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A new interpretation and model of the Moonie–Goondiwindi and Burunga–Leichhardt fault systems in Queensland

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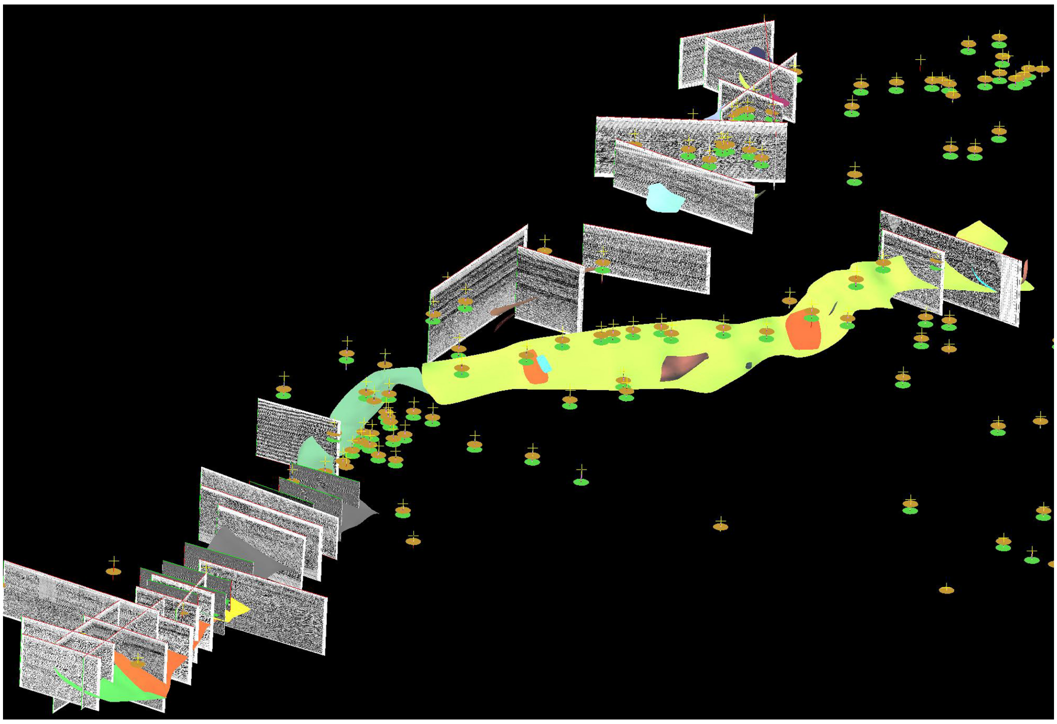

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SUMMARY

This study provides a new regional interpretation of the three dimensional geometry of the fault systems on the eastern flanks of the southern Bowen Basin and the Surat Basin. The objective of the model is to contribute to a geological framework as a basis for understanding the hydraulic significance of these large regional fault systems. Cataclasis associated with fault planes and fault tip breakage zones can provide conduits for fluid flow. This is significant in constraining subsurface uncertainty with regard to the migration behaviour of carbon dioxide injected into the subsurface. All available open file seismic and well stratigraphic data has been utilised and the GoCAD® software employed to create the fault plane surfaces. The fault surface data have been provided as AutoCAD DXF files in addition to the GoCAD® project and associated object files.

Keywords: Bowen Basin, Surat Basin, Carbon Dioxide, Carbon Geostorage, Seismic Interpretation, Hydrodynamics, Tingan Fault, Moonie Fault, Leichhardt Fault, Burunga Fault.

INTRODUCTION

The subsurface disposal of waste products from industrial processes demands a structured, hierarchical approach to geological analysis and interpretation (CO2CRC, 2008; Michael & others, 2009b). Commercial scale carbon geostorage presents particular problems due to the multiple factors that need to be considered. It is anticipated that the very large subsurface capacities required will necessitate the extensive exploitation of aquifer storage. Density contrasts, solubility, water-rock reactivity, stochastic migration pathways, resource conflicts and environmental and human health are all factors that must be considered in detail prior to subsurface injection (CO2CRC, 2008; Doughty, 2008; Doughty & others, 2008; Gibson-Poole & others, 2008; Hodgkinson & Preda, 2009; Hodgkinson & others, 2010b; Michael & others, 2009a,b; Preda & Hodgkinson, 2009).

The basis of any hydrodynamic model or reservoir simulation originates within a static geological model or regional geological framework (e.g. CO2CRC, 2008; Rawsthorn & others, 2009). The behaviour of fault systems is of particular interest, because of the multiple possibilities associated with displacement, geometry, potential fault reactivation and frictional heating during slip movements. In many cases regional geological framework models ignore faults and gross assumptions are made about their impact on the fluid flow system (e.g. Habermehl, 1980; Radke & others, 2000). In the case of oil and gas prospecting these assumptions can often be substantiated by the discovery of oil and gas in place. Palaeo oil column studies have shown that original oil columns are typically much greater than those exploited after discovery (Kivior & others, 2002). This is commonly attributed to seal failure due to faulting and fracturing over geological time.

Regional groundwater models typically ignore the potential influence of faults (Habermehl, 1980; Hitchon & Hays, 1971; Hodgkinson & others, 2010b; Radke & others, 2000). In most cases this is acceptable where the influence of fault propagation does not radically displace overlying and underlying geological units and deformation is minimal. Once the regional flow system has been acceptably constrained, the potential influence of large fault systems needs to be considered. The hydraulic behaviour of faults can be highly variable (Otto & others, 2001). To appropriately assess the migration pathways of injected CO_2 it is vital to know if a fault is breached, leaky or sealing with regard to fluid flow.

This study provides a regional interpretation of the three dimensional geometry of the Tingan, Moonie, Leichhardt, Burunga and unnamed fault systems on the eastern flanks of the Bowen and Surat basins (Figure 1). The naming of the eastern Bowen and Surat basin faults is that adopted by Korsch & others (2009). The interpretation is based on all available open file seismic and well data and is available as a GoCAD® object that can be integrated into an existing geological model and manipulated accordingly. The objective is to provide the basis for assessing the potential impact that this large thrust fault system may have on the regional flow dynamics in both basins.

GEOLOGICAL SETTING

The Bowen and Surat basins in Queensland (Figure 1) are the major source of the state's hydrocarbon wealth, predominantly from coal production with subordinate oil and gas reserves (Green, 1997; Hodgkinson, 2008). The Surat Basin also hosts significant groundwater resources, which are exploited for municipal supply, stock watering and agriculture (Habermehl, 1980; Hodgkinson & others, 2010b; Radke & others, 2000).

The Permo-Triassic Bowen Basin in Queensland has a complex burial and exhumation history, with tectonism resulting from both compressional and extensional phases of development. A substantial portion of the basin in southern Queensland is overlain by the Mesozoic Surat Basin (Green, 1997). The Surat Basin is largely undeformed, having experienced only minor tectonism resulting from the reactivation of Triassic thrust faults in the underlying Bowen Basin (Korsch & others, 2009). Although a significant amount of exploration has been conducted in these basins, the nature of many of the fault systems is not well understood. The Moonie-Goondiwindi and Burunga-Leichhardt fault systems *cf* Korsch & others (2009) on the eastern margins of the Bowen and Surat basins are the major tectonic features (Fielding & others, 1990). As with many major thrust fault systems, the region shows significant slip anisotropy and a complex fracture zone where the two major thrust faults coincide (Figure 2). Korsch & others (2009) suggest these eastern bounding faults are reactivated extensional faults, with the exception of the Burunga Fault which appears to be the result of more recent Triassic contractional events.

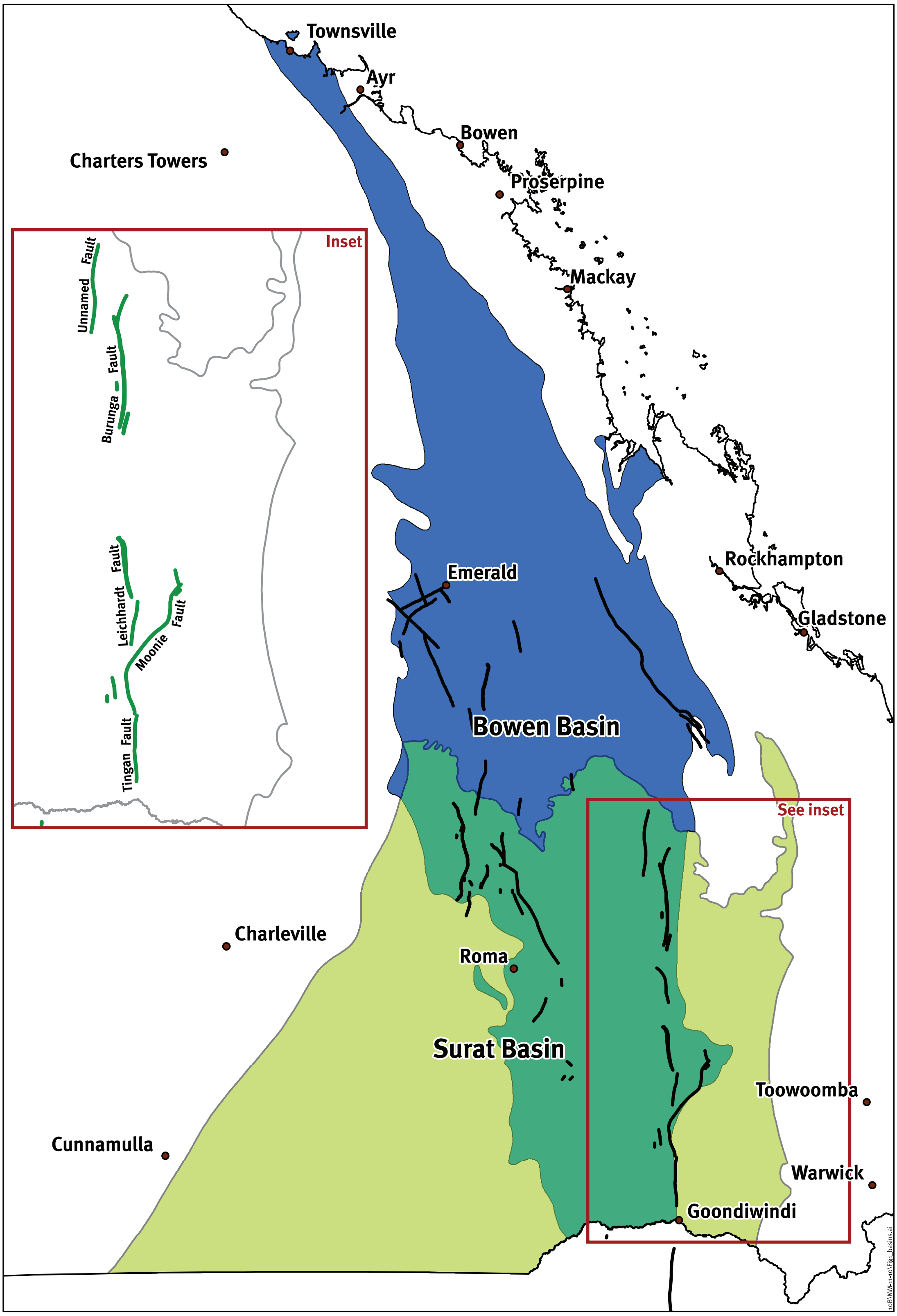

Figure 1. Location of the Bowen and Surat basins showing the study area and modelled faults

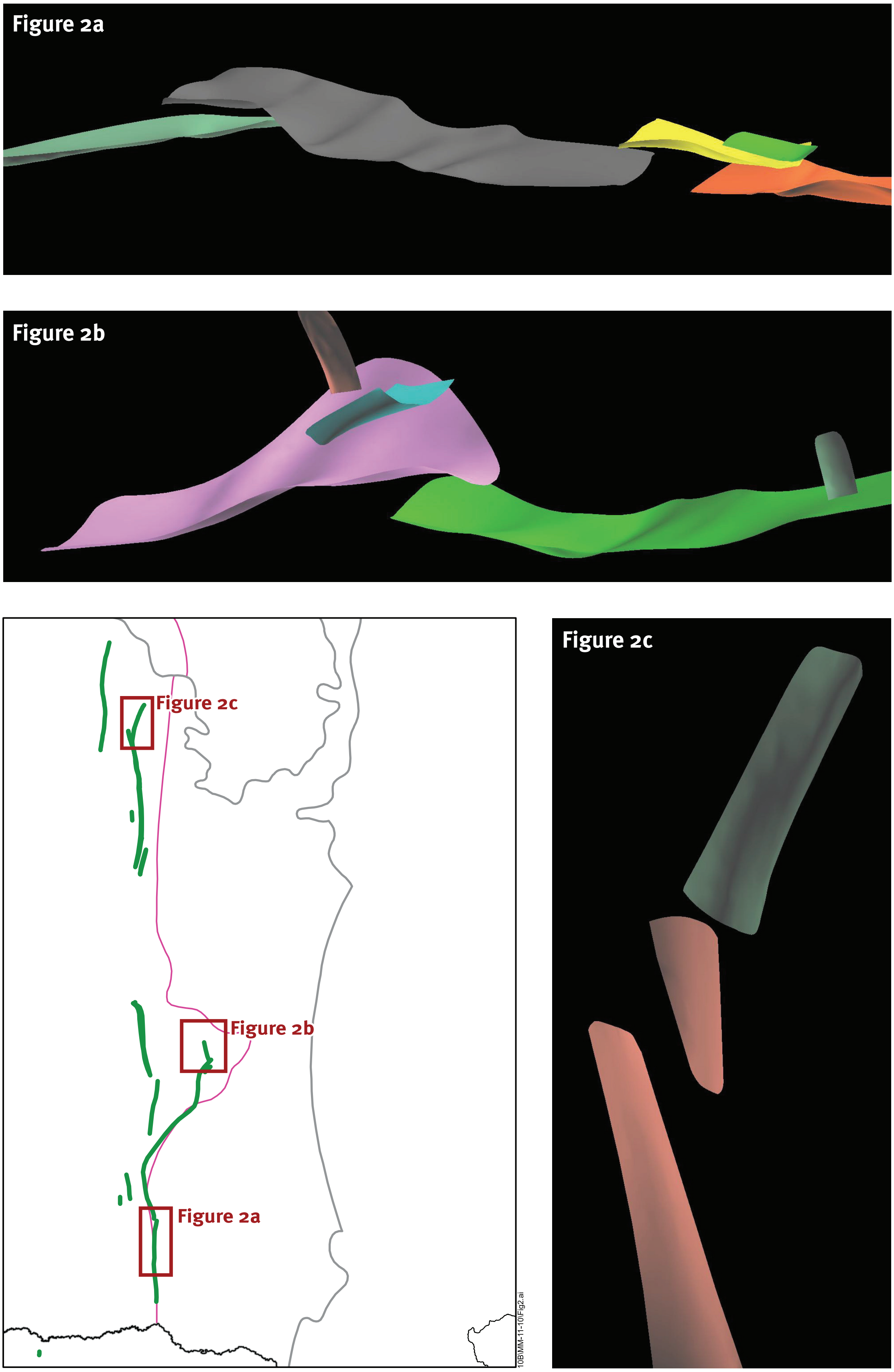

Figure 2. Examples of the interpreted fault planes. The region shows significant slip anisotropy and a complex fracture zone where major thrust faults coincide. In particular, Figure 2c illustrates the Burunga Fault phasing out to the north as several splays.

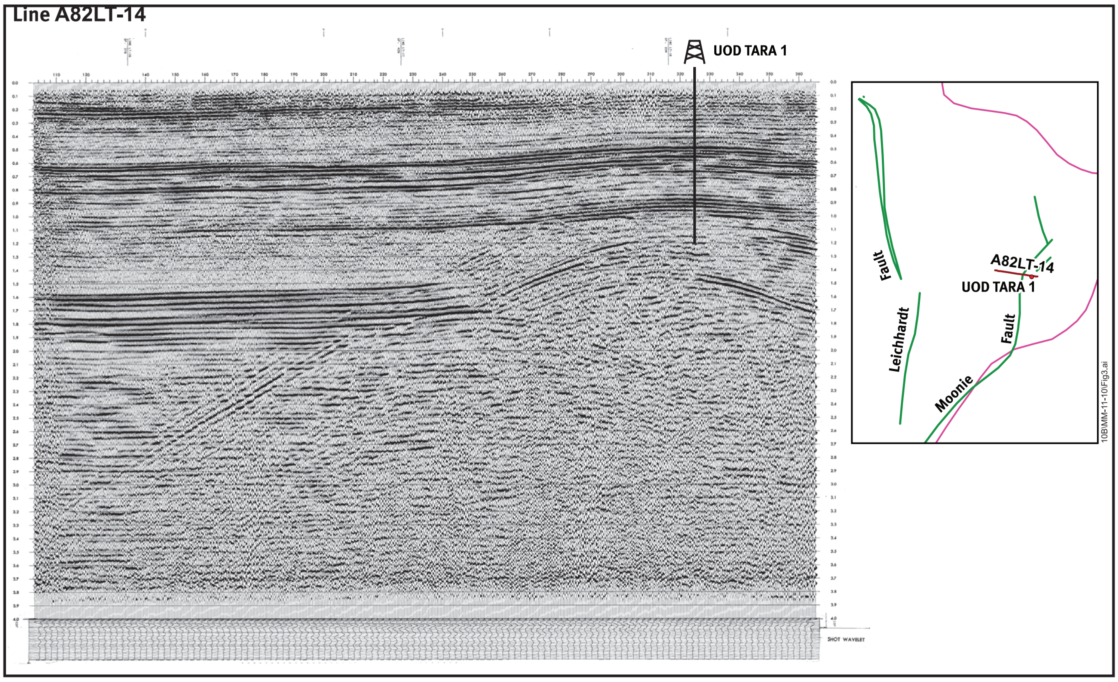

Figure 3. Example of the anticlinal structure formed in the hanging wall of the thrust fault system from seismic line A82LT-14 of the Lentara seismic survey. Drilling has taken place primarily to the east of the fault on these anticlinal structures.

Compressive tectonic stresses are first reflected in the Early Triassic in the Rewan Group with the formation of local unconformities (Fielding & others, 1990). During this time faults developed with a high angle reverse slip geometry and a component of transcurrent shear (Fielding & others, 1990). The Tingan, Moonie, Leichhardt and Burunga faults in the eastern Bowen Basin are major thrust faults which developed predominantly as a result of the Goondiwindi contraction event in the Middle to Late Triassic (Korsch & others, 2009). This compressive tectonic deformation resulted in the uplift and removal of up to 3000m of strata. During and following this period, right lateral movement and other adjustments created a series of small intermontane sedimentary basins east of the Bowen Basin (Fielding & others, 1990).

The faults are generally north-south trending except for the northern section of the Moonie Fault which trends to the north-east. Reactivation in the early Late Cretaceous led to the propagation of some of these faults a short distance up into the Surat Basin. The magnitude of fault displacement through the Jurassic strata is poorly constrained and is variable along strike. Initial interpretations of fault throw indicate that fault displacement in the Jurassic units is low, being in the range of zero to a few tens of metres (Hodgkinson & others, 2010a). More commonly however this contraction event caused folding and uplift of the Surat Basin above the reactivated thrust fault (Korsch & others, 2009). These low amplitude, open fold structures have been explored for oil and gas, but only the Moonie anticline has produced commercial quantities of oil from the Evergreen Formation and the Precipice Sandstone (Green, 1997). Non-commercial oil accumulations have also been discovered in some of the other structures (e.g. the Leichhardt anticline) however, most are ‘dry’ (Allen, 1975). All these small anticlinal structures formed in the hanging wall of the thrust fault systems and drilling, therefore, has taken place primarily to the east of the fault (Figure 3). No suitable hydrodynamic data exists to the west to assess the hydraulic behaviour across the fault planes and interpretations remain subjective (Hodgkinson & others, 2010a). There is a possibility that only the Moonie anticline was on a substantial hydrocarbon migration path or that hydrocarbons were hydrodynamically flushed from the other structures subsequent to accumulation (Hitchon & Hays, 1971).

METHODOLOGY

The fault model is compiled using the Geological Object Computer Aided Design platform (Gocad®). All available open-file seismic data are used in conjunction with stratigraphic well data (Figure 4). Well data imported into Gocad are from the Queensland Petroleum Exploration Database (QPED) and formation tops used are from the Geological Survey of Queensland (GSQ) stratigraphy table. Time/depth relational data are from downhole velocity surveys obtained from the well completion

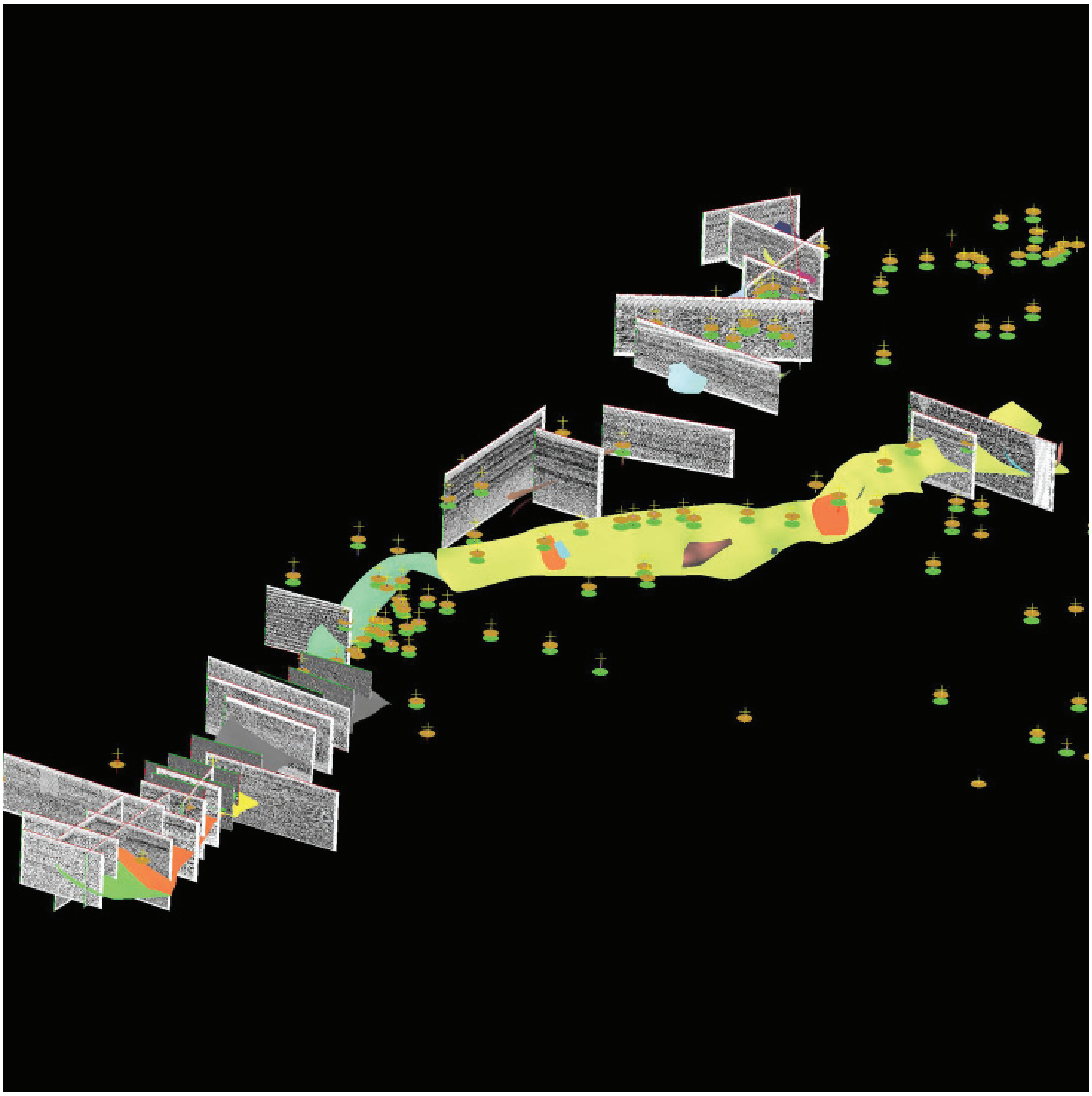

Figure 4. Open-file seismic data correlated with stratigraphic well picks for depth control were used to map the fault planes using the Geological Object Computer Aided Design (Gocad®) software.

reports. One time/depth curve is calculated from the seismic stacking velocity data as no velocity survey is available for this region.

Seismic data imported into Gocad are primarily image files, some of which date back to the 1960s. Imported seismic image files are brought in as jpeg files and resized down to approximately 1MB, so as not to exceed the visible display capacity of the 32 bit Gocad software package. Fourteen seg-y seismic files are also imported and correlated to scanned seismic images. Where possible, final stack seismic images are used as a more complete set of images is available. Migrated stacks are used in places for reference and where final stack seismic is not available or of poor quality.

Once loaded the seismic image data is adjusted to the correct position with shot point location data, obtained from the GSQ Shot Point Location Dataset (SPLOC). Seismic images are then stretched to two stratigraphic seismic horizons with two-way travel times obtained from well velocity survey data and the stratigraphic markers imported into Gocad.

The selection of stratigraphic well markers varies depending on well depth and thickness of the Surat Basin. Correlation between seismic data points is based mainly on two-way travel time. For correlation purposes, prominent seismic horizon markers, such as the top of the Walloon Coal Subgroup, base of the Surat Basin, the top of the Permian coal measures, or the Bowen Basin basement are used.

Fault traces are interpreted from the seismic images from which the fault surfaces are subsequently developed. Fault traces which combine to form one fault surface and the fault surfaces which overlap, backstep or show a degree of discontinuity are interpreted based on the most likely scenarios.

RESULTS

The Tingan Fault in the south terminates at approximately 28°00’00”S. The southern portion of theTingan Fault only penetrates strata to the top of the Bowen Basin. Further north fault penetration into the Walloon Coal Subgroup of the Surat Basin is evident.

The Moonie Fault is separated from the Tingan Fault by *en echelon* overlap and has a mainly north-east strike direction. It is a thrust fault dipping predominantly to the south-east. This fault does not penetrate the Surat basin in the south and there are only a few seismic lines in the central portion where displacement in the Surat Basin can be observed. The northern extent of the Moonie Fault has caused only minor flexure in the overlying Surat Basin strata.

The east dipping Leichhardt Fault extends from approximately 27°39’00”S to 27°01’00”S and is partitioned by a transition zone which separates the fault into two main sections. The southern section terminates at approximately 27°23’00”S where the four kilometre transition zone is present causing bending of Bowen Basin strata. A small west dipping fault is present to the east of the second segment forming a subtle horst structure in the southern end. Minor faulting in the overlying Surat Basin is also present in this region but is not a direct extension of the Leichhardt Fault. The northern section of this fault is low angle east dipping and splayed.

The Burunga Fault has a southern extent at approximately 26°24’00”S and phases out at approximately 25°35’00”S. Korsch & others (2009) describes the fault as a primarily west dipping backthrust however there is also an east dipping thrust fault which flanks the southern portion of the Burunga Fault. Fault splays are also common in this region, but the interpretation does not include all occurrences.

The fault to the north-west of the Burunga Fault is an unnamed reverse fault which extends from approximately 25°18’00”S to 25°49’00”S. This fault does not penetrate through to the top of the Bowen Basin. Fault displacement is minimal, however the fault trace extends approximately 50km in a northerly direction.

The results of this modelling show that thrust plane movement in some parts of the Surat Basin is minimal, however the exact degree of movement varies along faults with the central portions showing the most displacement or degree of breakage.

DISCUSSION

In the southern area along the Tingan, Moonie and Leichhardt faults, there is good well coverage where downhole velocity surveys have been conducted. The velocity surveys (Figure 5) were all conducted by Union Oil Development Corporation (UOD). In the southern Surat Basin the top of the Walloon Coal Subgroup is a primary anchor point showing as a prominent reflector in seismic profiles. The basal tie point varies depending on hole depth, however the base of the Surat Basin is used most frequently as many of these wells do not penetrate the sub-Surat Basin to any substantial depth (Figure 6). Where wells are correlated at deeper stratigraphic horizons the distortion on the base Surat Basin marker is minimal. Further north in the Burunga and Leichhardt Fault region the top of the Precipice Sandstone and an underlying Bowen Basin marker are used as the Surat Basin cover is thin. Once a seismic line is sworn in to an adjacent well, they are used as benchmarks for other seismic lines until another suitable well is available with a velocity survey.

Seismic stacking velocities are used from line AT90-6 (Survey AT90) for the well AGL Champagne Creek 1, because no velocity survey data are available. Line C83-52-8 (Taroom and Extension Survey) has no well or sworn in line with which to correlate. In this case the line is tied to line 84CT-03 using the non-perspective view to align the two-way travel times.

The degree to which these faults penetrate into the Surat Basin is determined by the horizon where diffraction can be observed. Although actual displacement can not be

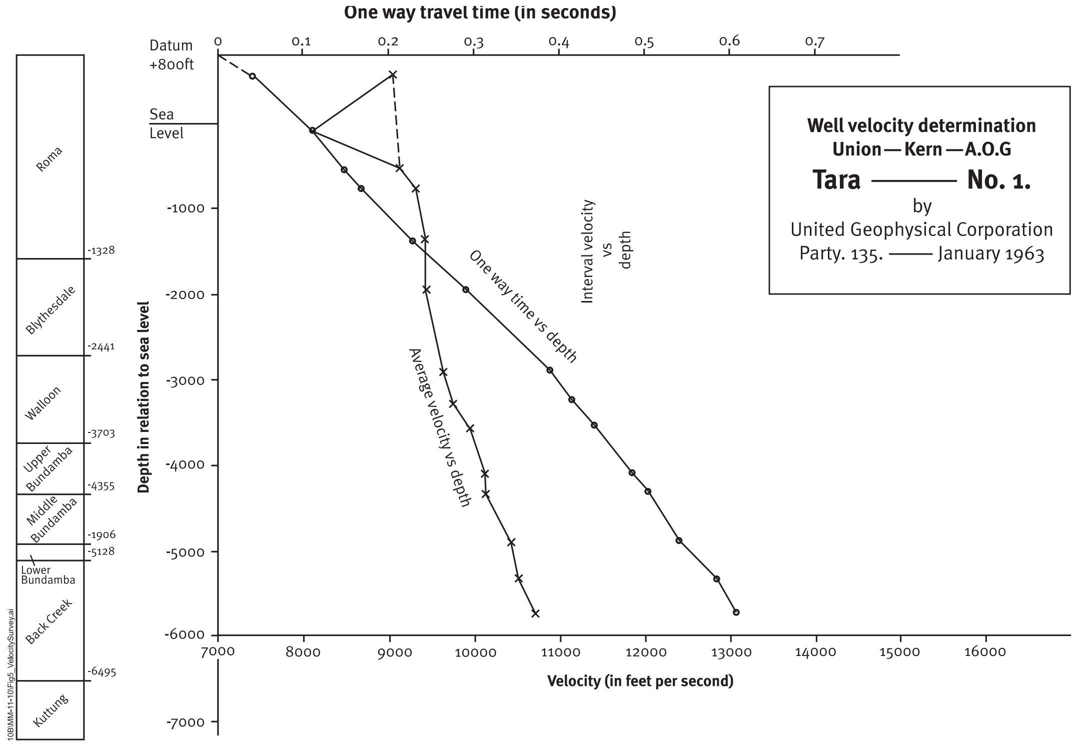

Figure 5. Example of a well velocity survey used for time-depth conversion - UOD Tara 1 velocity survey submitted as part of the well completion report.

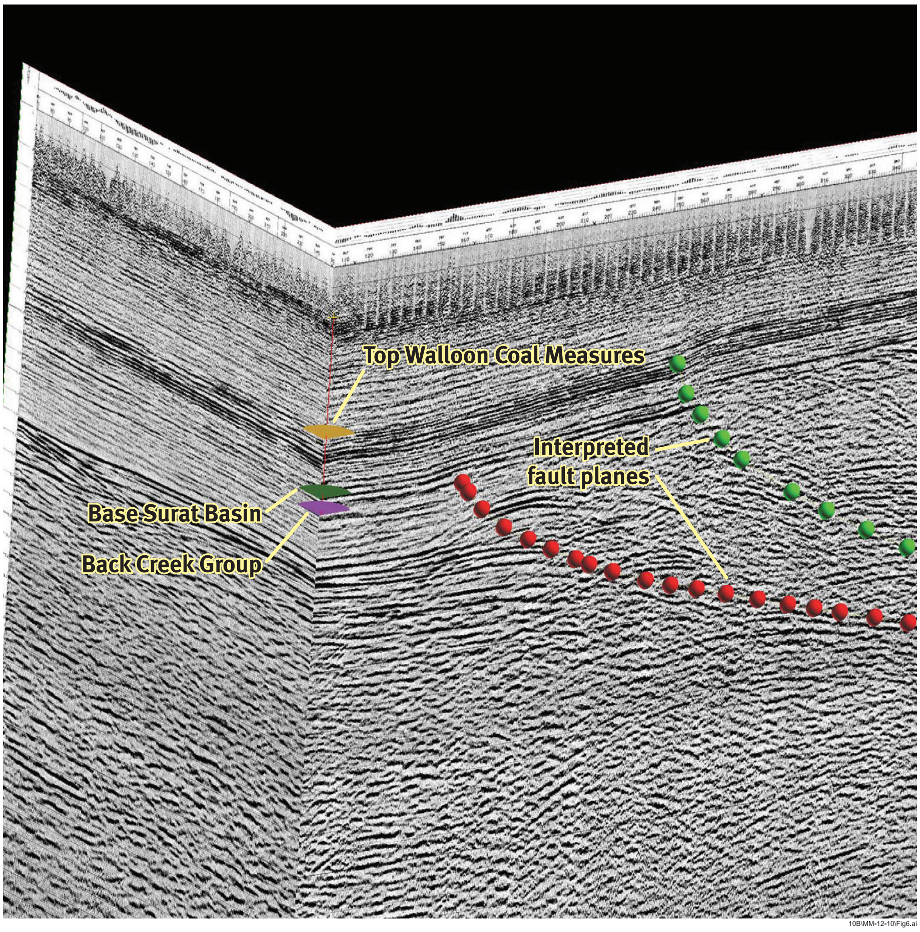

Figure 6. Seismic sections in two-way-time adjusted to stratigraphic well picks in depth. Once the seismic sections have been adjusted to depth the fault traces are picked and the fault surfaces extrapolated.

observed in the Surat Basin, this seismic diffraction is taken as representing breakage or flexure within the stratal column. This is important in regards to carbon geostorage as these breakage zones are potential leakage zones which will require investigation.

Interpreting the degree of fault penetration in the southern Leichhardt Fault is problematic, because penetration can only be observed to the top of the Permian coal sequence. The overlying Triassic section, however, does not have highly contrasting seismic reflectors in which to confidently trace fault displacements.

The fault section described by Korsch & others (2009) as the Miles Fault between 26°32’30” and 26°49’00”S cannot be traced, because seismic data in this area only shows bending of the strata, resulting from compression. If faulting is at all present the seismic resolution is inadequate for this to be modelled. This area is the transition zone where the east dipping Leichhardt Fault becomes the west dipping Burunga Fault.

The unnamed fault in the north has been interpreted with some seismic lines being older single fold. This results in the reliability of the fault curves being reduced. This fault appears unrelated to the Burunga Fault and most likely is the result of an earlier contractional event than that which caused the other faults discussed in this report.

CONCLUSIONS

The three dimensional fault model of the eastern Bowen Basin has applications for any basin modelling exercise in the eastern Bowen Basin area or overlying Surat Basin. The revised fault model presented here provides further constraints on the geometry and fault propagation extent into the Jurassic–Cretaceous succession of the Surat Basin. Identification of several ‘breakage’ zones beyond the extent of fault displacement propagation is significant for the analysis of hydraulic relationships across the fault boundaries. The model provides the basis for integrated three dimensional geomodelling frameworks that are constructed to analyse regional fluid flow regimes, which is essential for assessing the potential migration paths of injected carbon dioxide.

Accurate basin modelling especially in regard to interpreting most likely flow paths for super critical carbon dioxide is important in regard to carbon geostorage. Fault zones can act as barriers or as flow paths for fluids under pressure. The development of accurate models containing structural elements is important in developing a whole of basin overview. The development of three dimensional modelling software packages for geological applications has enabled the production of geological maps with a depth component. Major structural features, such as that provided in this dataset, will be required in order to maximise the potential of such tools.

Many areas within the fault zones of the eastern Bowen Basin consist of breakage zones and may encompass smaller fault splays. Very few wells have cut through these fault zones and no cores, which could have provided a better understanding of the nature of these fault zones, are available. This modelling shows the variable nature of the eastern Bowen Basin fault systems and illustrates that they are not a continuous breakage zone, but contain numerous *en echelon* overlaps. The Miles Fault is more likely to be a zone of flexure as opposed to a fault as no diffraction or breakage could be observed.

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