STRATIGRAPHIC RESULTS OF DIAMOND DRILLING OF THE HUNTERSTON DOME, TASMANIA: IMPLICATIONS FOR PALAEOGEOGRAPHY AND HYDROCARBON POTENTIAL

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(with seven text-figures)

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The structure known as the Hunterston Dome, in central Tasmania, was drilled to a depth of 1324 m, through Jurassic dolerite, Lower Parmeener Supergroup and into Precambrian dolomite basement. The base of the Lower Parmeener Supergroup does not outcrop in the area, and drilling revealed the absence of the extensive glacial diamictites present elsewhere in the Tasmania Basin. A conglomeratic facies is found in place of the Bundella Mudstone and Woody Island Siltstone. Basement to the Lower Parmeener Supergroup is shown to be deformed Precambrian dolomite, of similar lithology to the relatively undeformed Black River Dolomite of northwestern Tasmania. Significant hydrocarbons were not encountered during drilling, but stratigraphic drilling proved the maturity of potential source beds in the region and the nature of potential reservoir rocks, where they are found in close association with a dolerite intrusion.
Key Words: Lower Parmeener Supergroup, Hunterston Dome, dolomite, hydrocarbons, palaeogeography, stratigraphy, dolerite.

INTRODUCTION

The geology of the Waddamanna region, central Tasmania, was first described by Fairbridge (1949), after regional mapping work for the Hydro-Electric Commission. Fairbridge described the Permian and Triassic rocks of the area and their structural relationship with Jurassic dolerite intrusives, and was the first to note the presence of a domal structure southeast of Lake Echo. This structure is named the Hunterston Dome, after the pastoral property covering the area. Fairbridge gave an accurate description of the local Permian geology and gentle dip of the strata. However, the 'sandy facies' of Fairbridge (1949), outcropping on the eastern and northeastern limb of the dome, is in fact the lower part of the freshwater Triassic.

The Hunterston area provides some of the only Permian (Lower Parmeener Supergroup) outcrop through the central Highlands region. However, only the marine series above the freshwater interval is exposed (fig. 1). The nature of the lower marine interval of the Lower Parmeener Supergroup is unknown, but extensive tillites and pyritic mudstones are known to the east (Forsyth 1989) and southwest (Jago 1971). To the northwest in the Du Cane (MacLeod *et al.* 1961) and Mackintosh (Collins *et al.* 1981) mapsheet areas, conglomerates and siltstones are present in place of the pyritic mudstones known elsewhere in the Tasmania Basin. The nature of the pre-Parmeener basement was unknown in this central Tasmanian region until the work reported here.

The Hunterston Dome is of interest to hydrocarbon exploration in the Tasmania Basin, and was first drilled in August 1997 for Great South Land Minerals. The initial drilling, by a 15 cm down-hole hammer, went to a depth of 336 m. In July 2002 drilling recommenced with diamond coring (HQ, 63 mm diameter to 974 m and NQ, 45 mm diameter to base) to a total depth of 1324 m, passing through Parmeener sediments into a Precambrian basement. The drill core is stored at Mineral Resources Tasmania, Mornington Store. The location of the drill site is indicated in figure 1.

STRATIGRAPHY (FIG. 2)

Upper marine sequence (Late Permian)

Undifferentiated upper marine sequence 0–134 m

This section of the hole was produced by hammer drill and the resultant chip material shows little about this monotonous sequence of predominantly mudstone. Because of the lack of stratigraphic detail in this section it is unknown how much of the sequence has been displaced by movement associated with dolerite intrusion.

Dolerite (Jurassic)

Dolerite was encountered from 134 to 784.4 m, totalling 650.4 m thickness, and represents multiple intrusive events, evidenced by internal contacts between differing grainsize textures. The dolerite is massive and fine- to medium-grained. Baking effects on underlying Parmeener sediments are readily visible in the core sample for about 20 m beneath the margin of the dolerite. Vitrinite reflectance values from samples 65–85 m beneath the dolerite do not indicate significantly elevated temperatures.

Upper marine sequence (Early Permian)

Cascades Group correlate 784.4–848.5 m

The lower dolerite margin contacts directly with fossiliferous siltstones of the Cascades Group. From 784.4 to 811.5 m, is a baked fossiliferous siltstone, visible baking effects decreasing downward into grey bioturbated fossiliferous siltstone. Brachiopods, bivalves and bryozoans are abundant, with common fenestellid-dominant horizons. Fossils are thin-shelled and less common from 798 m. Thin, bioturbated, clay horizons are present at 801 m and 811 m. From 811.5 to 838.8 m, are bioturbated siltstone and sandy siltstone with

FIG. 1 — Locality map and geology in the immediate vicinity of the Hunterston DDH. A–A' approximate position of seismic line TB01-PA. See figure 7 for cross-section A–A'.

fossils in the upper part, and granules and scattered pebbles throughout. From 838.8–848.5 m are bioturbated pyritic mudstone and siltstone, with bioturbated sandstone and a prominent pebble horizon at 842.5 m. The lowermost part of this sequence is black mudstone with wispy bioturbation and heavy pyritisation.

The effects of contact metamorphism associated with the dolerite have destroyed much of the skeletal detail of the bryozoans, but a Bernacchian age is indicated, for the richly fossiliferous siltstones at 797.5 m, by the presence of *Levifenestella expansa* (Faunizones 2–5 of Clarke & Banks 1975) and *Stenopora berriedalensis* (Faunizones 4–10). The presence of Bernacchian species is in agreement with the Cascades Group in the Tunbridge Tier DDH where a probable Bernacchian age is indicated for the lower 45 m of Cascades beds (Reid 2003).

Freshwater beds (Early Permian)

Liffey Group 848.5–870.1 m

The Liffey Group is divided into three units within the Hunterston DDH: an upper carbonaceous fine-grained sand, middle sandy siltstone and lower carbonaceous fine sandstone. The uppermost unit, from 848.5 to 853.6 m, is of carbonaceous, silt-laminated and cross-bedded, fine-grained micaceous sandstone that is bioturbated at its upper boundary with the overlying Cascades Group correlate. Thin carbonaceous siltstone bands occur in the lower part, with a prominent coarse-grained sandstone with plant fragments at 850.45 m. The middle unit, from 853.6 to 862 m, is of thinly-laminated, carbonaceous, sandy siltstone. Pyritisation and soft sediment deformation are common, with the latter intense at 855.5 m. The siltstone becomes gritty at 860 m and grades into the lower unit, from 862 to 870.1 m. The lower unit is of carbonaceous, laminated, micaceous, fine-grained sandstone, with minor, soft carbonaceous siltstone horizons. The grain-size increases downward with medium- to coarse-grained sandstone over the last two metres. The base of the Liffey Group is sharp and conglomeratic at 870.1 m.

Lower marine sequence (Early Permian)

Bundella Mudstone correlate 870.1–900 m

From 870.1 m is a bioturbated, silty, pebbly, sandstone, fining rapidly to dark grey-black foraminiferal siltstone. Black siltstone grades to a grey bioturbated siltstone, typical of Bundella Mudstone, by 876 m. The main body of the Bundella Mudstone correlate is of bioturbated grey siltstone which becomes increasingly pebbly downwards. Fossil horizons are rare, containing brachiopods and trepostome bryozoans.

Conglomeratic beds 900–980 m

The typical fossiliferous lower Bundella Mudstone facies and Woody Island Siltstone are absent from the core, and are replaced by conglomerates, conglomeratic siltstones and pebbly siltstone. From 900 to 908.5 m are poorly-sorted, silty conglomerates and pebbly siltstones. Clasts are generally rounded, up to 7 cm in diameter, mostly of dolomite, chert and limestone. From 908.5 to 949 m, pebbly siltstone predominates, with isolated bands of conglomerate and conglomeratic siltstone. The siltstone becomes better-sorted and darker from 924 to 944 m. Bands of silty conglomerate and conglomeratic siltstone are common from 944 to 949 m. From 949 m, to the base of the Parmeener sequence at 980 m, conglomerate and conglomeratic sandstone dominate. Clasts are mostly of dolomite, with some sandstone and metamorphic clasts

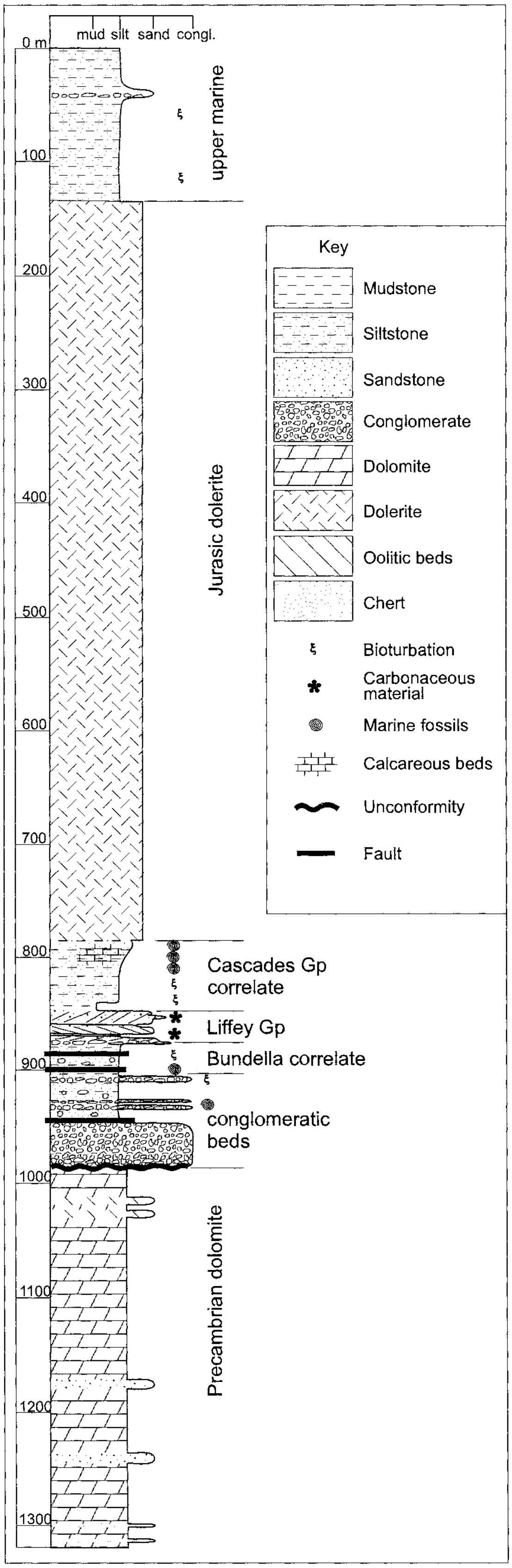


FIG. 2 — Schematic stratigraphic column of the Hunterston DDH.

occurring. Rounding is variably subangular to well-rounded, with isolated beds of well-sorted, well-rounded, conglomerate, within poorly-sorted subangular to rounded, conglomeratic sandstones. Poorly-sorted conglomeratic sandstones, with wispy carbonaceous silt bands, dominate the lowermost 18 m. The basal beds are dolomitic conglomerate with a sharp and steep erosional contact with a dolomite basement.

The lowermost conglomerates are poorly-sorted and may be termed diamictites. However, they are not the tillites typical to the Tasmania Basin. Their glacial origin cannot be proven and they are not correlated with the Wynyard Tillite.

Basement (Precambrian)

Precambrian Dolomite 980.5–1323.6 m

The sequence is dominated by grey to black fine-grained dolomite, the darker beds being finer grained. Minor green sandstone, and red and green chert beds occur, and the siltstone shows deformation throughout. Two small intervals at 1025 m and 1036 m have dark grey ooids approximately 5 mm across in a light grey matrix. Bedding planes vary from near horizontal to vertical and are rarely consistent for more than 500 mm. In most cases bedding is convoluted and in places shows slump structures. Stylolites were observed in a number of places outlined by graphitic material.

Much of the core is broken and crumbly but competent sections show complex calcite veining patterns. Many veins are broken and displaced by minor faulting. Two vein sets are observed, one fine and generally less than 1 mm thick, and the other 10–20 mm, both cross-cutting each other and the bedding. The larger calcite veins are more common below 1250 m.

The dolomite sequence is non-fossiliferous except for unidentified stromatolites at 1180 m, and apparent algal lamination at 1170 m. In a number of places core breakage may have occurred along algal laminated layers.

From 1041 m fine disseminated pyrite is present through the dolomite, and as crystalline coverings of fracture planes. Fine dissolution cavities are present, particularly in thicker calcite veins. Decomposed black clay occurs towards the bottom of the hole.

Textures become schistose from 1240 m, where a black sheen is visible on cleavage surfaces. Cleavage becomes crenulated and from 1320 m the core can be described as schist. The last two metres are partly decomposed with pyrite crystals up to 1 mm across.

The dolomite intersected at Hunterston can be lithologically correlated with the Black River Dolomite of northwestern Tasmania. The interbeds of green sandstone, small oolitic intervals and chert within the Hunterston core are similar to the Black River Dolomite (C.R. Calver, pers. comm.). The Black River Dolomite has been correlated with the Success Creek Group of western Tasmania (Brown 1989) and the Weld River Group of south-central Tasmania (Calver 1989). All these groups are recognised as Neoproterozoic (~750–650 Ma) (Calver 1998).

PALAEOGEOGRAPHY

The freshwater beds and upper marine sequence encountered in the Hunterston DDH are similar to these units elsewhere in Tasmania. However, the absence of Wynyard Tillite and the presence of conglomeratic facies, in place of the Woody Island Siltstone and part of the Bundella Mudstone, is of interest. To the east in the Tunbridge and Ross DDHs are thick sequences of tillite (Wynyard Tillite) overlain by pyritic pebbly mudstone and siltstone (Woody Island Siltstone). These areas are in closer proximity to Hunterston than the thick conglomeratic deposits observed in the Mackintosh area (Collins *et al.* 1981), or the thinner, but significant, conglomerates in the Du Cane area (MacLeod 1961). The absence of thick diamictites or identifiable tillite, and the presence of conglomeratic sequences at Hunterston in place of the Woody Island Siltstone, signifies a regional high, that may extend to the northwest, to link with that shown by Collins *et al.* (1981) (fig. 3). Whether the high is a series of peaks or a continuous southeast trending mountain range is unknown.

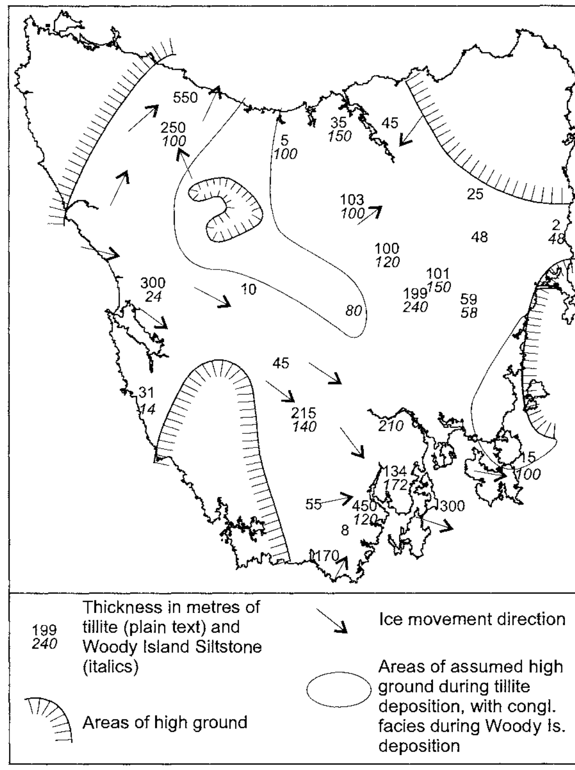


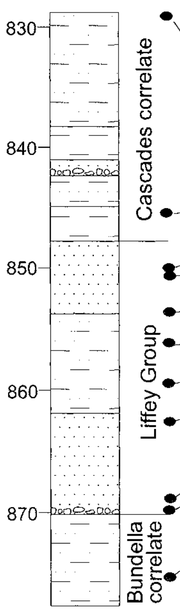
FIG. 3 — Palaeogeography of the Tasmania Basin, during deposition of the Wynyard Tillite (Carboniferous) and Woody Island Siltstone (late Carboniferous/early Permian. Updated from Clarke (1989), with additional ice movement indicators from Hand (1993). Extension of Mt Inglis area conglomerates into central area of basin based on drilling results of Hunterston DDH.

HYDROCARBON PROSPECTIVITY

Source rock

The absence of the Woody Island Siltstone removes this otherwise regionally extensive potential source rock from any hydrocarbon play within the immediate Hunterston area. The conglomeratic mudstones at this stratigraphic level, while often having a dark mud matrix, are not of source quality. Toward the base of the conglomeratic beds wispy carbonaceous mud lenses appear in the matrix, with moderate Total Organic Carbon (TOC) and Type I kerogens; however, these are too thin and discontinuous to contribute to a hypothetical hydrocarbon play. The Tasmanite Oil Shale, or abundant *Tasmanites,* found within the Woody Island Siltstone elsewhere in the Tasmania Basin, and of potential source quality, are also absent.

However, potential hydrocarbon source rocks are contained within the carbonaceous siltstones and sandstones of the Liffey Group. Discrete coal beds are not developed but mudstones with disseminated carbonaceous material, and plant fragments, show TOC levels up to 3.1% (fig. 4), comparable to non-coal beds in this unit elsewhere in the Tasmania Basin. Kerogen types are dominantly type III, as characterised by Hydrogen Index versus T_{max} plots.



	Reservoir		Reflectance			Rock Eval			Comments
	porosity %	perm. mD	inertinite	vitrinite	*vitrinite range*	TOC	T_{max}	S_1/S_2	
828.5			2.09	NA		1.25	492	0.6/.61	bioturbated carbonaceous siltstone
845.6						2.9	463	0.46/1.24	bioturb., carbonaceous pyritic siltstone
850.15						3.1	459	0.54/1.9	fine sand, with carb. silt lamination
850.5	0.9		2.10	1.28	0.90-1.55				sandstone, carb. lamination & oil inclusions
853.25	8.7	0.06							fine sand, with carb. silt lamination
856.5			2.10	1.06	0.94-1.26	2.35	464	0.38/1.84	carbonaceous siltstone, with oil inclusions
859.2						2.24	458	0.41/1.49	carbonaceous pyritic siltstone
862.9	4.1	0.04							fine sandstone, carbonaceous lamination
869.3	5.6	0.05							medium-coarse sandstone, oil inclusions
869.5			NA	1.23	1.11-1.31	2.2	464	0.55/1.51	coarse sandstone, woody frags, oil incl.
874.4			2.02	NA		1.26	447	0.36/1.01	carb., bioturb., siltstone, w. oil inclusions

FIG. 4 — Summary data for the Liffey Group and adjacent rocks. Data given for principal potential source and reservoir rocks.

Type III kerogens are gas prone, and their low atomic hydrogen to carbon ratio means they generate and expel less petroleum products than other kerogen types (Hunt 1996).

Samples from the Liffey Group and underlying and overlying marginal marine beds of the Bundella Mudstone and Cascades Group were analysed for vitrinite reflectance. Only the Liffey Group samples contained vitrinite in the dispersed organic matter (Cook 2003), all samples contained inertinite, and liptinite is absent. The basal contact of the dolerite sill complex is at 784.4 m, 44.1 m above the Cascades sample, 66.1 m, 72.1 m and 84.9 m above the Liffey Group samples and 90 m above the Bundella sample. The relative consistency in the reflectance of inertinite and vitrinite material (fig. 4) indicates that heating effects of contact metamorphism are negligible at these distances from the dolerite intrusion. The nature of the vitrinite also indicates that any alteration from contact metamorphism is mild, as carbonised organic matter is not present (Cook 2003).

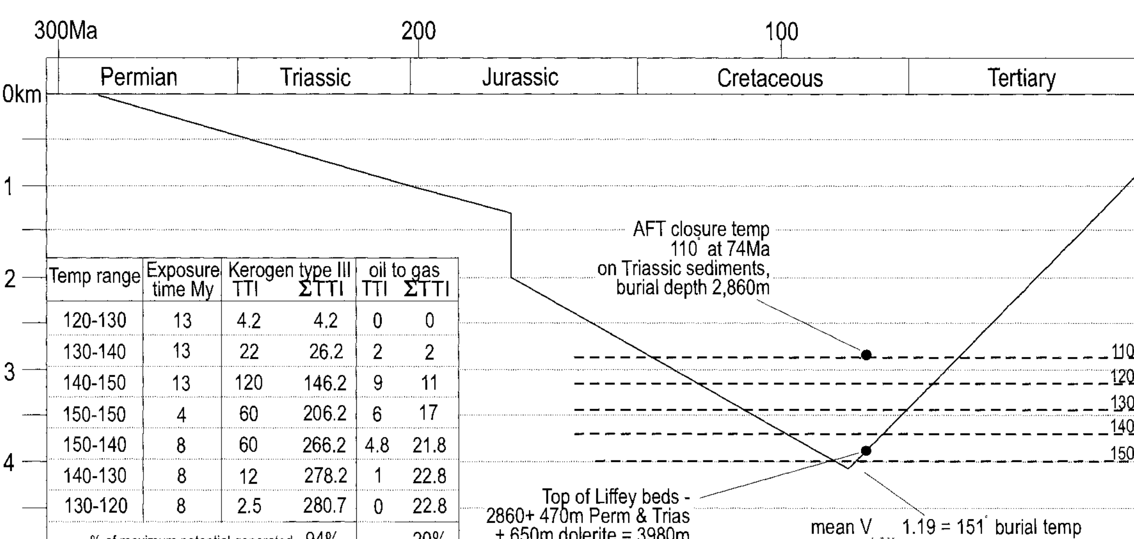
Calculated petroleum generation, using time-temperature index graphs (Hunt & Hennet 1992) based on the Arrhenius equation (TTI_{ARR}) (Wood 1988), is difficult to determine, as the total sedimentary overburden in the Hunterston region is not known. The thickness of Triassic sediments can be roughly assumed, but there is an unknown amount of upper Jurassic to Tertiary sediment. Burial profiles based on the known Permian to Jurassic overburden do not bury the Liffey Group to depths great enough for hydrocarbon generation. Yet the vitrinite reflectance values indicate maturity was achieved, with probably only a small increase from dolerite effects. The overburden required to account for vitrinite reflectance is consistent with cover rock erosion calculated from denudation rates given by Kohn *et al.* (2002). Given a mean vitrinite reflectance value of 1.19%, the corresponding burial temperature (from data in Barker & Pawlewicz 1994) would be approximately 151°C. Although there is debate over the thermal history of the Tasmania Basin (Leaman 2003) and the implication of apatite fission track data, maximum burial is here taken to have been reached in the mid-Cretaceous (O'Sullivan & Kohn 1997, Kohn *et al.* 2002). Constructing a theoretical burial curve to match a temperature maximum of 151°C, with mid-Cretaceous maximum burial, type III kerogens may have generated 94% of maximum potential hydrocarbon generation, and 20% petroleum may have cracked to gas (fig. 5). Type III kerogens generate only about 25.2% of carbon in their total TOC to oil and gas as the quantity of petroleum generated is determined by the hydrogen content of the kerogen (Hunt 1996). In this case the kerogen type reduces the overall potential productivity of the system, despite an otherwise favourable burial curve.

Reservoir rock

Traditional potential hydrocarbon reservoir rocks exist within the sandstones of the Liffey Group, as they do across much of the Tasmania Basin. However, in the Hunterston DDH, carbonate cementation is present in medium to coarse sandstone, and is later than both silica and clay, but may replace both (fig. 6). In many Liffey Group samples original quartz clasts have been eroded, and orthoclase feldspar has been pervasively replaced by calcite. In the Hunterston DDH carbonate cement is well-developed, and it is the late dissolution of carbonate that produces a secondary porosity. However, reduced connectivity of pore spaces has lowered permeability. Permeability in potential reservoir beds ranges between 0.04 and 0.06 mD.

It is postulated that dolerite intrusion has affected fluid chemistry, and the calcareous beds of the Cascades Group have contributed carbonate to the pore fluids, increasing pH, and resulting in carbonate precipitation in the more porous Liffey sandstones.

Some Liffey Group sandstones contain oil inclusions, within microfractures in both quartz and carbonate (Cook 2003). Oil inclusions form during crystallisation of



Temp range	Exposure time My	Kerogen type III TTI	ΣTTI	oil to gas TTI	ΣTTI
120-130	13	4.2	4.2	0	0
130-140	13	22	26.2	2	2
140-150	13	120	146.2	9	11
150-150	4	60	206.2	6	17
150-140	8	60	266.2	4.8	21.8
140-130	8	12	278.2	1	22.8
130-120	8	2.5	280.7	0	22.8
% of maximum potential generated			94%		20%

FIG. 5 — Theoretical burial profile and calculated hydrocarbon generation for Liffey Group beds, based on Time Temperature Index (TTI_{ARR}). Constraints on the burial profile are the known thickness of Permian sediments and Jurassic dolerite, and assumed thickness of Triassic sediments. Maximum burial depth plotted according to mean vitrinite reflectance maximum (Barker & Pawlewicz 1994) and assumed geothermal gradient of 35°/km. Time of maximum burial based on AFT closure temperature of 110°C in Triassic sediments (O'Sullivan & Kohn 1997).

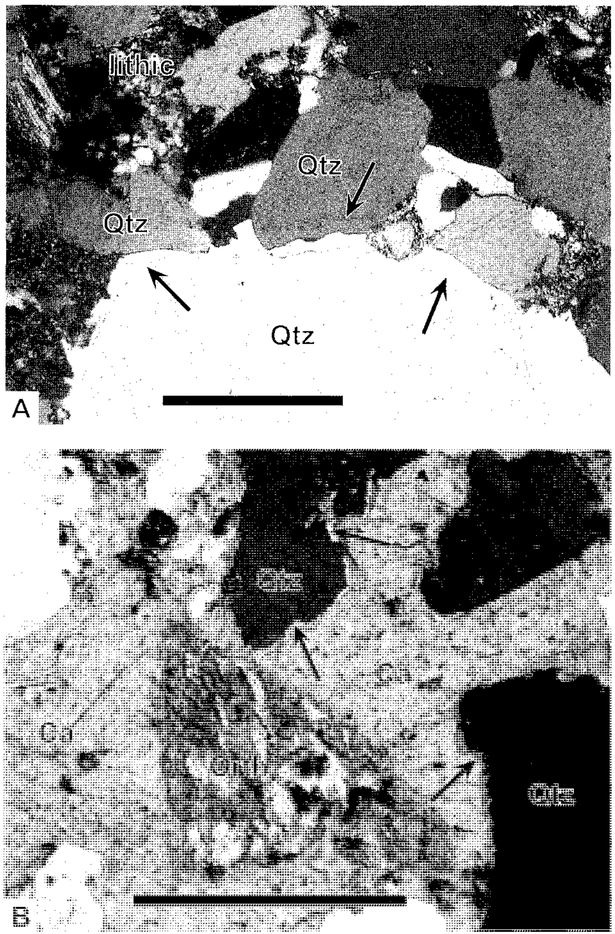


FIG. 6 — Diagenetic features of Liffey Group sandstone in the Hunterston DDH, all scale bars 0.5 mm. (A) 869.3 m polarised light view showing quartz overgrowths, with grain boundaries indicated by arrows. (B) 850.5 m polarised light view showing perthitic dissolution of orthoclase feldspar and dissolution of quartz cement and grains, and replacement with calcite cement indicated by arrows. Qtz = quartz, Ca = calcite, Orth = orthoclase feldspar, lithic = lithic clast.

diagenetic minerals, and through brittle deformation and fracturing of detrital and diagenetic grains during burial (George *et al.* 1996). The presence of oil inclusions in carbonate cement indicates hydrocarbon movement either during or after mid-Jurassic, probably after if maximum burial of source rocks was achieved in the Cretaceous.

Down-hole Fault Zones

There is potential for localised reservoirs within brecciated fault zones in the lower marine sequence. Several of these brecciated zones occur around 900 m depth, each with an associated 'halo' of carbonate dissolution, and replacement by silica, ranging from 0.5 to 10 m in thickness. The dissolution of carbonate material is assumed to be by fluids introduced along fault structures. The degree of brecciation is severe, and the high porosity and permeability led to loss of drilling pressure, indicating such horizons would be highly suitable reservoirs, providing there is a suitable seal on the fault away from the zone of dissolution.

Near the base of the Lower Parmeener Supergroup in the Hunterston DDH at 957 m, strong carbonate dissolution and siliceous replacement of a conglomerate, over 3 m, has not been brecciated and mean porosity is 16.9% while mean permeability is 6323 mD.

Structure

Figure 1 shows the local strike and dip of beds that form a dome-like structure. The drillhole was placed at the estimated central position of this structure. The Hunterston Dome is reflected at the surface in Permian and Triassic sediments, and was assumed to continue as a subsurface feature. The seismic data show the subsurface dip of the Parmeener beds as regionally flat lying. The seismic data also show the continuity of the eastern outcropping dolerite with the intrusion encountered between 134 and 784 m in the hole. On a regional scale it appears there is only one major dolerite body across the central Highlands, as partly shown in figure 7. The deformation of Triassic sandstones and the upper marine beds of the Parmeener Supergroup, producing the Hunterston Dome, either preceded or was coincident with dolerite intrusion. Dips adjacent to the dolerite contact east of the DDH site steepen towards the boundary, and may indicate bed drag effects.

Within the basement Precambrian dolomite complex, minor faulting and intersecting veining patterns noted in the core indicate a complex tectonic history and a number of episodes of movement. Bedding directions, where visible, repeatedly vary between near horizontal to vertical indicating that the drilled section passed through multiple folds. The extremely contorted bedding near the bottom of the hole may indicate proximity to a thrust plane. The presence of black clay, evidence of partial dissolution, in this region may be due to fluids introduced along a permeable thrust plane.

Permo-Carboniferous glacial erosion and retreat has produced conglomeratic beds of rounded pebbles of Precambrian dolomite, supported in a silty matrix, immediately on top of the massive Precambrian dolomite. A series of thrusts can be traced in the Fossey Mountains region of northern Tasmania (Woodward *et al.* 1993) and the existence of stacked thrusts in the area drilled has been interpreted from geophysical data (Leaman *et al.* 1973, Leaman 1989, 2001). In the Hunterston area the geology of associated thrust blocks is unknown.

CONCLUSIONS

The Parmeener Supergroup stratigraphy in the Hunterston DDH includes undifferentiated upper marine sequence, possibly part Ferntree Mudstone, the Cascades Group, freshwater Liffey Group and Bundella Mudstone as expected. A thick, 650 m, multiple dolerite intrusion is present between the upper undifferentiated marine sequence and the Cascades Group. The presence of basal conglomerates in place of Woody Island Siltstone, and Wynyard Tillite, proved the extension of Mackintosh–Du Cane regional high to the northwest through this central part of the Tasmania Basin. Basement to the Parmeener Supergroup is Precambrian dolomite, with its closest lithological correlate near Smithton in far northwest Tasmania.

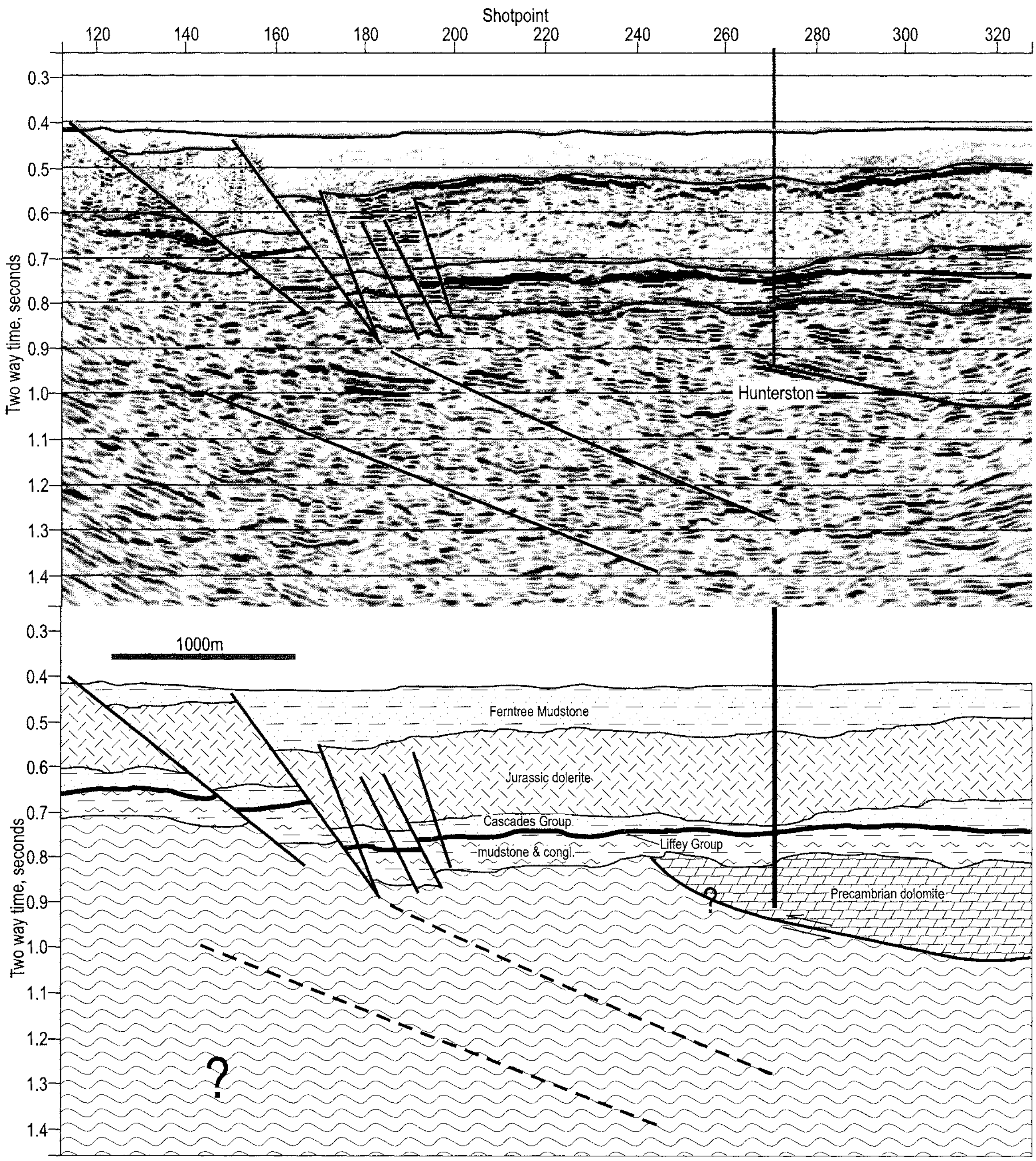


FIG. 7 — Seismic profile line TB01-PA (shown in fig. 1 as A–A'). Geological interpretation based on seismic data and drillhole correlation.

The absence of the Woody Island Siltstone, a potential hydrocarbon source rock, and dispersed or concentrated *Tasmanites* commonly contained within it, reduces the previously assumed distribution of this unit. Potential hydrocarbon source rocks exist within the freshwater Liffey Group, and a calculated burial curve and time temperature index indicates the potential for hydrocarbons to have been generated. Oil inclusions within sandstones of the Liffey Group indicate that hydrocarbons have migrated through the section, either from the reservoir unit itself, or from adjacent source areas. The timing of possible oil migration is not well defined, but is mid-Jurassic or younger. Carbonate precipitation has reduced reservoir quality within the Liffey Group.

Despite a thick dolerite intrusion, direct heating effects are confined to the immediate (lower) boundary. As little as 44 m from the 650 m multiple dolerite intrusion vitrinite reflectance values are apparently unaffected.

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