

Seeing through the dolerite-seismic imaging of petroleum systems, Tasmania, Australia



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ABSTRACT

Prior to the onshore work of Empire Energy Corporation International (Empire) it was widely believed that the widespread sheets (>650 m thick) of Jurassic dolerite (diabase) would not only have destroyed the many potential petroleum source and reservoir rocks in the basin but would also absorb seismic energy and would be impossible to drill. By using innovative acquisition parameters, however, major and minor structures and formations can be identified on the 1,149 km of 2D Vibroseis. Four Vibroseis trucks were used with a frequency range of 6–140 Hz with full frequency sweeps close together, thereby achieving maximum input and return signal.

Potential reservoir and source rocks may be seismically mapped within the Gondwanan Petroleum System (GPS) of the Carboniferous to Triassic Parmeener Supergroup in the Tasmania Basin. Evidence for a working GPS is from a seep of migrated, Tasmanite-sourced, heavy crude oil in fractured dolerite and an oil-bearing breached reservoir in Permian siliciclastics.

Empire's wells show that each dolerite sheet consists of several intrusive units and that contact metamorphism is usually restricted to within 70 m of the sheets' lower margins. In places, there are two thick sheets, as on Bruny Island. One near-continuous 6,500 km² sheet is mapped seismically across central Tasmania and is expected, along with widespread Permian mudstones, to have acted as an excellent regional seal.

The highly irregular pre-Parmeener unconformity can be mapped across Tasmania and large anticlines (Bellevue and Thunderbolt prospects and Derwent Bridge Anticline) and probable reefs can be seismically mapped beneath this unconformity within the Ordovician Larapintine Petroleum System. Two independent calculations of mean undiscovered potential

(or prospective) resources in structures defined so far by Empire's seismic surveys are 596.9 MMBOE (millions of barrels of oil equivalent) and 668.8 MMBOE.

KEYWORDS

Helium, Centralian Petroleum System, Larapintine Petroleum System, Gondwanan Petroleum System, Ordovician, Permian, Jurassic, Cenozoic, Longford Basin, Tasmania Basin, seismic acquisition, dolerite, iodine.

INTRODUCTION

Since the publication of Burrett and Martin's 'Geology and Mineral Resources of Tasmania' in 1989, many scientific advances have been made in Tasmania, one of which includes the onshore seismic detail of the geology below the Tasmania Basin, which has contributed to the evolving three dimensional map of Tasmania (Corbett et al, 2014). The 45,000 km² Tasmania Basin is a typical Gondwana glacimarine, pericratonic basin that extends across 30,000 km² onshore and probably another 15,000 km² offshore (Fig. 1). The petroleum potential of onshore Tasmania was recognised with the mining of Tasmanite Oil Shale from 1910–35 and the production of a wide variety of distilled petroleum products. The modern search for subsurface petroleum was, however, inhibited by the belief that the extensive and thick sheets of dolerite (diabase) would have thermally destroyed any potential source rocks (e.g. Late Carboniferous–Permian, Woody Island Formation and Tasmanite) and occluded porosity in potential reservoirs (e.g. Permian Liffey–Faulkner Groups and Lopingian coal measure sandstones, Fig. 2). It was also believed that the dolerite sheets would preclude the seismic imaging of sequences beneath the dolerite. Seismic surveys carried out by Empire Energy Corporation International (Empire) and its subsidiary companies between 2001–07, however, have shown that 2D Vibroseis surveys may image sequences and structures both within and below the Tasmania Basin (including the Precambrian structures on the west coast of Tasmania around Zeehan), and Empire's fully cored wells have shown that the thermal effects of the dolerite sheets were not as pervasive as once thought. Indeed, the high seismic velocities shown by the dolerite strongly suggests that it would have acted as a very effective seal except within 40–50 m of the surface where joints are open (Mulready, 1995; Stacey and Berry, 2004; Leaman, 2006).

From the 1980s to the present, Empire and its subsidiary and predecessor companies expended AU\$56 million meeting licence conditions (Great South Land Minerals Ltd, 2009), and have employed petroleum industry consultants to review progress on its onshore exploration and to help plan and implement exploration programs (e.g. Barrett, 2010; Blackburn, 2004; Carne, 1992, 1997; Mulready, 1987, 1995; Treadgold, 2001; Wakefield, 2000; Young, 1996). Most recently, international consultant companies have been commissioned to evaluate the potential petroleum resources, audit expenditure and assess the potential economic value of onshore tenements based on Empire's geophysical, geological, geochemical and drilling programs (RPS Energy 2008, 2009; Anderson and Schwab, 2004; Hockfield and Eales, 2013; Odedra et al, 2013; WHK Denison Ltd, 2009).

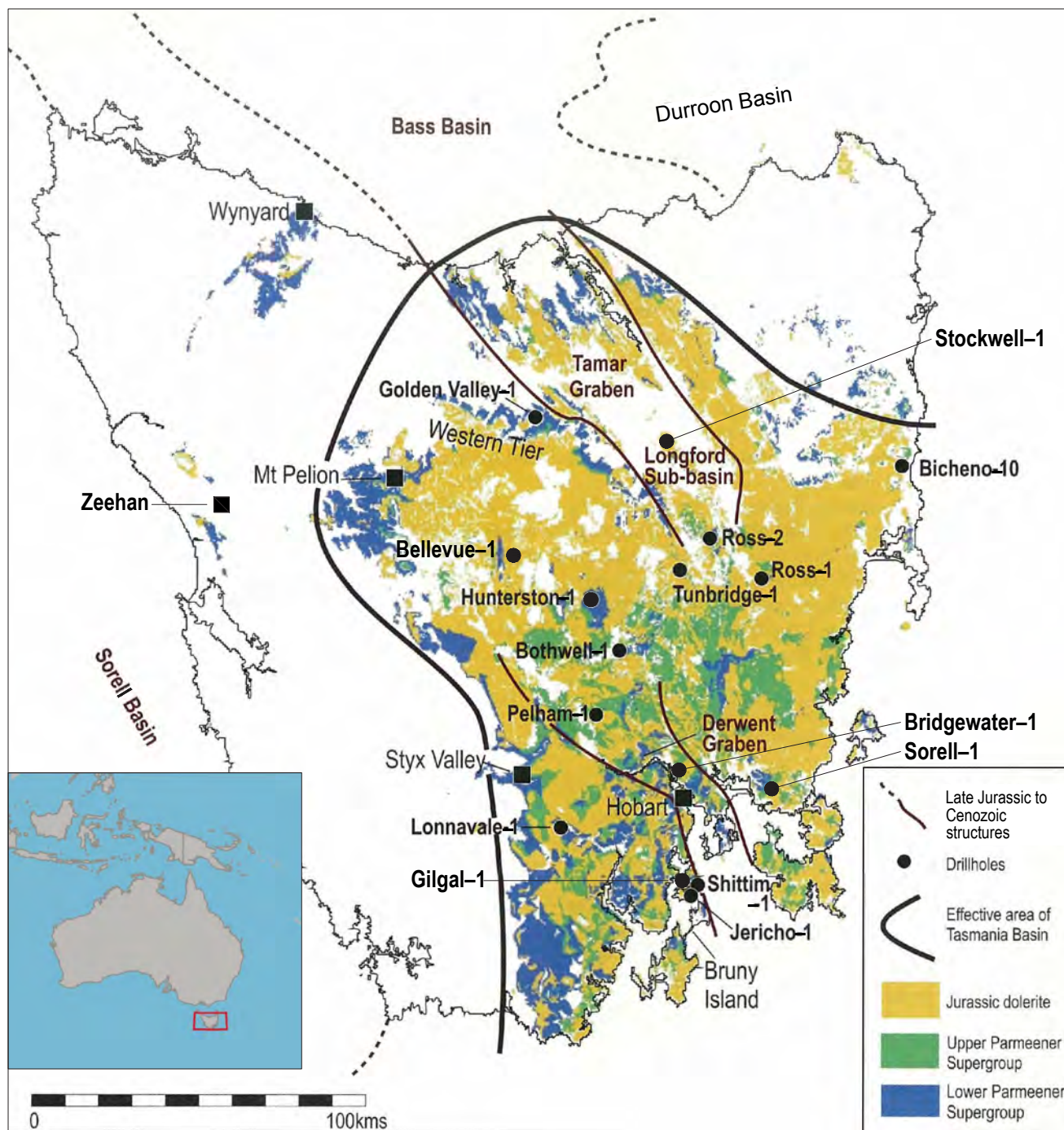


Figure 1. Extent of the Late Carboniferous-Late Triassic Tasmania Basin. The Tasmania Basin extends offshore southwards beneath the extensive south Tasmanian shelf, adapted from Reid and Burrett (2004). Ten stratigraphic wells—Bellevue-1 (completed to 272 m), Bridgewater-1 (252 m), Gilgal-1 (51 m), Hunterston-1 (1,324 m), Jericho-1 (640 m), Pelham-1 (503 m), Lonnvale-1 (557 m), Shittim-1 (1,751 m), Sorell-1 and Stockwell-1—were drilled by Empire and predecessor companies. Other wells were drilled by Mineral Resources Tasmania (MRT). Geological base map from MRT.

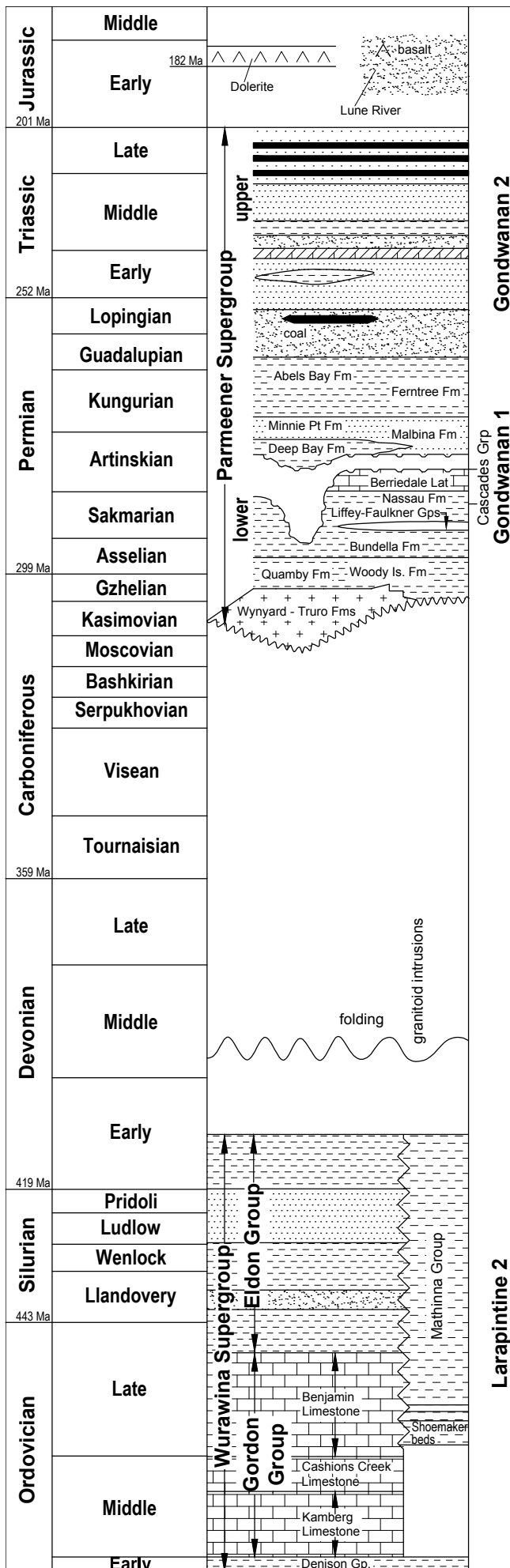
The aim of this paper is to briefly summarise some of the evidence for the petroliferous nature of onshore Tasmania, and provide examples of the range of major structures and sequences that have been imaged and interpreted during Empire’s surveys and discuss their relevance to both the geological history and petroleum exploration in the state. A summary of the calculated potential (or prospective) undiscovered resource within the seismically identified structures is also included.

Onshore Tasmania geological summary

The geological history of onshore Tasmania has been summarised by Stacey and Berry (2004), and most recently by Corbett et al (2014). Proterozoic metasediments cover much of the wilderness areas in northwest and southwest Tasmania.

Younger Proterozoic sequences occur in central Tasmania and have been incorporated in a Devonian fold-thrust system, along with Cambrian volcanics and sediments and Ordovician to middle Devonian shelf and basinal sediments. Deformed Late Proterozoic quartzites-pelites-dolomites have been cored in two of Empire’s stratigraphic holes at Hunterston-1 (between 980 m and TD at 1,324 m) in central Tasmania, and Shittim-1 on Bruny Island (between 1,585 m and TD at 1,751 m; see Fig. 1; Bendall et al, 2000, fig. 13; Reid et al, 2003). Precambrian Tasmania consists of several blocks that probably originated near southern Laurentia (Burrett and Berry, 2000; Halpin et al, 2014) and coalesced during the late Proterozoic and Cambrian (Moore et al, 2015).

During the Ordovician, western Tasmania was a small platform with highlands and alluvial fans that were gradually transgressed



westwards by a tropical sea leading initially to the establishment of a siliciclastic platform (consisting of the Lower Ordovician Denison Group), followed by a carbonate platform (consisting of the Gordon Group) from the Middle to Late Ordovician (Calver et al, 2014). The Gordon Group carbonates are mainly shallow water but deep water sedimentation is known along the southern and eastern margins of the platform and graptolitic shales are found across most of eastern Tasmania dating from the Early Ordovician to Early Devonian (Burrett et al, 1984; Calver et al, 2014). Platform carbonate sedimentation was replaced by the mainly shallow marine, siliciclastic latest Ordovician to Early Devonian Eldon and Tiger Range Groups. From the Ordovician to the Devonian, Tasmania may be divided into Western and Eastern Tasmanian terranes separated by a wide belt of faults parallel to the Tamar Lineament. The Western Tasmanian Terrane was characterised by platform sedimentation from the Late Cambrian to the Early Devonian (the Wurawina Supergroup) and the Eastern Tasmanian Terrane by basinal turbidites of the Mathinna Supergroup, from the Early Ordovician to Early Devonian. The Early Palaeozoic successions were deformed in the mid-Devonian into a fold-thrust belt. Granites intruded during the Late Devonian to Early Carboniferous and form a horseshoe-shaped belt in the west, southwest, north and east of Tasmania (Seymour et al, 2014).

The Tasmania Basin was initiated during the Late Carboniferous along an axis paralleling the Tamar Lineament and surrounded by the crescent of Devonian granites (Clarke, 1989). This north-northeast to south-southeast axis acted as a north-south shifting depocentre through the Permian. Initial tillite dominated sequences gave way to Late Carboniferous-Early Permian high to moderate total organic carbon (TOC) black shales (including the Tasmanite Oil Shale) of the Woody Island Formation, in the south of the basin, and Quamby Formation, further north. Glacimarine conditions continued to near the end of the Permian. An irregular Early Permian topography with considerable relief is evident in the modern Central Highlands area. Glaciated valleys were filled with tillite and younger glacimarine sequences, leaving highlands and islands that were progressively on-lapped by younger Permian sequences (Banks and Clarke, 1987). Marine conditions gave way to terrestrial sedimentation in the Lopingian with the deposition of the Cygnet Coal Measures and correlatives. Widespread fluviatile sands and silts were deposited during the Triassic (Reid et al, 2014).

Plant and tree-bearing Jurassic volcanogenic sandstones dated to 182 Ma are found at Lune River in southern Tasmania interbedded with basaltic andesite, which is co-magmatic with widespread dolerite intrusions across Tasmania (Bromfield et al, 2007; Everard et al, 2014; Leaman, 1975). These sediments were intruded by dolerite during a short period from 181–180 Ma in the Toarcian (Everard et al, 2014). Dolerite sheets are exposed across about 14,500 km², and formed—along with the Ferrar basalts of Antarctica—a large igneous province.

Cretaceous uplift was followed by Cenozoic terrestrial sedimentation in small extensional basins such as the Longford Basin and Derwent Graben (Quilty et al, 2014). The morphology of the uplifted Central Plateau and parts of western and eastern Tasmania were modified by glacial erosion and sedimentation during the Quaternary (Colhoun et al, 2014).

Figure 2 (opposite). Summary Ordovician to Jurassic geological column for onshore Tasmania, adapted from Bendall et al (2000). For further details of Tasmanian stratigraphy see Corbett et al (2014). Traditionally, the Parmeener Supergroup has been informally subdivided into a lower marine sequence (Late Carboniferous–Sakmarian), a lower freshwater sequence (Liffey and Faulkner Groups; Late Sakmarian to Early Artinskian), an upper marine sequence (Artinskian–Guadalupian) and an upper freshwater sequence (Upper Parmeener Supergroup; Late Permian–late Triassic). These informal terms are sometimes used on the seismic interpretations as they are easily recognised seismic units. The Cascades Group, which is labelled on some seismic interpretations, is a correlate of the Berriedale Limestone plus the calcareous shales of the Nassau Formation.

Petroleum systems onshore Tasmania

Early exploration in Tasmania was encouraged by the presence of a world-class source rock, the Tasmanite Oil Shale and by the presence of electrical conductivity anomalies, iodine anomalies, oil seeps and a breached oil-bearing reservoir (see Figs 3 and 4).

Numerous oil seeps have been reported in Tasmania, and the geochemistry of some of these is consistent with derivation from indigenous source rocks, and several seeps were geochemically matched to the Gordon Group limestones (Bendall et al, 1991; Volkman and O'Leary, 1990).

The seep at Lonnavale, 40 km due west of Hobart, was discovered in a quarry in an unusually highly fractured and veined Jurassic dolerite by Bottrill (2000), and subsequent detailed geochemistry of biomarkers showed that it is a migrated, low sulphur, heavy crude derived from an anoxic *Tasmanites* rich source. Methylphenanthrene maturity indices show that it was generated from a mature source rock with a vitrinite reflectance (R_0) equivalence of 0.75–0.85 (Revill, 1996; Wythe and Watson, 1996) but not from a source that had been overheated, for instance, by proximity to a dolerite intrusion where much higher R_0 vitrinite equivalent values of at least R_0 1.3 should be found (Othman et al, 2001).

Outcrops of sandstones, shaley coal and siltstones south of Zeehan, near to the western margin of the Tasmania Basin (Fig. 1), are correlates of the latest Permian Cygnet Coal Measures (stippled pattern with coal above the Abels Bay Formation in Fig. 2) and 'contain abundant brightly fluorescing oil' and bitumen with a maturation level of the oil at R_0 0.75–0.8% (Cook, 2003, 2007). 'The presence of such abundant evidence of oils and bitumens within the Permian sections of Australia is unusual' (Cook, 2003). These Zeehan outcrops are interpreted as a breached Late Permian reservoir containing Permian sourced oil. Oil generation and migration is suggested by oil inclusions in both the Zeehan and Hunterston-1 Permian siliciclastics (Cook, 2003, 2007; Reid et al, 2003).

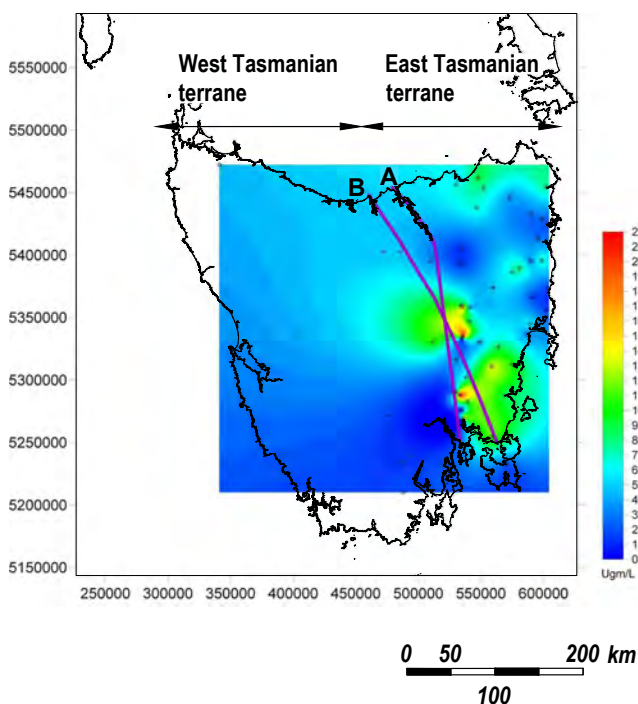


Figure 3. Iodine occurrences in surface waters of Tasmania based on data supplied by Dr Paul Richards (from Burrett et al, 2007). Trend of Tamar Fracture (or Lineament or Fault Zone)—A is based on Williams (1978) and B is based on Seymour and Calver (1995).

Empire's stratigraphic wells drilled on Bruny Island (Shittim-1, Jericho-1 and Gilgal-1, 1,751 m, 640 m and 50 m, respectively) yielded gas, condensate and oil. The induced flow of Shittim-1 measured at the choke manifold was 120 psi and bright-green oil flowed, was collected in vacuum flasks by independent mud loggers and tested by gas chromatograph, and the gas was flared (Great South Land Minerals Ltd, 2009). Carbon isotope analysis of the Jericho-1 methane shows that it is thermogenic (Bendall et al, 2000, fig. 15). The high helium values (up to 4.83% air corrected) along with nitrogen and condensate/oil up to C8 are also indicative of an oil and gas field source (Bendall et al, 2000, fig. 14; Burrett, 1997; Nikonov, 1973). A chromatographic analysis of a core sample of black shale/slate from 1,676 m in the Shittim-1 well yielded an algal sourced oil with a chromatogram extremely close to that of an Ordovician sample from the Gordon Group limestone at Lune River, southern Tasmania (Burrett, 1997, fig. 8; Volkman and O'Leary, 1990). The oil is hypothesised to have migrated from the Ordovician into the Proterozoic along the near horizontal thrust fault separating the Parmeener Supergroup rocks from the underlying Late Proterozoic metamorphics (Bendall et al, 2000; Burrett, 1997).

Further encouragement was provided by electrical conductivity studies in northeast Tasmania by Parkinson and Hermanto (1986) and Parkinson et al (1988) along the previously geologically (rather than geophysically) identified Tamar Lineament (also termed the Tamar Fracture System, Tamar Fault Zone, Tamar Thrust, and Tamar Thrust Zone by various authors) that separates the Western Tasmanian from the Eastern Tasmanian terranes (see Figs 3 and 4). Parkinson and Hermanto concluded that the most likely cause of the conductivity anomaly:

'...seems to be fractured rock saturated with highly conducting fluids. Archie's Law suggests that porosity of 20–40% is necessary with a fluid conductivity of the order of 10 Sm^{-1} . Fluids with such a high conductivity have been reported, but are generally confined to oilfields' (Parkinson and Hermanto, 1986).

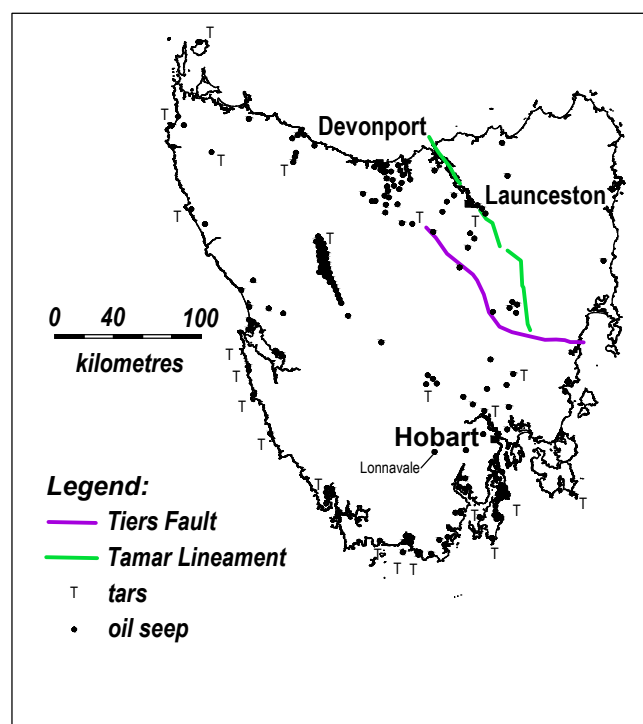


Figure 4. Possible, probable and confirmed oil seeps in Tasmania, adapted from Bendall et al (1991).

In central Tasmania, this wide fracture zone has been confirmed as east dipping by teleseismic and magnetotelluric studies and coincides with an area of anomalously high surface heat flow (Holgate et al, 2010; Rawlinson et al, 2006).

More recently, studies on iodine in surface waters in Tasmania (Burrett et al, 2007) showed that high concentrations are present close to or on the major faults in central Tasmania (Fig. 3). Meteorological and geochemical modelling showed that these inland areas should be deficient in iodine (Butler et al, 2007, fig. 8). Iodine is abundant in petroleum basin brines and surface iodine anomalies have proved useful in petroleum exploration (Gallagher, 1983; Kudelsky, 1977; Tedesco, 1998). The most likely source for the iodine anomalies shown in Fig. 3 is, therefore, from brines of a petroliferous basin leaking along major faults.

The abundance of Cenozoic faults has caused many to suggest that any petroleum generated within the Tasmania Basin would have leaked. A study of fault shale smear factor by Collings (2007), however, has shown that simple normal faults in Tasmania are mostly impermeable due to an infilling of Permian mudrocks, such as the widespread Ferntree Group, and are unlikely to have acted as major fluid flow conduits. As helium has a very small atomic radius, the abundance of helium in the Shittim-1 and Hunterston-1 wells at depth and below the dolerite is evidence for the seal characteristics of much of the Permian shale sequence and of the Jurassic dolerite sheets (Bendall et al, 2000).

Using Bradshaw's (1993) classification, Empire identified three petroleum systems in onshore Tasmania: a possible latest Proterozoic (Centralian Petroleum System); an Ordovician-Early Devonian (Larapintine Petroleum System) within the Wurawina Supergroup; and, a Pennsylvanian-Triassic (Gondwanan Petroleum System) within the Parmeener Supergroup of the Tasmania Basin (Bendall et al, 2000; Reid and Burrett, 2004).

The Centralian Petroleum System onshore Tasmania is based mainly on a helium-dry gas found in the latest Proterozoic but not in the Permian, in Empire's Hunterston-1 stratigraphic well in central Tasmania (Great South Land Minerals, 2009). The Larapintine Petroleum System in Tasmania is analogous to the producing fields in the Amadeus Basin of central Australia and in the Tarim Basin of northwest China (Bradshaw, 1993; Li, 1995).

The oil-prone Gondwanan Petroleum System is considered more prospective than the gas, condensate and helium prone Larapintine Petroleum System. Maturation of the Gondwanan Petroleum System—as measured by vitrinite reflectance, pollen colour alteration, thermal alteration index (TAI) and geochemical parameters—increases towards the south of the basin, being undermature in the north to mature for oil in the south (Reid and Burrett, 2004). The Gondwanan Petroleum System in Tasmania is considered to be closely comparable to the producing Cooper Basin of central Australia and to the South Oman Basin of Oman (Bendall et al, 2000).

Modern exploration in the Tasmania Basin commenced in 1984 with the issue of exploration licence EL 29/1984. Stratigraphic wells were drilled between 1995 and 2008 (by Empire and its predecessors), resulting in six wells with oil and gas shows and five pre-collar wells (Bendall et al, 2000; Great South Land Minerals, 2009; Reid et al, 2003).

SEISMIC SURVEYS

Early seismic surveys

In 1989, the Bureau of Mineral Resources (BMR, now Australian Geoscience) conducted a 2,010 km offshore multichannel seismic survey around Tasmania that included circumnavigation of Bruny Island in the south (Exon et al, 1989). Preliminary processing showed that Permian sediments and dolerite

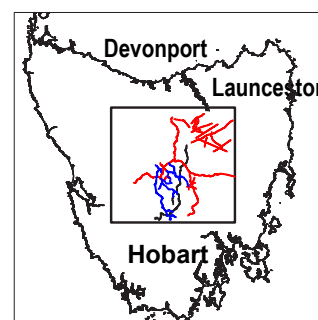
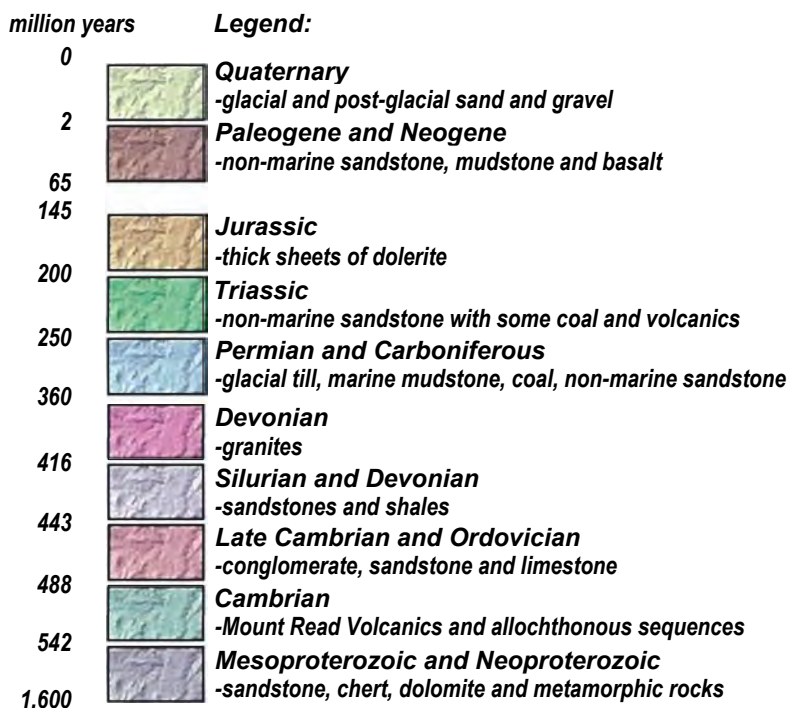
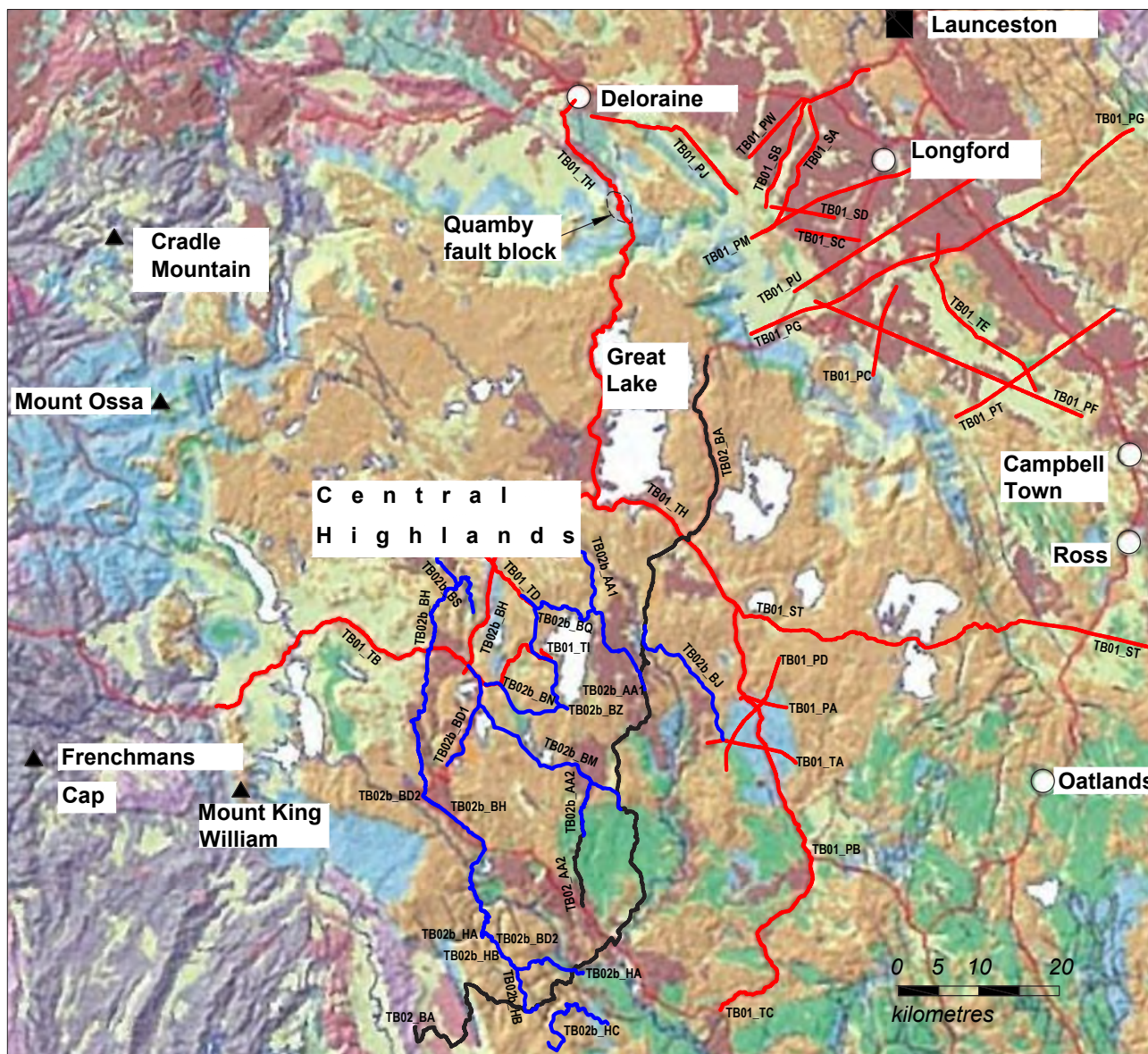
could be provisionally identified. The earliest onshore seismic surveys were carried out by Mineral Resources Tasmania (Leaman, 1978; Richardson, 1987). Richardson's test survey, using explosives, showed that the seismic reflection technique could be used successfully in the area of North Bruny Island, that energy was transmitted through a thick dolerite sheet, and that good-quality reflections were obtained from below the dolerite. Later drilling of Shittim-1 by Empire showed that Richardson had correctly predicted that the low-amplitude zone at depth corresponded to homogenous Precambrian units (Bendall et al, 2000). Unfortunately, the seismic data were not processed and remained unpublished, and the belief persisted that seismic reflection surveys would not work in Tasmania.

Modern seismic surveys

The first modern onshore seismic survey was carried out by AGSO (Australian Geological Survey Organisation, now Geoscience Australia) in 1995, the purpose of which was primarily to image deep crustal structures, and only 20 km of the survey was devoted to imaging shallow structures in the centre of the Tasmania Basin (Barton et al, 1995; Drummond et al, 2000). An interpretation of the seismic data of this short line, however, showed that where dolerite was not at the surface, dolerite margins, faults, the basal Parmeener Supergroup unconformity and some formations within the Parmeener Supergroup could be identified (Leaman, 1996; Bendall et al, 2000, fig. 16). Later, a teleseismic study across northern Tasmania revealed significant but deep differences between the Western and Eastern Tasmanian terranes. The Eastern Tasmanian Terrane is shown to have a dense, probably oceanic, crust beneath the Mathinna Group sedimentary rocks in contrast to the continental crust of the Western Tasmanian Terrane (Rawlinson et al, 2006).

The first extensive 2D seismic surveys onshore Tasmania were carried out by Empire in the southern hemisphere summers of 2001, 2006 and 2007, and covered a total of 1,149 line km using Vibroseis (Fig. 5). In the Tasmanian lowlands, it was possible to design straight survey lines across fields and along straight roads and tracks. In the Tasmanian highlands, however, the steep topography and the widespread presence of boulder fields and/or dense areas of environmentally sensitive vegetation often necessitated surveying along sinuous roads and the construction of new tracks.

Empire's seismic surveys were preceded by completion and analysis of regional geochemical, geological, magnetic and gravity data bases (Leaman, 2006). These processed data were then overlain on digital terrain maps of Tasmania and models created with differing sun angles (e.g. Fig. 6a), which were used to identify major geological structures. This method is particularly useful in the Tasmania Basin because of the topographic contrast created by the weathering-resistant dolerites. The potential field data were then used to construct contacts along maximum gradients in the data. These lines or worms (Fig. 6b–e) are, on a horizontal plane, similar to lines drawn by geologists when manually interpreting potential field data sets. In 3D, the worms form surfaces that are a function of the 3D geometry of rocks with contrasting properties (Archibald et al, 1999; Holden et al, 2000). The program identifies inflection points in the combined gravity and magnetic data and draws them as lines at different depths. Domal structures containing dolerite are easily identified with this technique due to the density and magnetism of the dolerite contrasting with sedimentary rocks of the Tasmania Basin. The Bellevue Dome is apparent both in a map of geology draped over topography (Fig. 6a) and in the worms (Fig. 6b). The major domes and faults were therefore identified prior to Empire's seismic surveys.



Prospect location

Seismic survey legend:

- 2001 2D seismic (659 km acquired)
- 2006 2D seismic (152 km acquired)
- 2007 2D seismic (345 km acquired)

Figure 5. Map showing onshore seismic lines surveyed by Empire in 2001, 2006 and 2007. Geological base map from Corbett et al (2014). Reproduced with permission of the Geological Society of Australia.

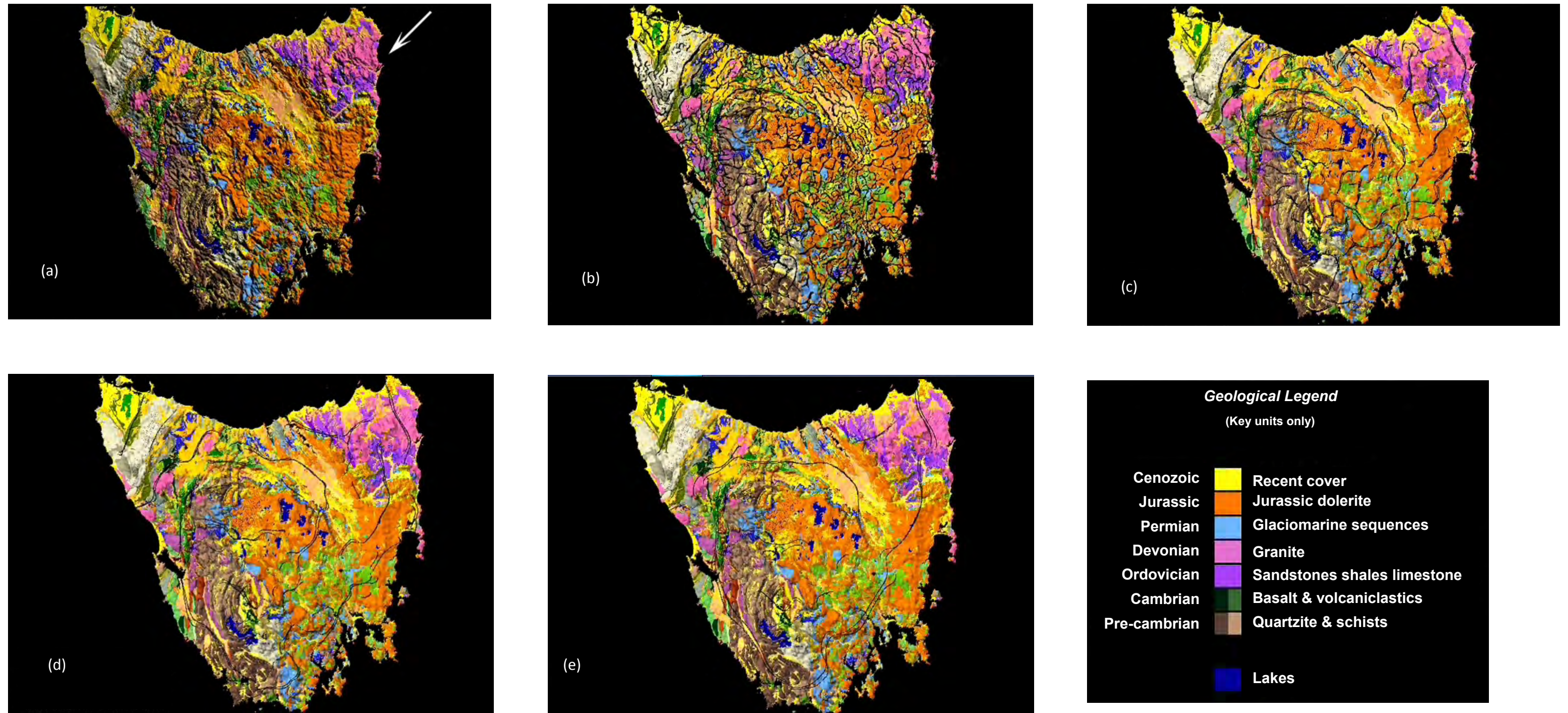


Figure 6. Tasmania with geology draped over topography with different sun angles and multiscale mapping of potential field data worms carried out by fractal graphics. Geological map is from Mineral Resources Tasmania. Digital Terrain Model is from Department of Primary Industries, Parks, Water and Environment (Tasmania). (a) Geology of Tasmania with a northeast sun angle, perpendicular to most structures and the Tasmania Basin axis; (b) geology and worms at 1,000–5,000 m depth; (c) geology and worms at 5,000–10,000 m; (d) geology and worms at 10,000–20,000 m; and, (e) geology and worms at 20,000–34,000 m depth.

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The seismic surveys were designed to cross the worms, faults and major structures at 90° to their long axis and also along the long axes of folds as close to structural culminations and as far away from identified faults as possible. Maximum reflector response and minimum diffraction of the signal was thereby achieved and, therefore, there was minimum loss of already weak return signals. Four Vibroseis trucks were used with a frequency range of 6–140 Hz. Many full frequency sweeps close together achieved maximum signal input and, therefore, maximum return signal, and the truck spread ensured good contact and, therefore, good energy propagation into the ground.

Any background noise, such as wind and traffic, was decreased by stacking three seismic sweeps in the seismic acquisition truck and sending the composite stack to the seismic processing company. The number of geophones was increased to further minimise noise. Extra care was taken to ensure that all geophones were firmly secured. The fold was increased by reducing the standard regional geophone spacing from 50 m (20 readings/km) to 20 m (50 readings/km).

The standard industry practice of shooting at 6–40/60 Hz was replaced by shooting the full frequency sweep, and geophone receiving frequencies were matched accordingly.

RESULTS

The seismic surveys conducted by Empire have shown that with the careful choice of acquisition parameters and specialised processing—described in the previous section and tabulated in Table 1—the sub-dolerite structures may be sufficiently imaged to determine a structural history and to delineate prospects and leads.

Important results of Empire's seismic surveys are shown in Figures 7–20. These surveys have been tied to surface geology (Fig. 8) and to the results of deep stratigraphic drilling by Empire (Shittim-1, Hunterston-1 and other wells shown in Fig. 1; Bendall et al, 2000; Reid et al, 2003) and by Mineral Resources Tasmania (Fig. 1). Interpretations were refined using crooked line processing and the seismic velocities measured in a down-hole seismic survey of Empire's Hunterston-1 well by Stacey (2004). Measured velocities for the following stratigraphic units are:

- Ferntree Formation (4,100 m/s);
- top dolerite (5,170 m/s);
- intermediate dolerite (7,190–6,040 m/s);
- basal dolerite (6,550 m/s);
- Cascade Group (5,190 m/s);
- Liffey Group (4,160 m/s); and,
- Bundella Formation (4,350 m/s).

The high quality of Empire's seismic across the Cenozoic terrestrial infill of the Longford Sub-basin (or Longford Basin) allowed Lane (2002) to construct isopachs (see fig. 9.29 in Quilty et al, 2014) and to recognise and map six sedimentary seismic packages and correlate these with drill hole logs (Fig. 7).

Pre-Tasmania Basin rocks were deformed during the Middle Devonian Tabberabberan Orogeny (Seymour et al, 2014). The rocks beneath the Cenozoic Longford Basin (Longford Sub-basin in Fig. 1) consist of a series of stacked thrusts dipping northeast. This zone is about 40 km wide and coincides with the trend of the Tamar Fracture System. To the west and southwest of the Longford Basin, the structural style is progressively modified from thrusts and through thrusts and folds to a region dominated by large folds such as the Bellevue Anticline and prospect (see Figs 10 and 11).

Numerous structures seen on the seismic sections are either prior to or coeval to the intrusion of dolerite in the Early

Jurassic. Both extensional and compressional structures are observed. Events associated with the break-up of Gondwana are responsible for the gross modern morphology of Tasmania. Uplift in the Middle to Late Cretaceous followed by significant east-northeast extension was associated with the opening of the Tasman Sea. Faults and folds related to this series of events are the most numerous in the seismic sections. Many of the faults interpreted from the seismic data in the Tasmania Basin are probably reactivated or located over faults in the pre-Parameener Supergroup rocks.

Figure 8 shows an interpretation of a structurally simple seismic line along the road from northern Tasmania southwards on to the Central Highlands dolerite plateau. More structural complexity is evident along other lines following roads from the Midland lowlands to the Central Highlands dolerite plateau. Figure 9 shows a section from the lowland Midlands of Tasmania westwards to the highlands. Thrust Zone 2 is interpreted as a Permian growth fault and a considerable thickening of Permian strata is evident on the eastern side of the fault (Stacey and Berry, 2004). This normal fault was subsequently thrust and later converted to a transcurrent fault in post-dolerite (i.e. post Early Jurassic) times (Blackburn, 2004). Thus, the present transition from the central lowlands to the highlands appears to be a long-lived feature with it being close to or coincident with an Ordovician carbonate platform edge, the boundary between Western and Eastern Tasmanian terranes, and the transition from Early Permian land to basinal sedimentation.

Seismic imaging of the Gondwanan Petroleum System

The Gondwanan Petroleum System in Tasmania has been described by Bendall et al (2000) and Reid and Burrett (2004). Structural traps within the Gondwanan Petroleum System consist of shallowly dipping domes above older steeper domes—as at Bellevue and Thunderbolt—or as anticlines or fault traps, as in the leads and prospects shown in Figure 12. Many of these structures are Cenozoic in age, though a more precise age cannot be ascertained and some are Jurassic in age (see Figs 10 and 11). Reid et al (2003) showed that deformation of the Upper Parameener Group in central Tasmania either preceded or was coincident with dolerite intrusion in the Early Jurassic. Exploration is focusing on defining Jurassic-age traps as all thermal modelling has shown that maximum hydrocarbon generation was mid-Cretaceous (Bendall et al, 2000; Reid et al, 2003). Given the complex structural history of some areas in Tasmania, however, there is scope for petroleum migration and filling of Cretaceous-Cenozoic traps.

Exploration is focusing on situations where potential reservoirs are at a distance from intrusive sheets of dolerite. Empire's seismic surveys show that one major sheet extends across most of central Tasmania (see Figs 10 and 11) and its very high seismic velocity indicates that this would make an excellent regional seal. Empire's fully cored stratigraphic wells at Shittim-1 and Hunterston-1 showed that the thick (>650 m) dolerite sheets are composite with many internal contacts between different grain size textures (Bendall et al, 2000; Reid et al, 2003). The dolerites, therefore, intruded in several pulses and obvious contact metamorphic effects such as calc-silicate hornfels are limited to 20 m below the dolerite sheet at Hunterston-1 (Reid et al, 2003). If the dolerite had intruded in one intrusive event, pronounced contact metamorphic events would be expected at distances of up to 1,000 m or more from the dolerite sheet (Holford et al, 2012). Moreover, vitrinite reflectance values from samples at

65 m beneath the Hunterston dolerite do not indicate elevated temperatures. The porosity of the Liffey Group, 60 m below the dolerite, has been substantially reduced by secondary calcite cementation. The basal Permian conglomerate (not tillite), however, has had dolomite clasts dissolved, presumably by circulating hydrothermal fluids, thereby forming an excellent potential reservoir with a mean porosity of 16.9% and a mean permeability of 6,323 mD (Reid et al, 2003).

Table 1. Acquisition parameters used in Empire's onshore Tasmania seismic surveys.

	Vibroseis source
Acquisition type	Sercel 388 24 Bit Telemetry System
Energy source	Three input-output 42,000 lb (19,051 kg) peak force 6 × 6 truck-mounted vibrators online
Vibrator point interval	20 m
Vibrator array	15 m pad-pad/no moveups
Vibrator array location	Centred on station pegs (centred at shot point 100)
Receivers	12 × 10 Hz SM24 Geophones per group
Receiver interval	20 m
Receiver array	20 m (12 phones with 1.67 m phone spacing)
Receiver array location	Centred between stations (centered at SP 100.5)
Sweep length	12 sec sweeps
Number of sweeps	Two 12 sec sweeps per velocity point
Sweep type	Monosweep
Sweep frequencies	6–140 Hz
Sweep taper	200 ms taper
Sweep energy per km	1,200 sec/km or 800 sec/km
Sweep control	Pelton Advance 2 Model 5
Accelerometers	Pelton M5 High Performance
Similarity system	Pelton VIBRA-SIG
Peak force	44,000 lbs (20,000 kg)
Hold down weight	44,200 lbs (20,048 kg)
Vibrator drive level	Force control on—80% peak force
Phase lock	Ground force phase lock
Number of channels	300 channels
Spread geometry	Symmetric split spread
Maximum offset	2,990—10—0—10—2,990 m
Fold	150 fold with 10 m common depth point interval
Record length	6.0 sec
Correlation sample rate	2 ms
Written to tape source receiver	2 ms

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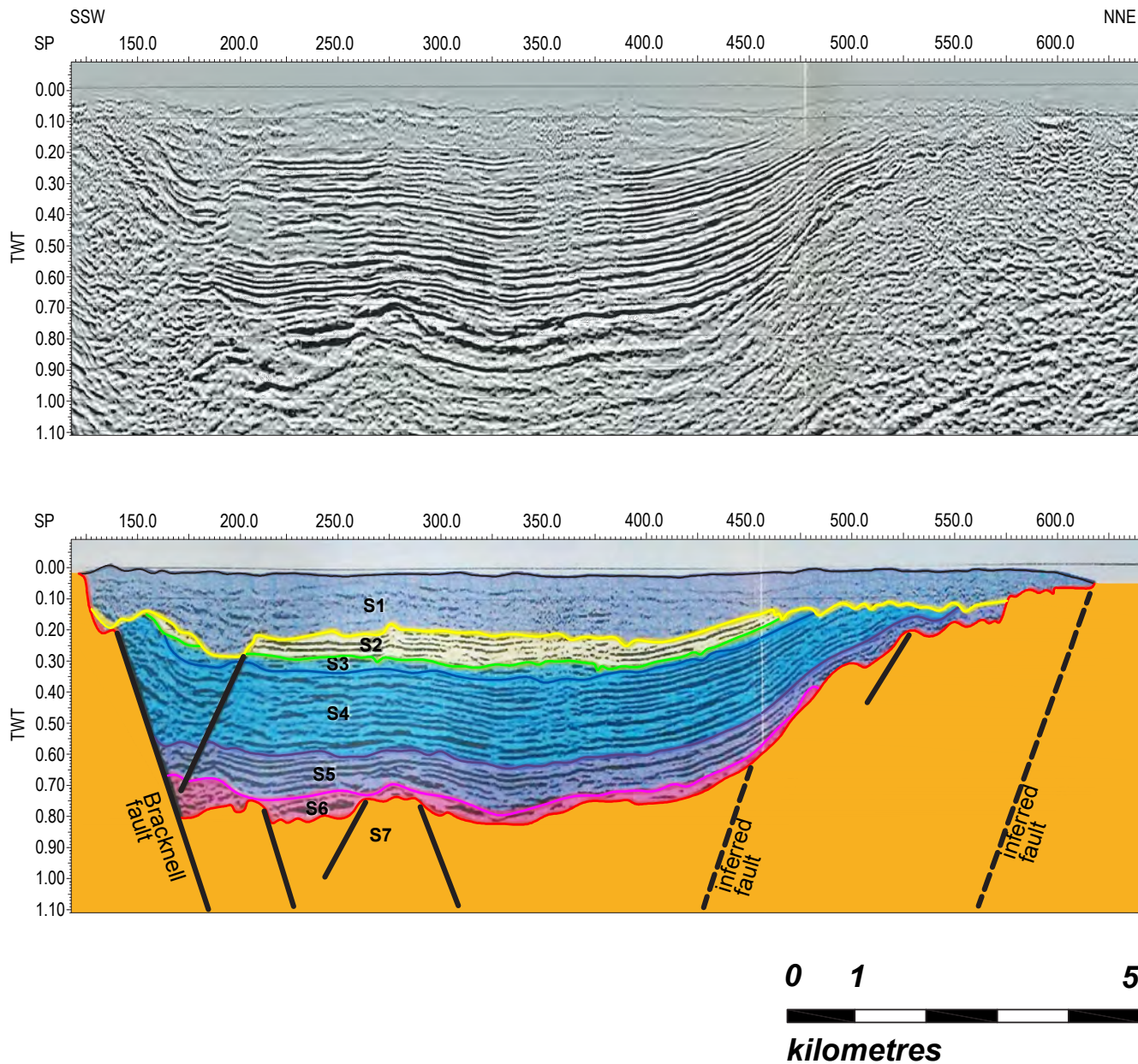


Figure 7. Seismic section along Empire seismic line TB01-SB (see Fig. 5 for locality) across the Longford Basin (Longford Sub-basin in Fig. 1). S1-S7 are Paleocene-Oligocene, non-marine sedimentary sequences recognised by Lane (2002) and tied to downhole logging in Sulzberger Ltd well OP-1 (Matthews, 1983). S1 is the youngest sequence. For details of Longford Basin sequences based on Empire's seismic see Lane (2002) and Corbett et al (2014).

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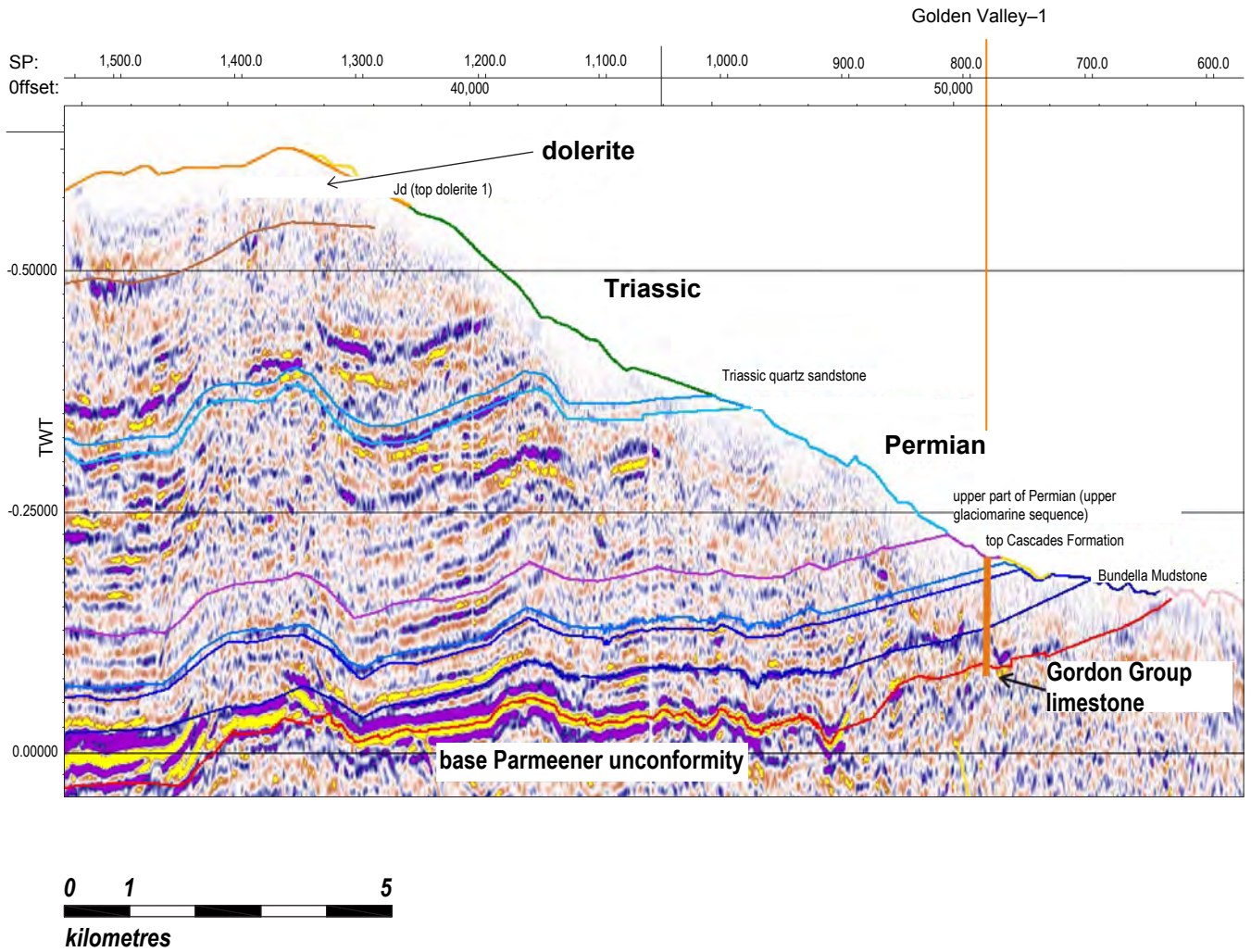


Figure 8. Seismic section along Empire seismic line TB01-TH, tied to surface geology along the road on to Central Plateau and to MRT stratigraphic well Golden Valley-1. (Blackburn, 2004). Note that individual units within the Pennsylvanian-Triassic Parmeener Supergroup, the base of the dolerite sheet and the basal Parmeener Supergroup unconformity are readily identified on the seismic section and correlated to outcrops along the road.

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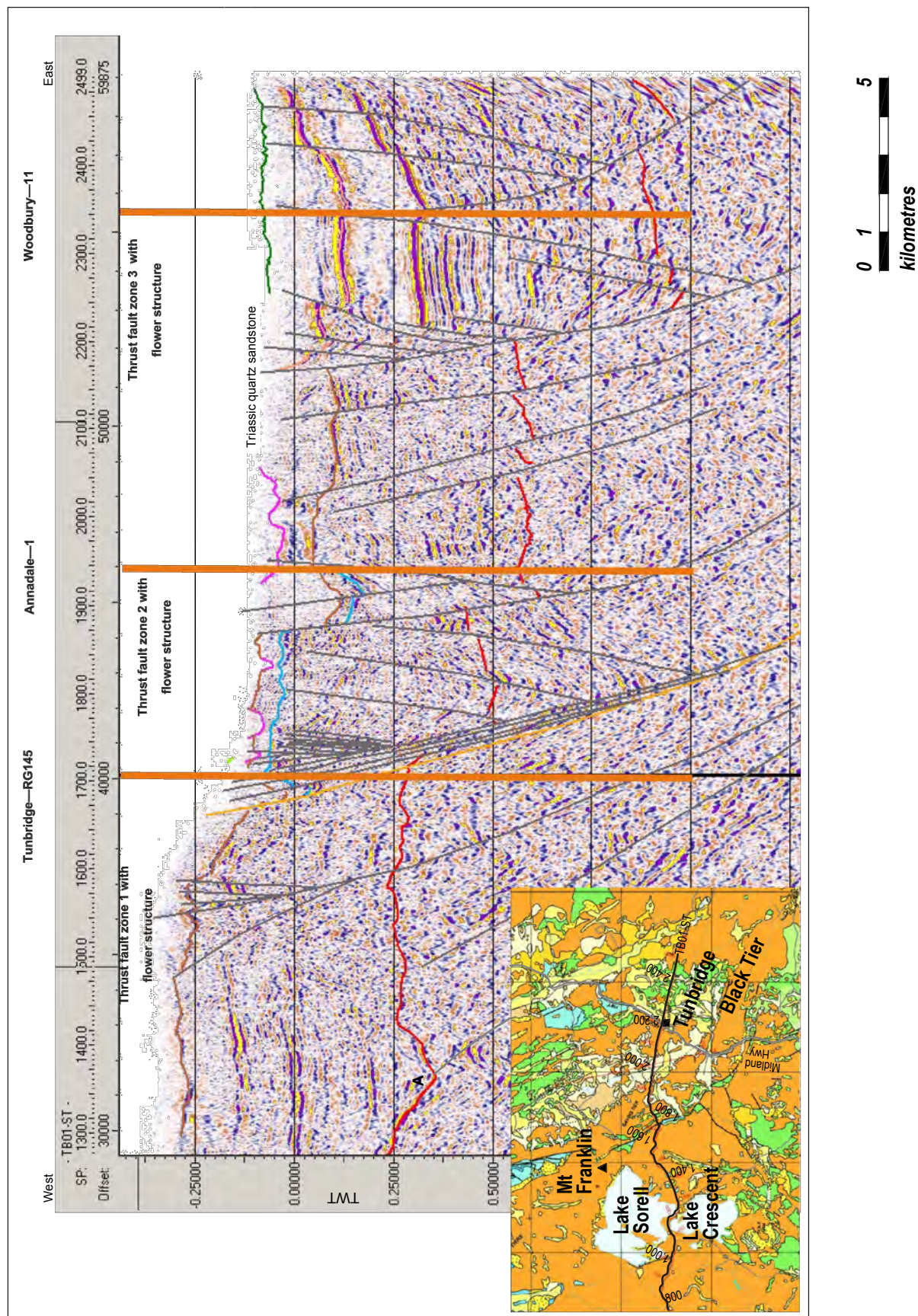
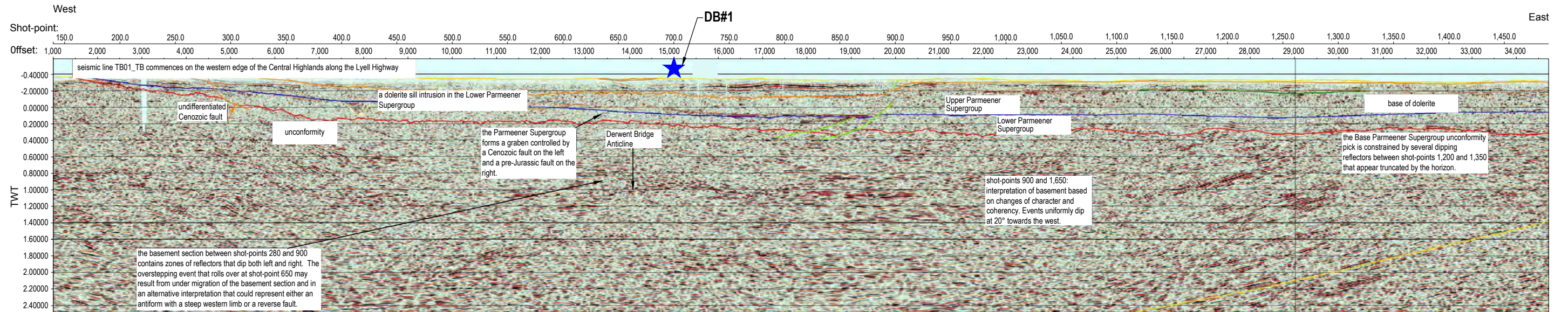
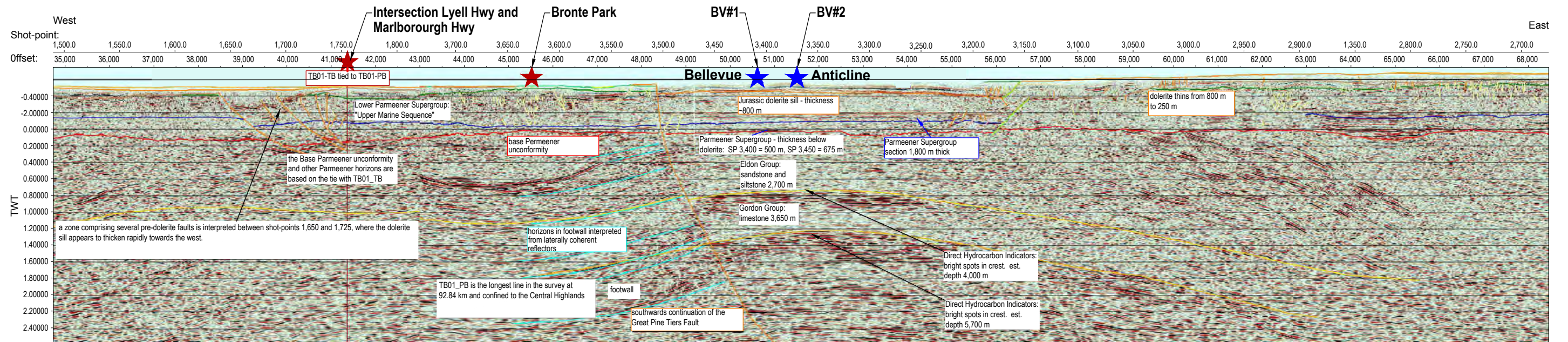


Figure 9. Interpreted Empire seismic line TB01-ST. See Figure 5 for locality. Locations of MRT wells are shown in Figure 1. Note thickening of the basal Parmeener Supergroup across the thrust faults. These three thrust zones have been wrenched later to form flower structures (Blackburn, 2004). Also note relief on the sub-Parmeener Supergroup unconformity, and note the western wall of a palaeovalley is steep (at point A on left of diagram) and is probably the trace of a pre-Parmeener thrust and that the valley has probably been infilled by latest Carboniferous–Permian tillite. Extract of MRT geological map published with permission of IMRT. Blue is Lower Parmeener Supergroup (late Carboniferous–Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments.



(a)



(b)

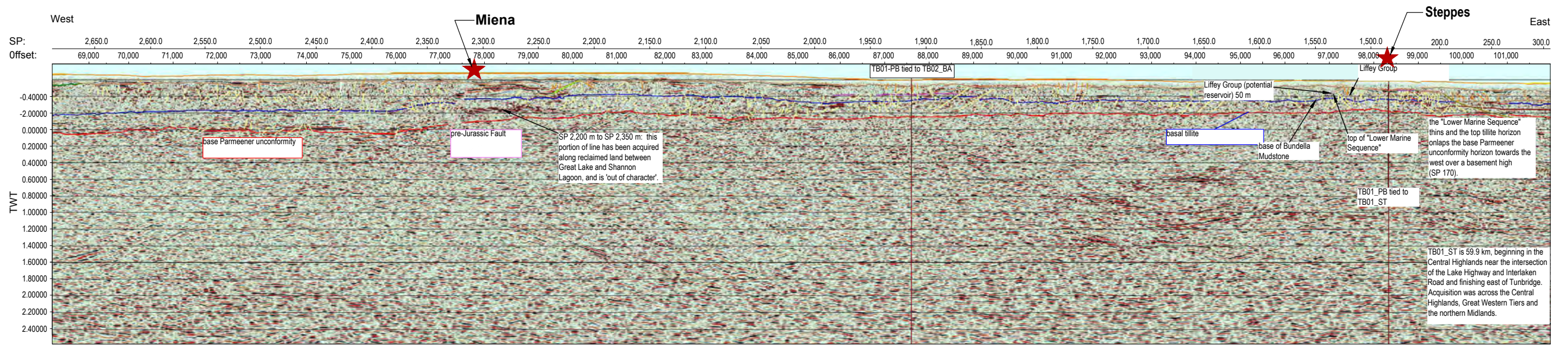
Legend:
 ★ Location (town, intersection)
 ★ Drill Site



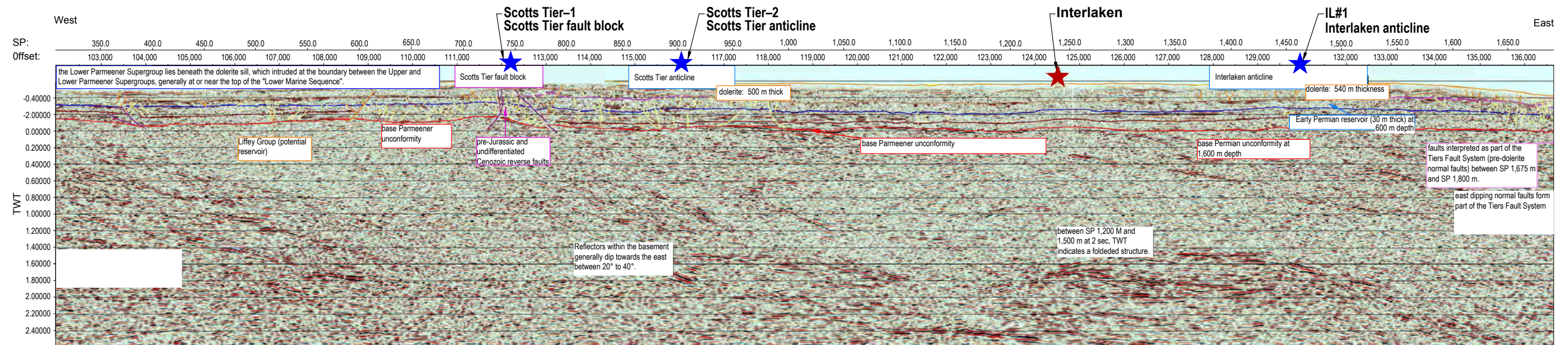
Figure 10a and b. Composite east–west seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous–Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments. Figure 10 continued on next page.

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(c)



(d)

Legend:

- ★ Location (town, intersection)
- ★ Drill Site



Figure 10c and d. Continued from previous page. Composite east–west seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous–Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments. Figure 10 continued on next page.

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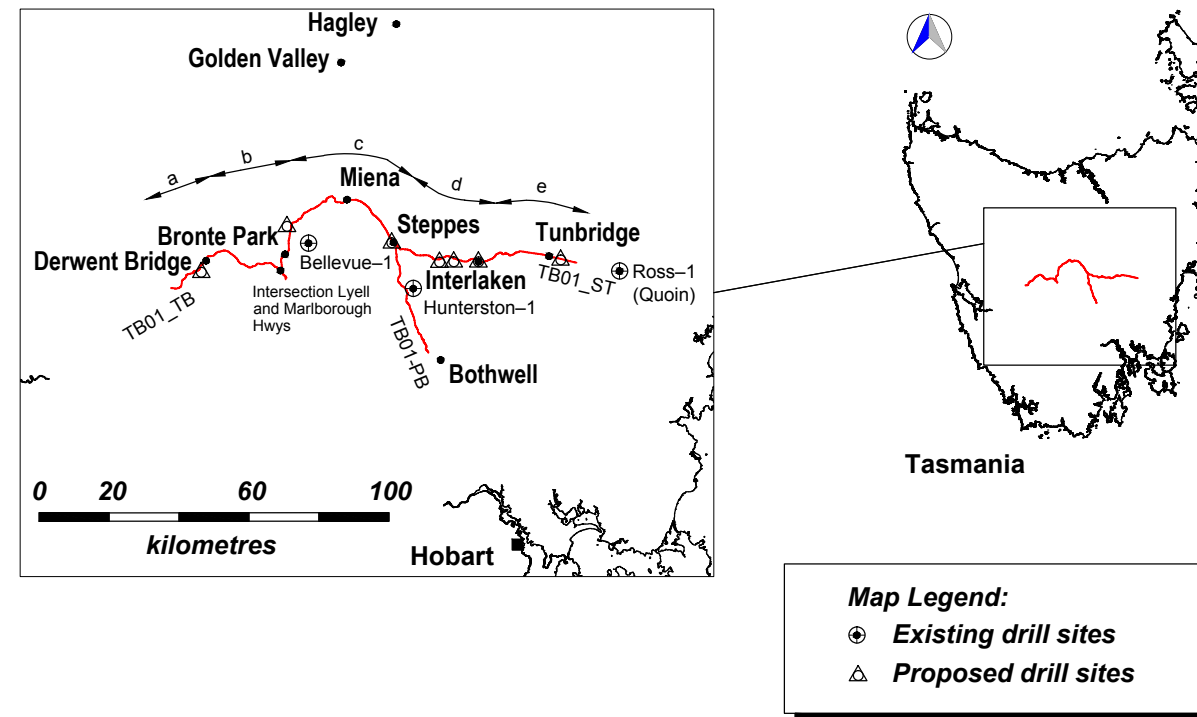
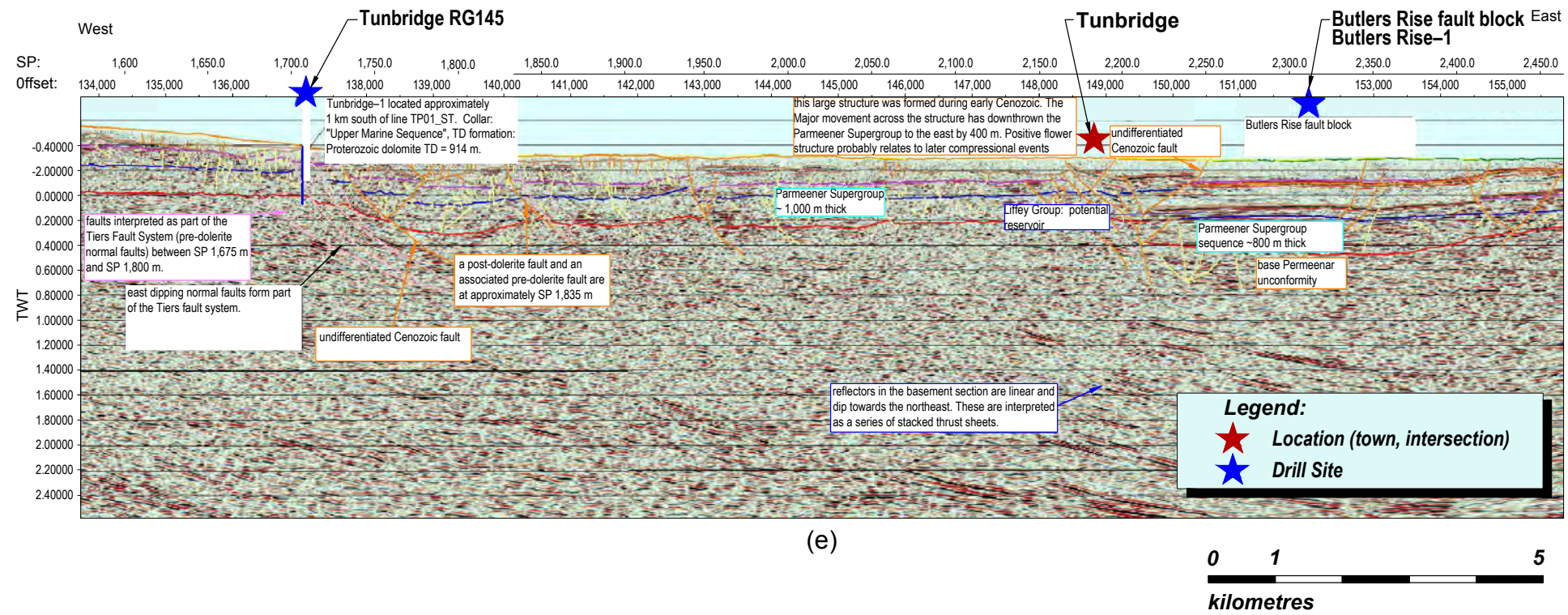
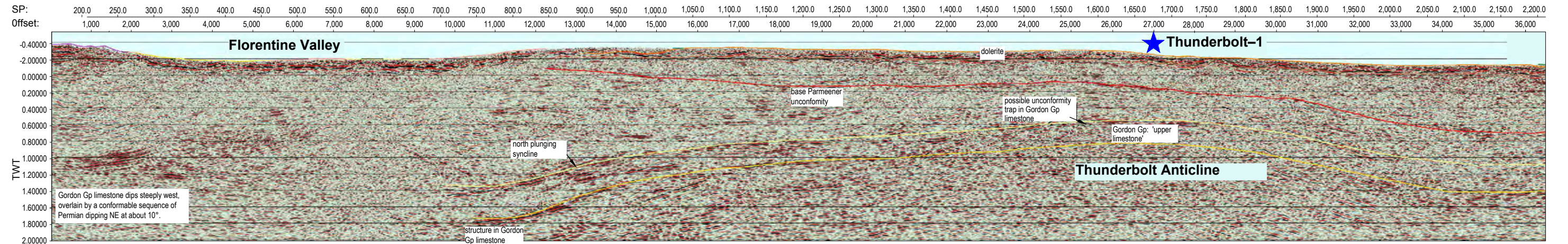
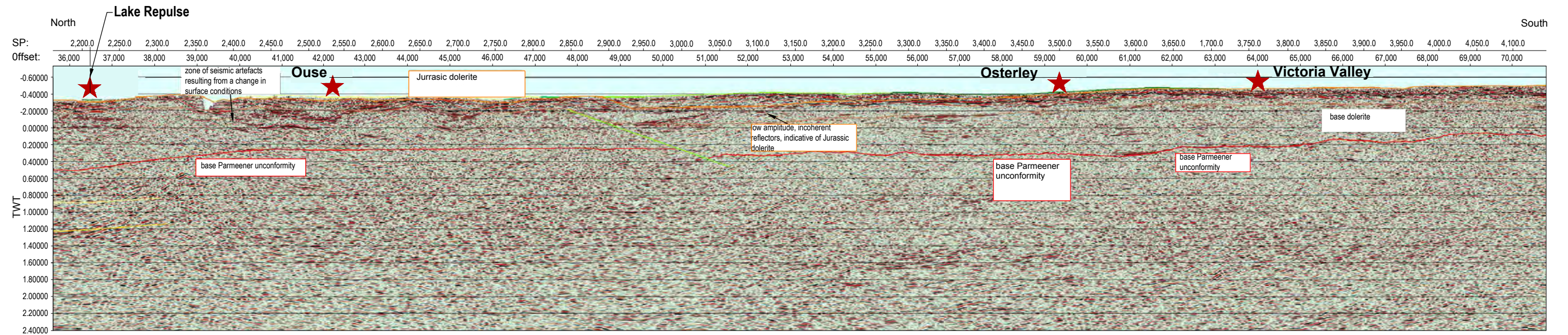


Figure 10e. Continued from previous page. Composite east-west seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous-Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments.



(a)



(b)

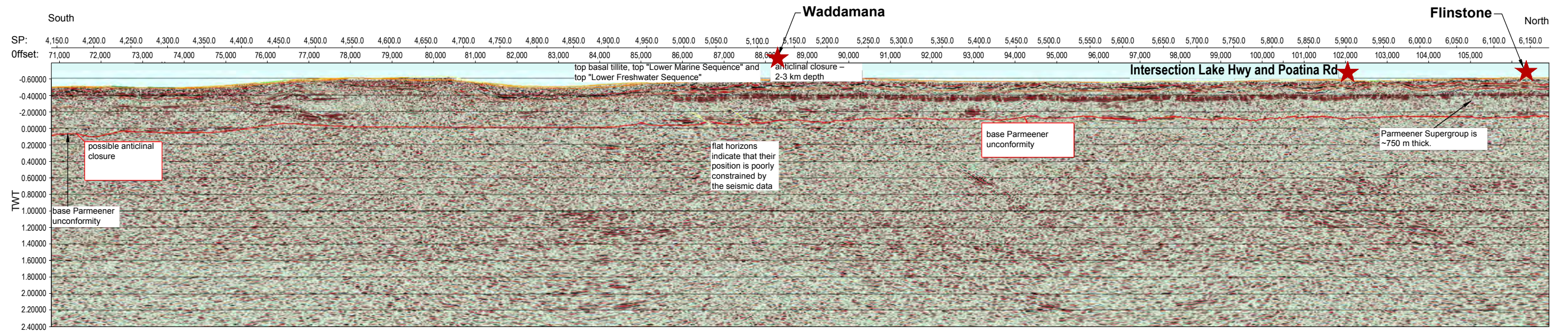
Legend:
 ★ Location (town, intersection)
 ★ Drill Site



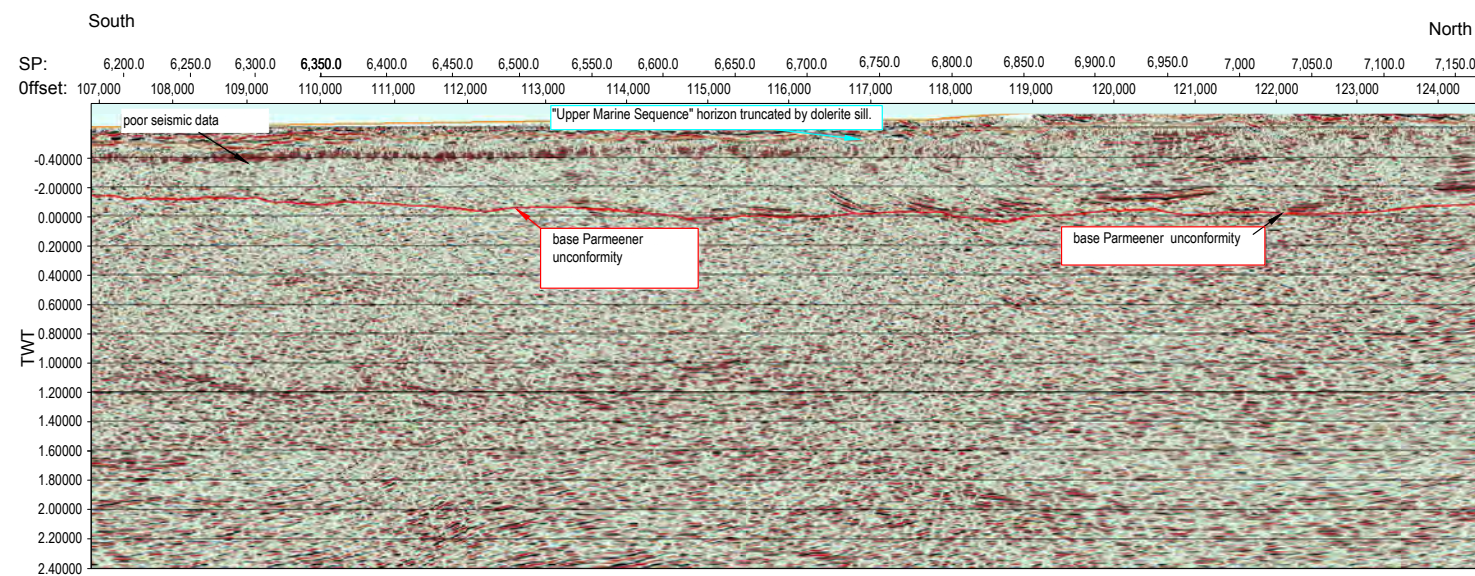
Figure 11a and b. Composite north–south seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous–Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments. Figure 11 continued on next page.

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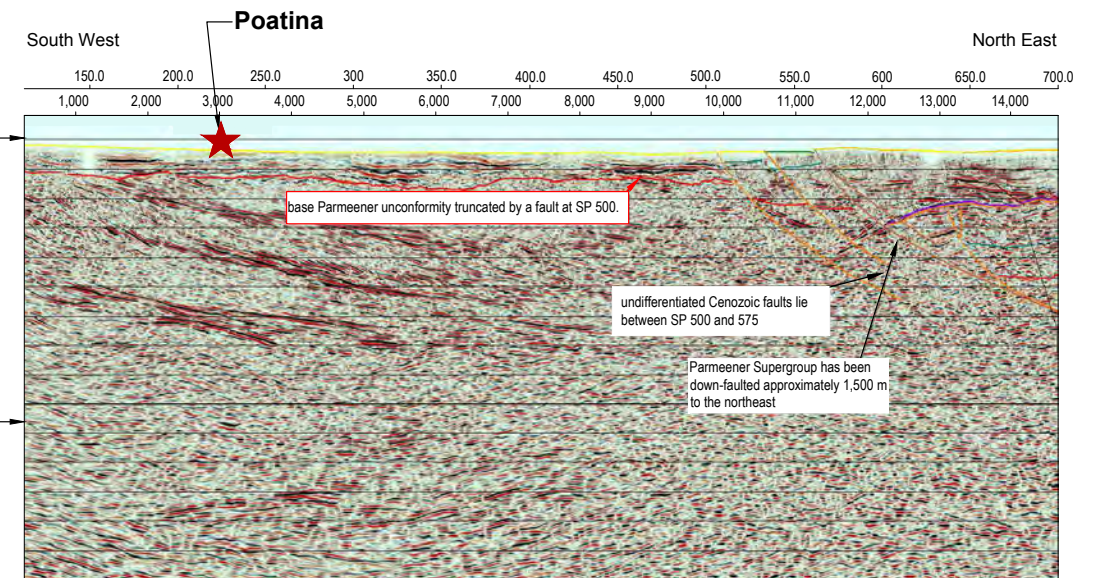
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(c)



(d)

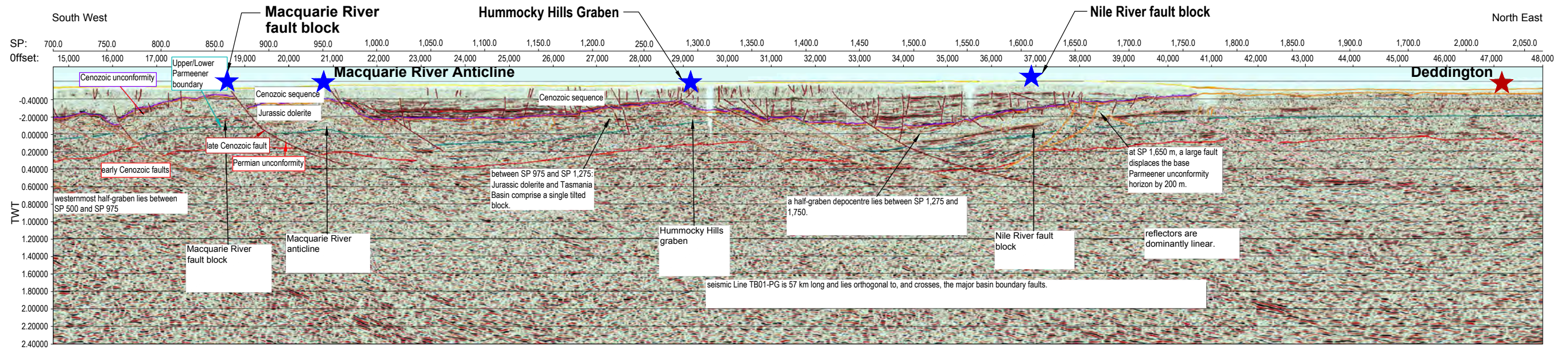


(e)

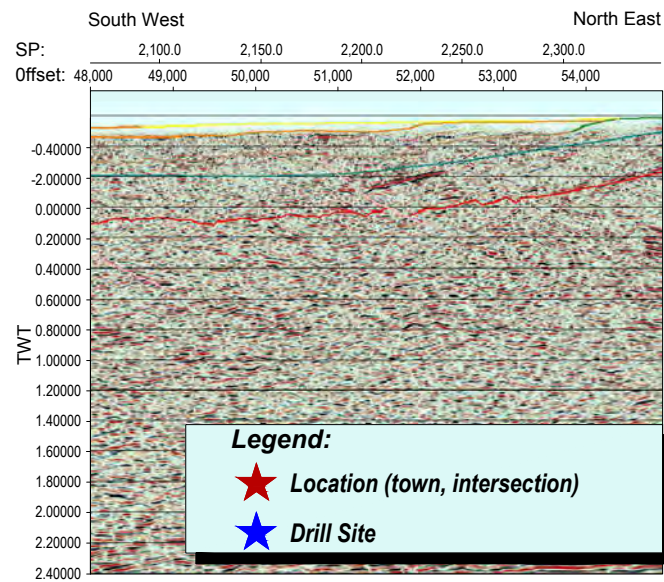
Legend:
 ★ Location (town, intersection)
 ★ Drill Site



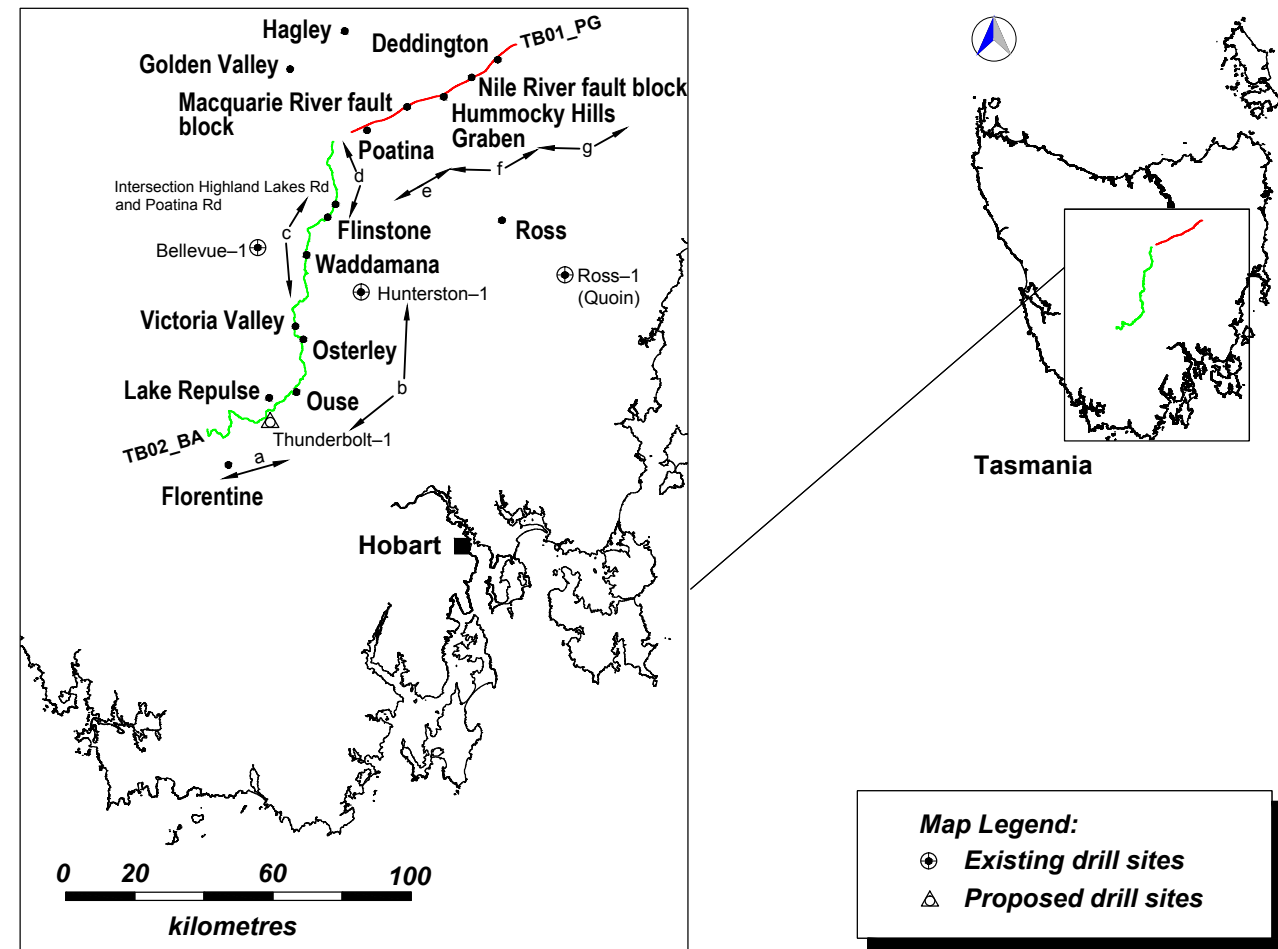
Figure 11c, d and e. Continued from previous page. Composite north-south seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous-Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments. Figure 11 continued on next page.



(f)



(g)



Map Legend:
 ⊕ Existing drill sites
 △ Proposed drill sites

Figure 11f and g. Continued from previous page. Composite north-south seismic cross-section across Tasmania. Red is basal Parmeener Supergroup unconformity, blue is Lower Parmeener Supergroup (late Carboniferous-Permian), green is Upper Parmeener Supergroup (latest Permian to Triassic), dark orange is Jurassic dolerite, orange is Cenozoic basalt, and light brown is Quaternary sediments.

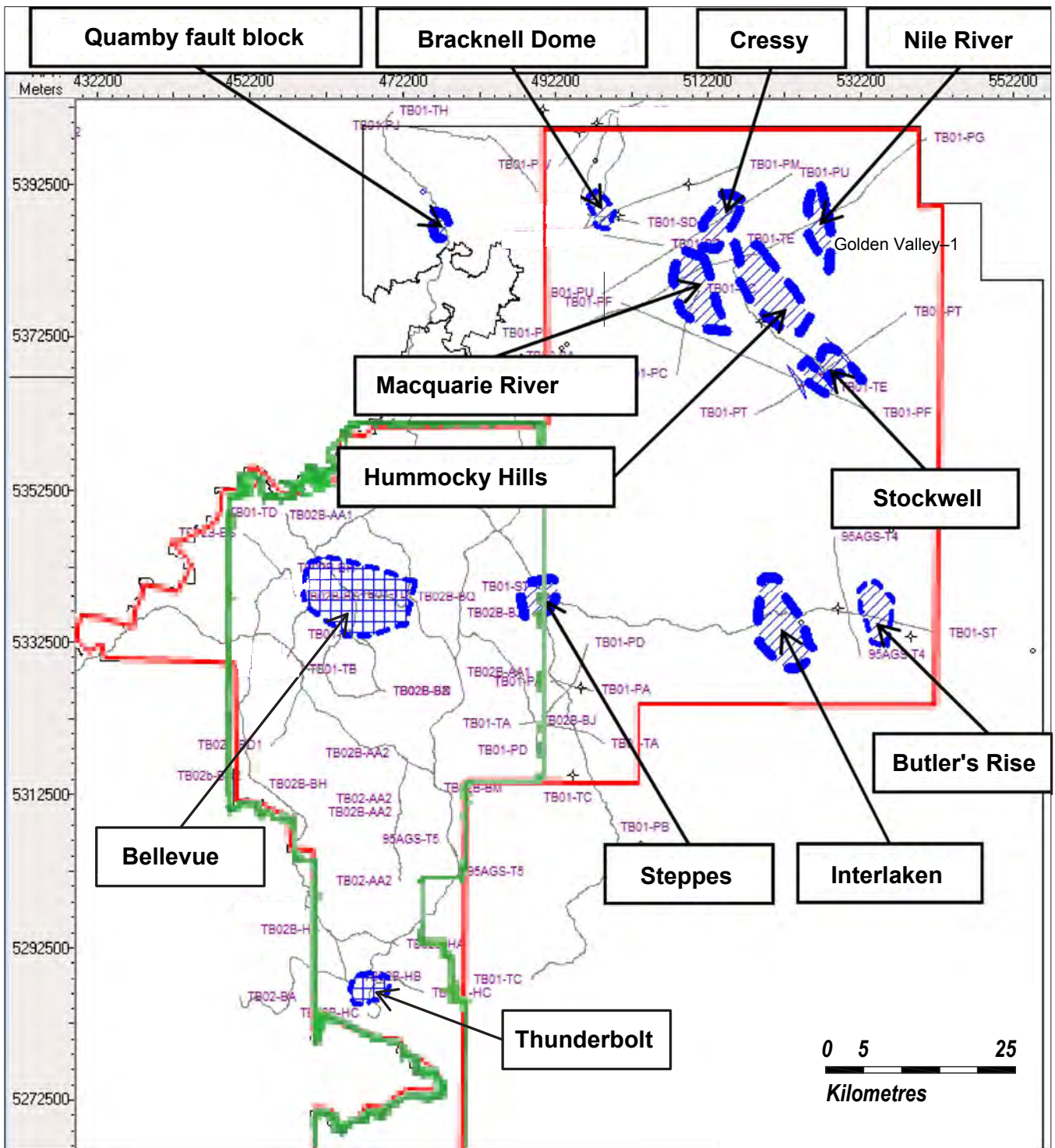
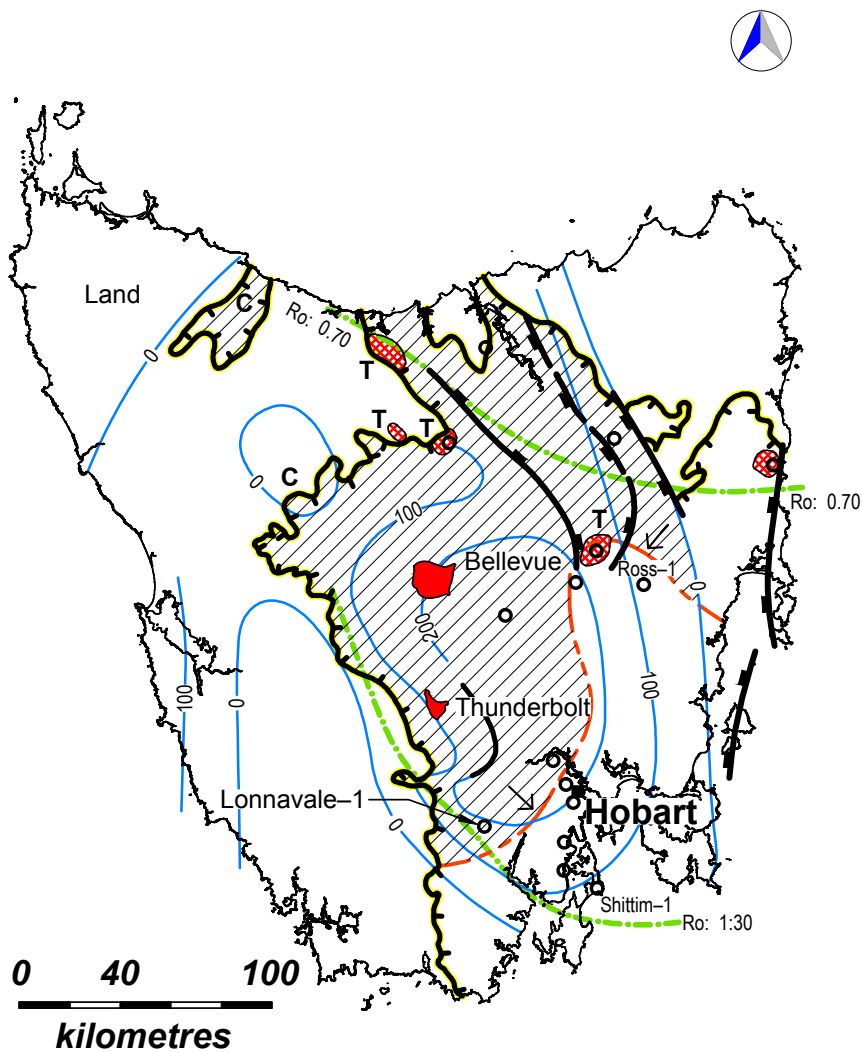


Figure 12. Location of some Gondwanan Petroleum System leads and prospects (Hockfield and Eales, 2013). Blue is leads and prospects, cross-hatched areas are prospects Bellevue and Thunderbolt. Green is part of the EL14/2009 licence boundary, red is former proposed licence boundary application, black is Special Exploration Licence 13/98 licence boundary 2004–09 second five-year term.

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Legend:


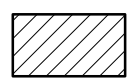








-  **Ro Isoreflectance**
-  **LFSW (Lower Freshwater Sequence)
(Reservoir, Lower Permian)**
-  **Reservoir Limit**
-  **Isopach (Woody Island Fm.)
(Source, Lower Permian)**
-  **Borehole**
-  **Prospect**
-  **Fault**
-  **Tasmania Basin**
-  **Tasmanite**
-  **Coal**

Figure 13. Summary of Gondwanan Petroleum System in Tasmania (Global Exploration Services, 2013).

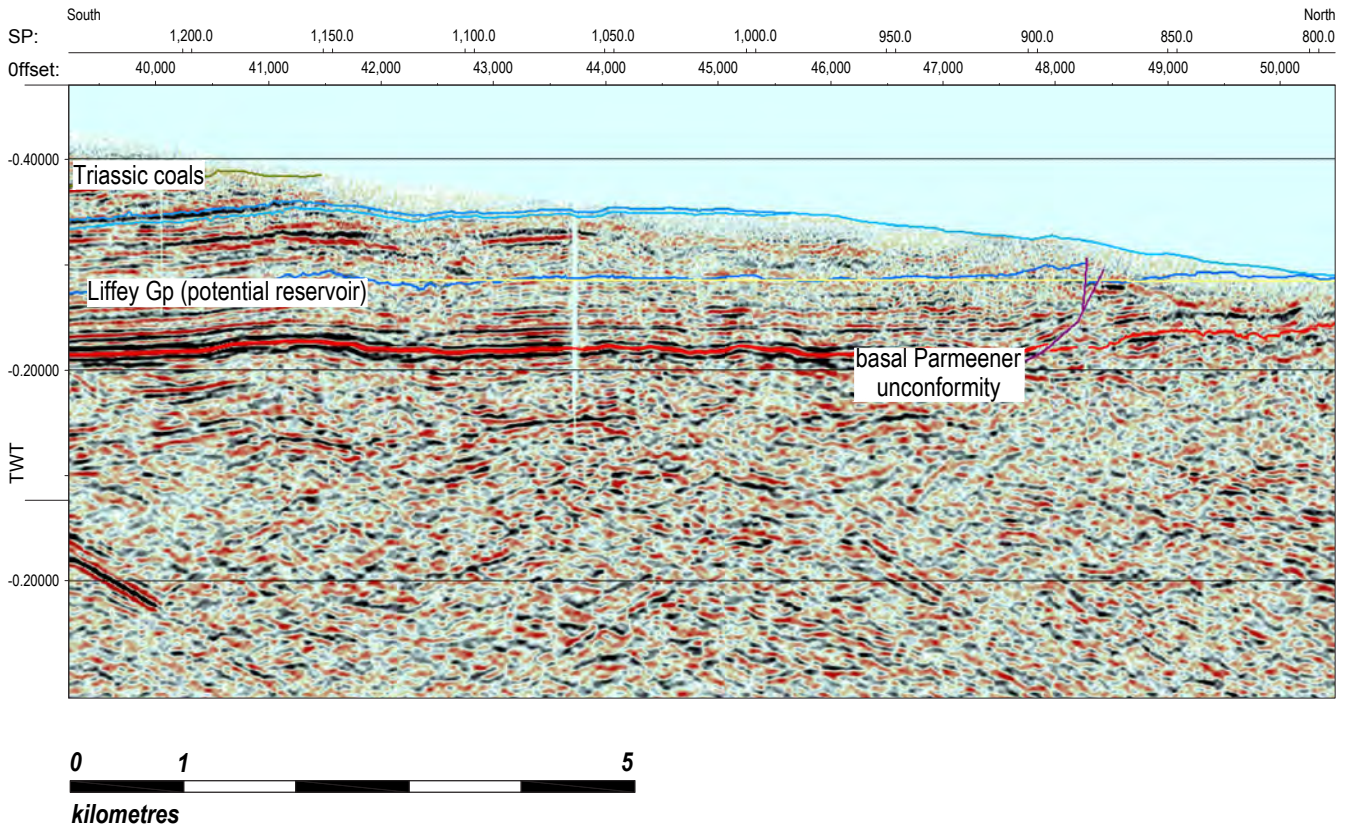


Figure 14. North–south seismic section TB01-TH, across structure, showing the Quamby prospect within the Gondwanan Petroleum System. See Figure 12 for location and Figure 5 for seismic line location. Liffey-Faulkner Group is Early Permian freshwater sandstones and potential reservoir. The southern part of this section is shown in more detail in Figure 8.

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Seismic imaging of the Larapintine Petroleum System

The Larapintine Petroleum System in Tasmania (Bendall et al, 2000) is based on Ordovician black shales and micritic limestones as potential sources, enhanced porosity platform carbonates and coral-stromatoporoid reefs as potential reservoirs, and Ordovician micrites and Silurian-Devonian shales as seals (Fig. 15). A reef-rimmed carbonate platform is confirmed in southern Tasmania (Burrett et al, 1981, 1984) and it is likely that the reefs identified on the seismic (Fig. 17) within the Gordon Group carbonates in the east of the Bellevue lead and at the Thunderbolt lead are also close to the platform margin (Fig. 15). There is considerable potential for palaeokarst traps (Fig. 11) beneath the tillites and shales of the basal Parmeener Supergroup unconformity as, in a few places, Gordon Group limestones were karsted in the Devonian, and Devonian cave deposits have been palynologically dated (Seymour et al, 2014). Seal for these potential palaeokarst reservoirs is provided by latest Carboniferous to Asselian tillites and shales, above the unconformity, at the base of the Parmeener Supergroup. Other large Tabberabberan (Devonian) structures, such as the Derwent Bridge Anticline, are evident on the seismic lines (Fig. 10) but need to be defined by cross lines. The Ordovician sequences, fauna and flora are comparable with those in the producing fields of the Tarim Basin of northwest China (Bendall et al, 2000; Li, 1995), which was also part of Greater Gondwana in the Ordovician and connected by shallow seas to the Larapintine Seaway of central Australia (Burrett et al, 1990).

POTENTIAL OR PROSPECTIVE RESOURCES

The estimated mean undiscovered potential resource (or estimated undiscovered prospective resource) of the Larapintine and Gondwanan petroleum system structures have been independently evaluated by RPS Energy (2008, 2009), Odedra et al (2013) and Hockfield and Eales (2013), and summarised in Tables 2 and 3. Volumetrics were calculated using Kingdom Suite software and a range of likely porosity and permeability scenarios were input into standard petroleum industry software. For resource definitions, Empire’s external consultants used definitions and guidelines set out in the Petroleum Resources Management System prepared by the Oil and Gas Reserves Committee of the Society of Petroleum Engineers (Society of Petroleum Engineers, 2007). These have been used along with London Stock Exchange Alternative Investments Market (AIM) guidelines (London Stock Exchange, 2009) and Australian Stock Exchange Disclosure Rules (2012).

Fault traps and relatively small anticlinal traps within the Gondwanan Petroleum System contain an estimated mean undiscovered potential resource (or best estimate undiscovered prospective resource) of 221.8 MMBOE (RPS Energy 2008, 2009) or 144.7 MMBOE (Hockfield and Eales, 2013). The two large anticlinal structures (Bellevue and Thunderbolt prospects, see Fig. 12 for localities) have, so far, been seismically delineated in the Larapintine Petroleum System and are estimated to have a mean undiscovered potential resource (or best estimate prospective resource) of 447 MMBOE (RPS Energy 2008, 2009) or 452 MMBOE (Odedra et al, 2013). The total estimated mean undiscovered potential resource (or best estimates of undiscovered prospective resource) in structures seismically identified by Empire are 668.8 MMBOE (RPS Energy, 2008, 2009) and 596.9 MMBOE (Hockfield and Eales, 2013; Odedra et al, 2013).

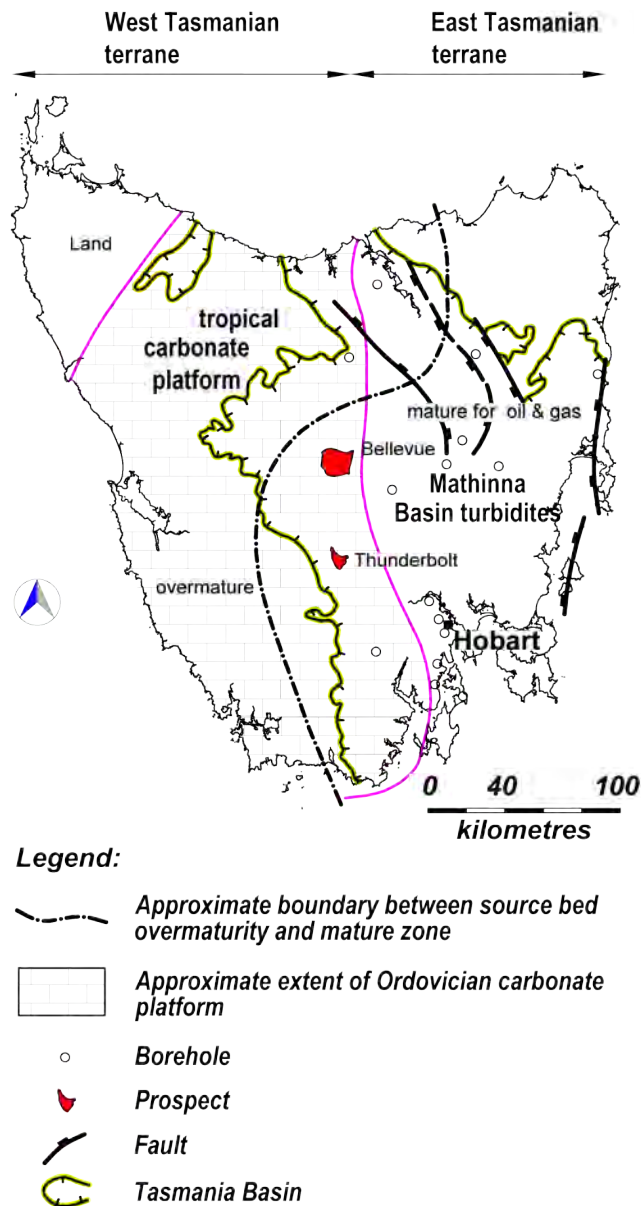


Figure 15. Larapintine Petroleum System onshore Tasmania summary (Global Exploration Services, 2013). Maturity based on conodont geothermometry (Burrett, 1992).

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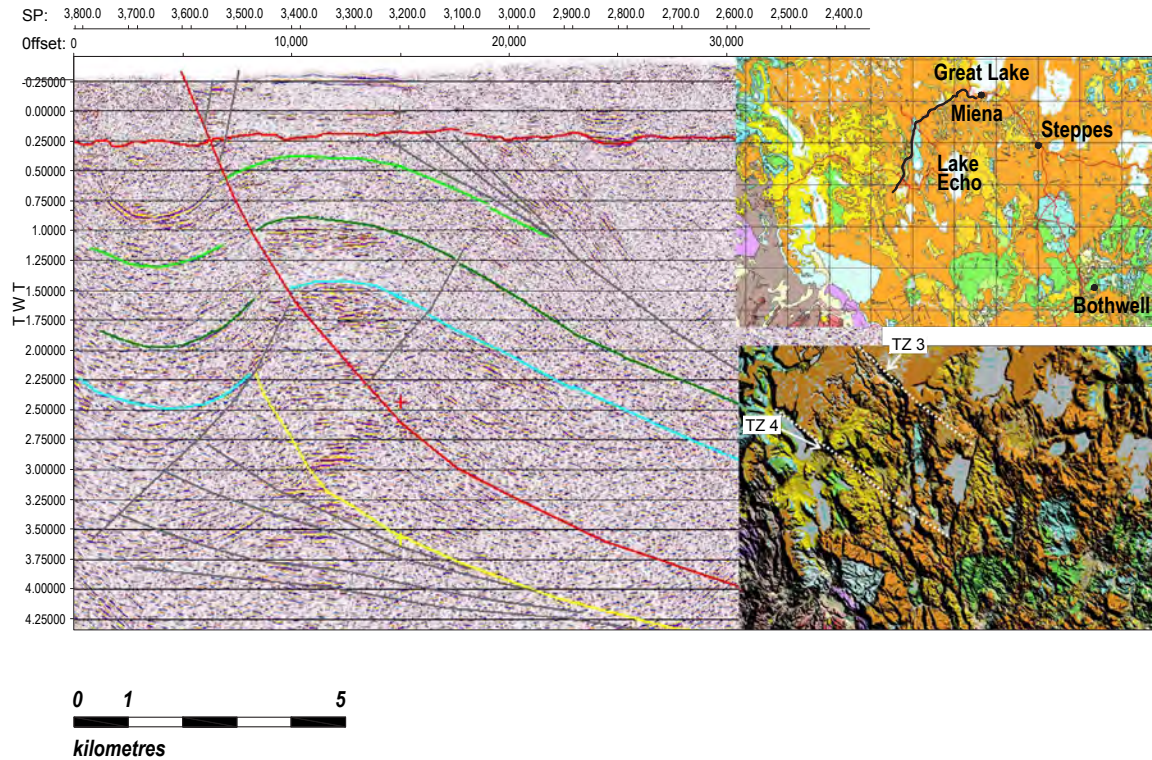


Figure 16. Bellevue prospect. Note irregularity of base-Parmeener unconformity shown as red line (Blackburn, 2004). Part of seismic line TB01-PB. See Figure 12 for location and Figure 5 for seismic line location.

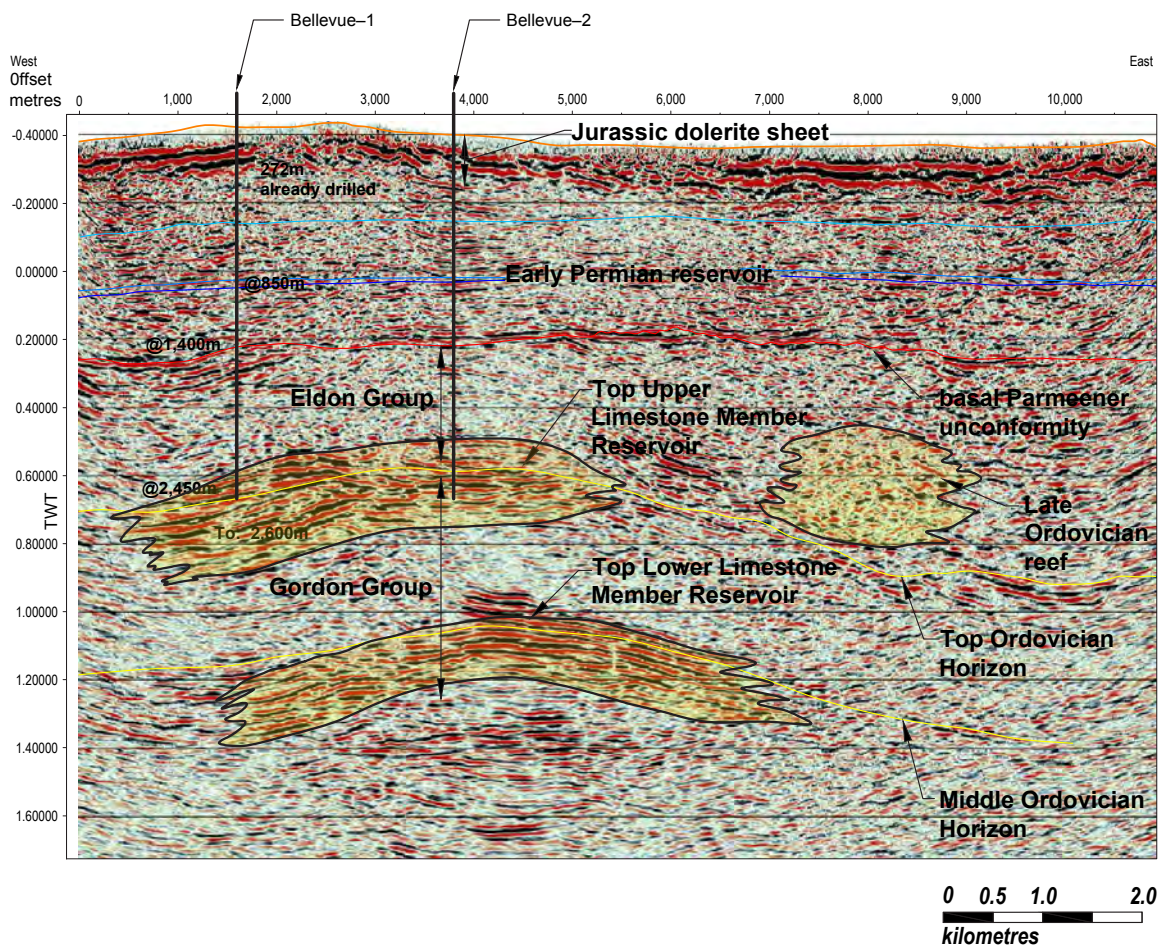


Figure 17. Seismic section TB02b-BQ of Bellevue prospect showing interpreted Ordovician reservoirs and coral-stromatoporoid reef reservoir in the Gordon Group limestone (Global Exploration Services, 2013). Bellevue-1 was drilled to 272m; Bellevue-2 is planned. See Figure 12 for location and Figure 5 for seismic line location.

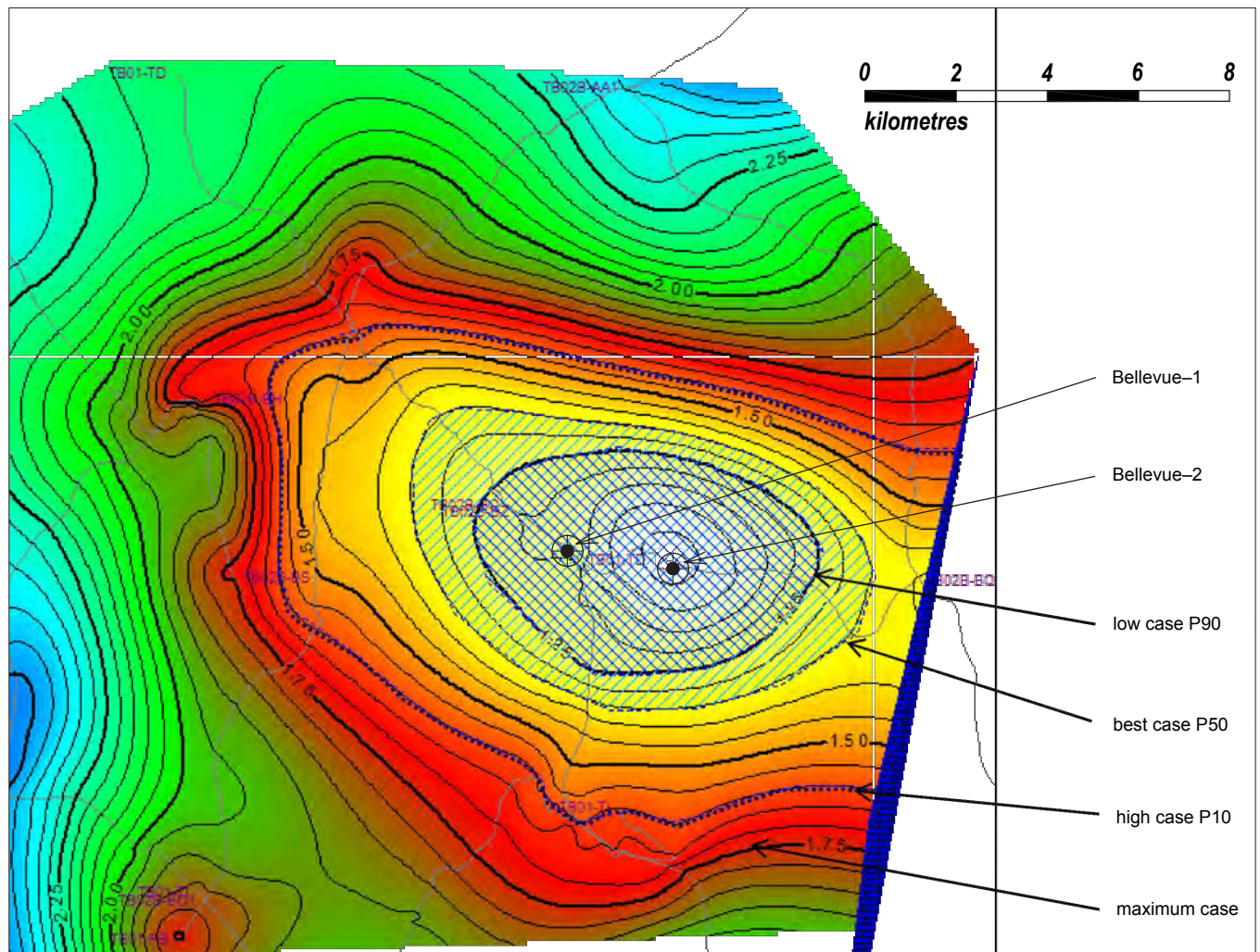


Figure 18. Seismic two-way time (TWT) map of Bellevue prospect (Odedra et al, 2013). Bellevue-1 was cased and cemented to 234 m; Bellevue-2 is planned. See Figure 12 for location and Figure 5 for seismic line location.

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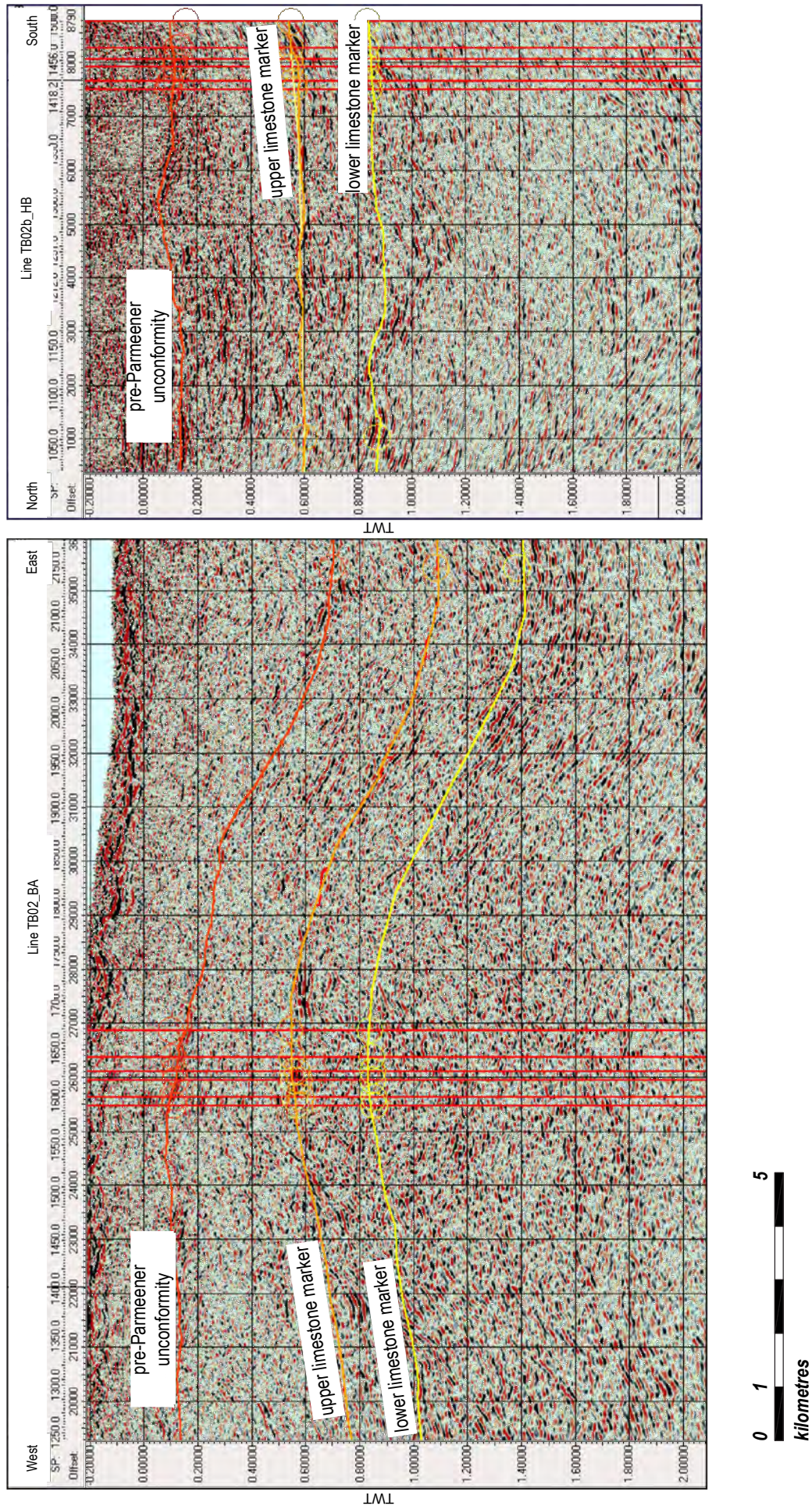


Figure 19. Seismic section TB02-BA and TB02b-HB of the Thunderbolt prospect (Odedra et al, 2013). See Figure 5 for locality and Figure 12 for seismic line locations.

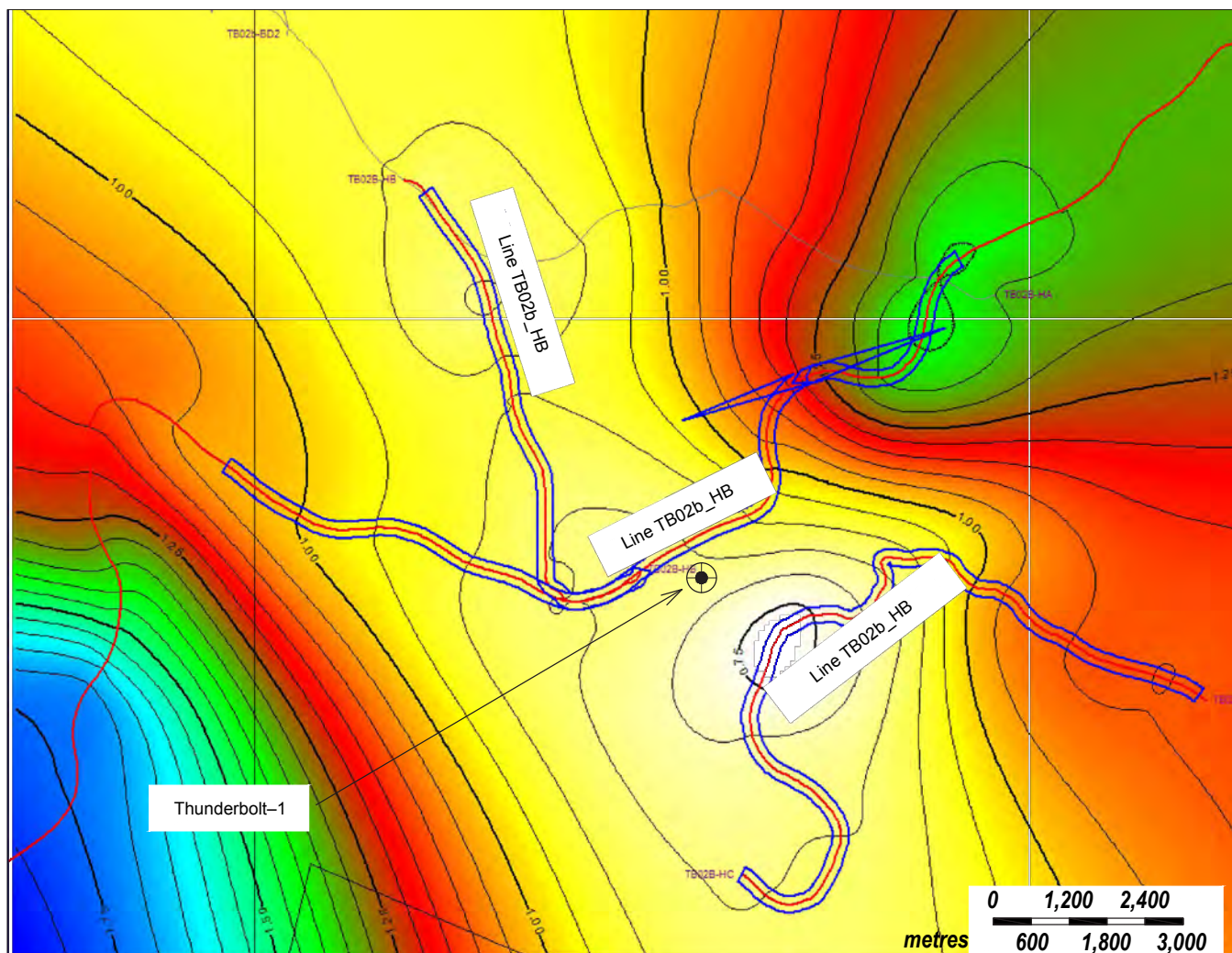


Figure 20. Seismic TWT map of the Thunderbolt prospect (Odedra et al, 2013). Position of the planned well Thunderbolt-1 is shown. See Figure 12 for location and Figure 5 for seismic line localities.

Table 2. Prospective Undiscovered Resources Assessment for Licence SEL13/98. See Figure 12 for localities of leads and prospects. Units are in MMBOE.

Prospect/lead	Low estimate (P90)	Best estimate (P50)	High estimate (P10)	Mean
Bellevue Upper	38	151	484	220
Bellevue Lower	24	95	307	139
Thunderbolt	12	53	198	88
Bracknell Dome	3	18	90	37
Butler's Rise	2	14	63	25
Interlaken	2	10	40	17
Cressy	3	12	48	21
Hummocky Hills	5	30	138	58
Macquarie River	3.5	13.1	42.4	19.7
Nile River	3.5	13.1	42.4	19.7
Quamby	0.4	1.5	5.0	2.3
Steppes	2.0	7.4	24.0	11.1
Stockwell	2.0	7.4	23.6	11.0
Total (MMBOE)	100.4	425.5	1,505.4	668.8

Source: RPS Energy (2008).

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Table 3. Prospective Undiscovered Resources Assessment for Licences EL14/2009 and EL30/2011. See Figure 12 for localities of leads and prospects. Units are in MMBOE.

Prospect/Lead	Low Estimate (P90)	Best Estimate (P50)	High Estimate (P10)	Mean
Bellevue (Larapintine-Ordovician and Silurian)	23.3	159.5	973.3	403.2
Thunderbolt (Larapintine-Ordovician and Silurian)	2.2	16.7	115	49
Bellevue and Thunderbolt (Gondwanan-Permian Triassic)	2.2	11.8	62.2	25.7
Bracknell Dome	1.5	5	15	7
Butler's Rise	1.3	6	28	12
Interlaken	1.5	8	45	18
Cressy	1.3	6	26	11
Hummocky Hills	1.5	8	46	19
Macquarie River	1.5	8	45	18
Nile River	1.2	5	24	10
Quamby	0.9	3	8	4
Steppes	1.2	5	22	10
Stockwell	1.2	5	24	10
Total (MMBOE)	40.8	247.0	1,433.5	596.9

Source: Hockfield and Eales (2013).

CONCLUSIONS

Despite considerable scepticism from many in the Australian geoscience community, the Vibroseis reflection seismic technique may be used effectively in Tasmania. Four Vibroseis trucks were used with a frequency range of 6–140 Hz and full frequency sweeps close together achieved maximum input and return signal. Numerous structures have been interpreted on the seismic sections. In particular, the faults near the junction of the Western and Eastern Tasmanian terranes define a broad belt of reactivated faults rather than a simple lineament. Reactivation from thrust to normal to transcurrent movement was probably due to the changing Australian plate stress regime acting on the margins of crustal blocks with differing rheological properties (Muller et al, 2012). The Western Tasmanian Terrane has a rheologically stronger crust underlain by thick and rigid Precambrian, whereas the Eastern Tasmanian Terrane consists of more easily deformed Mathinna Group turbidites overlying dense, probably oceanic, crust (Rawlinson et al, 2006). The terrane marginal fault belt is coincident with surface water iodine anomalies, suggesting that petroleum basin brines have leaked from depth. Elsewhere in the Tasmania Basin, a study of fault shale smear factor by Collings (2007) has shown that less complex normal faults are mostly impermeable and are unlikely to have significantly breached most potential reservoirs. Widespread Middle Permian shales and a near-continuous Jurassic dolerite sheet provide effective regional seals across central Tasmania. Because of its very low molecular size, the high values of helium in the C1-C8 gas beneath the dolerite in the Shittim-1 well confirms the excellent seal characteristics of the dolerite (Bendall et al, 2000).

Fault traps and relatively small anticlinal traps within the Gondwanan Petroleum System contain an estimated mean undiscovered potential resource (or best estimate prospective resource) of 221.8 MMBOE (RPS Energy, 2008, 2009) or 144.7 MMBOE (Hockfield and Eales, 2013). The two large anticlinal structures (Bellevue and Thunderbolt leads), so far seismically delineated in the Larapintine Petroleum System, are estimated to have a potential undiscovered mean resource (or best estimate prospective resource) of 447 MM-

BOE (RPS Energy, 2008, 2009) or 452 MMBOE (Odedra et al, 2013). Total estimates of mean undiscovered potential resource (or best estimate prospective resource) in structures seismically identified by Empire are 668.8 MMBOE (RPS Energy, 2008, 2009) and 596.9 MMBOE (Hockfield and Eales, 2013; Odedra et al, 2013). These resource estimates shown in Tables 2 and 3 are based on the structures identified on the limited seismic surveys carried out so far, and there is considerable potential for the discovery of many more structures in future seismic surveys within both onshore and offshore Tasmania.

ACKNOWLEDGMENTS

The authors are indebted to the Right Honourable Senator Eric Abetz for help and encouragement. Empire Energy Corporation International and its predecessor and subsidiary companies are indebted to their US and Australian auditors for their careful auditing of exploration expenditure. Funding through the Australian Federal Government ARC/SPIRT (Australian Research Council/Strategic Partnerships with Industry-Research and Training) scheme is gratefully acknowledged. The authors thank Ardilaun Energy for commissioning and financing the preparation of this paper, and thank John McKeon, Susan McKeon, Mark Pearson, Eoin Ryan, Cathal Jones and Karl Prenderville who provided substantial support.

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Dick Hancock is acknowledged for his help on a blow-out at Shittim-1 on Bruny Island, which took three days to bring under control and necessitated the emergency import of blow-out control experts from the US, along with wellhead control equipment provided by Joel Bodin. Shittim-1 was later successfully induced and flow-tested, and sampled by drilling engineer Ted McNally of Pectil Engineering. The results

from Pectil Engineering proved the production at 120 psi of helium, thermogenic dry gas, thermogenic wet gas and green crude oil.

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