Clarence-Moreton SEEBASE™ & Structural GIS Project

F/T Project Code: **MR707**

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NSW DEPARTMENT OF
PRIMARY INDUSTRIES

FrOG Tech

Clarence-Moreton SEEBASE^{TM} and Structural GIS Project, February 2008

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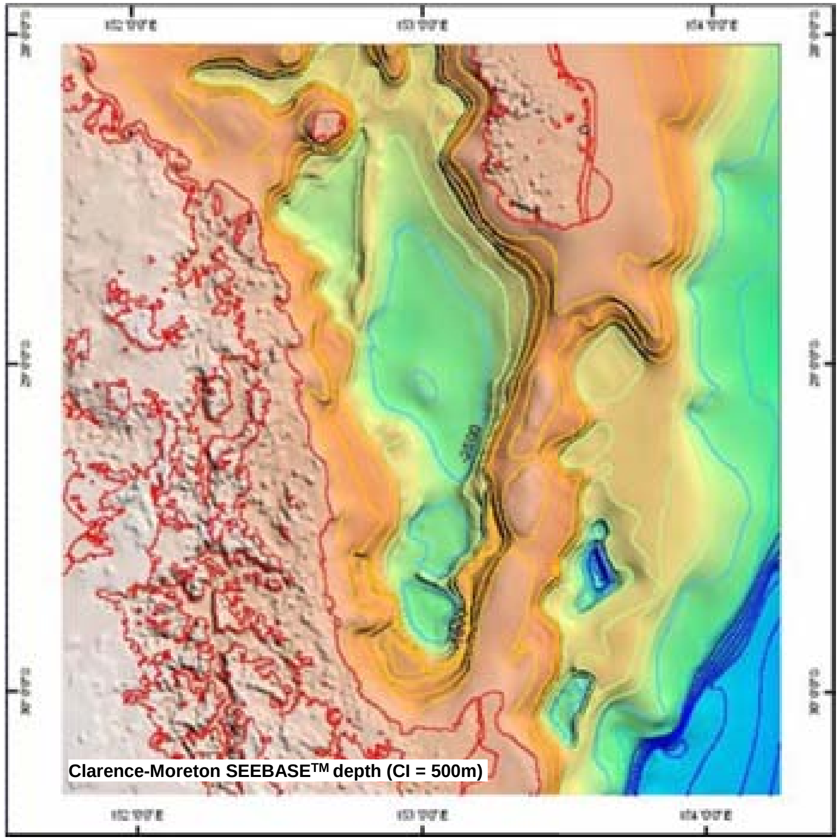


Clarence-Moreton SEEBASE^{TM} depth (CI = 500m)

The main objectives of the Clarence-Moreton *SEEBASE^{TM} and GIS Project study were to provide the NSW Department of Primary Industries with an integrated regional interpretation of the basement composition, lithology, structure and depth of the Clarence-Moreton Basin in New South Wales. This included the construction of a depth to basement image (SEEBASE™) for the area.

The effects of the basement geology on the evolution of the Clarence-Moreton Basin (both onshore and offshore) and of its precursors, the Esk Trough and the Ipswich Basin have been investigated. Attention was focused on the formation and reactivation of the basin controlling structures. The evolution of these structures has been evaluated in the light of the different tectonic events that have affected the area.

Maturity and fluid flow migration maps derived from SEEBASE^{TM} grids indicate that the central axis of the onshore depocentres and parts of the offshore basin are mature for present-day oil generation. However, these maps probably underestimate the maturity along the eastern margin of the basin, due to significant uplift and erosion that occurred during the Cenomanian. Such areas are likely to be mature for hydrocarbon generation provided adequate source rocks are present at depth.

Available gravity and magnetic data have been reprocessed and enhanced with an extensive set of wavelength and amplitude filters. An ArcMap 9.0 GIS product has been constructed that includes all structural interpretations, as well as the potential field data.

The revised and expanded interpretation of the structure and basin architecture in the area of the Clarence-Moreton Basin provides an improved understanding of basin evolution in the region, which will contribute to the reduction of exploration risks in the area.

Key results of the Clarence-Moreton Project

- The Clarence-Moreton Basin overlies the core of the sheared New England Orocline.
- Orocline folding took place in the Early Permian, setting a lower limit on basement age.
- Basement was also affected by the Late Permian to Middle Triassic Hunter-Bowen compressional event.
- The basal Nymboida Formation is interpreted to be late stage Hunter-Bowen foreland basin sediments that have been folded prior to the deposition of the Ipswich Formation.
- The Ipswich Formation is interpreted to be a late to post Hunter-Bowen flooding event that fills topography.
- The Clarence-Moreton Basin sediments onlap the western margin, the eastern margin is a structural boundary produced by uplift of the basin margin in Cenomanian time.
- Cenomanian folding results from basin sediments accommodating E-W shortening of the basin through conjugate strike-slip faults.
- There is minimal evidence preserved onshore of the Tasman Sea extension.
- Offshore continuation of the basin has been confirmed, with a sedimentary sequence that would incorporate correlatives of the onshore Evans Head and Ipswich Coal Measure sequences as well as of the Marburg Subgroup.

*SEEBASE™ = Structurally Enhanced view of Economic Basement

Recommendations

- Very limited well data is available within the Clarence-Moreton Basin in the MR707 project area, with only two wells intersecting basement in the NSW part of the basin and limited intersections of the main basinal sequences. A reconnaissance stratigraphic drilling program to test the stratigraphy and basement composition would help to constrain the model of basin evolution.
- A regional deep seismic line across the basin (and potentially extending across the offshore basin) would provide more constraints on basin evolution – in particular, basement involved deep structures which are not imaged on conventional industry seismic data.
- Develop and validate a regional maturity map using all available organic geochemistry data and 2D burial history models to constrain the timing of hydrocarbon generation in the context of regional tectonic and magmatic events.
- The acquisition of new high-resolution gravity data is recommended. This data will enable the mapping of deep folds within the basement. These folds probably had a significant influence on the deposition of the deep coal measures – as indicated by the distribution of these units on seismic data (filling relic topography).
- The Clarence-Moreton-Basin (and underlying infrabasins) formed over basement that is intensely intruded by granites. These granites may have potential as a geothermal energy source and, if highly radiogenic, may have also influenced the maturity of the overlying coal measures. Further work to assess the radiogenic potential of these granites is warranted to understand this aspect of resource potential.
- NSW DPI have also undertaken a program to compile all existing industry seismic data during 2007, and some of this data was available for the current study. A full mapping program of all reprocessed seismic data using the results of this SEEBASE™ study is strongly recommended. An updated mapping program will help to better predict facies distribution and resource potential based on the integration of basin forming events, subsidence history and depositional environments.
- The results obtained in this study should be incorporated into OZ SEEBASE™. A revision and update of the SEEBASE^{TM} model presented in this study is recommended as more seismic and well data become available. Depth values from the present model can then be tied to depth values from seismic and well data to significantly reduce errors and uncertainties.

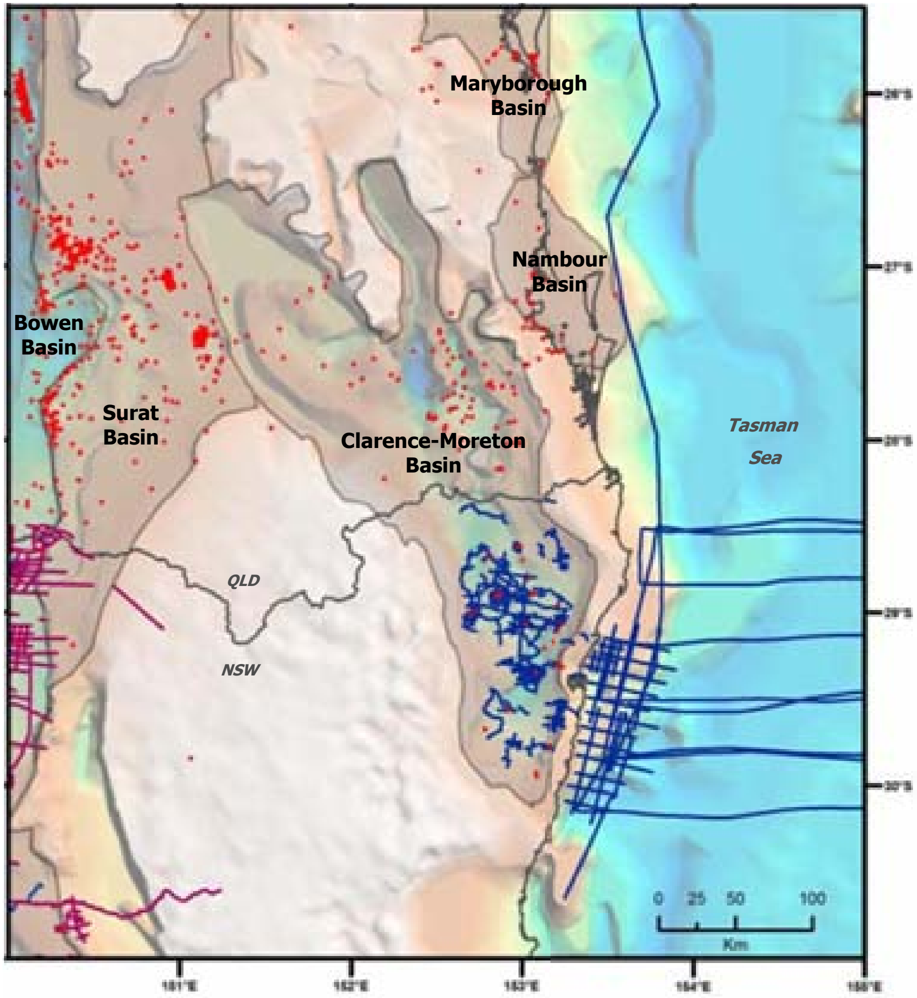
Introduction

The Clarence-Moreton Basin is an emerging high-priority exploration area for NSW. Similar to other New South Wales sedimentary basins, the Clarence-Moreton Basin is under-explored for conventional petroleum resources and coal seam gas. Only 21 exploration wells have been drilled in the NSW part of the basin and limited seismic data are available. Very little is also known about the nature and extent of the offshore depocentre although Shaw et al (2004) suggest that adequate sediment thickness and structures are present to host conventional petroleum accumulations. The Clarence-Moreton Basin is prospective for gas, oil, oil shale, coal and coal seam methane, and there are known hydrocarbons accumulations, including the presently sub-commercial Hogarth gas field and gas in the Clifden field. There is also an emerging interest in basement rocks underlying the basin and their potential as a source of geothermal energy.

FrOG Tech has considerable experience in using a range of non-seismic tools to evaluate basement topography and map fluid systems in basins and basement where adequate non-seismic data are available. The **Clarence-Moreton SEEBASE™ and GIS Project** aims to capitalise on existing and newly acquired geophysical and geological datasets to provide a rapid, cost-effective geological model in a frontier area where seismic and well data are limited. The approach taken in this study follows a similar "basement-up" approach to that employed in other FrOG Tech studies involving systematic calibration, integration and interpretation of non-seismic and seismic datasets. FrOG Tech PL has carried out previous studies in the Murray-Darling Basin (2005) and reservoir predictions studies in the Darling and Sydney basins (2007). The SEEBASE™ framework will also facilitate the conceptual development, design and scientific focus of more costly acquisition programs in this frontier region.

Aims

The main objective of the **Clarence-Moreton Basin SEEBASE™ and Structural GIS Project** is to provide the New South Wales Department of Primary Industries (Petroleum) with a tectonic, structural and stratigraphic framework that will serve as the basis to evaluate the prospectivity of this frontier basin. By providing a new view of basin architecture and basin evolution, the project will also improve the understanding of the geology of northeastern NSW. These aims will be accomplished by refining the OZ SEEBASE^{TM} (2004) interpretation with a higher resolution study of the Clarence-Moreton Basin based on newly acquired aeromagnetic data and recently reprocessed seismic data. The study also aims to investigate the effects of basement geology on basin evolution and a preliminary analysis of resource potential of the area, focusing on structural evolution/reactivation, basin architecture and tectonic history. All interpretations have been captured in an ArcMap 9.0 GIS product that accompanies this report.



Location map showing the Late Triassic to Early Cretaceous Clarence-Moreton Basin and other depocentres (grey polygons) in northeastern NSW and southeastern Queensland overlain on the OZ SEEBASE™ image (FrOG Tech, 2004). The locations of petroleum exploration wells and seismic data (NSW only) are also shown. In Queensland, the Clarence-Moreton Basin merges with the Surat Basin. About 16,000km^2 of Clarence-Moreton sediments outcrop in NSW and basin sediments are estimated to be 2500 to 4000 m thick (Scheibner and Basden 1996).

FrOG Tech Methodology

FrOG Tech has developed SABRE™ - Systematic Approach to Basin Resource Evaluation – as the backbone of its rapid basin evaluation workflow.

SABRE™ is divided into:

- **Province and Terrane Analysis**
- **Basin and Basin Phase Analysis**
- **Petroleum System and Play Evaluation**

The SABRE™ workflow will be illustrated and discussed in the following sections. One of the key products of SABRE™ is a SEEBASE™ image.
SEEBASE™ stands for Structurally Enhanced view of Economic BASEment.

Methodology

The evolution of sedimentary basins is controlled by a response in the crust and lithosphere to tectonic forces. The nature of this response depends both on the magnitude of the tectonic forces and on the character and kinematic response of the underlying basement. The strength, composition and fabric of basement at the time of a tectonic event controls crustal response, while sediments record the resultant changes in basin morphology. A rigorous model for basin evolution can be developed through an understanding of basement character beneath and adjacent to sedimentary basins, coupled with a a knowledge of tectonic events that were responsible for basin formation (i.e. basin phases). This model provides a basis for more accurate prediction of the occurrence and distribution of petroleum play elements throughout basin evolution.

Individual basin phases are separated from one another by changes in the type of subsidence mechanism or the magnitude or rate of subsidence. Basin phase boundaries correspond to plate-scale tectonic events and in turn to major megasequence boundaries. Stresses operating during each basin phase cause reactivation of basement structures and reactive fabrics, as well as the development of new structures. Understanding the kinematics of each tectonic event allows a predictive model for structural reactivation to be applied to the interpreted faults from fault history data calibrated with geological observations (e.g. seismic, maps).

Potential field data (principally gravity and magnetic data) **provide a window to the basement that can cover a wide area with uninterrupted data at constant resolution**. Such “map view” interpretation contrasts with the “cross section view” interpretation conventionally used in the petroleum industry. The combination of map-based and cross-section-based interpretation is a powerful method to extract more geological information more quickly than is possible with either dataset on its own. This is the basis of the FrOG Tech approach that has been developed over many years.

The methodology used to develop a comprehensive structural model relies on the integration of all appropriate geophysical and geological information. Individual datasets alone can be ambiguous and often produce poorly constrained results when interpreted in isolation. Through integration, the model can be tightly constrained, since the datasets can be used to calibrate one another.

Potential field data provides geological information on the structure and composition of the basement rocks The interpretation of potential field data can be calibrated with surface geology, seismic, and wells, which allows the development of a predictive structural model based on basement composition and structure. Depth to magnetic basement can be modeled from magnetic data and used to produce a structurally-controlled model of basement topography: SEEBASE™. Geological information contained within the SEEBASE™ model, can be used to predict and evaluate basement-involved and basement-detached structures, first-order fluid focus points, and both the distribution and quality of source, reservoir, and seal facies throughout the basin. FrOG Tech’s interpretation techniques and tools are efficient and cost-effective from continental to concession scales.

The model can be applied and tested by re-calibrating and checking against the seismic interpretation. Adjustments can be made as needed to both the model and the seismic interpretation at this stage.

The following report provides a model for the structural evolution of the Southeast Brazilian margin that explains its current location, its geometry, and its history and constrains modelling of potential petroleum systems. The model is consistent with all the data examined and it can be improved with the acquisition of new data and concepts.

Importance of Basement

The basement of any basin provides the foundation onto which the sediments are deposited. The rheology, or mechanical behaviour, of the basement controls the rate of subsidence and geometry of each phase of the evolving basin. The composition of the basement will determine its strength or stiffness. The age and early history of each basement terrane will dictate the intensity and character of the structural fabric. This inherent fabric plays a major role in the manner in which the crust deforms during major periods of extension or compression.

Understanding basement structures allows models to be developed that can predict which structures will reactivate, how they will move under an applied stress, and how they will propagate into the overlying sediment pile. Using plate tectonic reconstructions, the far-field stress state during past events can be estimated and a kinematic reconstruction produced for each event. Since basin sediments deform in response to movements in the basement and to gravity, knowing how and when the basement moves provides a basis for predicting the most likely locations of depocentres and structures (both basement-involved and basement-detached) in the sediments. In addition, basement topography controls the localisation and geometry of many basement-detached systems.

The faults described in this study have been interpreted primarily using non-seismic datasets and are mainly basement-involved. The reactivation history of these faults reflects the changes in the crust’s stress regime in response to specific tectonic events. Event maps show structures at top-basement level that are interpreted to have been active during a specific basin phase. Details of the influence of these basement-involved structures on the evolution of structures in the overlying sediments provides the basis for future studies, from prospect to basin scale.

By building such a “bottom-up” model for basin evolution, combining it with the “top-down” knowledge generated from seismic and wells, petroleum systems can be better understood and targeted. This approach is described in more detail by Pryer et al. (2002) and Teasdale et al. (2003).

The characteristics of basement provide the first-order control on basin architecture with the potential for influencing:

- **Source rock distribution and volumetrics**
- **Heat flow patterns**
- **Migration focusing and pathways**
- **Trap timing, distribution, type, integrity, and size**
- **Sediment supply and stratal geometry**
- **Distribution and quality of reservoirs and seals**

Data Compilation and Processing

As many datasets as possible were compiled into GIS format for this study. Datasets can be divided into **Core Datasets** (those which are interpreted and integrated in detail) and **Calibration Datasets** (those which are used selectively to constrain the interpretation). Our interpretations are based largely on potential field data (i.e. gravity and magnetics), since these data provide the most continuous coverage in the map view. Our interpretations are not static; with the acquisition of new data that allow more precise calibration, they can be updated.

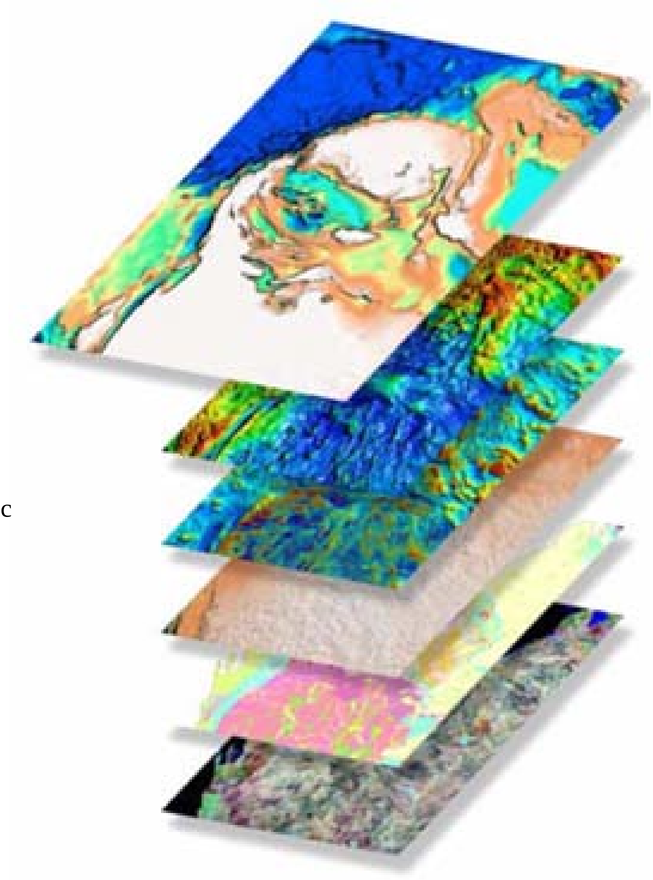
Core Datasets

Gravity	xyz point data & grids
Magnetics	processed flight line data & grids
Digital Elevation Model (DEM)	grids
Surface Geology	digital coverage & maps

Calibration Datasets

2D seismic	workstation access, screen captures, navigation data
Wells	location, formation tops, basement penetrations, etc.
Airborne Electromagnetic Data	conductivity depth images and cross sections
Plate tectonic reconstructions	animations, maps, Paleomap, published plate tectonic models
Sequence stratigraphy	stratigraphic charts, palaeogeography, tectonostratigraphy
Seismic refraction data	cross sections
Landsat	images
FrOG Tech regional knowledge-base	reports & intellectual property
Publications, papers, maps, cross sections	extensive reference list

The following section outlines the datasets used for this project, and their processing history:



Georeferenced Calibration/Integration/Interpretation of non-seismic & seismic data

Gravity Data

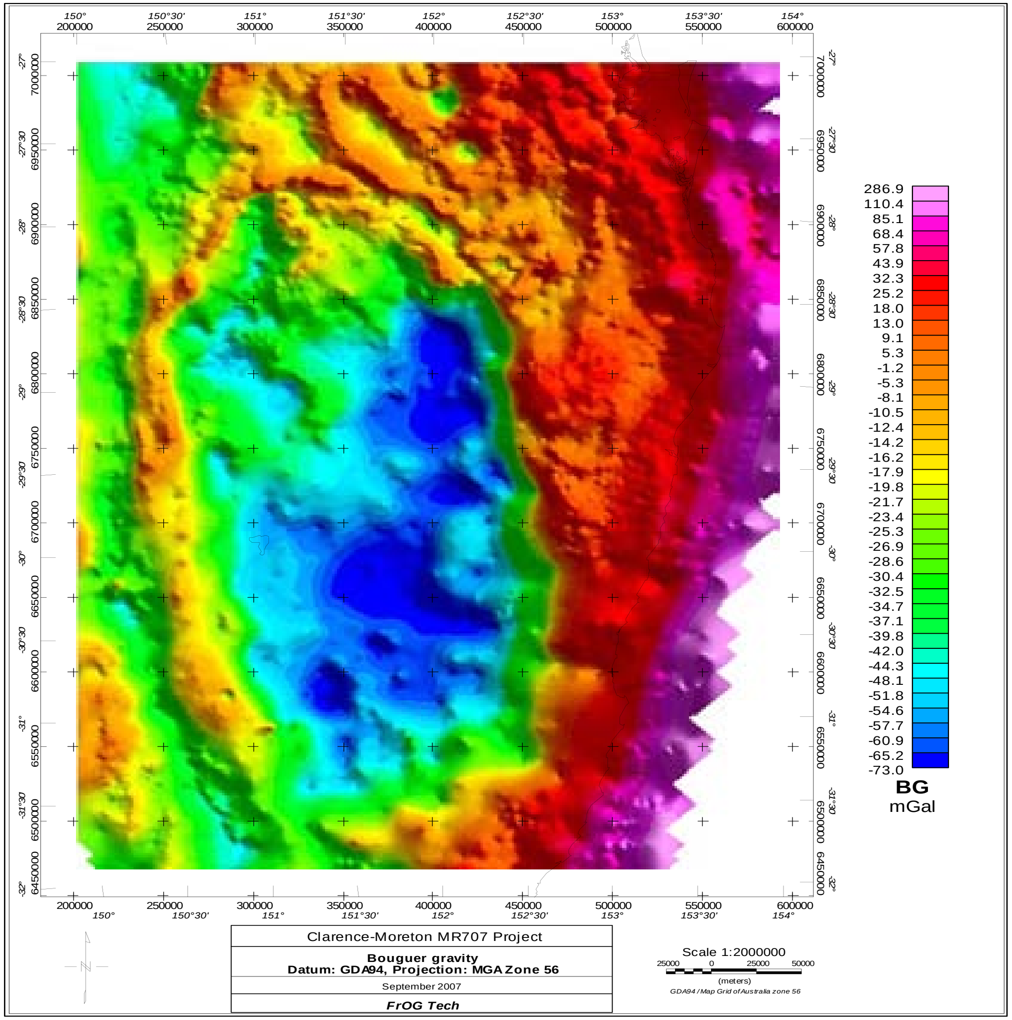
Gravity is a very important tool for interpreting basins. It maps subtle changes in the Earth's gravitational field caused by variations in density of the underlying rocks and it provides valuable information on basement topography and the nature of the deeper parts of the crust and mantle beneath the basins as well as on shallow sources such as faults, dykes and sills.

A standard Free-air image will contain information from all these sources. However, in order to interpret the geological source of a gravity anomaly, the data must be calibrated. Gravity images show density contrasts within the crust, but the source of the contrast is not unique. Thus, the nature of each anomaly as crust or mantle must be distinguished. The major aims of image processing are to highlight the more subtle features from the various sources, separate anomalies from different source depths, and to accurately position anomalies (i.e. so that they sit over their source).

In this project, we have examined:

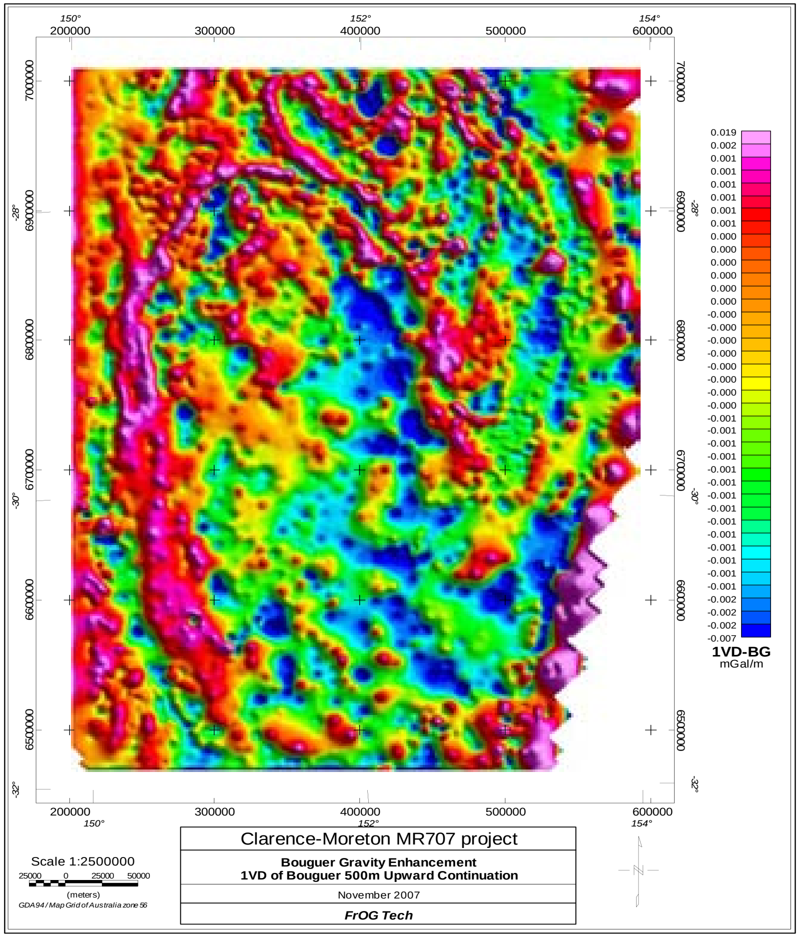
- NSW DPI Bouguer 500m grid, GA 2005 version Bouguer gravity 900m grid
- GA gravity survey location data.

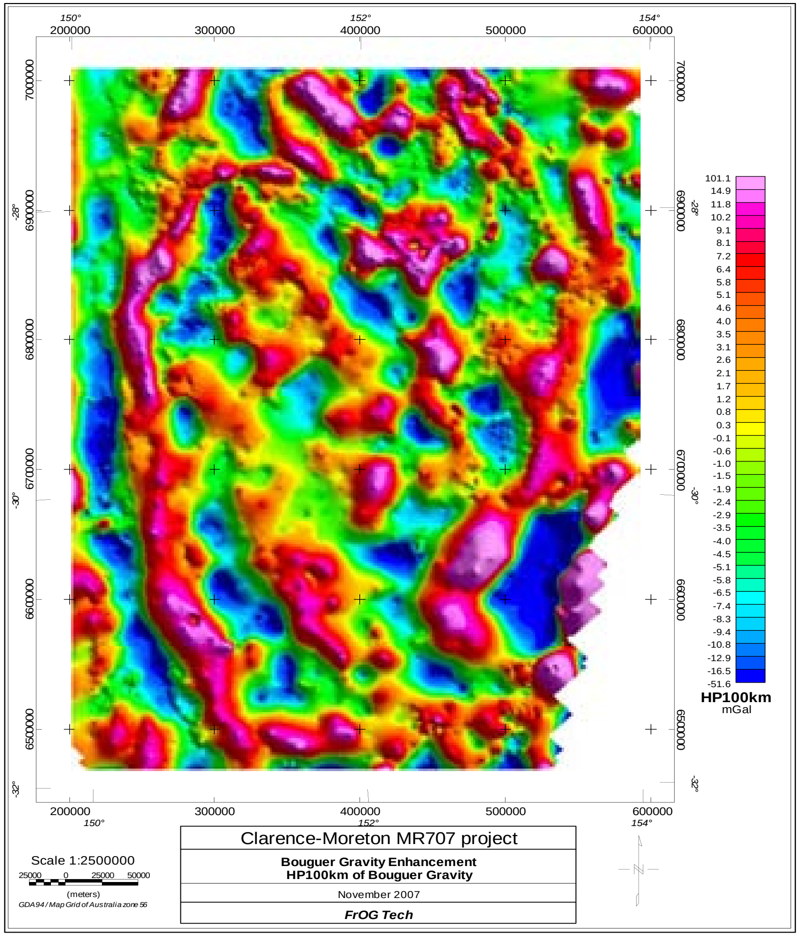
A series of enhancement filters have been applied to the Bouguer gravity grid. In this part of the report a few examples of these enhancements are shown. A more comprehensive description of all processing can be found in Appendix 1.



Bouguer Gravity:

Corrects the raw gravity (Free Air) data for effects of topography and effects of density variation due to bathymetry and topography.





1VD of 500m Upward Continuation:

The first vertical derivative (1VD) filter enhances near surface contrasts in density by amplifying the high frequency component of the spectrum (linear increasing filter). When applying high frequency enhancement filters to the Bouguer Gravity grid and its derivatives a 500m upward continuation filter is also applied to reduce noise level.

100km High-pass Filter of Bouguer Gravity

Wavelength cutoff techniques such as highpass, lowpass and bandpass filters are used for anomaly separation. The 100km High-pass Filter is a powerful tool for discerning 'shallow' sources of anomalies from 'deep' sources.

Magnetic Data

Aeromagnetic data measures variations in the Earth's magnetic field caused by variations in the magnetic susceptibility of the underlying rocks. It provides information on the structure and composition of magnetic basement and intra-sedimentary magnetic units, if present. Most bodies within the basement have a distinctive magnetic signature which is characterized by the magnitude, heterogeneity, and fabric of the magnetic signal. When calibrated with known geology, magnetic data can be used to map basement terranes under a cover of sedimentary rock, regolith, water, or ice.

The most important and accurate information provided by magnetic data is the structural fabric of the basement. Major basement structures can be interpreted from consistent discontinuities and/or pattern breaks in the magnetic fabric. Once the structures have been evaluated and combined with those interpreted from gravity data, a model for the evolution of the basement and overlying basins can be developed.

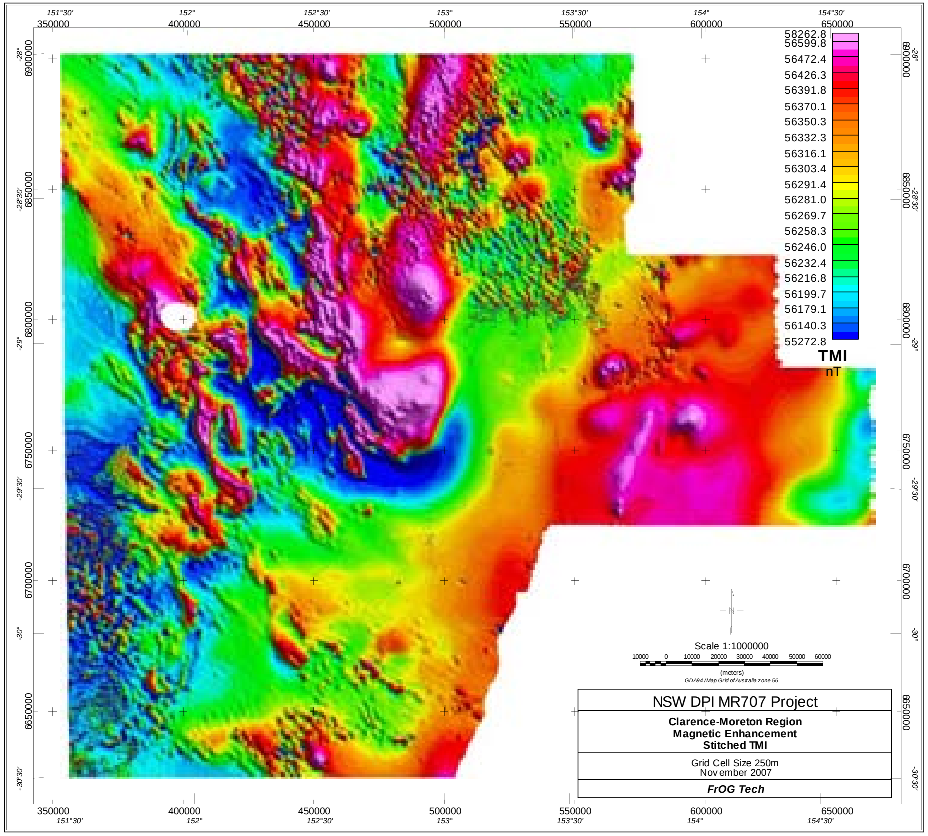
Where the source of the magnetic signal is very deep and not resolvable after standard data processing, enhancement techniques are applied that reveal information on the geometry and structure of the basement at depth. Enhancement processing techniques are chosen specifically for each magnetic dataset depending on the type of information that needs to be extracted. Enhancement processing is critical for evaluating deep basins.

Magnetic data is also valuable for determining the distribution of magnetic sources within the sediments ranging from heavy mineral deposits (e.g. fans) to basalts**.**

In this project two sets of magnetic grids were created for further enhancements, these included:

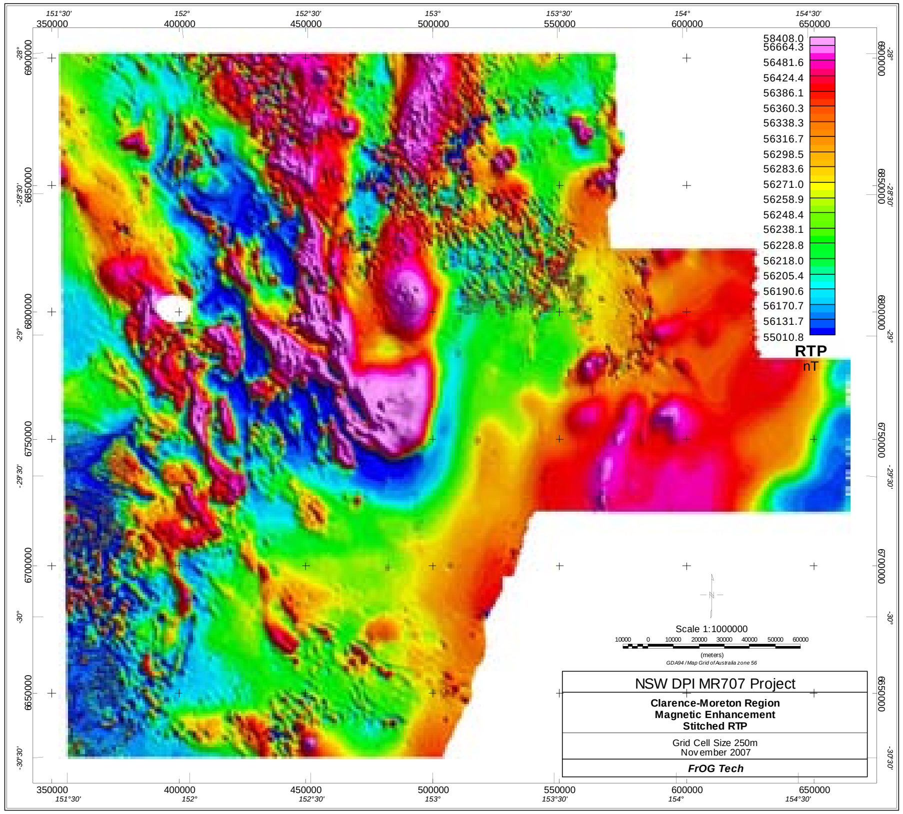
- Clarence-Richmond detailed Survey grid with 50m grid cell size
- Stitched regional magnetic grid with cell size 250m.

A detailed description of the different filters applied to the TMI grids is given in Appendix 2, a few examples are shown on the next pages.



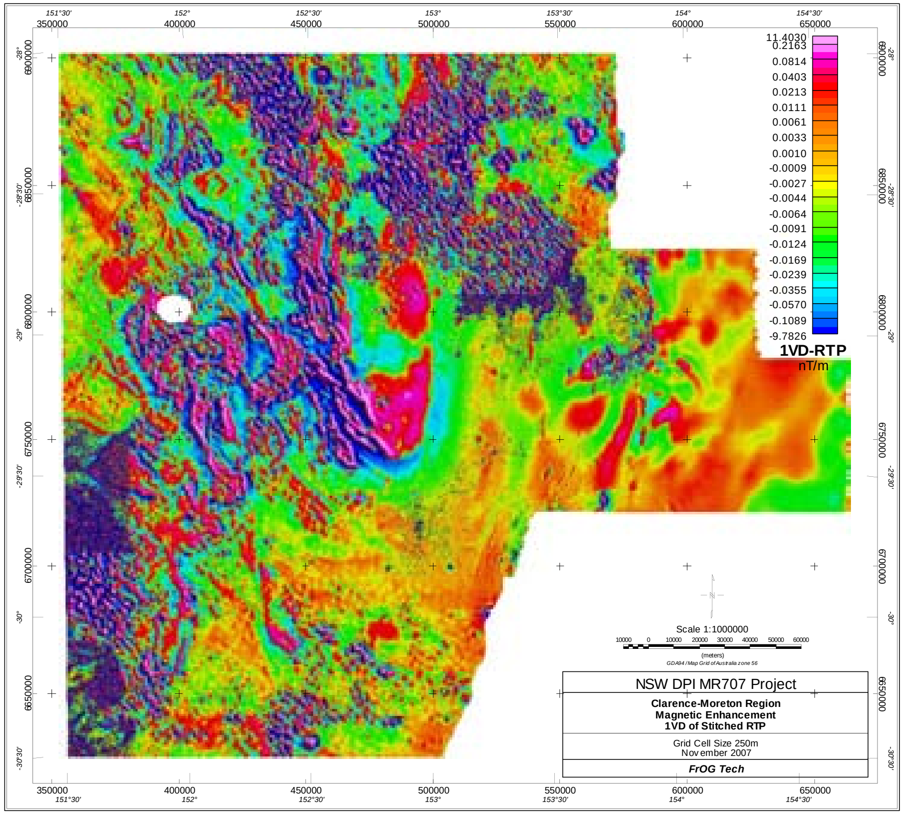
Stitched TMI Grid with grid cell size 250m

Although the TMI dataset does not provide information on the correct position of anomalies, it is the primary dataset and is therefore a key reference image when evaluating features in enhanced images.



Stitched RTP Grid with grid cell size 250m

TMI data is routinely reduced to the pole to shift anomalies directly over their source and for the case of vertical dipping body it produces a symmetric anomaly. The location of sources, particularly source edges, can more readily be determined when the magnetic data has been reduced to the pole.



1VD of Stitched RTP Grid with grid cell size 250m

The first vertical derivative filter enhances near surface contrasts in magnetization. The 1VD measures the rate at which field intensity varies with elevation. Shallow sources produce high amplitude vertical gradients, where deeper sources produce weaker vertical gradients. Therefore, near surface features such as volcanics and intrasedimentary structures, as well as culture and geology noise are enhanced in this process.

Magnetic Depth Modelling

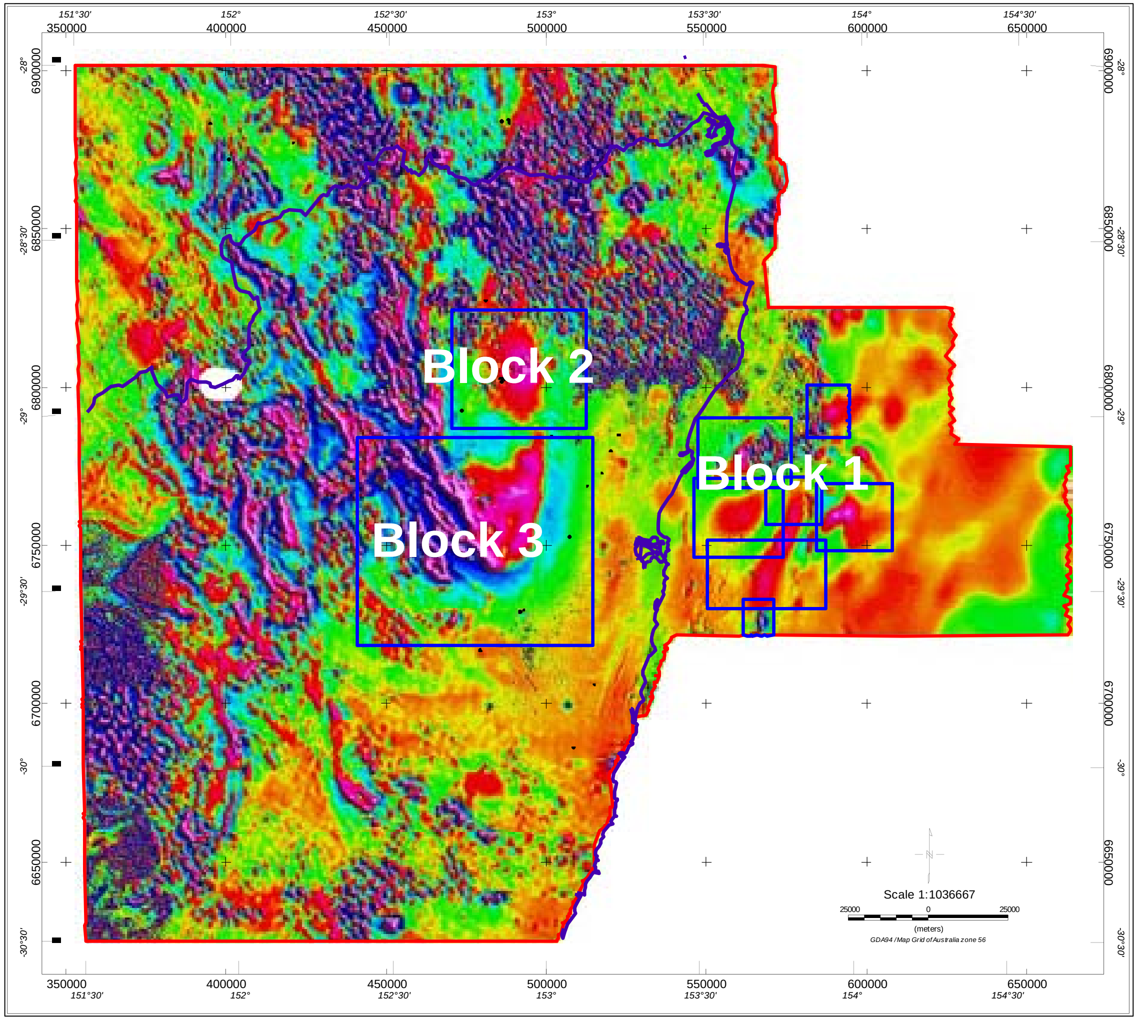
FrOG Tech has developed techniques using Encom Technology's 3D forward and inverse magnetic modelling package ModelVision Pro^{TM} to provide estimates of depth, dip, width, depth extent, and susceptibility of magnetic sources. The process is as follows:

First, suitable profiles are selected across the TMI grid. These profiles are then modelled individually to match observed magnetic field variations using tabular or pipe models of uniform magnetization and sharp margins with distinct edges. An initial array of bodies is created based on inspection of the profile. These bodies are adjusted using forward modelling, with strike, position, and azimuth corrected to match the anomaly extents mapped by the TMI image.

The model is then adjusted by inversion of the body positions (along profile), widths, dip, susceptibilities, and depths to closely match the observed magnetic field variation along that profile. The source bodies can be converted to point depth values at the centre of their top faces. With images of the depth sections used for reference, the most reliable depth points are selected based on geological understanding of the study area. These depth points and inferred faults are incorporated into a (possibly discontinuous) surface to represent the faulted top of basement or, where appropriate, of any intra-sedimentary surface at which sources generate magnetic field variations.

- Step 1: A traverse is selected through the anomaly of interest to pass through maxima/minima roughly perpendicular to strike. Bodies created for each anomaly are positioned, strike and azimuth adjusted to match the anomaly extents.
- Step 2: A regional field gradient is assigned and then the bodies are inverted to match the field variation along the extracted traverse.
- Step 3: A data point containing the source parameters is generated for each body.

For this project Magnetic Depth Modelling was done in three block areas'. (see adjacent figure for their location). A detailed description of the modelling processing as well as the results obtained are presented in Appendix 3.

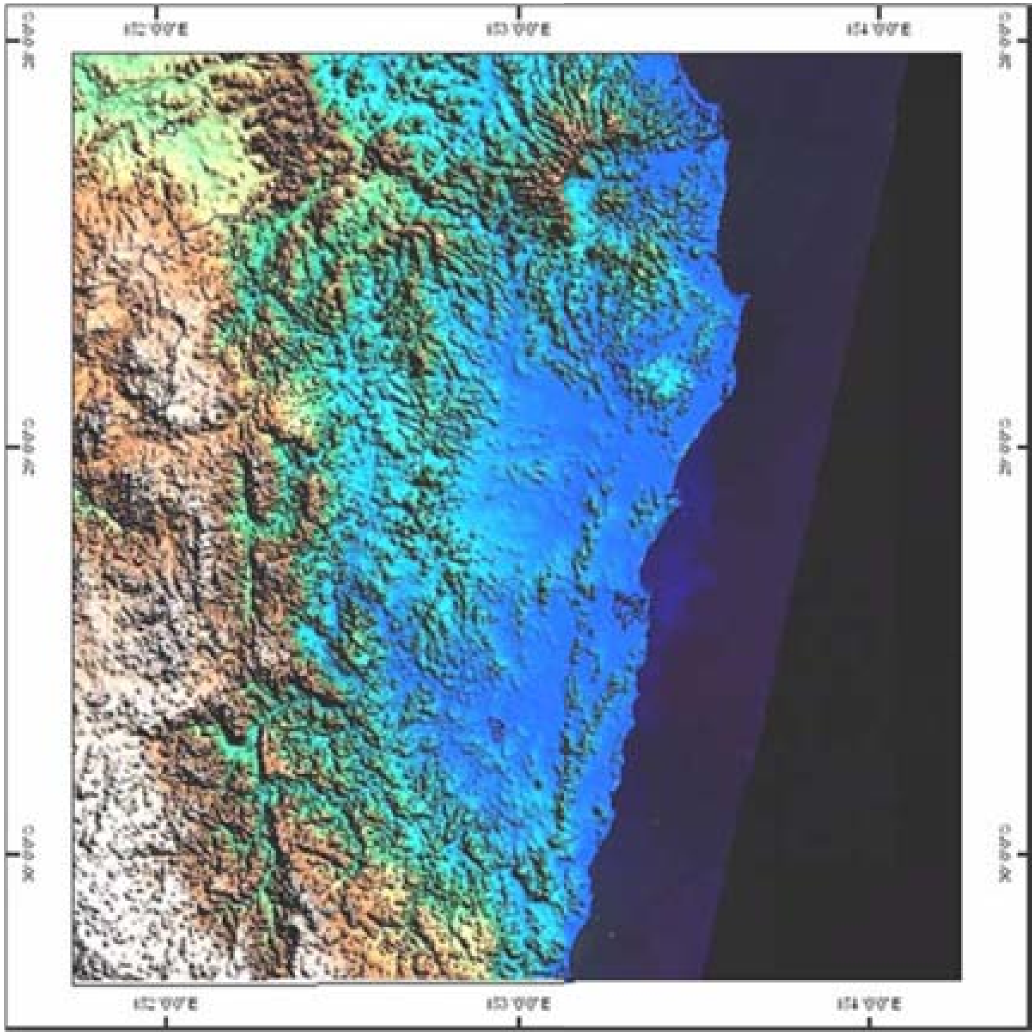


Model Area Distribution

Block 1 – 7 Areas Offshore
Block 2 – North Clarence-Moreton
Block 3 – South Clarence-Moreton

Digital Elevation Model (DEM)

- Digital Elevation Models often show the youngest and/or active geological structures. They are widely used for neotectonic analysis. DEMs can also be used to distinguish different compositional domains because the composition of an eroding terrain controls its resistance to weathering.
- To provide the best possible digital elevation model, two available datasets, the ETOPO2 and the SRTM30 (see below) were used.



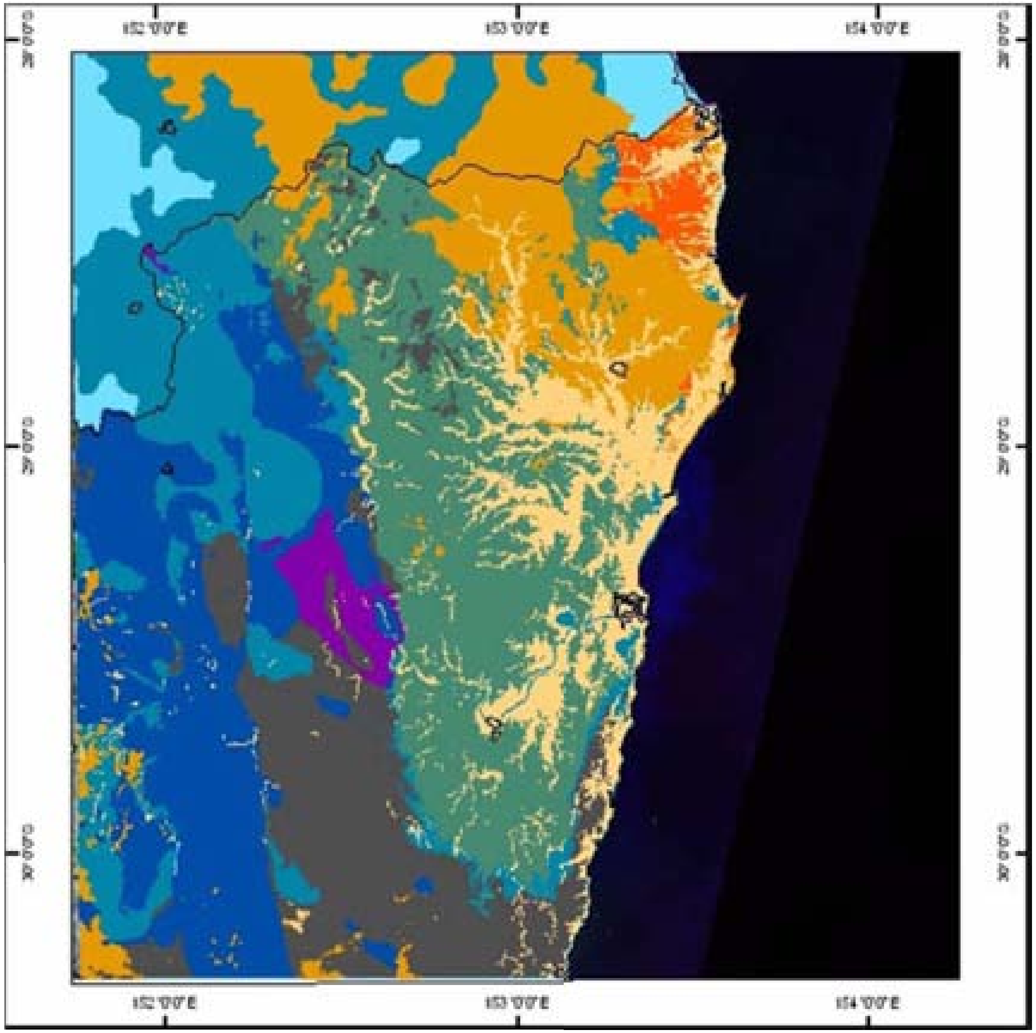
Global Topography

- The ETOPO2 dataset is a combined topography/bathymetry model with a grid spacing of 2 minute (lat/long) resolution from the National Geophysical Data Center (NGDC). It is based on five different sources, with the highest resolution taking precedence in any given area: GLOBE, Smith/Sandwell, IBCAO, DBDBV, and DBDB5.
- For details see the [ETOPO2 Homepage](http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html): http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html
- SRTM30 is a global DEM with a horizontal grid spacing of 30 arc-seconds (approximately 1 kilometer) comprising a combination of data from the Shuttle Radar Topography Mission, flown in February, 2000, and the U.S. Geological Survey's GTOPO30.
- For details see the [SRTM Homepage](http://www2.jpl.nasa.gov/srtm/): http://www2.jpl.nasa.gov/srtm/
- This image is a mosaic of the SRTM30 (onshore) and ETOPO2 (offshore).

Surface Geology

Surface geology is a key dataset for any geological interpretation. Surface geological maps provide calibration for interpretation of DEM, gravity, and magnetic data. Where basement is outcropping, the direct correlation of geological units with patterns in geopotential field data is possible. Once the magnetic and/or gravity response of different basement lithologies has been calibrated, it is possible to extrapolate beneath basins to interpret basement character.

The main surface geology dataset used for interpretation was the NSW 250K digital surface geology.



Legend

🟧 Cainozoic
⬛ Carboniferous
🟩 Jurassic
🟦 Palaeozoic
🟦 Permian
🟨 Quaternary
🟪 Silurian
🟧 Tertiary
🟦 Triassic

Landsat

Landsat data is useful for identifying surface geology and structure which may be reflected in outcrop, vegetation patterns or soil types.

These Landsat images are GeoCover™ Orthorectified Landsat Enhanced Thematic Mapper (ETM+) Compressed Mosaics provided by NASA. The Mosaic consists of three Landsat ETM+ bands, each sharpened with the panchromatic band:

- Band 7 (mid-infrared light) is displayed as **red**
- Band 4 (near-infrared light) is displayed as **green**
- Band 2 (visible green light) is displayed as **blue**

Pixel size is 14.25 meters, and the Absolute Positional Accuracy is ±75 meters RMSEr.

More detailed information is available in the metadata or from [NASA's Landsat webpages](https://zulu.ssc.nasa.gov/mrsid/mrsid.pl):
https://zulu.ssc.nasa.gov/mrsid/mrsid.pl

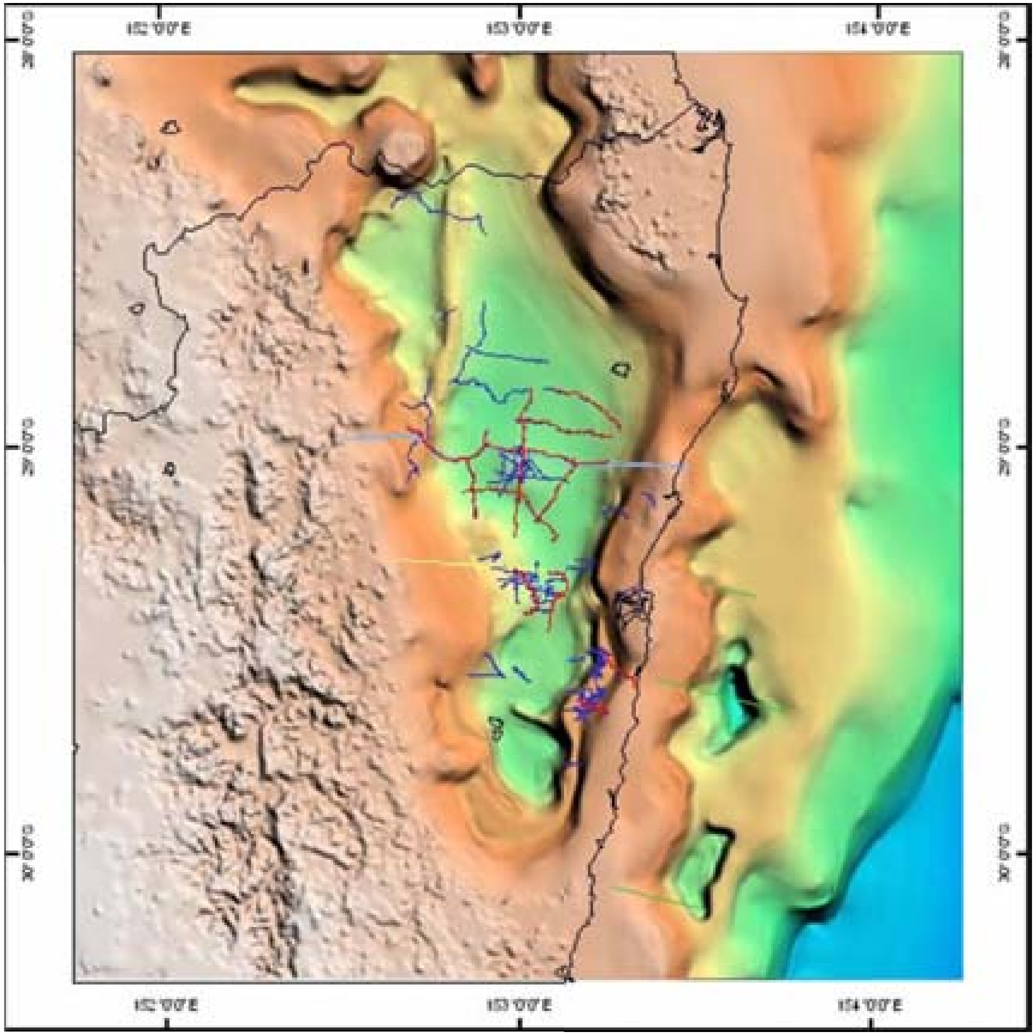
2D Seismic and Published Cross Sections

Selected 2D seismic lines and published cross sections were used to calibrate the structural interpretation and constrain the SEEBASE^{TM} surface.

Seismic data are important for calibration of basement depth and structure. In particular, the interpretation of fault movement histories, essential for calibration, is not readily obtained from other data sources.

NSW DPI supplied available seismic data (SEG-Y files and JPG images scanned from paper copies) for use in the Clarence-Moreton Project. Data provided refers exclusively7 to the onshore part of the basin, while no offshore seismic data has been provided by DPI.

Published cross sections provide important regional constraints on the structural geometry of basement blocks and basins and on the movement histories of major structures.



Legend

- SEGY navigation

Cross sections

- DPI scan
- Elliott, 1993
- Geary et al, 1984
- Shaw et al., 2001

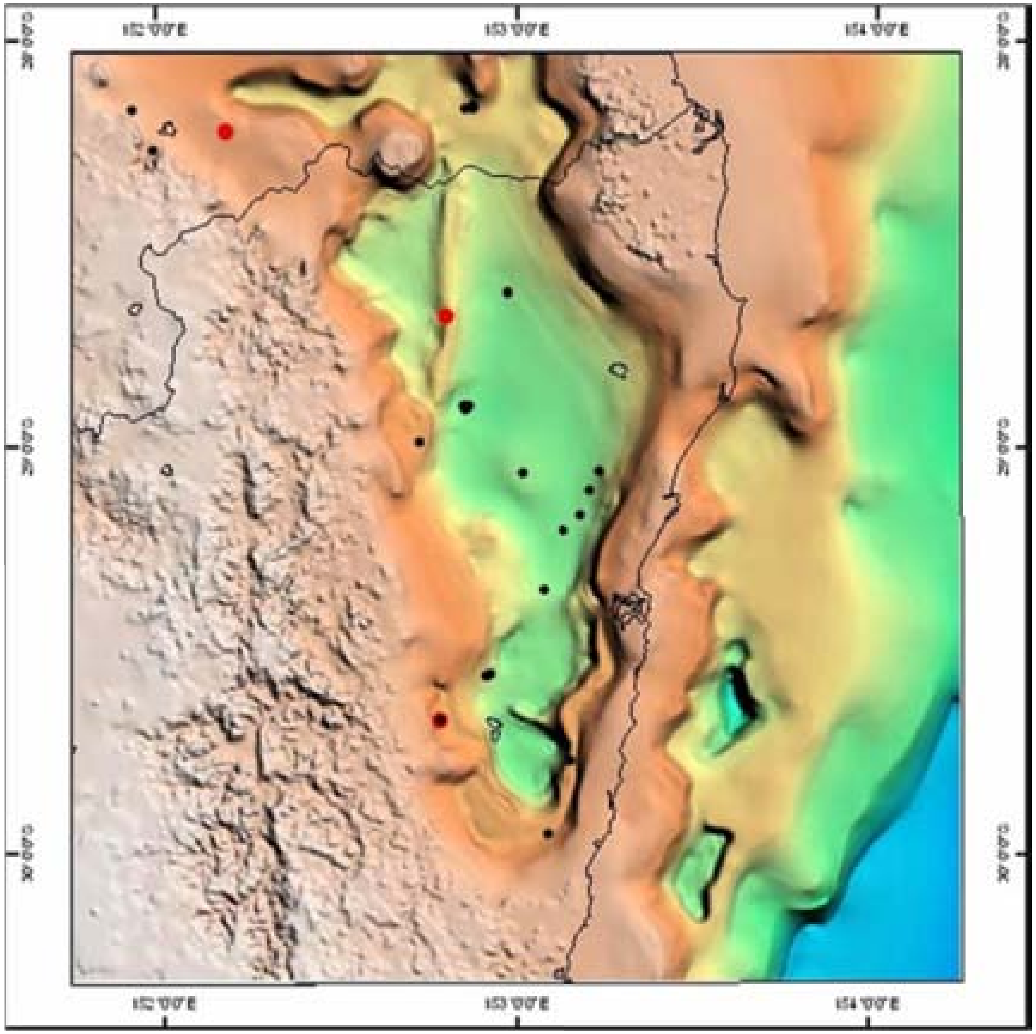
Location of seismic lines in the Clarence-Moreton Basin available for this project, overlain on the CM SEEBASE™ image produced for this report. All of the seismic jpegs shown have been 'hyperlinked' in the GIS project that accompanies this report.

Wells

The well database was compiled from the NSW well database supplied by DPI.

Basement penetrating wells were then extracted and used to constrain the SEEBASE™ surface.

In many cases, well logs also provide the only direct evidence of basement lithology.



Legend

- ● No
- 🔴 Yes

Location map showing well data in the Clarence-Moreton Basin, overlain on the SEEBASE™ image produced for this report. Basement wells are shown in red, while other wells are shown in black .

SEEBASE™ Structurally Enhanced View of Economic BASEment

Traditional techniques for generating depth to basement generally rely on one basement detection method which is in turn based on one rock property such as seismic (velocity), magnetic (susceptibility), or gravity (density). The SEEBASE™ method generates a model that relies on a rigorous structural interpretation plus the three rock properties mentioned above.

What is SEEBASE™?

SEEBASE™ is a depth-to-basement model that represents the culmination of a number of calibration and integration steps:

- Integrated structural/kinematic interpretation
- Geophysical modelling
- Seismic & well calibration
- Integration of tectonic events & responses

SEEBASE™ is a qualitative model of economic basement topography that is consistent with the structural evolution of the basin. SEEBASE™ defines basin architecture and forms the basis for the systematic evaluation of exploration strategies. SEEBASE™ is not static; with the acquisition of new data that allow more precise calibration, SEEBASE™ can be updated.

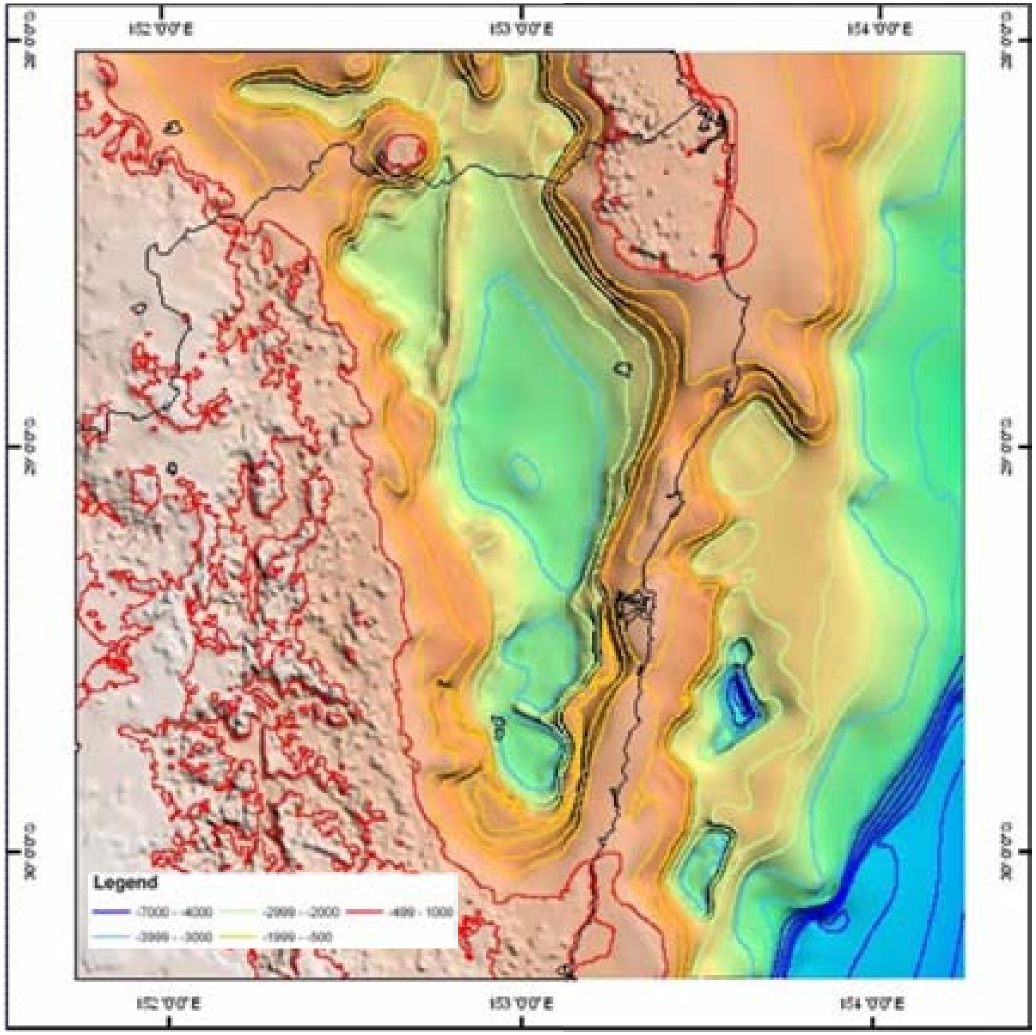
SEEBASE™ provides a foundation for petroleum systems evaluation, including play element distribution and quality (source/reservoir/seal), fluid focusing, zones of structural complexity, trap distribution, trap type and integrity, palaeogeography, oil vs. gas distribution, etc.

"Map View / 3D" versus "Cross Section View" Interpretation

A powerful aspect of the SEEBASE™ workflow is that the interpretation is performed in 2D map view and in 3D. This is a significant departure from conventional seismic-based basin analysis which is predominantly carried out in 2D cross-section view, especially when evaluating large areas. The FrOG Tech method is very effective in defining spatial variation in basin architecture in extensional, compressional, and strike-slip settings.

With cross section view interpretation, too many margins are categorised by the geometry seen on seismic lines without reference to any variation in geometry that might occur nearby and with little understanding of the processes that created those geometries.

The more we apply the FrOG Tech method, the more we realise the power of non-seismic datasets for predicting the location of prospective areas within a basin. The FrOG Tech method has proven to be very efficient and effective for locating spot 3D surveys over such prospective areas.



The conclusions and recommendations expressed in this material represent the opinions of the authors based on the data available to them. The opinions and recommendations provided from this information are in response to a request from the client and no liability is accepted for commercial decisions or actions resulting from them. Please cite this work appropriately if portions of it are copied or altered for use in other documents. The correct citation is *Sommacal et al 2008, Clarence-Moreton SEEBASE™ and Structural GIS Project, Confidential Report to NSW DPI by FrOG Tech Pty Ltd.*

SEEBASE^{TM} CRAP Map

CRAP: Confidence, Reliability, Accuracy, and Precision

The CRAP (Confidence, Reliability, Accuracy, and Precision) Map aims to communicate the interpreters' evaluation of various datasets in terms of supporting the development of the SEEBASE^{TM} model.

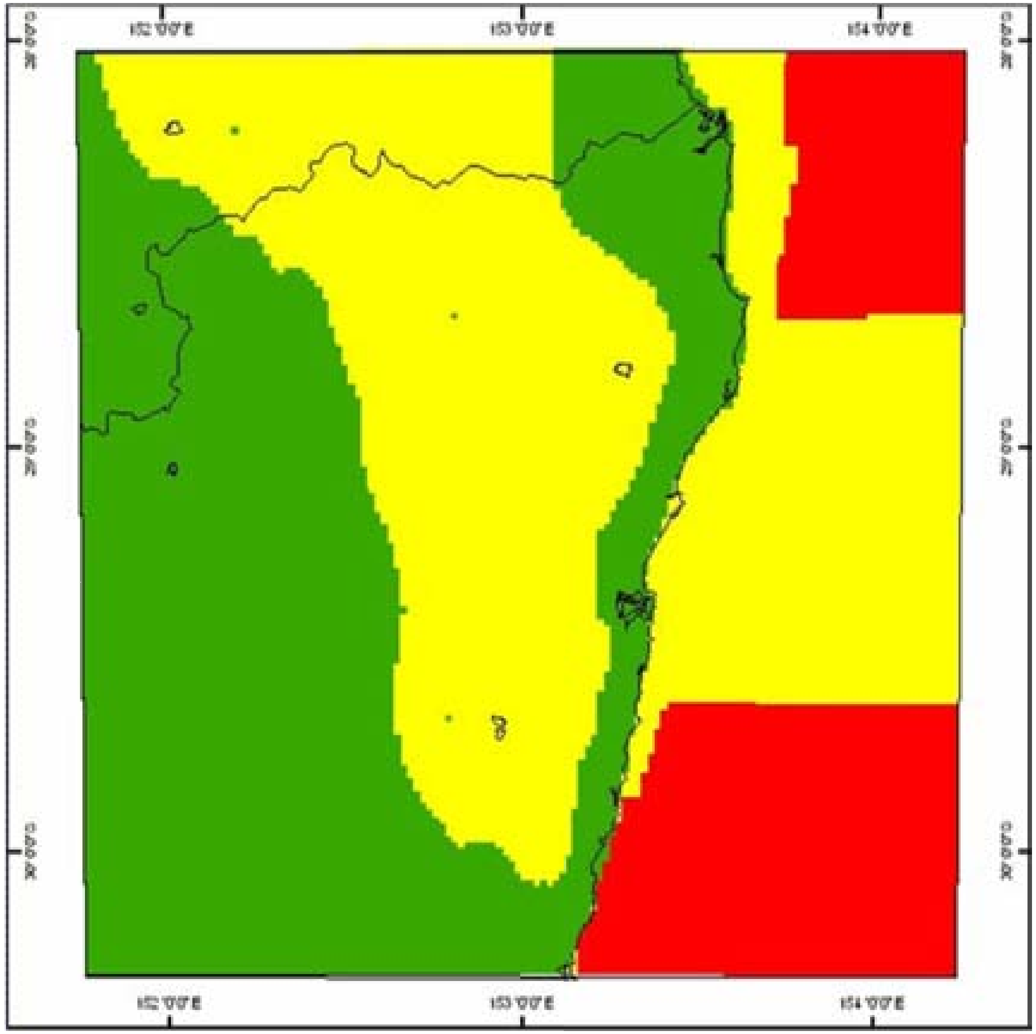
For Clarence-Moreton SEEBASE^{TM} project, the CRAP Map value is the resulting maximum confidence value at any X, Y location from the following input datasets:

- Mapped basement outcrop
- Basement wells locations: High reliability
- Selected seismic lines imaging basement: Moderate reliability
- Published cross sections: Moderate reliability
- Magnetic models: Moderate reliability
- Gravity and Magnetic coverage reliability varies with data quality and basement composition

During the interpretation process the interpreter evaluates the various datasets available to support the SEEBASE^{TM} model, and assigns confidence percentages to each feature. These values can be a constant value like 100% for basement outcrop or 70% for Cross Sections. Magnetic surveys are treated more independently depending on the survey specification. Note that the presence of volcanics also influences the reliability of the SEEBASE^{TM} model. Magnetic depth to basement models are less reliable in areas of thick, remnantly magnetised volcanics.

The Clarence-Moreton SEEBASE^{TM} ranges from 100% in areas with basement wells or outcropping basement, to 50-40% in areas with only magnetic and gravity data (i.e. with no well control, and no good quality seismic control).

FrOG Tech is currently considering methods to enhance the information content of the CRAP Map to include representations of geological continuity to enhance the Confidence and Reliability elements of the map.



Legend

🟥 Low

🟨 Moderate

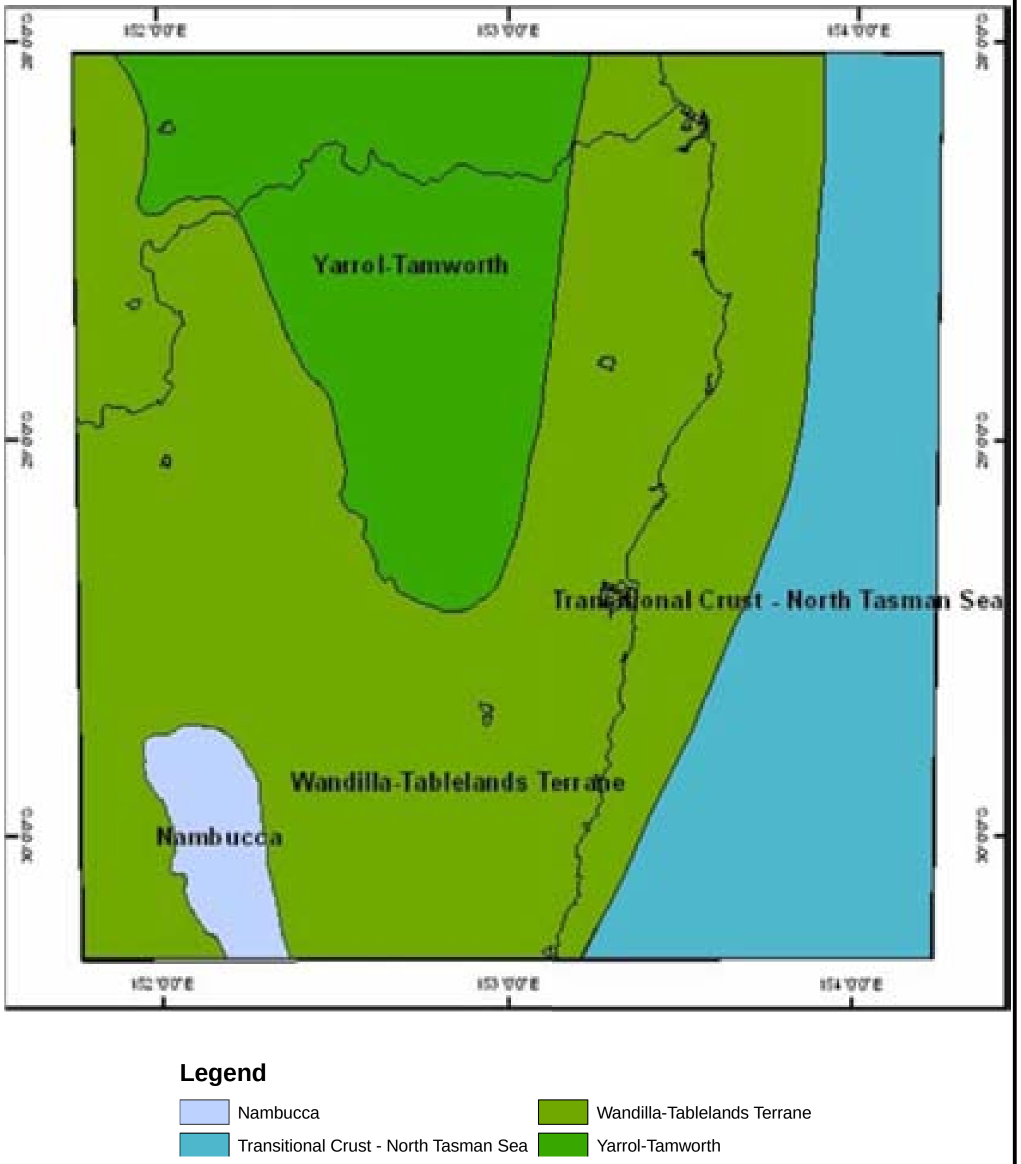
🟩 High

Basement Terranes

A *basement terrane* is defined as a discrete, mappable, structurally bounded block of crust of regional extent with a tectonostratigraphic history different to that of neighbouring terranes (e.g. Jones et al, 1977; Howell, 1995).

The basement terranes that surround and underlie the Clarence –Moreton Basin form part of the New England Super-Terrane and have a complex geological history.

During the Devonian and Carboniferous the region was dominated by a west-dipping subduction zone (Leicht, 1975), with a fore-arc basin bounded to the west by a volcanic arc and to the east by an accretionary wedge. The basement terrane beneath the Clarence-Moreton Basin is interpreted to be tightly folded pre-Permian forearc and accretionary wedge material. The present-day distribution of basement terranes in the project area has been interpreted from the magnetic and gravity data-sets, calibrated with outcrop data.



Wandilla-Tablelands Terrane: This is a composite terrane comprising several different accretionary prism complexes of Devonian to Carboniferous age which formed during subduction. It accreted during the Late Carboniferous but it experienced strong reactivation and deformation during the late Carboniferous-early Permian, which lead to the formation of orocline bends. Paleomagnetic data suggests that within the Wandilla-Tablelands Terrane clockwise rotation of the Texas and Coffs Harbour blocks was underway by 293 Ma and complete by 265 Ma (Aubourg et al., 2005). Harrington and Korsch (1987) suggested that the position of such orocline possibly controlled the southern limits of sedimentation of the Clarence-Moreton Basin.

Yarrol-Tamworth Terrane: This terrane is composed of Devonian to Carboniferous sediments and volcanics, locally metamorphosed, which formed in a volcanic-forearc setting (Scheibner and Basden, 1996). Accretion of the terrane took place in the late Carboniferous, although it also subsequently experienced strong deformation during the late Carboniferous-early Permian.

Nambucca Terrane: This terrane is composed of latest Carboniferous to Early-Permian meta-sediments believed to represent the sediments that filled in an extensional basin (Nambucca Basin) during the Early Permian (Leitch, 1988). Veevers, Conaghan & Powell (1994) suggested that accretion of the terrane took place during the late-Permian Hunter Orogeny. Equivalent basement may also occur above the other terranes beneath the Clarence-Moreton Basin sediments.

Transitional Crust – North Tasman Sea: This terrane is composed of highly attenuated continental crust of late Cretaceous age with abundant oceanic intrusives and extrusives.

What is "Basement"?

The concept of "what is basement?" is non-trivial, since basement evolution in many terranes post-dates basin evolution in others. Hence the question "what is basement?" must be asked for each basement terrane. Additionally, the distinction between economic, magnetic, acoustic, or metamorphic ("crystalline") basement must be made. By definition, SEEBASE™ maps depth to *economic* basement.

Economic basement is defined as the base of all petroleum systems (with a few exceptions – e.g. fractured basement reservoirs). In general, economic basement is also metamorphic basement.

Metamorphic or "crystalline" basement is defined as the top of metamorphosed basement lithologies.

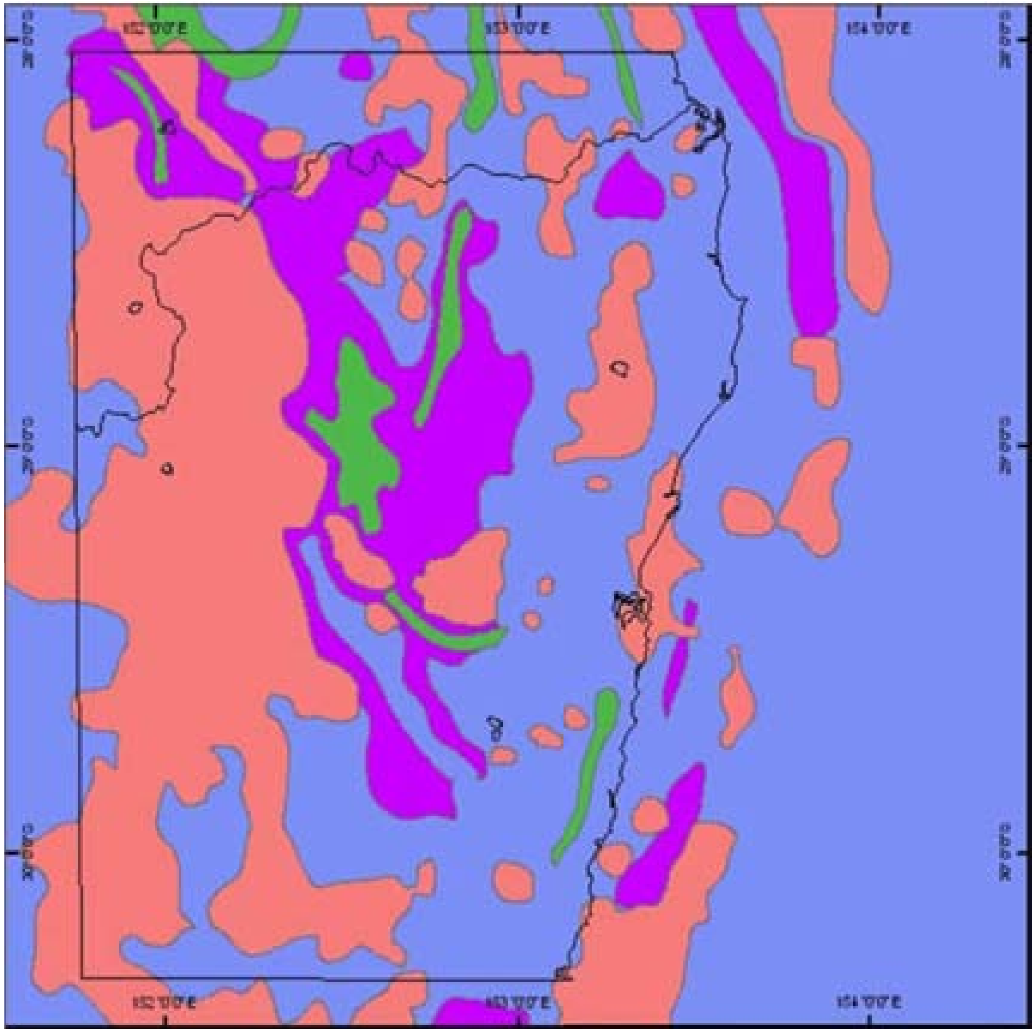
Magnetic basement is defined as the top of magnetic lithologies (with the exception of subtle, intra-sedimentary sources).

In the Clarence-Moreton project, we have defined basement as the deformed rocks of the New England Orogen, which include metasediments and metavolcanics of possible Early Palaeozoic to Permian age, overlying folded Early Permian metasediments equivalent to those of the Nambucca Terrane, and the granitoids that were emplaced in the region from the Late Permian and Early Triassic.

Basement Composition

The basement composition consists of mainly island and continental volcanic arc and related volcaniclastic and accretionary wedge-type sediments. General composition of basement lithologies has been interpreted from gravity and magnetic data. Large granite bodies in the basement generally appear as negative gravity anomalies. Mafic extrusive/intrusive bodies as positive gravity anomalies, with very high gravity where serpentinite bodies are interpreted. Areas with an intermediate gravity response have been assigned a general metasediment/metavolcanic composition.

The age of the basement granites probably varies from Carboniferous to Triassic with associated variation in minor element composition.



Legend

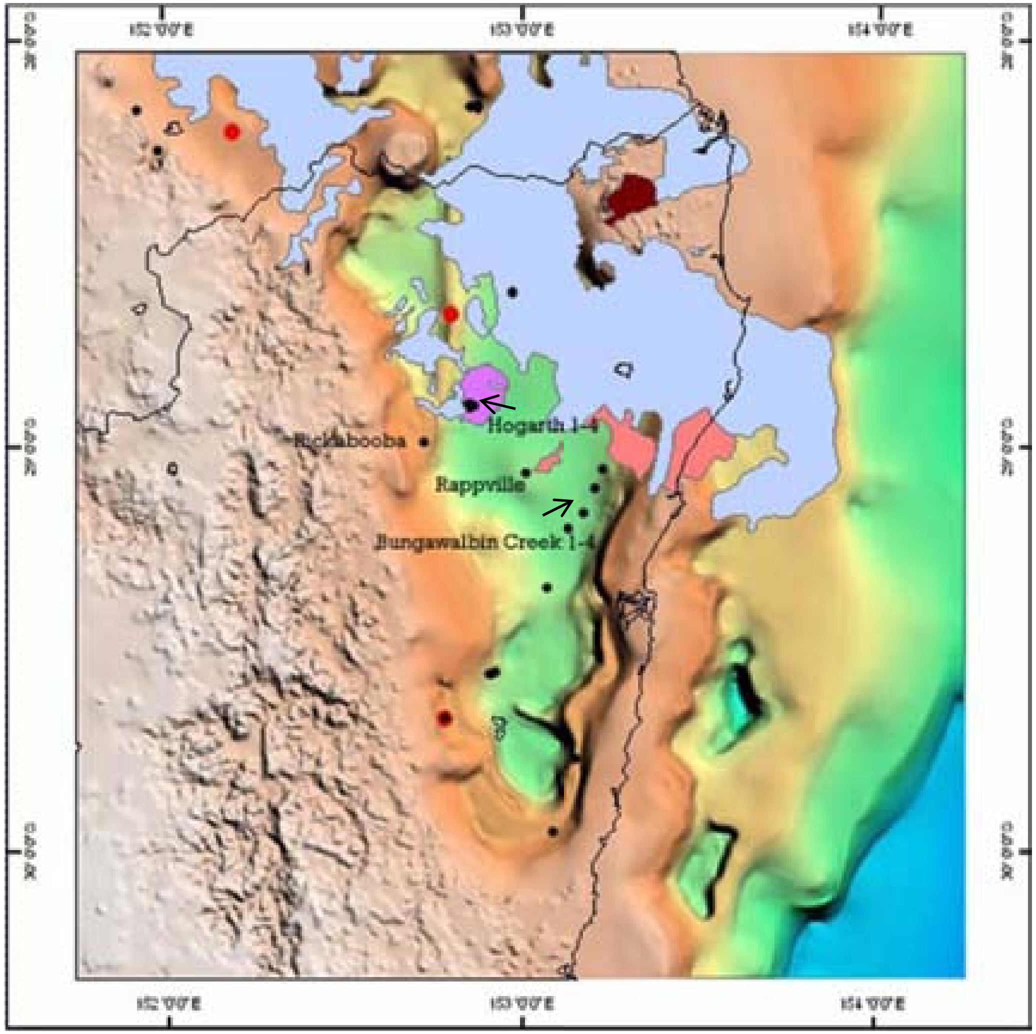
🟪 Mafic volcanics
🟦 Metasediments, metavolcanics
🟥 Granite
🟩 Serpentinite

Interpreted Distribution of Volcanic Features

Extensive Neogene (23-20 Ma) volcanics occur throughout the basin but are concentrated in the north of the basin associated with the Mount Warning Complex and the Main Range and Lamington Volcanics. These volcanics extensively crop out and their distribution can be readily mapped by both magnetic (mainly 1VD RTP) and Landsat data.

Wells data provide additional constraints to determine the maximum extent of the volcanics towards the south of the basin, as no volcanic layers have been encountered during the drilling of Bungawalbin Creek 1-4 and Rappville 1 (see map on the right).

A sill of dolerite/basalt, 50 to 130 m thick, has been encountered in the drilling of Hogarth 1-4 and Shannon 1 at a depth of ~270m. Owing to its highly magnetic character and shallow depth, its subsurface presence and extension could also be interpreted from the magnetic data. No volcanics/sills have been recorded in the drilling of Pickabooba 1 further southwest.



Legend

● Well

● Basement Well

🟥 Mt Warning Complex: intrusive & extrusive; syenite, monzonite, granite, basalt

🟪 Sill of dolerite/basalt

🟦 Tertiary Volcanics

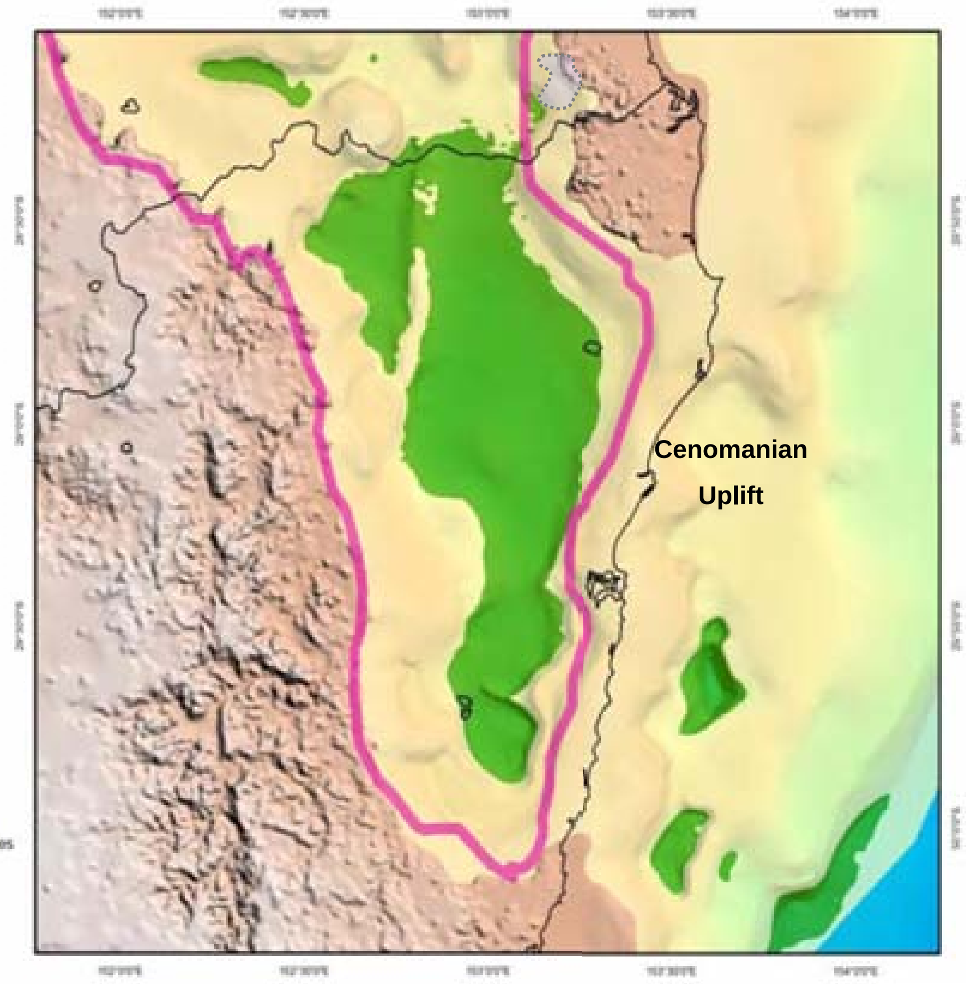
🟥 Tertiary Volcanics: thin layer of mainly volcano-clastics sediments

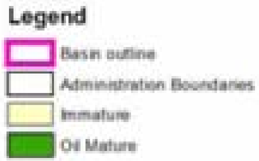
Potential Source Maturity at Basement

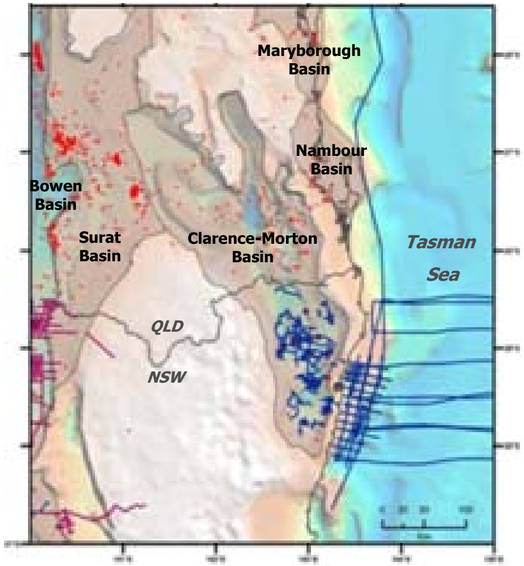
A present-day maturity map shows areas within the Clarence-Moreton Basin where potentia source rocks that overlie basement are currently within the oil generation window. Th maturity map is a derivative grid that was generated using the sediment thickness an SEEBASE™ depth-to-basement grids. The top to the oil window was defined at 2500m.

The maturity map shows that the present-day oil mature areas (green) lie along the axis of th onshore basin depocentre, while some parts of the offshore basin are also oil mature. Thi map is relevant for the Middle and Late Triassic successions which include the Nymboida an Ipswich Coal Measures that were deposited within topographic lows during the early stages o basin formation. The map is less predictive for the shallower Middle Jurassic Walloon Coa Measures that occur within the sag succession across much of the basin.

Although the shallow areas flanking the basin are modelled as immature at their presen depth, the entire eastern margin of the basin has been subjected to major uplift (Moonie Event/95Ma) and heating (Tasman Sea rifting) events. Thus, these areas are also likely to b mature for hydrocarbon generation if potential source rocks extend into these regions. A similar scenario is relevant for the offshore depocentre, although total sediment thickness i this region is poorly defined. The eastern part of the main onshore depocentre was als affected by uplift, and these areas are probably mature for gas generation.







This map is useful as a guide to screen areas of potential exploration interest, although further work is required to consider the local effects of uplift, erosion and heating events to more accurately determine maturity trends. Haselwood et al (2004) report high maturities in sediments along the eastern margin of the Clarence-Moreton Basin in Queensland, and a similar trend is expected in the NSW part of the basin system. In this context, other issues relating to an effective petroleum systems, such as the timing of hydrocarbon generation, trap development and preservation, can also be considered. Information on regional basement-derived heat flow can be inferred from the terranes information.

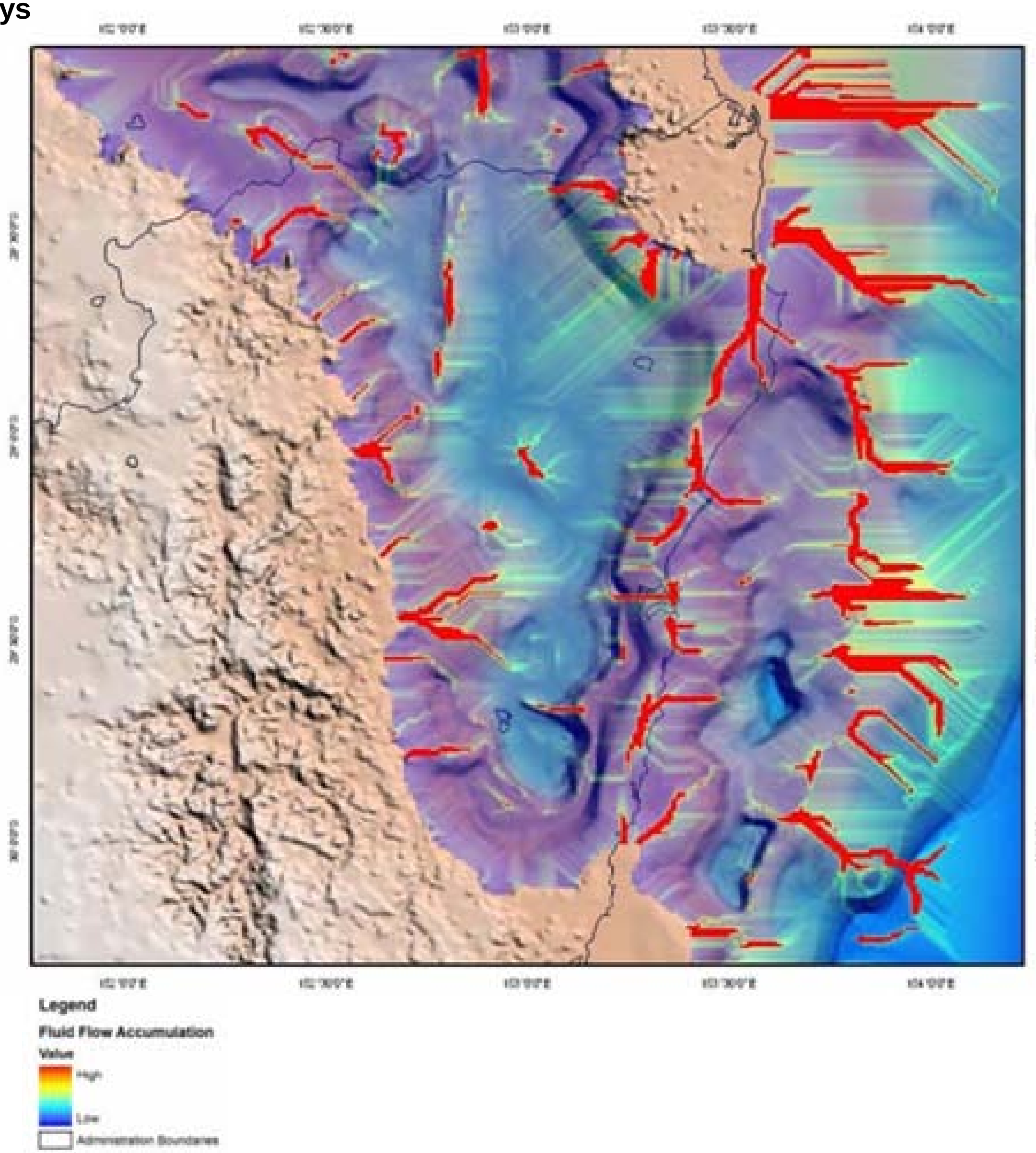
Basement Controlled Fluid Focus and Migration Pathways

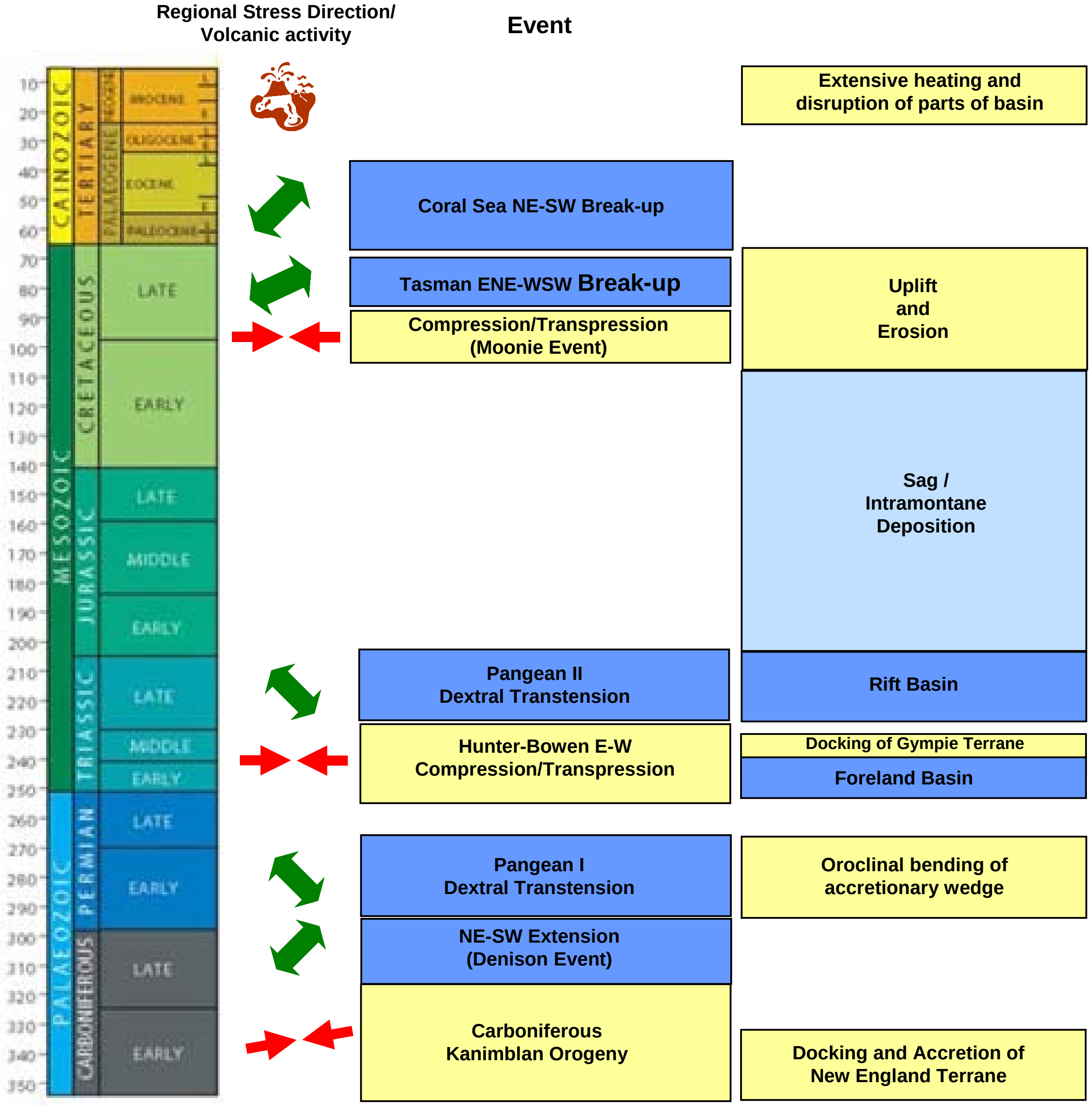
A map of fluid migration pathways based on basement topography has been calculated using the SEEBASE™ grid. Similar to the present-day maturity map, the predicted pathways are most relevant for hydrocarbons generated from potential source rocks that overlie the basement, or where deposition of deeper source rocks was strongly controlled by basement topography. In this context, the model predicts strong migration upward along steep gradients and towards basement highs or the basin flanks (SEEBASE™). The model also assumes homogenous source distribution, adequate source maturities and open pathway conditions.

The predicted pathways map shows strong migration and areas of possible fluid accumulation (shown in red) along the western and eastern flanks of the onshore Clarence-Moreton Basin. This trend probably over-emphasises to some degree the effects of Cenomanian uplift along the eastern basin flanks. Along this margin, the model is most relevant for hydrocarbons generated after the mid-Cretaceous event.

Interestingly, predicted migration in the offshore region is towards the nearshore basin flanks. This part of the offshore basin is more likely to have potential top seal facies as a result of Late Cretaceous and Cenozoic progradation. However, the offshore basin was strongly affected by structuring related to Tasman Sea rifting and Cenomanian uplift, thus hydrocarbons migrating prior to deposition of a Late Cretaceous and younger top seal may have been lost if not trapped within structures by existing intraformational seals.

These pathways provide an excellent prospecting tool for block selection and optimisation of seismic survey location.





**Regional Stress Direction/
Volcanic activity**

Event

Extensive heating and disruption of parts of basin

Coral Sea NE-SW Break-up

Tasman ENE-WSW Break-up

Compression/Transpression (Moonie Event)

Uplift and Erosion

Sag / Intramontane Deposition

Pangean II Dextral Transtension

Rift Basin

Hunter-Bowen E-W Compression/Transpression

Docking of Gympie Terrane

Foreland Basin

Pangean I Dextral Transtension

Oroclinal bending of accretionary wedge

NE-SW Extension (Denison Event)

Carboniferous Kanimblan Orogeny

Docking and Accretion of New England Terrane

Summary of tectonic events and regional stress directions that controlled the development of the Clarence-Moreton Basin.

The Clarence-Moreton basin is set regionally within the New England Orogen, which was dominated by strike-slip faulting from the Early Permian onwards (O’Brien et al, 1994). The basin developed as a result of thermal relaxation following a period of dextral transtension of a basement cut by major long-live strike-slip faults.

In the area of study a major episode of dextral transtension in the Early Permian led to the re-organisation in the tectonic pattern of the basement blocks and to the development of major oroclines that bent the accretionary wedge material (Korsch at al.; 1989). Although the extent to which the basin margins have been controlled by major structures is not clear, Harrington and Korsch (1987) suggested that the position of the Coffs Harbour orocline is likely to have controlled the southern limit to sedimentation.

During the final phase of the Hunter-Bowen orogeny a period of crustal loading persisted in the Clarence-Moreton area.

This period of compressive deformation was immediately followed by a Late Triassic right transtensional event. In the project area, dextral transtension along the West Ipswich Fault produced a rift basin beneath the Laidley Sub-basin (Korsch et al, 1989). Transtension then stepped eastward to site of the present Logan Sub-basin and Ipswich Basin, which formed by thermal relaxation subsidence and continued minor strike slip faulting.

From the Late Triassic to the early-Late Cretaceous, thermal subsidence accommodated deposition of the Clarence-Moreton Basin while minor dextral strike slip movements along the basin forming faults produced locally enhanced subsidence or uplift.

An early-Late Cretaceous compressional/transpressional event (Moonie Event) reactivated many of the earlier structures in the basin and in the basement and inverted some normal faults.

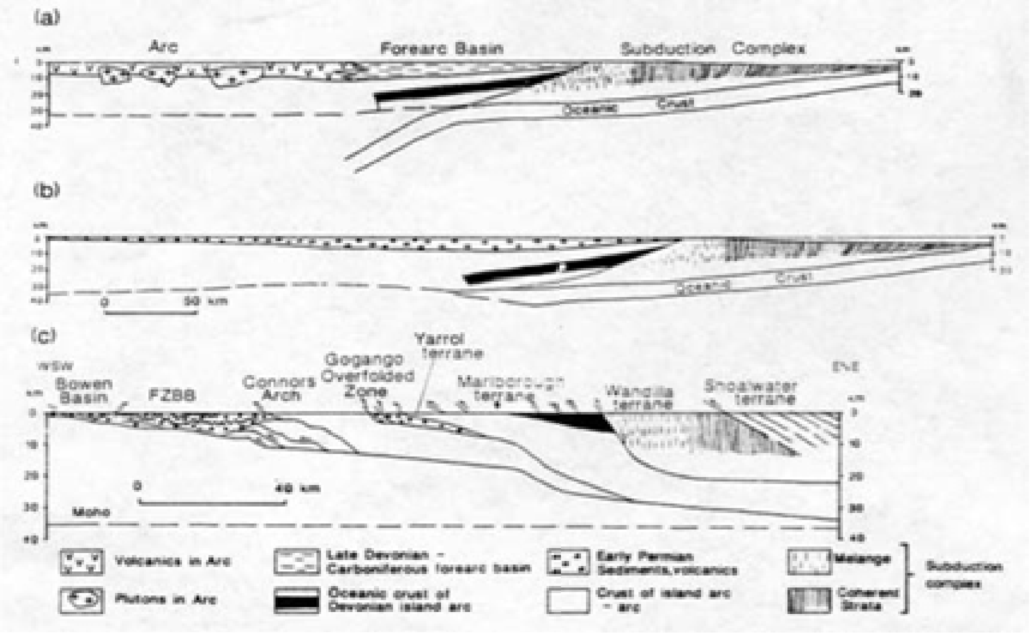
Initiation of rifting and sea floor spreading along the eastern Australian continental margin in the Late Cretaceous resulted in the heating and uplift of the eastern part of the Clarence-Moreton Basin.

Intermediate to basic volcanics and intrusions produced extensive heating and disruption of parts of basins during the Miocene.

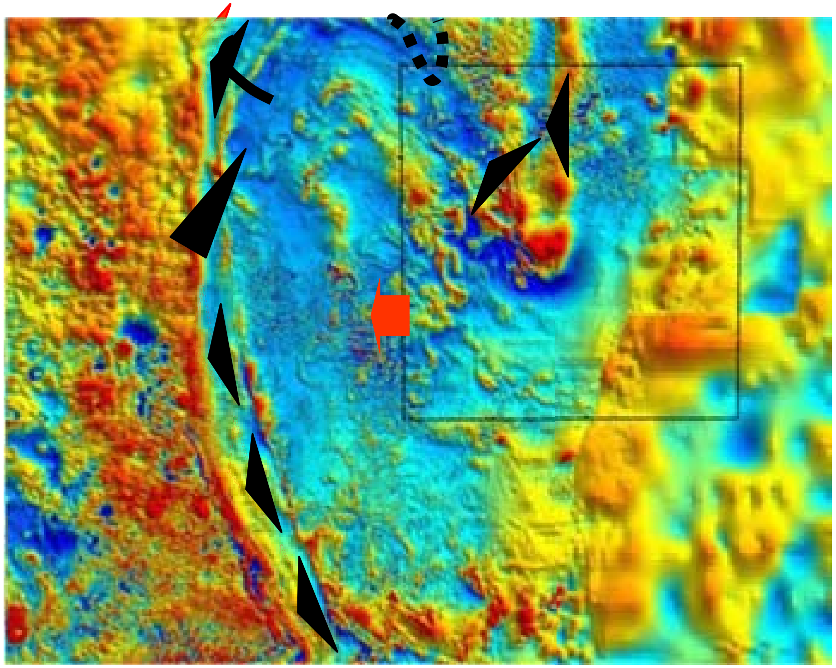
Kanimblan Carboniferous: 350-315 Ma
E-W Compression

The Kanimblan event (~350-325Ma) is a major NE-SW to E-W compressional event on the eastern margin of Gondwana which culminates in the amalgamation of the New England Terrane with Gondwana. During the Carboniferous, the east Gondwanan margin was riding over a west-dipping subduction zone. West of the subduction zone was a continental magmatic arc intruding the previously accreted Monaro Terrane. The Tamworth belt was the Devonian to Carboniferous forearc basin and the Yarrol Belt, the accretionary wedge. Small "inclusions" of anomalously high magnetic and gravity material may have been obducted oceanic crust.

Most of the basement relevant to the area of study has been interpreted as ancient accretionary wedge material (e.g. Coffs Harbour, Beenleigh and South D'Aguilar Blocks) accreted during the Kanimblan Orogeny and subsequently folded during the Early Permian Pangean I Event.



Schematic diagram from Fergusson (1991) showing the temporal evolution of the eastern margin of Gondwana, from a subduction-related arc/forearc/accretionary wedge complex during the Devonian-Carboniferous to its present faulted configuration.



Approximate location of the New England suture west of the project area (black box). Dashed line shows the approximate position of the (now folded) suture beneath the Clarence-Moreton Basin. TMI image of Geoscience Australia National Magnetic data.

Denison Event: Late Carboniferous-Early Permian (315-295 Ma) NE-SW Extension

The Kanimblan collision on the eastern margin of Gondwana was followed by the extensional Denison Event which stretched from far north Queensland to southern New South Wales with the initiation of the Sydney, Bowen and Gunnedah Basins in a back-arc setting. In the Connors Arch, east of the Bowen Basin, extension was marked by core complex formation (Holcombe et al., 1994a) with associated volcanism and granite intrusion. The large volume of igneous material intruded at this time into the accretionary wedge may indicate subduction of the mid-ocean ridge beneath the wedge (Veevers, 2000). This mechanism would also account for the change from a compressional to an extensional regime. This event is also documented in the Nambucca Terrane which may have occupied a similar tectonic position at that time.

In Late Carboniferous time the basement to the Clarence-Moreton was not yet folded. A similar setting of ‘back-arc’ basin and extension-driven volcanic arc is envisioned for the Clarence-Moreton basement as well. Denison Extension precedes Orocline folding so structures of this age will be transposed during the next (Pangean I) event

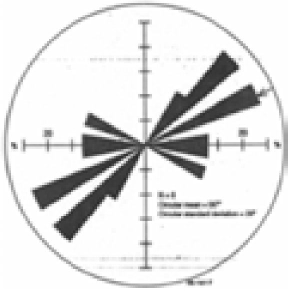
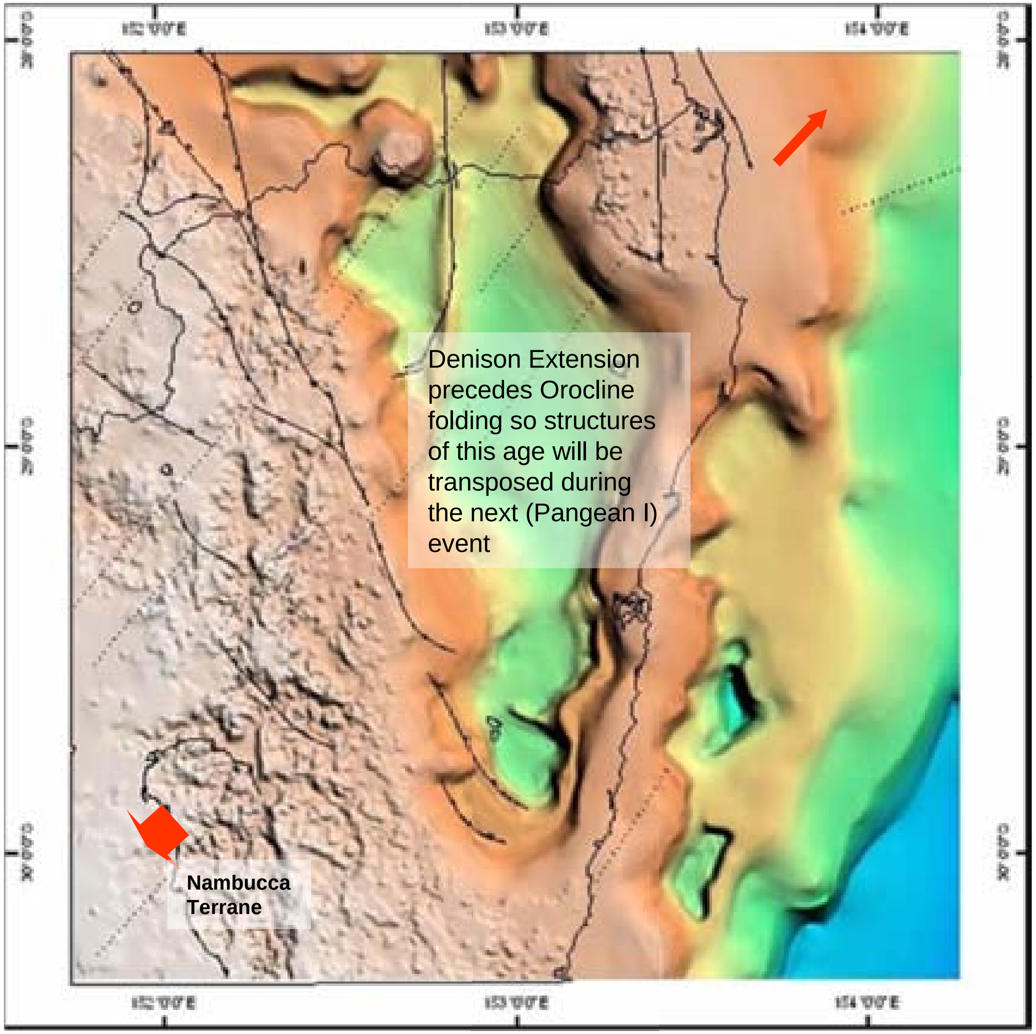


Diagram showing results of the dip analysis conducted by Korsch et al. (in press) to infer the kinematics of the extensional fault system. Outcome of the dip analysis is consistent with extension direction previously proposed by Hammond (1988) (figure on the right).



Denison Extension precedes Orocline folding so structures of this age will be transposed during the next (Pangean I) event

Legend

MOVEMENT

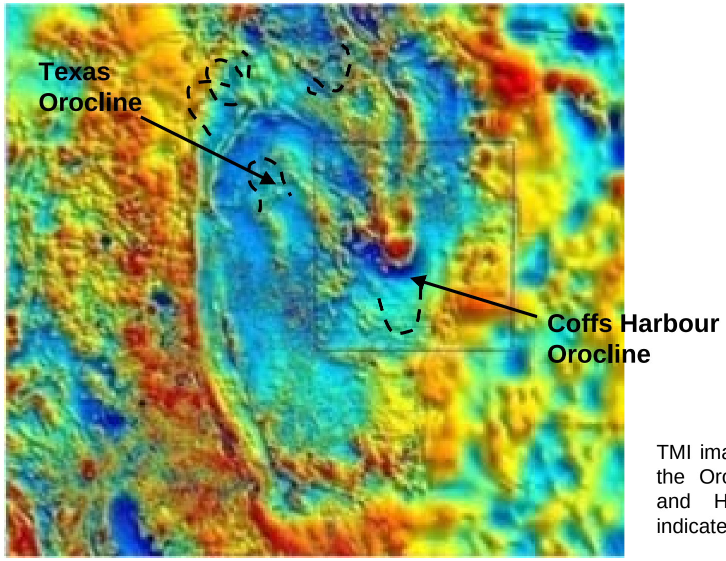
—? — ?
⇌ Dextral
▪⇌ Dextral Normal
▲— Dextral Reverse
—▪— Normal
—▲— Reverse
⇋ Sinistral
▪⇋ Sinistral Normal
▲— Sinistral Reverse
······· Transfer

Early Permian (295-265 Ma) Dextral Transtension - Texas Event

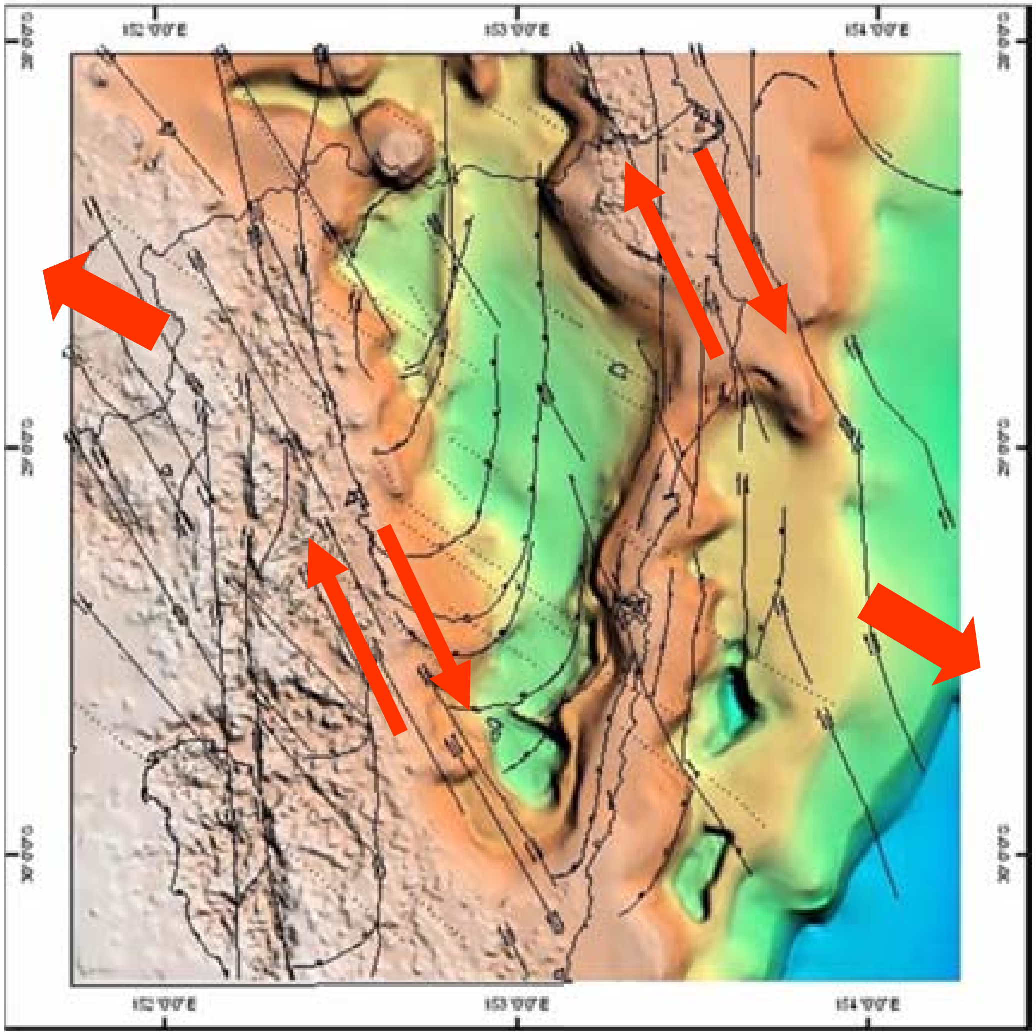
In the area of study, this transtensional event led to reorganisation in the tectonic pattern of the basement blocks, including later development of major oroclines that bent the accretionary wedge material (Korsch at al.; 1989). Harington and Korsch (1987) suggested that the Clarence-Moreton Basin was deposited on the inside of the Coffs Harbour oroclinal bend, and hence the southern limit to sedimentation was possibly controlled by the position of the orocline.

An important component in the development of the accretionary wedge, oroclinal bending and accretion of exotic terranes (e.g. the accretion of the Gympie terrane in Mid-Late Triassic) has been strike-slip faulting. It is likely that displacement of the order of hundreds of kilometers took place (Harrington and Korsch 1985c); proven displacements are an order of magnitude lower, with about 23 km documented for the Demon Fault (McPhie & Fergusson 1983).

Within the above tectonic framework, the Clarence-Moreton and its precursors, the Esk Trough and Ipswich Basin, developed on a basement cut by major, longlived strike-slips faults.



TMI image showing evidence of the Orocline model of Korsch and Harrington (1987) (box indicates the project area).



Legend

MOVEMENT

? — ?

Dextral

Dextral Normal

Dextral Reverse

Normal

Reverse

Sinistral

Sinistral Normal

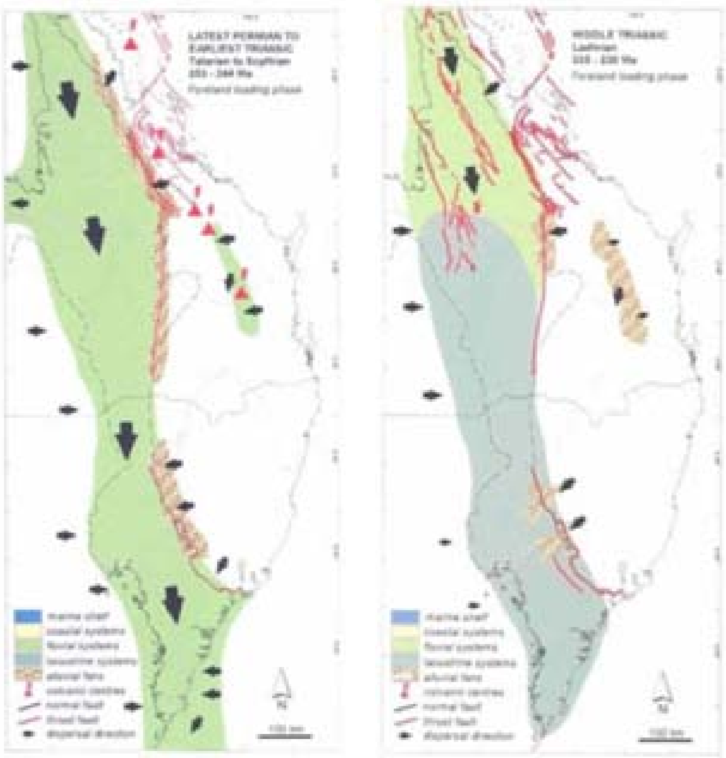
Sinistral Reverse

Transfer

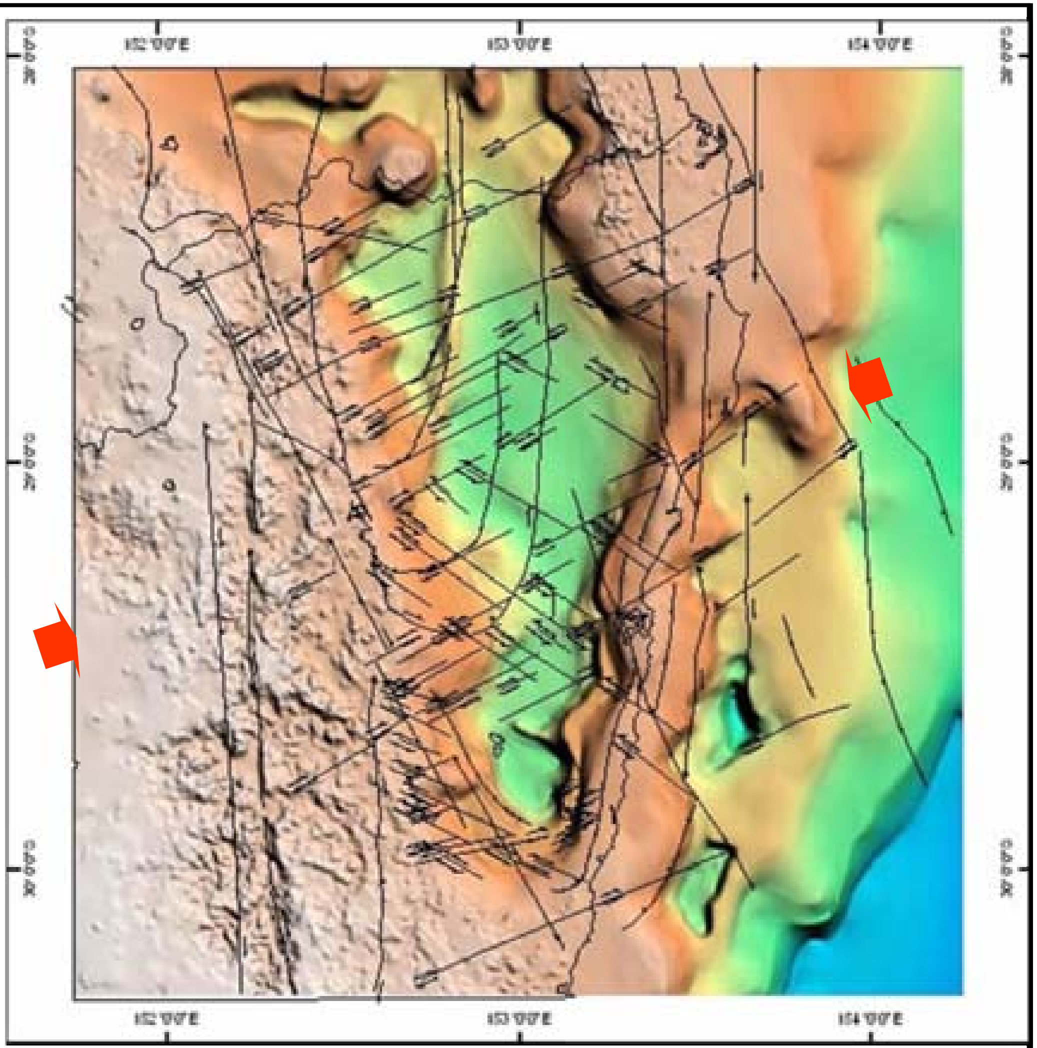
Hunter-Bowen Orogeny: 255Ma - 228Ma

The Late Permian to early-Late Triassic was dominated by the Hunter-Bowen Orogeny. ENE-WSW compression took place in at least two pulses. The Neara Volcanics at the base of the Esk Trough in SE Queensland unconformably overlie thrust faults from the early phase and are dated at ca.241Ma (Holcombe et al., 1994). Between 241 and 230Ma, this early sequence is folded into 1km folds (Holcombe et al., 1994) . In Queensland, the folded sequence is overlain by flat lying extension-related 228Ma volcanics.

A similar tectonic environment is likely to have persisted in the Clarence-Moreton area during the latest stages of the orogeny, in the early-Late Triassic. During this period of foreland crustal loading, the conglomerates and volcaniclastic sediments of the Nymboida Coal Measures were deposited over the unconformity related to the early pulse of thrusting. Open folds in the Nymboida Sequence beneath the Ipswich Sequence are interpreted to be contemporaneous with those in the Esk Trough.



Paleogeographic maps showing the period of foreland crustal loading which persisted across the Bowen-Gunnedah-Sydney Basin system from Late Permian to Middle Triassic in response to propagation of thrust sheets during the Hunter-Bowen Orogeny (from Fielding et al., 2001). As similar tectonic regime is likely to have persisted also in the Clarence-Moreton area, at least during the latest phase of the orogeny.



Legend

MOVEMENT

? — ?
Dextral
Dextral Normal
Dextral Reverse
Normal
Reverse
Sinistral
Sinistral Normal
Sinistral Reverse
Transfer

Late Triassic Right Lateral Transtension: 227Ma - 200Ma - Pangean Extension II

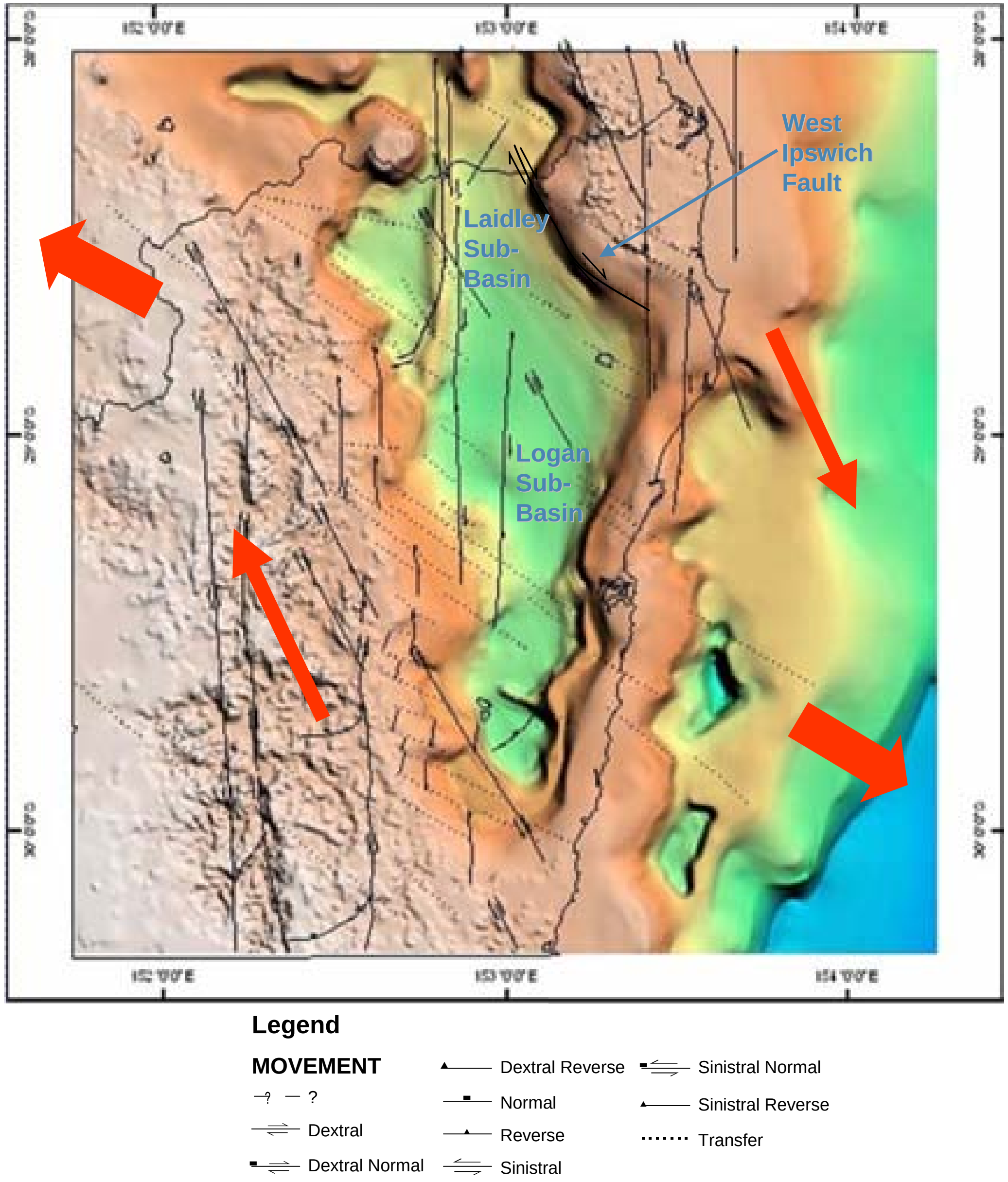
In the project area, dextral transtension on the West Ipswich Fault produced a rift basin beneath the Laidley Sub-basin; transtension then stepped eastward to the Logan Sub-basin and the Ipswich Basin formed by thermal relaxation subsidence and continued minor strike slip faulting.

Late Triassic rift-related deposition was restrictive, confined to several localised extensional basins. The Evans Head and Red Cliff Coal Measures (time equivalent to the Ipswich Coal Measures in Queensland) along the eastern margin of the basin, which unconformably overlie the Nymboida Coal Measures, most likely represent the initial ‘syn-rift’ phase of basin development.

This event has nearly identical kinematics to the Early Permian Texas folding/transtensional event and reactivates some of the structures produced at that time. However, the deformation and granite intrusion of the Hunter-Bowen Orogeny had “stitched” many of these structures, thus hardening the basement and drastically reducing the number of structures available for reactivation. Some of these structures were inverted during a Late Cretaceous compressional event (Moonie event)

Localised uplift during the final phase of the deformation led to an unconformity between the Nymboida and Ipswich equivalent Coal Measures sequences and the Bundamba Group (beginning of ‘proper’ Clarence-Moreton sequences).

After transtension ceased, from the Late Triassic to probably the Early-Late Cretaceous, thermal subsidence accommodated deposition of the Clarence-Moreton Basin while minor dextral strike slip movements along the basin forming faults produced locally enhanced subsidence or uplift.

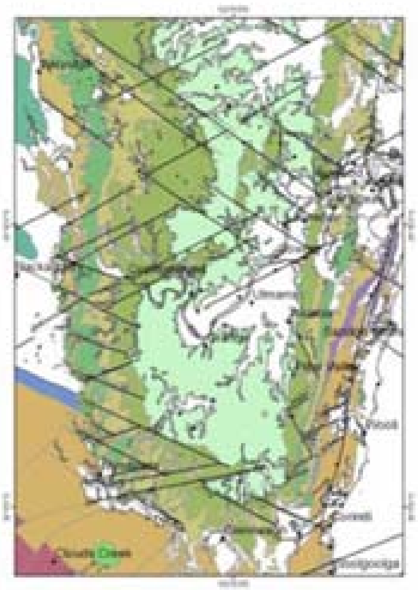


Early Late Cretaceous Contraction: 95 Ma - Moonie Event

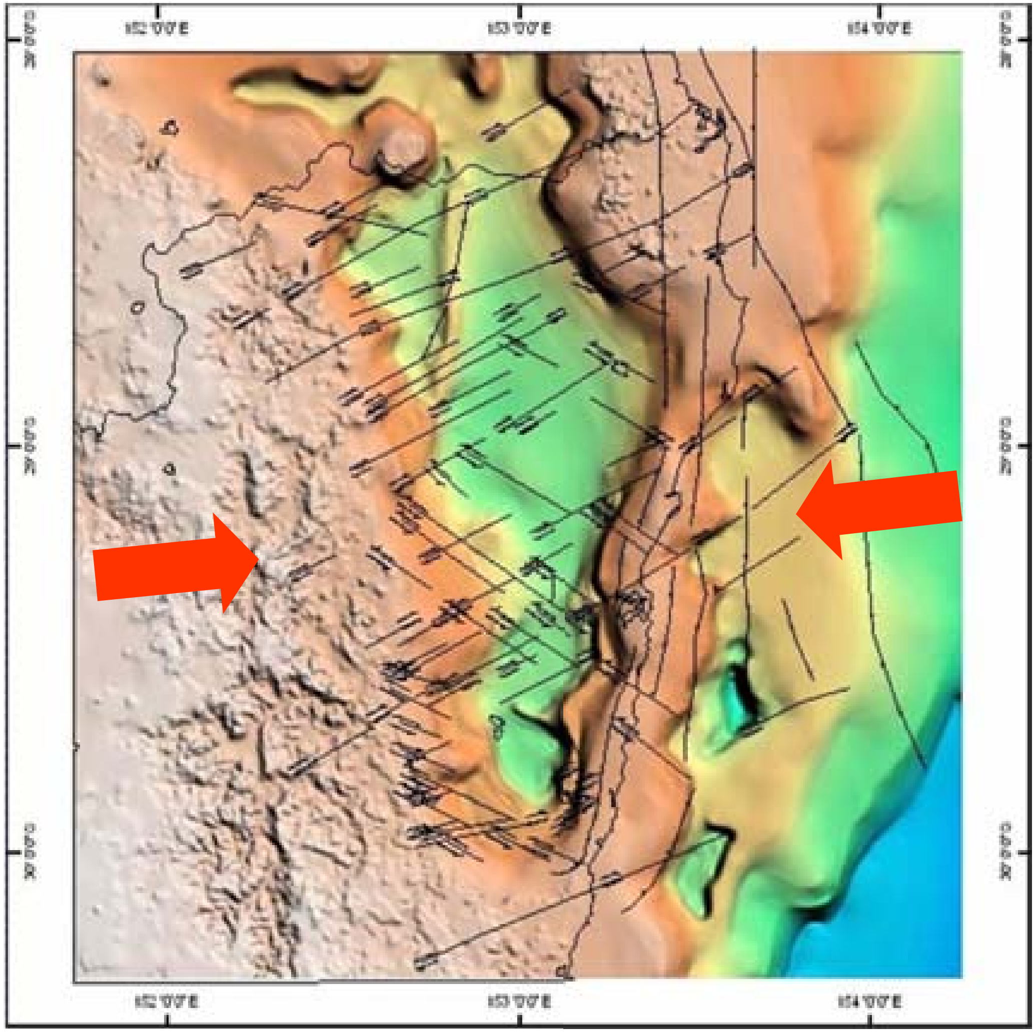
A major global plate re-organisation took place in the Cenomanian when the Pacific plate trajectory changed from E to NE (Veevers, 2000). In northeast Australia this inversion event is seen in the Maryborough Basin where it is strongest in intensity (e.g. Hill, 1991). The event is also recognised in the Gippsland Basin and New Zealand.

In the Clarence-Moreton Basin, many of the earlier Hunter-Bowen structures were reactivated. Conjugate strike-slip faults accommodated crustal shortening, essentially narrowing the basin. This resulted in shortening (folding) of the basin sediments as they were forced to occupy a smaller space. The eastern margin of the basin underwent major uplift, upturning what had been a flat-lying sequence. This reactivation is important as it has produced or enhanced anticlines and structural traps. Such traps are attractive exploration targets in the basin with both types having hydrocarbon productive analogues in the Cooper, Eromanga, Surat and Bowen Basins.

The contractional event occurred immediately prior to continental extension, where it is likely that footwall uplift prior to seafloor spreading led to the formation of passive margin mountains and the regional uplift.



Geological map of the Clarence-Moreton Basin showing the effect of the Moonie Compression on the outcrop pattern of the basin. The western margin has been modified into a series of rectangular steps overprinting the early onlap margin. The eastern margin has been sharply upturned, probably localised on a reactivated Hunter-Bowen thrust fault.



Legend

MOVEMENT

⇀? — ?	▲—— Dextral Reverse	■⇌ Sinistral Normal
⇌ Dextral	■—— Normal	▲—— Sinistral Reverse
■⇌ Dextral Normal	▲—— Reverse	······ Transfer
	⇌ Sinistral	

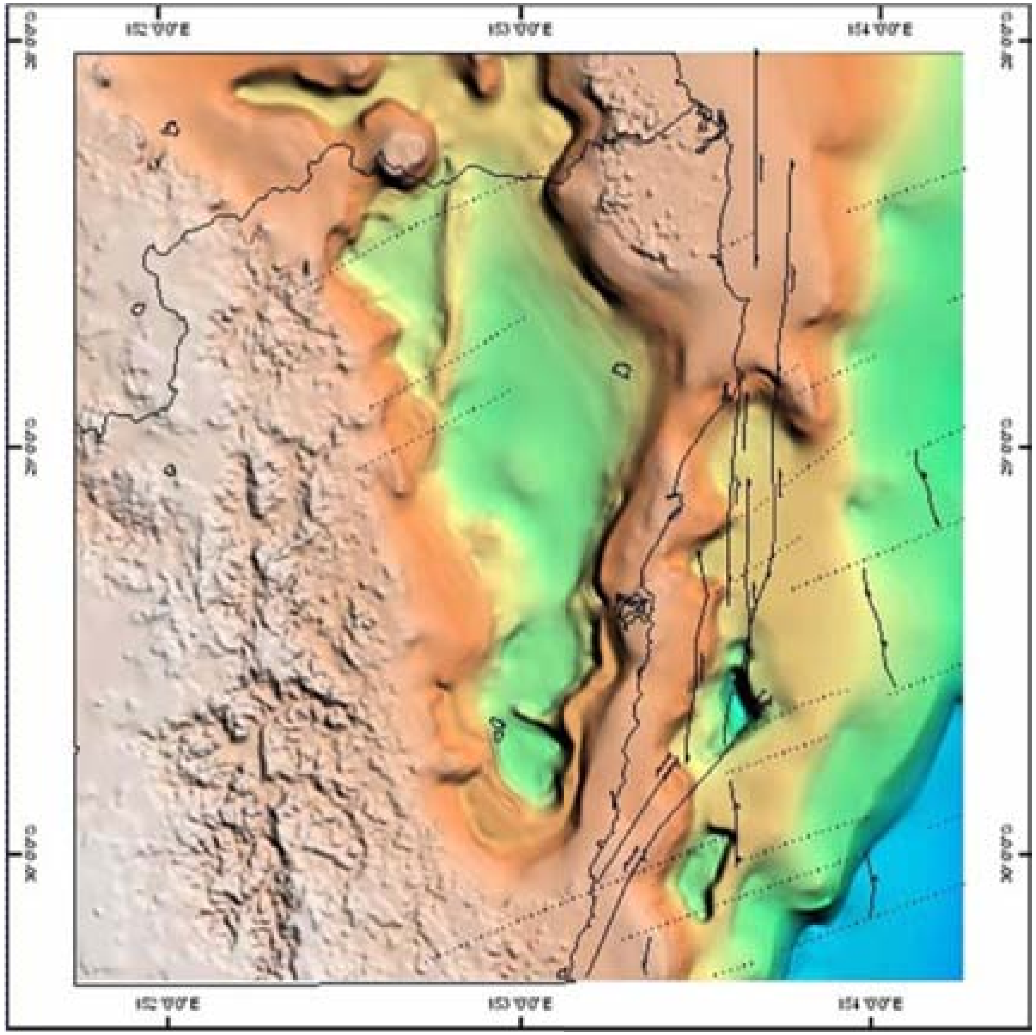
Tasman Late Cretaceous: 90-85 Ma
N-S & ENE-WSW Extension

In the Late Cretaceous, during the final phases of breakup between Australia, Antarctica and the Lord Howe Rise, back-arc extension occurred along eastern and southern margins of Australia. This extensional event started at approximately 95 Ma and culminated with the spreading of Tasman Sea at ~84 Ma (Gaina et al, 1998; Muller, 2000).

Pre-breakup extension along most of eastern Australia was oriented ~ENE-WSW and included substantial crustal stretching and thinning of the Lord Howe Rise, the Norfolk Ridge and the westernmost parts of New Zealand (Lister & Etheridge, 1989).

The initiation of rifting and sea floor spreading along the eastern Australian continental margin saw heating and uplift of the eastern part of the Clarence-Moreton Basin.

Along this portion of the New South Wales margin, seafloor spreading and the subsequent post-breakup margin-subsidence phase initiated around 68 Ma (Shaw et al., 2001). Thus, it would appear that in the project area the timing of elevated heat flow and alteration effects related to the opening of the Tasman Sea are significantly later than the period of Clarence-Moreton Basin intracratonic deposition and may have brought about its cessation (Shaw et al., 2001).



Legend

MOVEMENT

? ?

Dextral

Dextral Normal

Dextral Reverse

Normal

Reverse

Sinistral

Sinistral Normal

Sinistral Reverse

Transfer

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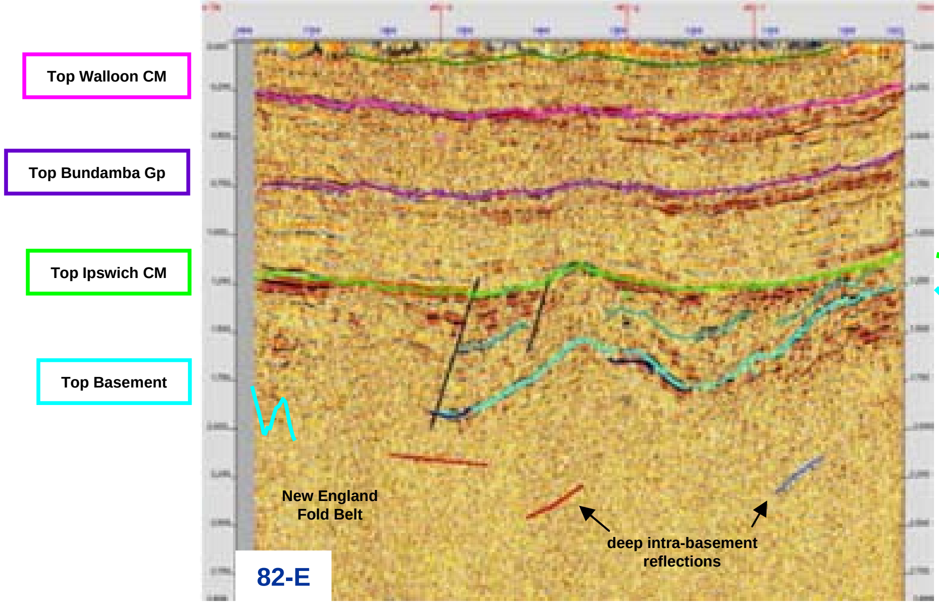
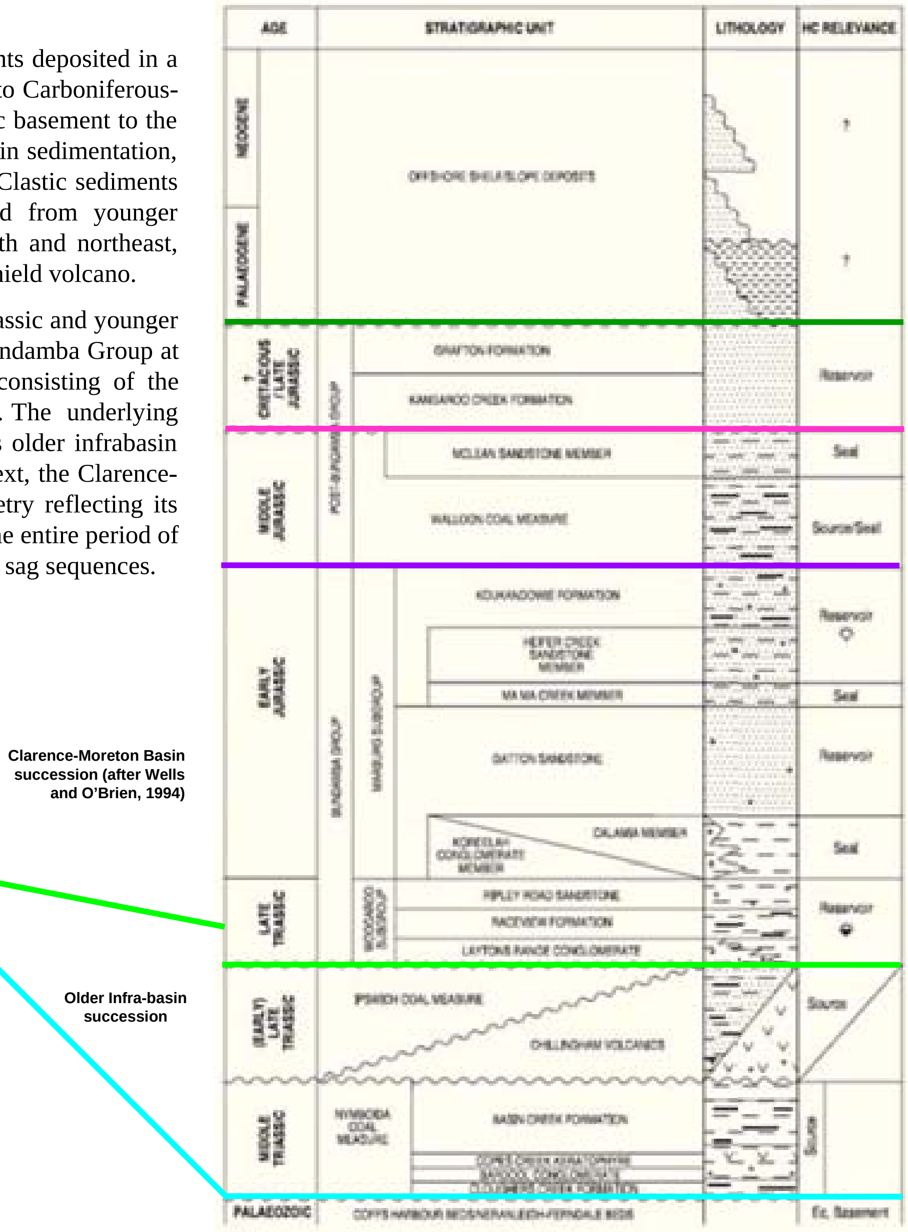
Stratigraphy

The Clarence-Moreton Basin contains 2500 to 4000 m of fluvial, lacustrine and paludal sediments deposited in a proximal to distal foreland basin. The basin sediments unconformably overlie Early Palaeozoic to Carboniferous-Permian metasediments and metavolcanics of the New England Fold Belt which forms economic basement to the basin succession. During the Permo-Triassic, prior to the initiation of the Clarence-Moreton Basin sedimentation, extensive plutonic suites (mainly granites) were emplaced, concomitant with silicic volcanism. Clastic sediments of the Clarence-Moreton Basin were sourced from the surrounding Palaeozoic rocks and from younger volcaniclastics associated with the Mesozoic fragmentation of eastern Gondwana. To the north and northeast, basinal sediments are overlain and intruded by Tertiary basalts associated with the Mt Warning shield volcano.

Wells and O’Brien (1994) define the Clarence-Moreton Basin succession as comprising Late Triassic and younger age sediments that can be subdivided into three basic groups: 1) Woogaroo Sub-group of the Bundamba Group at the base; 2) Marburg Sub-group of the Bundamba Group, and the post-Bundamba Group consisting of the Walloon Coal Measures, Kangaroo Creek Sandstone, Woodenbong beds and Grafton Formation. The underlying Ipswich (early Late Triassic) and Nymboida (Middle Triassic) Coal Measures are described as older infrabasin successions belonging to the Esk Trough and Ipswich Basin (O’Brien et al., 1994). In this context, the Clarence-Moreton Basin succession (as defined by Wells and O’Brien, 1994) has an overall sag geometry reflecting its depositional during a period of continuous subsidence. As the SEEBASE™ study encompasses the entire period of basin evolution, the ‘older infra-basin succession’ is not considered separately from the overlying sag sequences.

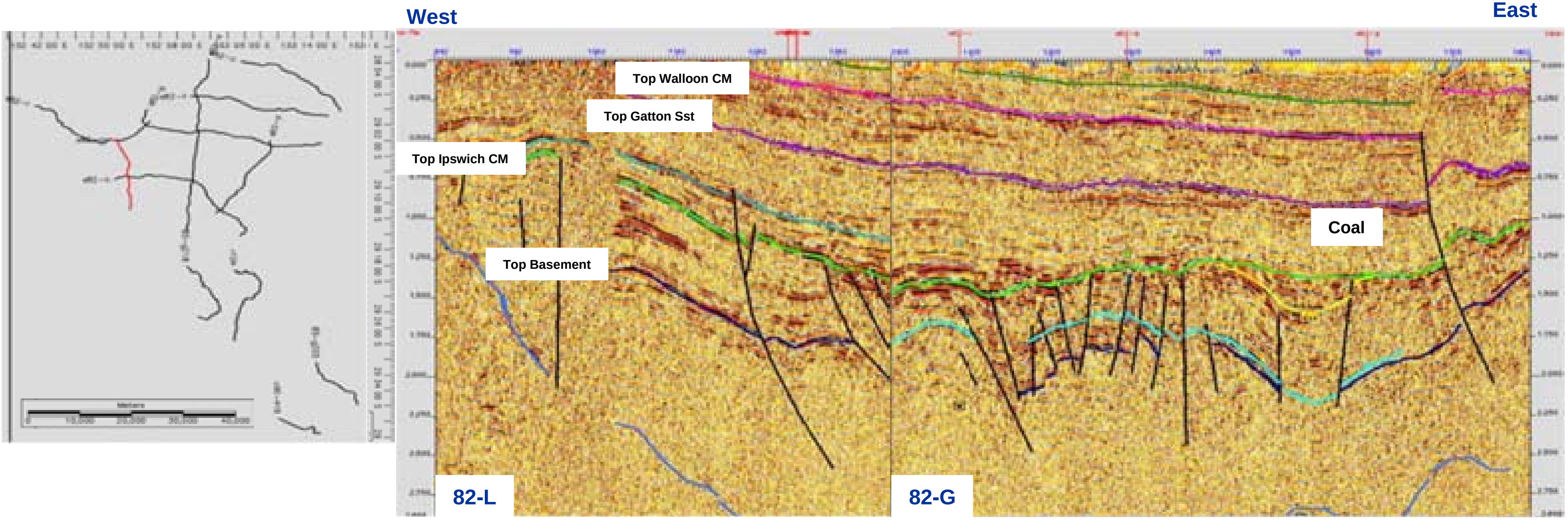




Although the stratigraphic column that is often used for the Clarence-Moreton Basin (e.g., Wells and O'Brien, 1994; Shaw et al., 2001) shows the oldest sediments to be Middle Triassic in age, seismic data across the Esk Trough (west of the West Ipswich Fault) indicates a thick, older syn-rift succession overlying basement rocks of the New England Fold Belt (Willey, 2000; Korsch et al., 1989). These sediments have not been intersected and do not outcrop, thus their age is speculative. These rocks may be Permo-Carboniferous, but are likely to be thin and/or strongly deformed in the southern part of the basin. The resource potential of any deeper Permo-Carboniferous section is probably low due to deformation (metasediments). Sedimentation in the basin began in the Middle Triassic with deposition of the Nymboida Coal Measures along with conglomerates and volcanics of the Toogoolawah Group (O'Brien et al., 1994). These units unconformably overlie an undulating basement surface that formed during a pulse of thrusting. The Nymboida Coal Measures were deposited and mildly folded during the Hunter-Bowen Orogeny and are time equivalent to sedimentary rocks in the Esk Trough. Seismic images show thinning and thickening of the sediments that is the result of inherent topography.

Deposition of the overlying Chillingham Volcanics, Evans Head and Red Cliff Coal Measures occurred during a phase of transtension in the early Late Triassic (Pangean II event). The Evans Head and Red Cliff Coal Measures are up to 300m and 600m thick, respectively, and are time equivalent units to the Ipswich Coal Measures in Queensland. Although patchy, the regional seismic dataset shows some evidence of rift faults that actively controlled deposition.

Collectively, the Nymboida, Evans Head and Red Cliff Coals Measures have been described as the 'infrabasin that occupies the axis of the Clarence-Moreton Basin' (Wells and Brien, 1994). The distribution of coaly intervals in the infrabasin is marked by distinctive high amplitude, low frequency reflectors on seismic data, although some of these intervals may also contain volcanic rocks. Overall, the distribution of coal is patchy and largely controlled by basin topography with high amplitude 'seismic packages' occurring within the lows (or shallow depocentres). Coaly intervals within the units have hydrocarbon source (gas) and some reservoir potential. The top of the infrabasin succession is marked by truncation indicating some uplift and erosion. This unconformity marks the end of strong topographic control on deposition and the onset of sag phase sedimentation.

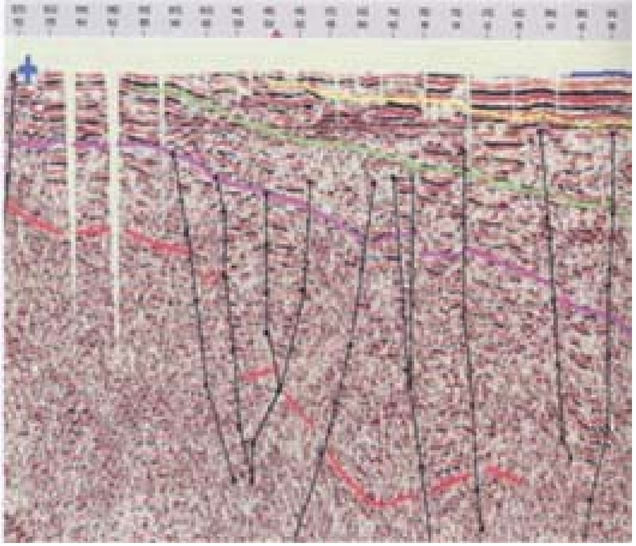


The Bundamba Group is conglomerate and sandstone succession up to 1200 m that was deposited in fluvial to lacustrine environments during sag phase conditions. These rocks mark the onset of the Clarence-Moreton Basin succession as defined by Wells and O'Brien (1994). These rocks outcrop both on the basin margins where they have been shown to unconformably overlie the Nymboida and Evans Head/Red Cliff Coal Measures Wells and O'Brien (1994). The Bundamba Group is commonly divided into a Lower (Woogaroo) and an Upper (Marburg) Subgroup, each consisting of several different units. Within the Woogaroo Subgroup the sandstones of Pillar Valley Formation ('Mid Bundamba Sandstone') represent a major potential reservoir with hydrocarbon shows and minor oil (e.g. Sextonville-I) having been reported. The Marburg Subgroup also has significant reservoir potential, with gas and minor oil shows recorded throughout the basin. The sub-economic Hogarth gas field (14000 m^3/day from Hogarth-2) occurs within this formation. In the Middle Jurassic a major episode of widespread fluvial and lacustrine to paludal conditions in the region saw the deposition of the Walloon Coal Measures, which are present throughout the Clarence-Moreton Basin as well as in the Surat and Eromanga Basins. These coal measures outcrop at the basin margins and thicken towards the basin axis, to a maximum of about 400 m in the north-central part of the basin. The base of the Walloon Coal Measures appears as a marked disconformity and/or a distinct seismic marker on seismic sections. Sandy units within these coal measures can be considered as a secondary reservoir target due to their high content of interstitial clays and other poor reservoir properties. Unconformably overlying the Walloon Coal Measures is the Late Jurassic – Early Cretaceous Kangaroo Creek Sandstone, a flat lying unit which forms prominent cliffs and scarps throughout the basin. These sandstones probably represent a fluvial to lacustrine deposit, with current directions indicating derivation from the south.

Fluvial to lacustrine to shallow marine environment conditions persisted within the basin throughout the Early Cretaceous. In this period the Grafton Formation, the uppermost unit in the Mesozoic succession of the New South Wales part of the Clarence-Moreton Basin, was deposited. The formation, which comprises about 100-250 m of clayey siltstone and soft sandstone, occupies the axial zone of the Clarence-Moreton Basin, where it outcrops poorly. In the Late Cretaceous the initiation of rifting and sea floor spreading along the eastern Australian continental margin saw heating and uplift of the eastern part of the Clarence-Moreton Basin and the cessation of the intracratonic deposition. Tertiary Late Oligocene-Early Miocene intrusives and extrusives occur throughout the basin but are principally concentrated in the northern New South Wales part of the basin. In these northern areas, the basic, intermediate and acid extrusives and intrusives of the Mt Warning central complex, and the Main Range and Lamington Volcanics, are widespread. Basaltic sills are commonly intersected in northern boreholes and are also recorded in several wells in the south near Grafton.

Offshore Clarence-Moreton Basin

Interpretation of reprocessed industry seismic data originally collected in 1969 off the southern part of the Clarence-Moreton Basin has confirmed an offshore continuation of the basin with a total sediment thickness of about 2500 m (~2.0 seconds in TWT; Shaw et al., 2001). Four sedimentary packages have been identified from the seismic data. The upper two packages have been interpreted as prograding sediment wedges that correlate with post-Gondwana break-up deposition. Package III is an interval of well stratified sediments and it appears to be faulted and to be bounded at both its top and base by erosional truncation. This package most likely corresponds to the offshore extension of the sediments of the Marburg Subgroup. The deepest package comprises a thick (2000m or more), well stratified, sometimes highly faulted succession, which has been interpreted to have been deposited during a "syn-rift" stage of the basin. These syn-rift sediments would incorporate offshore correlatives of the onshore Evans Head and Ipswich Coal Measure sequences as well as Chillingham Volcanics of Middle and perhaps Early Triassic age.



Portion of Line Ma-05 showing typical downfaulting interpreted across the inner shelf, adjacent to the margin where Clarence-Moreton sediments are truncated along the coastline. Colour annotations for horizons are:

Yellow – Top of Package II; **Green** – Base of Package II; **Purple** – Base of Package III; **Red** – Near Base of Package IV (from Shaw et al., 2001).

Conclusions

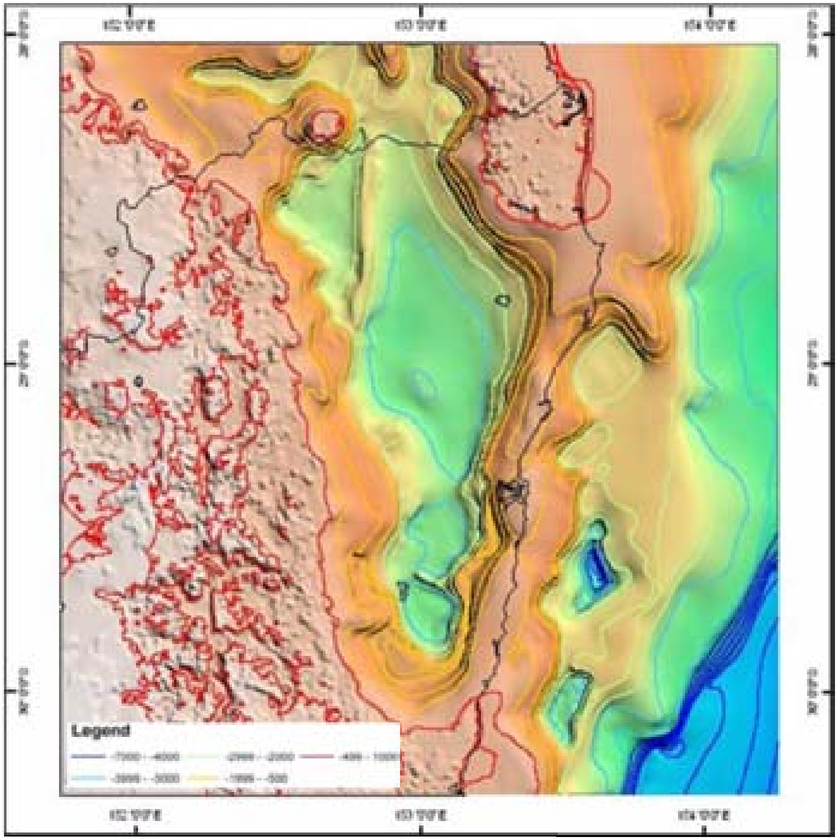
The main objectives of the Clarence-Moreton SEEBASE™* and GIS Project study were to provide the NSW Department of Primary Industries with an integrated regional interpretation of the basement composition, lithology, structure and depth of the Clarence-Moreton Basin in New South Wales. This included the construction of a depth to basement image (SEEBASE™) for the area.

The effects of the basement geology on the evolution of the Clarence-Moreton Basin (both onshore and offshore) and of its precursors, the Esk Trough and the Ipswich Basin have been investigated. Attention was focused on the formation and reactivation of the basin controlling structures. The evolution of these structures has been evaluated in the light of the different tectonic events that have affected the area.

Maturity and fluid flow migration maps derived from SEEBASE™ grids indicate that the central axis of the onshore depocentres and parts of the offshore basin are mature for present-day oil generation. However, these maps probably underestimate the maturity along the eastern margin of the basin, due to significant uplift and erosion that occurred during the Cenomanian. Such areas are likely to be mature for hydrocarbon generation provided adequate source rocks are present at depth.

Available gravity and magnetic data have been reprocessed and enhanced with an extensive set of wavelength and amplitude filters. An ArcMap 9.0 GIS product has been constructed that includes all structural interpretations, as well as the potential field data.

The revised and expanded interpretation of the structure and basin architecture in the area of the Clarence-Moreton Basin provides an improved understanding of basin evolution in the region, which will contribute to the reduction of exploration risks in the area.



Key results of the Clarence-Moreton Project

- The Clarence-Moreton Basin overlies the core of the sheared New England Orocline.
- Orocline folding took place in the Early Permian, setting a lower limit on basement age.
- Basement was also affected by the Late Permian to Middle Triassic Hunter-Bowen compressional event.
- The basal Nymboida Formation is interpreted to be late stage Hunter-Bowen foreland basin sediments that have been folded prior to the deposition of the Ipswich Formation.
- The Ipswich Formation is interpreted to be a late to post Hunter-Bowen flooding event that fills topography.
- The Clarence-Moreton Basin sediments onlap the western margin, the eastern margin is a structural boundary produced by uplift of the basin margin in Cenomanian time.
- Cenomanian folding results from basin sediments accommodating E-W shortening of the basin through conjugate strike-slip faults.
- There is minimal evidence preserved onshore of the Tasman Sea extension.
- Offshore continuation of the basin has been confirmed, with a sedimentary sequence that would incorporate correlatives of the onshore Evans Head and Ipswich Coal Measure sequences as well as the Marburg Subgroup.

***SEEBASE**™= **S**tructurally **E**nhanced view of **E**conomic **Base**ment

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