled hydrocarbon generation and expulsion from the Bremer 2 and Bremer 3 lacustrine source intervals; a) in-situ oil generation, b) oil expulsion.

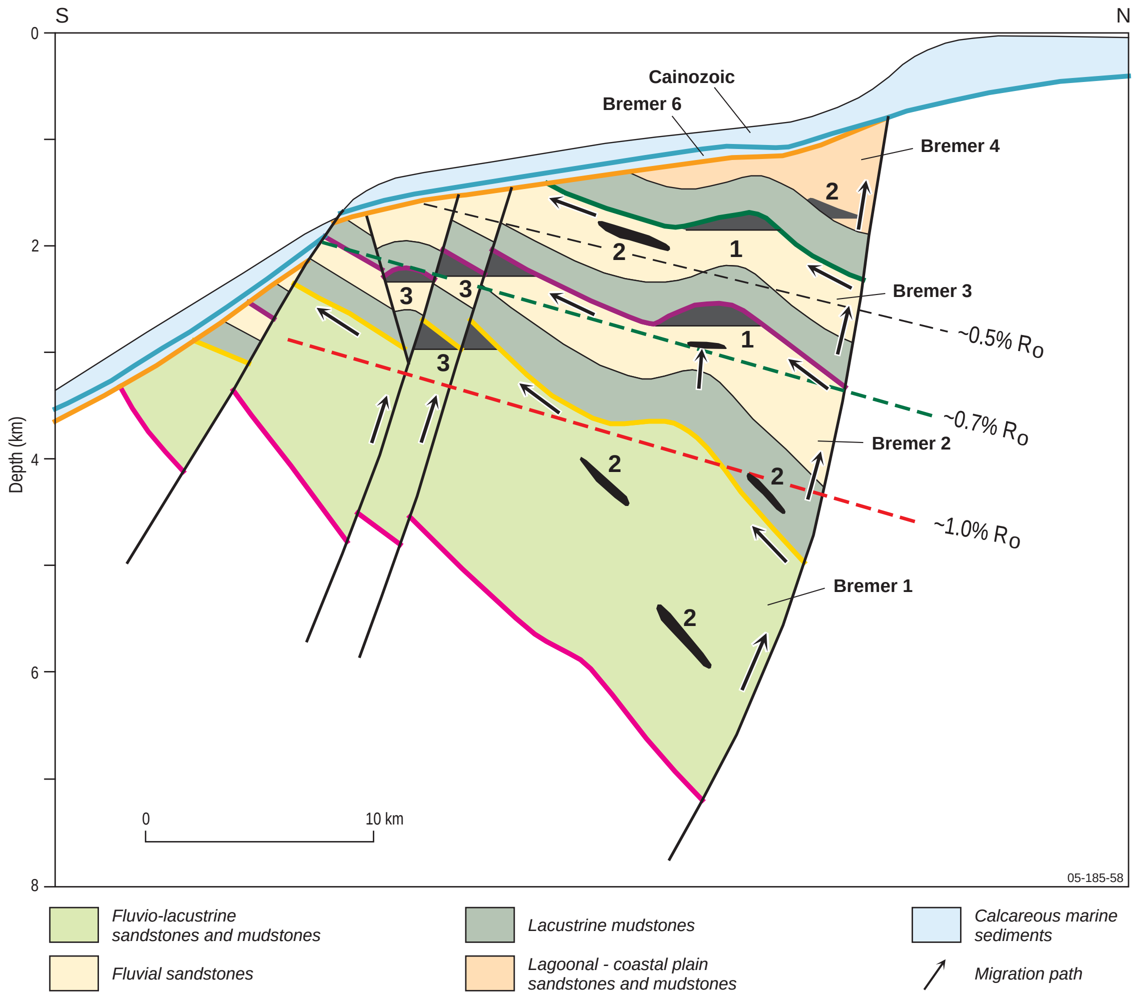


Figure 4.13: Schematic cross-section and play diagram for the Arpenteur and Leata depocentres (1 = anticlinal plays; 2 = combined structural /stratigraphic plays; 3 = fault block plays).

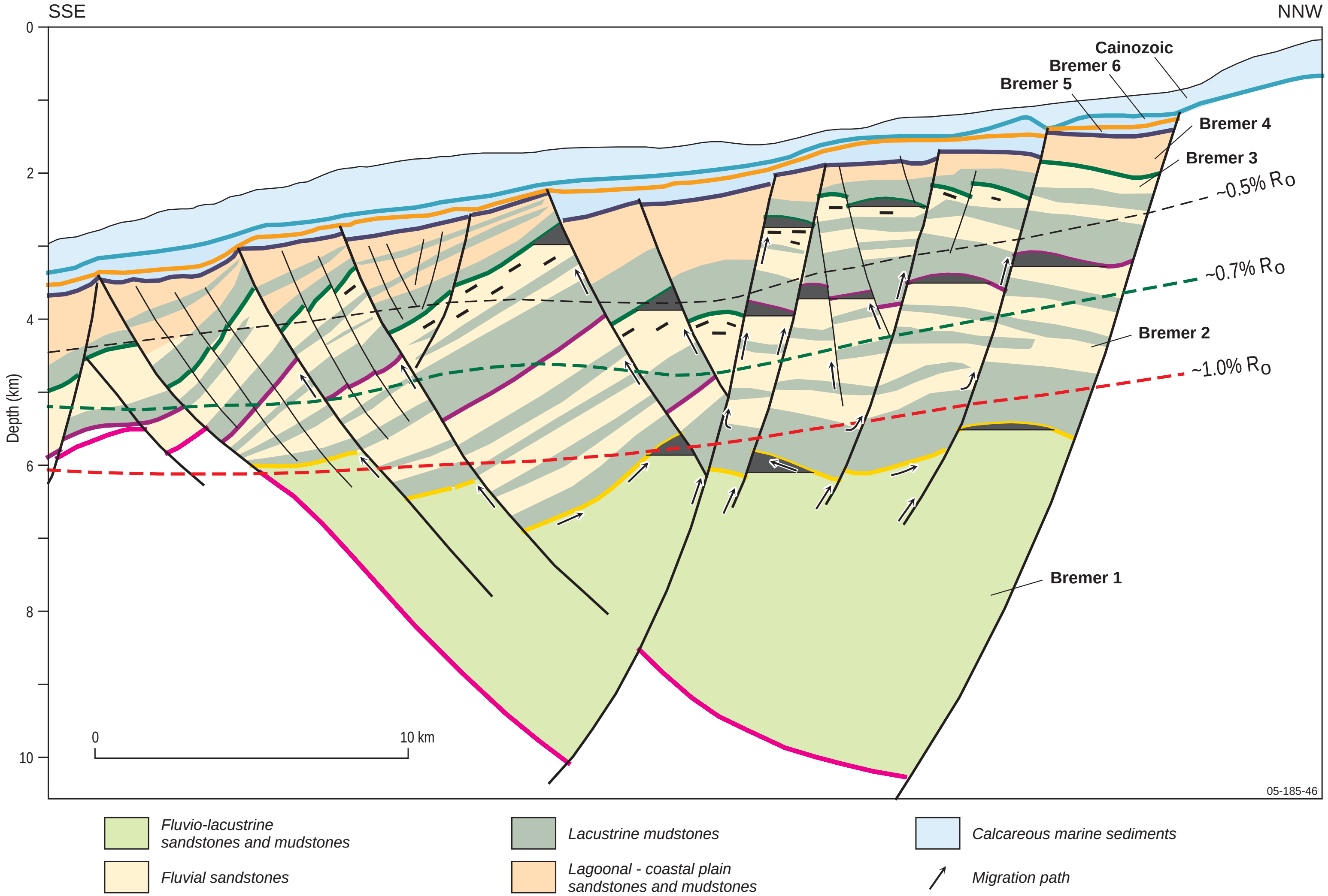


Figure 4.14: Schematic cross-section and fault block play diagram for the Zephyr depocentre.

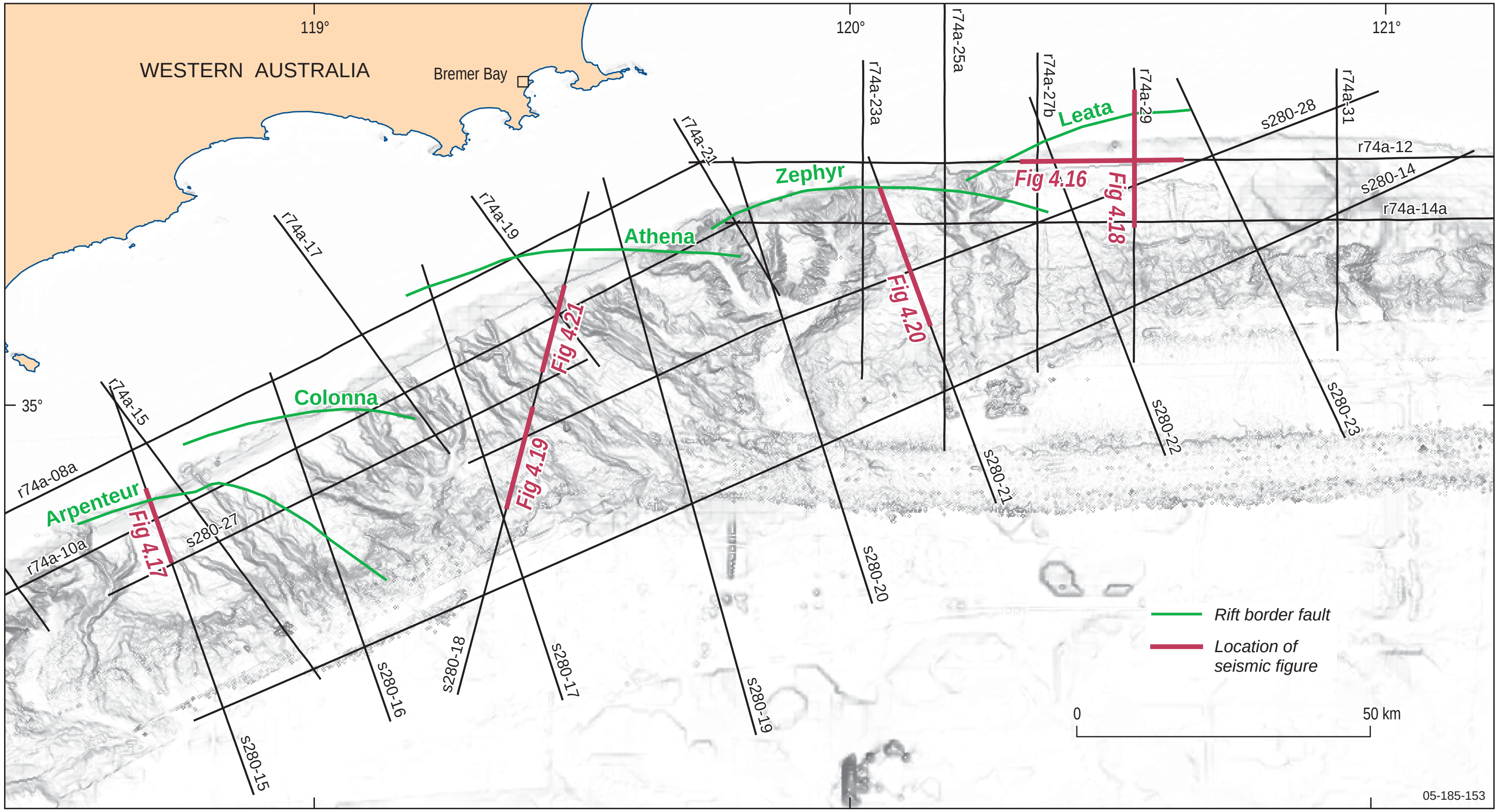


Figure 4.15: Location of play example figures superimposed over a bathymetry image.

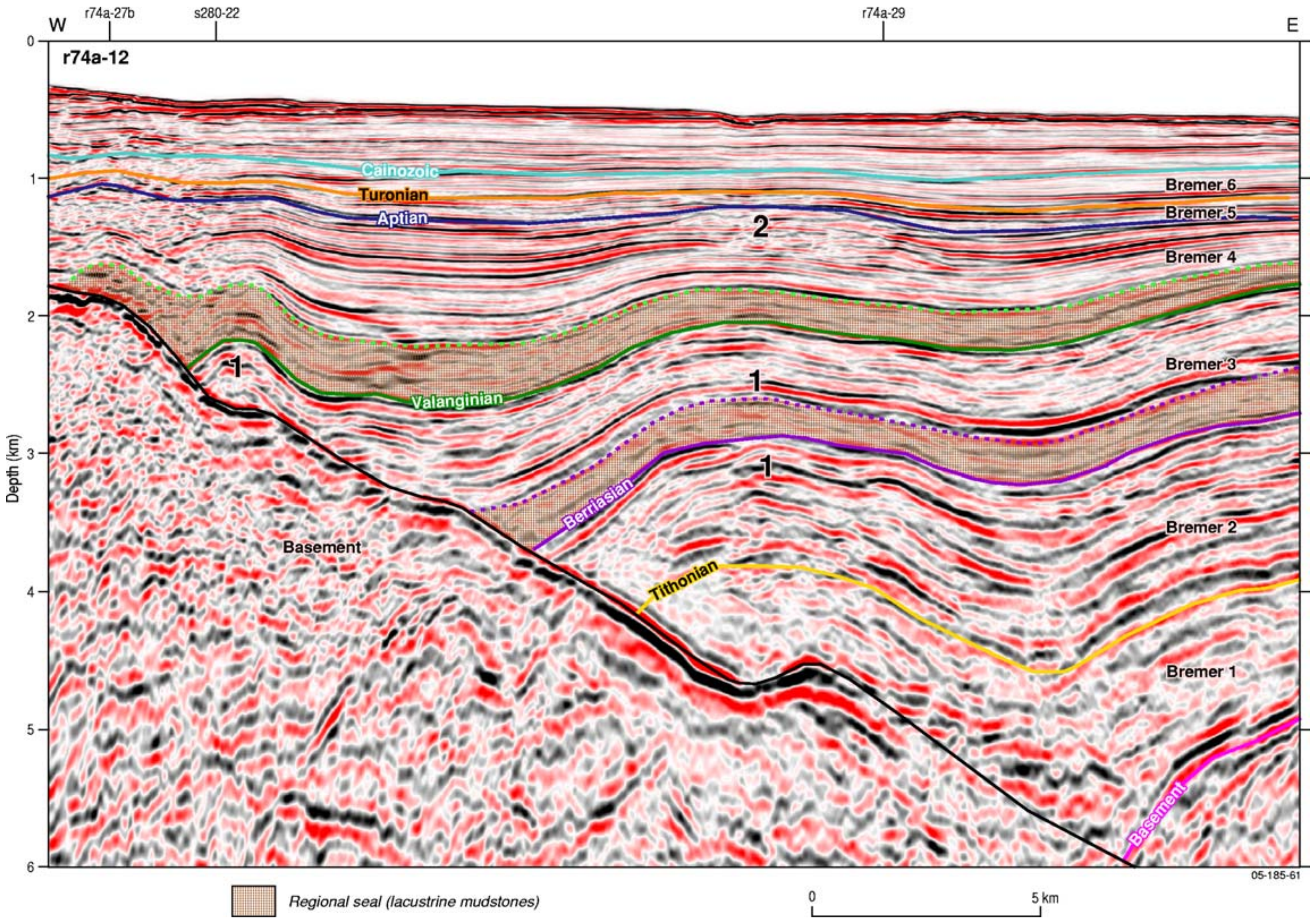


Figure 4.16: Depth-converted seismic strike line in the Leata depocentre (1 = anticlinal play; 2 = combined structural /stratigraphic play).

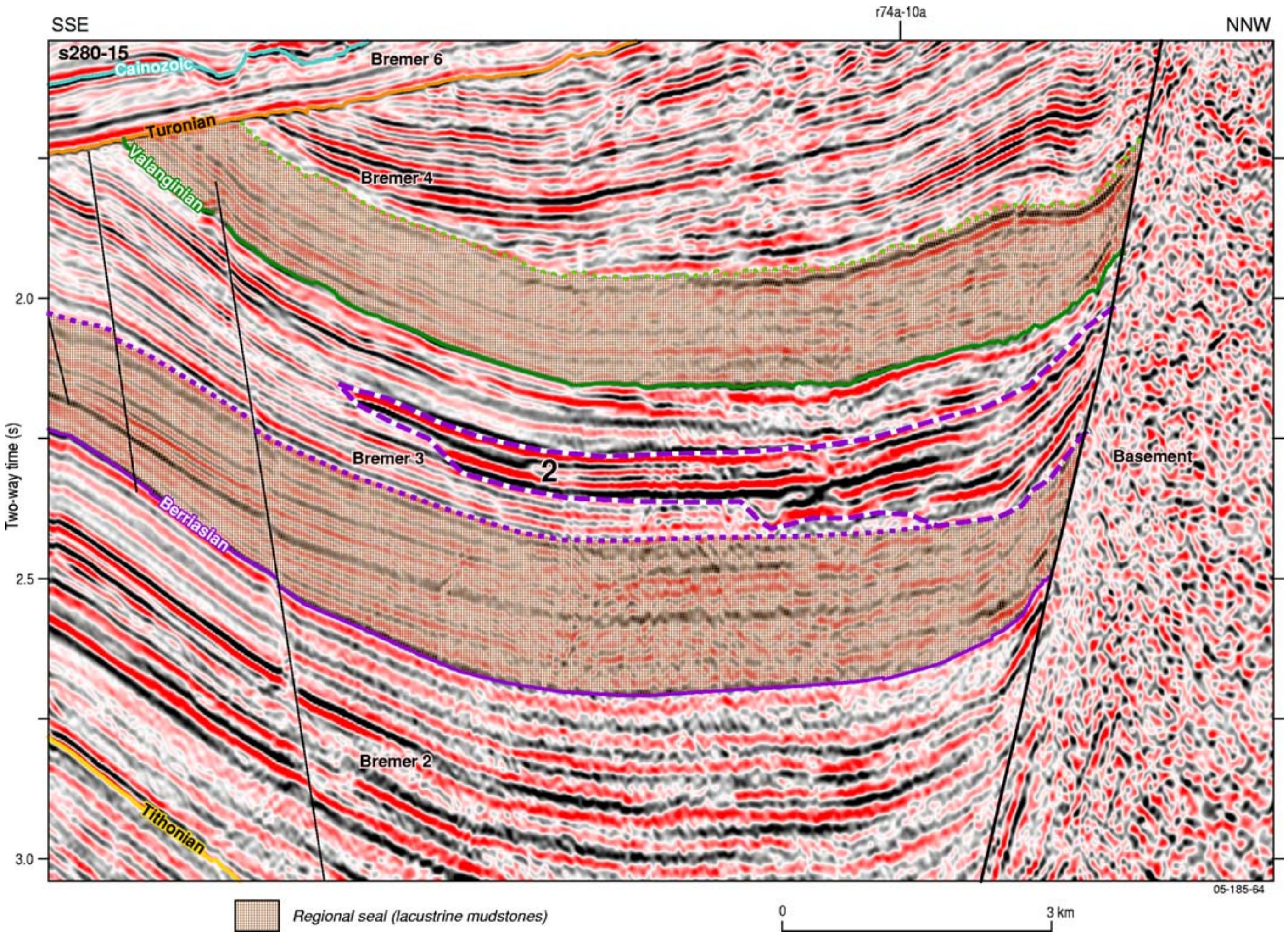


Figure 4.17: Seismic example of potential stratigraphic trap (2) in the Arpenteur depocentre.

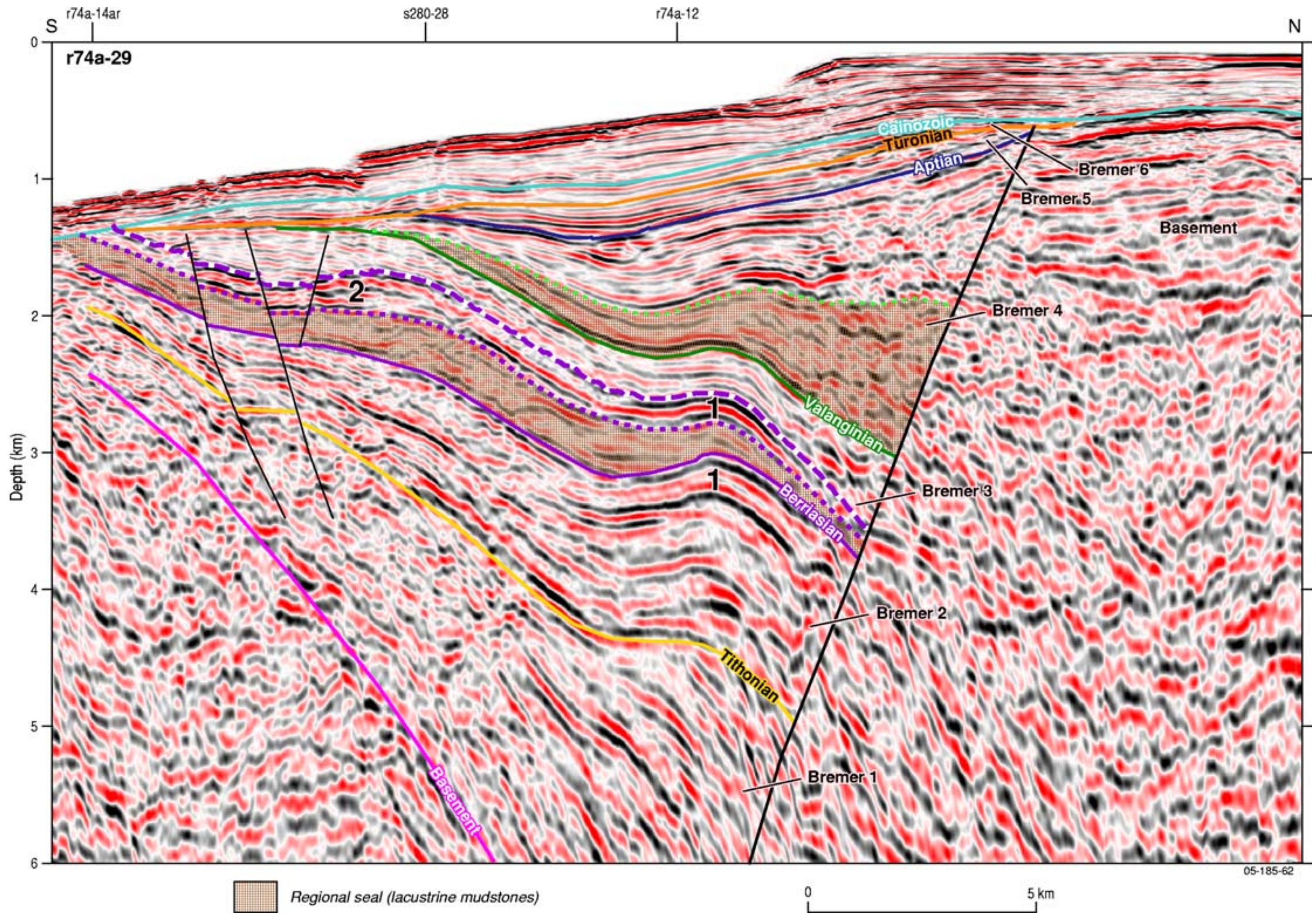


Figure 4.18: Depth-converted seismic dip line in the Leata depocentre (1 = anticlinal play; 2 = combined structural /stratigraphic play).

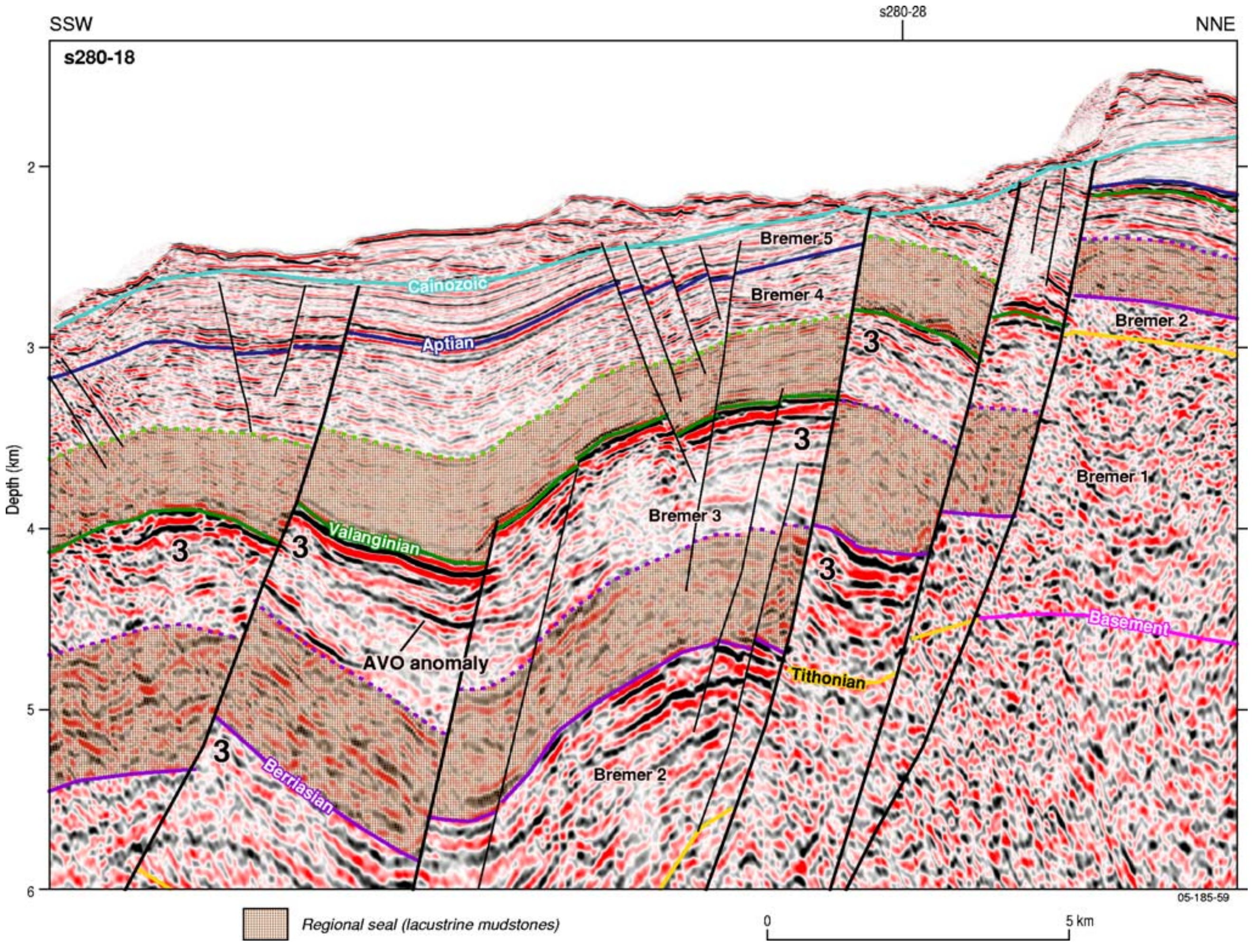


Figure 4.19: Depth-converted seismic dip line over potential fault-block traps (3) in a large roll-over anticline adjacent to the Lenita Fault.

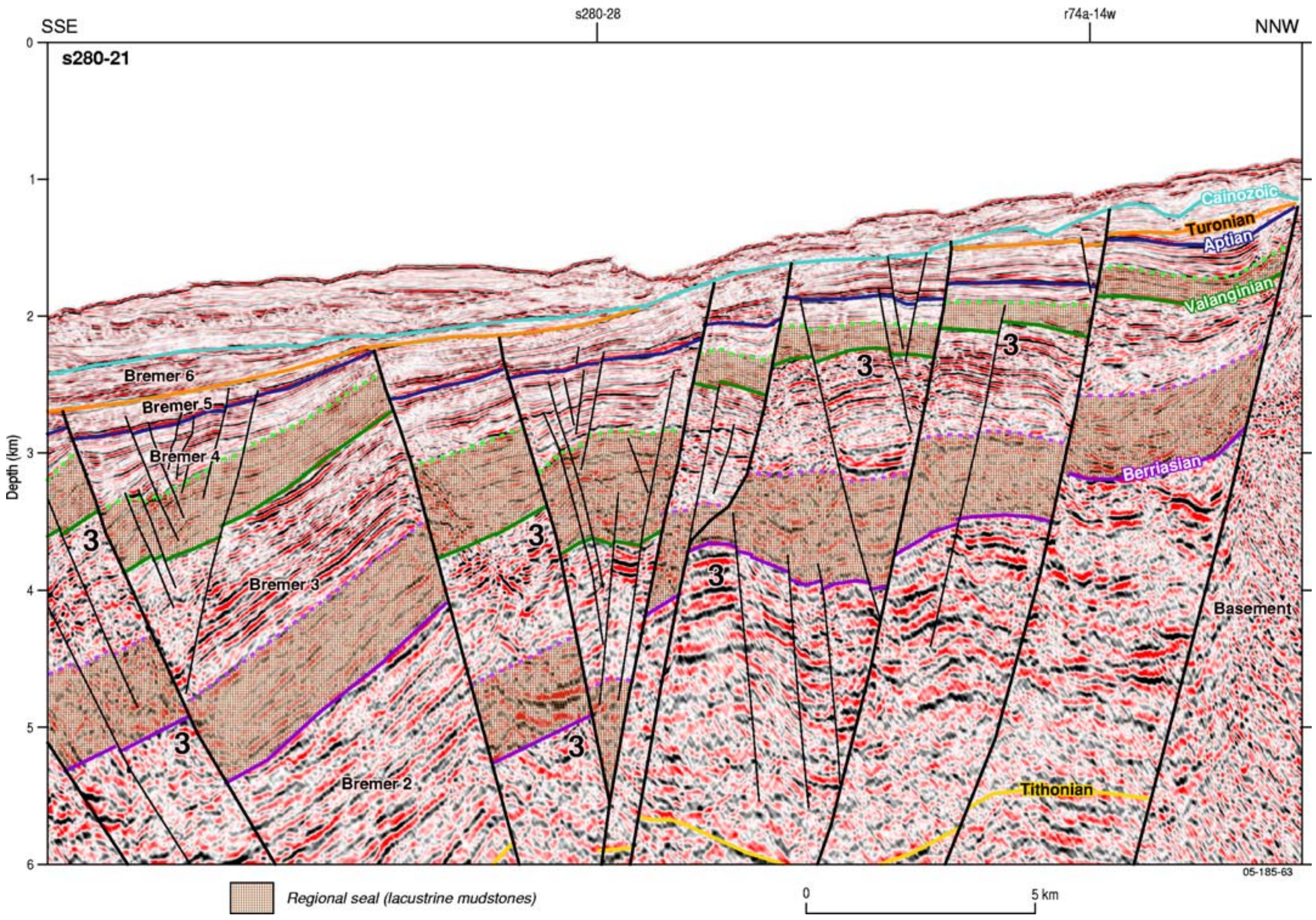


Figure 4.20: Depth-converted seismic dip line over potential fault-block traps (3) in the Zephyr depocentre.

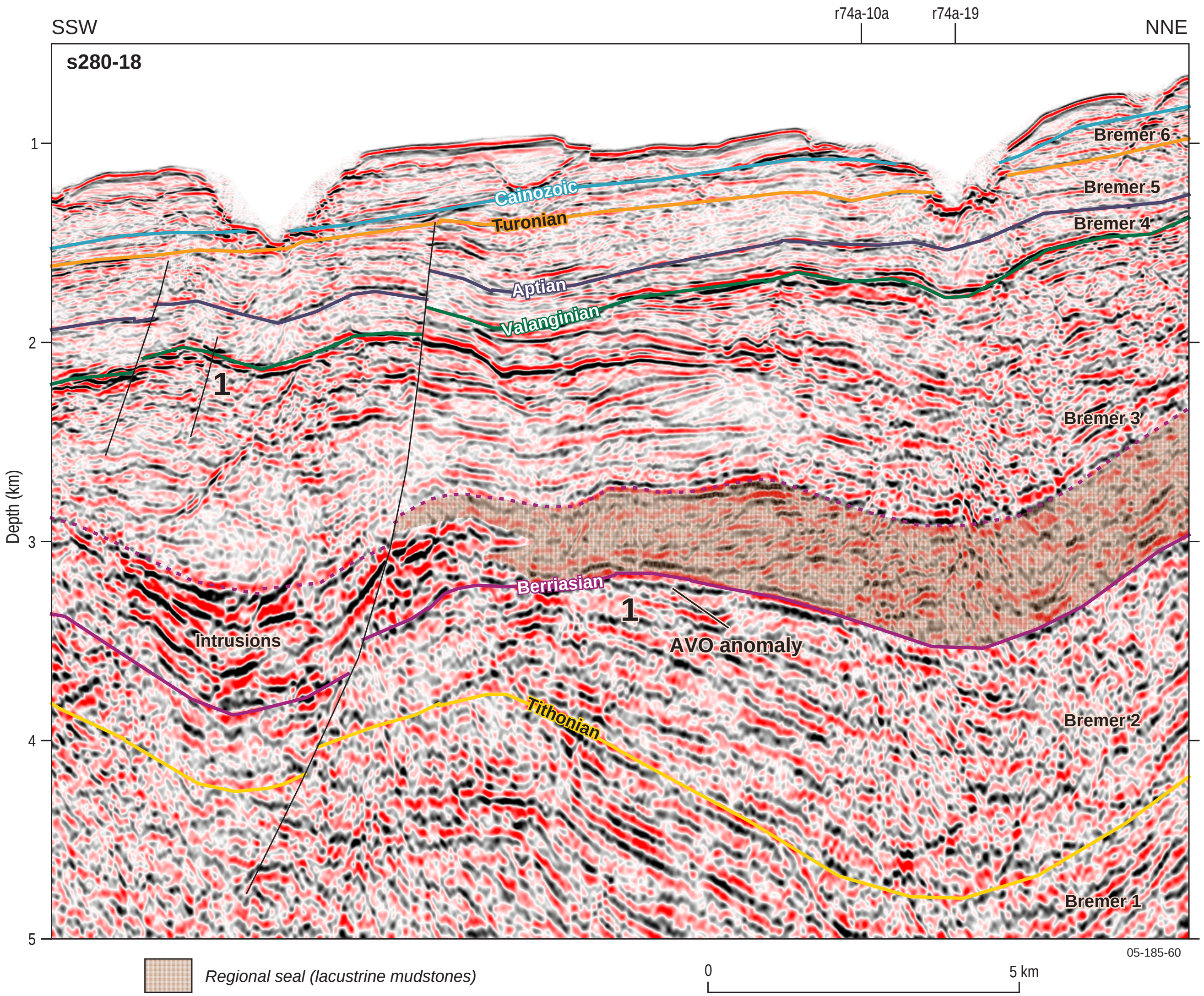


Figure 4.21: Depth-converted seismic dip line over a potential anticline trap (1) in the Athena depocentre.

Table 4.1: Summary of results for reservoir and seal analysis (modified from Boreham et al., 2005c*)*.

SAMPLE NO.	LITHOLOGY	UNIT	DEPOSITIONAL ENVIRONMENT	SEAL OR RESERVOIR POTENTIAL
265/15/DR15/C1.5	organic-rich claystone with mica and carbonaceous fragments	Bremer 4	fresh to brackish water lake	seal an oil column height of 42.4 to 70.7 m
265/19/DR19/A1.2	organic-rich mudstone with some mica, sandstone and coal	Bremer 1	a fluvial to fresh–brackish water lake	seal an oil column height of 36.3 to 60 m
265/19/DR19/B1.3	medium to very coarse grained, quartzose sandstone to conglomerate with lithic and coal fragments and minor carbonate cement	Bremer 1	fluvial	reservoir with a maximum porosity of 24% (note that traces of oil were identified during fluid inclusions analyses)
265/24/DR24/E1.4	fine grained calcarenite containing abundant sponge spicules	Eucla Basin	marine	reservoir with a maximum porosity of 27.4%
265/25/DR25/B1.2	shale/mudstone	Bremer 6	inner shelf	seal an oil column height of 87.6 to 146 m
265/27/DR27/A1.2	medium to coarse grained, sub-arkosic sandstone with biotite and lithic fragments, interbedded with organic rich claystones	Bremer 4	fresh to brackish water lacustrine	reservoir with a maximum porosity of 29.9% (note that traces of oil were identified during fluid inclusions analyses)
265/34/DR34/D1.2	fine grained quartz arenite with abundant mica and pink feldspar	Bremer 3 or Bremer 4	fresh to brackish water lacustrine	reservoir with a maximum porosity of 34.2%
265/52/DR40/A1.3	silicified quartz arenite with some feldspar	Bremer 1 or Bremer 2	fluvial	limited reservoir with a maximum porosity of 10.2% (note that traces of oil were identified during fluid inclusions analyses)
265/55/DR43/B1.2	claystone with carbonaceous zones	Bremer 6	marine	seal an oil column height of 51.2 to 85.4m
265/56/DR44/A1.1	medium to coarse grained, red (oxidised) fluvial sandstone with mica and traces of feldspar	Bremer 1 or Bremer 2		reservoir with a maximum porosity of 31.2%. Note that traces of oil inclusions were identified during fluid inclusions analysis

5. Conclusions

The Bremer Sub-basin is a frontier area for petroleum exploration. Through integrating dredge sample data with regional seismic interpretations, it has been possible to develop a structural and stratigraphic framework for the sub-basin, and assess the petroleum exploration potential using conventional basin analysis techniques. Results show that all the key elements of a potential petroleum system are present. The cyclic fluvial and lacustrine depositional history of the Bremer Sub-basin during the Late Jurassic and Early Cretaceous provides key petroleum system elements of source, reservoir and seal. Of particular importance to petroleum exploration are three intervals of lacustrine mudstone deposition during the Tithonian, Berriasian and Valanginian. These lacustrine mudstones form potential source rocks and thick regional seals. Subsequent phases of fluvial sandstone sedimentation provide potential reservoir intervals. An interval of thick coals in the Berriasian may also represent a potential source rock unit.

The sub-basin contains up to 9.5 km of sedimentary rocks, which is sufficient basin fill to generate and expel hydrocarbons from Jurassic–Early Cretaceous lacustrine mudstones and coals. Anticlinal structures and fault blocks that formed during a period of extension in the Valanginian–Aptian have potential to trap large volumes of hydrocarbons. Lacustrine mudstones at the base of the Late Jurassic Bremer 2 unit and the Early Cretaceous Bremer 3 unit have the greatest potential to charge these traps, with their main phase of hydrocarbon expulsion occurring during the Valanginian–Cenomanian.

Exploration opportunities and risks vary across the sub-basin. A large potential source kitchen area occurs in the central part of the sub-basin, where sediments are between 4–9.5 km thick. Here, the main exploration play is fault block traps in water depths of 1000–>2500 m, which have the potential to trap ~250 million barrel of oil in place (P_{50} estimate; P_{10} estimate = ~500 million barrels). Trap preservation is the main exploration risk in the central sub-basin area, with many faults reactivated during the Late Cretaceous. Smaller depocentres containing 4–5 km of sediments occur in the western and eastern parts of the Bremer Sub-basin. The main exploration play in these smaller depocentres is large anticlinal structures in water depths of 500–800 m, which have the potential to trap 500 million barrels of oil in place (P_{50} estimate; P_{10} estimate ~900 million barrels). Hydrocarbon charge is the main exploration risk in these smaller depocentres.

Acknowledgments

The Bremer Sub-basin Study has only been possible through the efforts of a team of scientific and support staff at Geoscience Australia. The authors wish to thank the following staff for their valuable contributions to the report:

- Jane Blevin for her scientific input into the stratigraphic framework study and petroleum play modelling.
- Jennifer Totterdell for her scientific input into the the stratigraphic framework and structural framework studies.
- Mike MacPhail for providing biostratigraphic data and scientific input for the stratigraphic framework study.
- Heike Struckmeyer and Ian Deighton for providing technical advice on the burial history modelling.
- Peter Petkovic and Alexey Goncharov for providing a time-depth velocity function and results of basement studies from refraction data.
- Andrew Barrett for providing trap volume estimates.
- Neville Exon for his work as chief scientist on the S-265 dredge sampling survey.
- Angie Jaensch, Veronika Galinec and Chris Fitzgerald for drafting figures.
- Jim Mason for producing the digital record.
- Jim Colwell and John Kennard for their constructive reviews of the manuscript.

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