Halladale-1 DW3
Well Completion Report
Interpretive Data

Photo: Damian White

VIC/P37(v)
Offshore Otway Basin
Victoria

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origin

Halladale-1 DW3 Document Information

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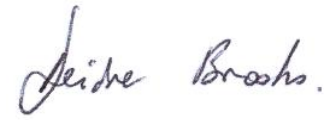
Deidre Brooks	Geoscience Leader Southern Australia	19/12/07	
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1. WELL INDEX SHEET

Well Name:	Halladale-1 DW3
Basin:	Offshore Otway
Permit:	VIC/P37(v)
Type:	Deviated Appraisal Well
Operator:	Origin
Water Depth:	44.8m (LAT)
Rotary Table:	21.5m
Latitude:	38° 34' 45.54"S (GDA 94)
Longitude:	142° 43' 50.95"E
Easting:	650 763.2 metres (MGA Grid Zone 54)
Northing:	5 728 485.2 metres

Rig Name:	Ocean Patriot
Rig on Location:	17:30 hrs 21/03/2005
DW3 sidetrack operations commenced:	15:00 hrs 21/04/2005
Reached TD:	15:00 hrs 24/04/2005
Total Depth:	1969m MDRT (Driller)
DW3 Abandoned:	
Rig Released:	05:30 hrs 02/05/2005
Total Time on Location	44.5 days (Halladale-1 DW1, 2 & 3 combined)
Seismic Reference:	Antares 3D MSS Inline 1938 Crossline 1115
Well Cost:	A$ 23,329,727 (Halladale-1 DW1, 2 & 3 combined)
Well Status:	Plugged & Abandoned

FORMATION TOPS

FORMATION	TOPS (m)			REMARKS/SHOWS
	mMDRT	mTVDSS	THICKNESS (mTVD)	
Port Campbell Limestone				
Gellibrand Marl				
Clifton Fm				
Narrawaturk Marl				
Mepunga Fm				
Dilwyn Fm				
Pember Mudstone				
Pebble Point Fm				
Massacre Shale				
Paaratte Fm			175.1	Kicked-off at 1197 mMD; interbedded sandstone and silty claystone with lesser argillaceous siltstone and claystone
Skull Creek Mudstone	1383.4	1342.6	144.4	Silty claystone with minor interbedded sandstone
Nullawarre Fm	1541.7	1487.0	4.5	Sandstone
FAULT	1546.9	1491.5		
Belfast Fm	1546.9	1491.5	205.9	Silty claystone
Flaxman Fm	1784.4	1697.4	74.7	Silty claystone with interbedded sandy claystone and sandstone toward base
Waarre Fm Unit C	1869.7	1772.1	31.9	Sandstone with lesser interbedded silty claystone
Waarre Fm Unit B	1906.2	1804.0	26.3	Silty claystone with minor interbedded sandstone
Waarre Fm Unit A	1935.9	1830.3	29.6	Interbedded silty claystone and sandstone
TOTAL DEPTH	1969.0	1859.9		

FORMATION EVALUATION WHILE DRILLING

Hole Size (mm)	Interval (mMD)	Logs Acquired
216	1197.0 – 1969.0	DGR-EWRP4-PWD-SLD-CTN-BATSonic-DM-ABI

WIRELINE LOGS

Suite #	Run #	Interval (mMD)	Logs Acquired
1	1	1094.2 – 1871.7	RCI-GR

CORE- CONVENTIONAL

Core #	Interval (mMD)	Cut (m)	Recovered (m)	Formation
None taken				

CORE – SIDEWALL

Suite#	Run#	Type	Interval (mMD)	Bullets	Mud	Empty	Low Rec	Recovered
None Taken								

PRESSURE TESTING AND FLUID SAMPLING

Suite#	Run#	Type	Interval (mMD)	Total Tests	Valid Tests	Supercharged	Tight Tests	Retests	Lost Seal	Samples Collected
1	1	RCI	1871.7 - 1904.2	10	10	0	0	0	0	0

HOLE & CASING DETAILS

Hole Size (inch)	Interval (mMD)	Casing Size (inch)	Shoe Setting Depth (mMD)
8 ½	1197.0 – 1969.0 (TD)		

2. WELL SUMMARY

Halladale-1 DW3 was the third well in a three well programme targeting two adjacent fault-dependent closures with AVO anomalies at the Late Cretaceous Waarre and Nullawarre levels in offshore exploration permit VIC/P37(v) at the eastern end of the Otway Basin (see Figure 1). The three wells were drilled in succession using the Ocean Bounty semi-submersible drilling rig in 44.8 m of water approximately 4 km from shore. The wells were drilled using the same top-hole section and then directionally steered toward their respective targets, with the first well, Halladale-1 DW1 (Location Black Watch), targeting the southern prospect (Black Watch), and the second and third wells, Halladale-1 DW2 and Halladale-1 DW3, targeting the northern prospect (Halladale).

Halladale-1 DW3 was as a side-track appraisal well off the Halladale-1 DW2 borehole designed to obtain a water gradient from the Waarre C in order to determine the gas-water contacts for the Waarre C at Black Watch and Halladale. Side-track operations commenced 21st April 2005 with the well reaching TD (1969 mMD / 1859.9 mTVDSS) on the 24th April 2005. The well was kicked off at a depth of 1197.0 mMD in Paaratte Formation and then directionally steered along an azimuth of approximately 055° and inclination of 28° toward the Waarre C target, bottoming in Waarre A approximately 337 m north-northwest of the top hole location, 302 m east-southeast of the Halladale-1 DW2 bottom hole location, and 651 m north-northeast of the Halladale-1 DW1 bottom hole location.

The top of the Waarre C in Halladale-1 DW3 came in 8.9 mTVD high to prognosis at a depth of 1772.1 mSS, with the top of the Waarre B coming in exactly on prognosis at 1804.0 mSS and the top of the Waarre A 4.7 m high to prognosis at a depth of 1830.3 mSS. No shows were observed in the well except for a small gas kick at the top of the Waarre C (1.8% TG) over the interval 1874.0 - 1878.8 mMD (1775.9 – 1779.0 mSS). After the well reached TD, formation pressure measurements were taken from the Waarre C and the well was then plugged and abandoned.

Petrophysical analysis of logs from Halladale-1 DW3 indicates the Waarre C and Waarre A in the well are both water wet. The Waarre C is 36.5 mMD thick with a net sand thickness of 30.3 mMD (82.3% N:G) and average effective porosity of 25.9%. Water pressure data from the Waarre C indicates the aquifer pressure is approximately 4 psi less than the Waarre A aquifer in Halladale-1 DW1 and DW2, indicating the two aquifers are not in pressure communication with each other with the intervening Waarre B probably acting as an intraformational seal.

3. INTRODUCTION

3.1 Exploration History

VIC/P37(v) is a shallow-water "three-mile zone" permit located in Victorian state territorial waters at the eastern end of the Otway Basin between the coastal townships of Port Fairy and Peterborough (see Figure 1). The permit was awarded to the VIC/P37(v) JV on 17 April 2003 and covers an area of about 493 km^2. It is approximately 78 km in length and extends seaward three nautical miles out from the high water mark. Water depth across the block ranges from zero to 60 m (see Figure 2).

The exploration history of VIC/P37(v) is remarkably sparse in comparison to the activity that has taken place over the last forty years in adjacent permits to the north and south. Prior to 2003, no wells had been drilled in VIC/P37(v) and only 427 line kms of 2D seismic had been acquired (see Table 1), 80% of which had been recorded between 1963 and 1966.

Table 1. 2D seismic previously acquired within VIC/P37(v)

Survey	Operator	Year	# Lines inside VIC/P37(v)	Line KM
OH94	BHP PETROLEUM	1994	10	41.1
OH91	BHP PETROLEUM	1991	17	26.7
OE81A	ESSO	1981	1	0.1
OE80A	ESSO	1980	1	3.0
H04	HEMATITIE	1974	2	9.7
OS66A	SHELL	1966	14	131.3
OS66C	SHELL	1966	18	59.3
OFBH63D	FROME BROKEN HILL	1963	14	155.6
TOTAL			**77**	**426.8**

The Black Watch and Halladale fields are located near the eastern end of VIC/P37(v) approximately 13 km west of the coastal township of Peterborough midway between the offshore Martha gas field and the onshore Croft gas field (see Figure 2). The closest offshore well is Martha-1 drilled by SANTOS in 2004. The closest onshore well is Flaxmans-1 drilled by Frome Broken Hill in 1961.

3.2 Tectonic History of the Otway Basin

The Otway Basin is a NW-SE striking passive margin rift basin approximately 500 km long that extends from Cape Jaffa in South Australia to the northwest tip of Tasmania. It is one of a series of basins that formed along the southern margin of mainland Australia during the Late Jurassic - Cenozoic as Australia began to separate from Antarctica. The sedimentary section in the basin is up to 10,000 m thick and ranges from Late Jurassic to Recent in age

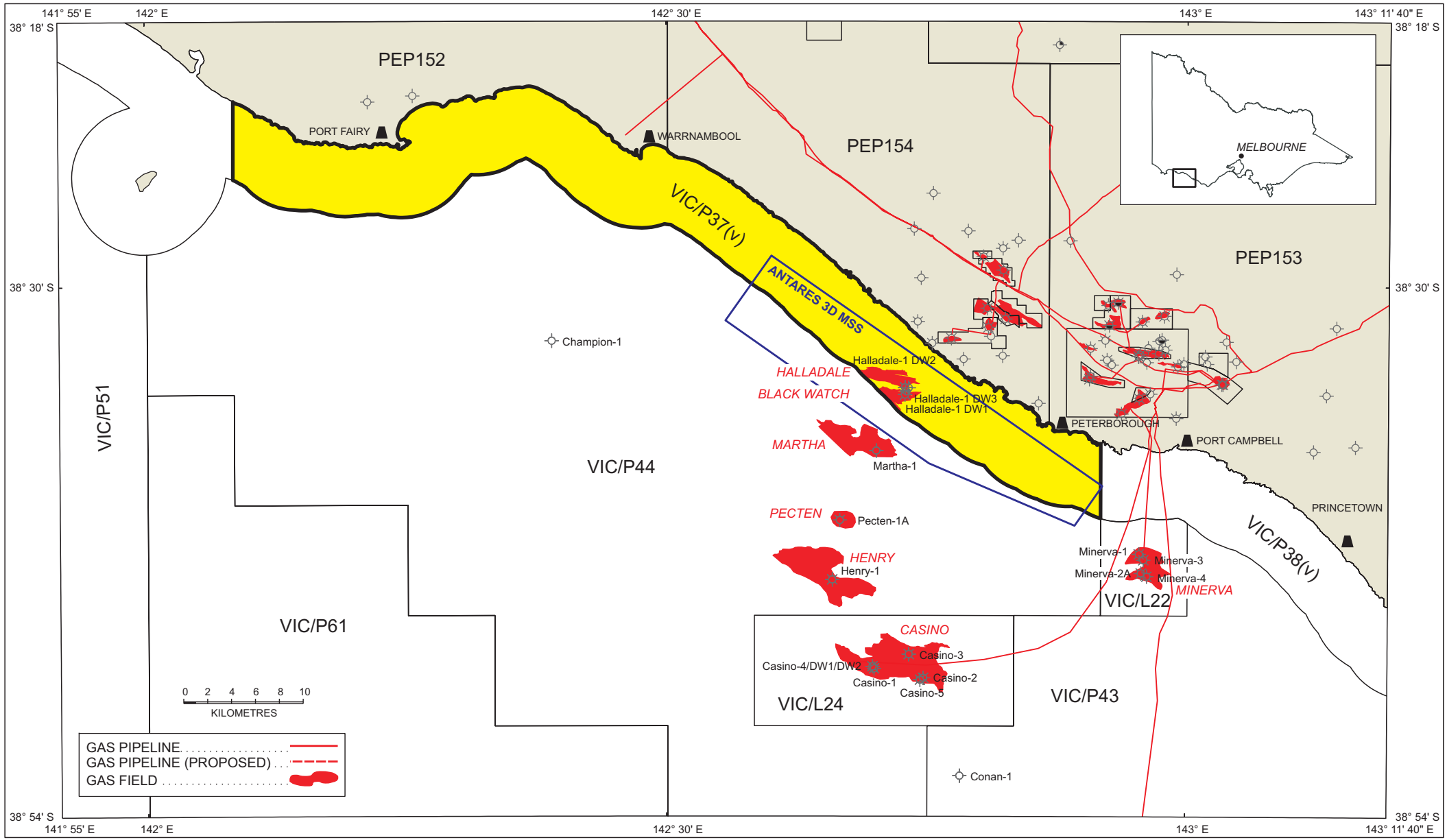

Figure 1. Permit location map.

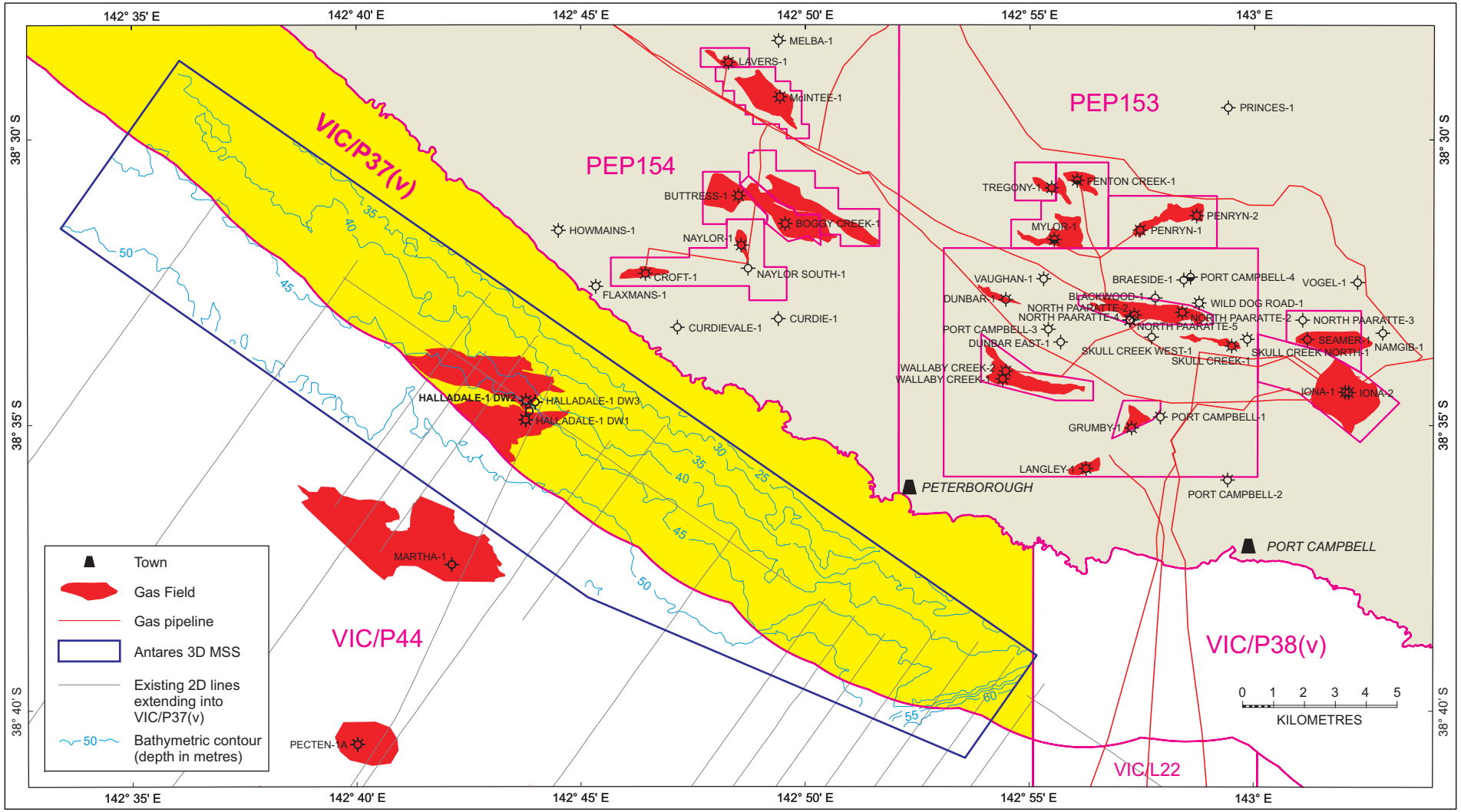

Figure 2. Antares 3D MSS bathymetry.

and covers an area of approximately 155,000 km^2, approximately 80% of which is located offshore.

The Otway Basin has a complex tectonstratigraphic history involving two periods of NE-SW extension punctuated by several episodes of compression, uplift and erosion, thermal subsidence, and inversion. The first period of rifting resulted in the formation of a series of small NW-SE and E-W striking half-grabens onshore that were filled with up to 5000 m of non-marine sediments and volcanics known as the Crayfish Group. This event was then followed by a period of tectonic quiescence and thermal subsidence that spanned the Aptian – Albian during which up to 3000 m of fluvial – lacustrine sediments known as the Eumeralla Formation were deposited.

During the Cenomanian, the basin experienced a short period of NW-SE compression, uplift and erosion, resulting in the development of a major regional unconformity known as the Cenomanian Unconformity. At the end of the Cenomanian, the basin began to undergo extension again, with the locus of extension shifting offshore. This extension continued all the way through the rest of the Late Cretaceous resulting in the deposition of up to 5000 m of fluvial to offshore marine clastic sediments known as the Sherbrook Group in the Voluta Trough.

Toward the end of the Maastrichtian, mainland Australia began to separate from Antarctica and the two continents started to drift slowly apart, with Tasmania still attached to both. This event in the basin is marked by a prominent unconformity at the top of the Sherbrook Group known as the Base Tertiary Unconformity. This slow period of spreading lasted until the middle Eocene during which up to 300 m of deltaic to shallow marine clastic sediments known as the Wangerrip Group were deposited on the shelf.

The end of the middle Eocene saw a significant increase in the spreading rate in the Southern Ocean when Antarctica finally separated from mainland Australia and Tasmania. This event caused the Otway margin to subside, resulting in a marine transgression and the deposition of up to 100 m of Middle Eocene to Early Oligocene nearshore to offshore marine clastic and carbonate sediments known as the Nirranda Group. This event was then followed by the deposition of up to 1600 m of marl and limestone belonging to the Late Oligocene – Late Miocene Heytesbury Group as the shelf edge began to prograde back out into the basin.

At the end of the Late Miocene, the Otway Basin experienced another period of NW-SE directed compression causing significant folding, uplift and erosion of the sedimentary fill, mostly at the eastern end of the basin, resulting in the development of a series of broad low-relief NE-SW striking anticlines and synclines across the eastern Otway Basin.

3.3 Geological Setting

The key structural elements in the eastern Otway Basin are the Shipwreck Trough and Port Campbell Embayment (see Figure 3). Over the past thirty years, twenty-four gas fields have been discovered in these two areas, five of them offshore in the Shipwreck Trough and nineteen onshore in the Port Campbell Embayment, with the bulk of the gas found occurring in the non-marine to marginal-marine Waarre Formation at the base of the Late Cretaceous Sherbrook Group.

The Shipwreck Trough is a N-S striking zone of Late Cretaceous transtension, wrenching and down-warping approximately 25 km wide and 100 km long bounded to the west and east by two broad Late Cretaceous highs called the Mussel and Prawn platforms respectively. The trough is believed to have formed in response to sinistral shear on a pre-existing basement weakness when the basin was undergoing NE-SW extension during the breakup of mainland Australia and Antarctica. The western edge of the trough is delineated by the western limit of Unit C of the Waarre Formation ("Waarre C") and its eastern edge by the Sorell Fault Zone.

The Port Campbell Embayment, the onshore extension of the Shipwreck Trough, is a broad semi-circular shaped Late Cretaceous depression up to 50 km wide that extends up to 20 km inland from the coast. Its western, northern and eastern limits are defined by the subcrop extent of the Waarre C.

VIC/P37(v) is located at the northern end of the Shipwreck Trough directly opposite the Port Campbell Embayment. Approximately two-thirds of the permit lies on the Mussel Platform with the eastern third extending about halfway across the Shipwreck Trough. The Black Watch and Halladale fields are located near the eastern end of the permit on the nose of a prominent NE-SW striking Late Cretaceous anticline called Pecten High.

3.4 Local Stratigraphy

The stratigraphy of the Port Campbell Embayment and northern Shipwreck Trough is illustrated in Figure 4. The late Early Cretaceous – Tertiary sequence in the area is divided into five groups comprising over twenty formations. For a detailed description of the lithology, thickness, distribution and depositional environments of these formations see Tickell et al (1992), GSV (1995) and Partridge (2001).

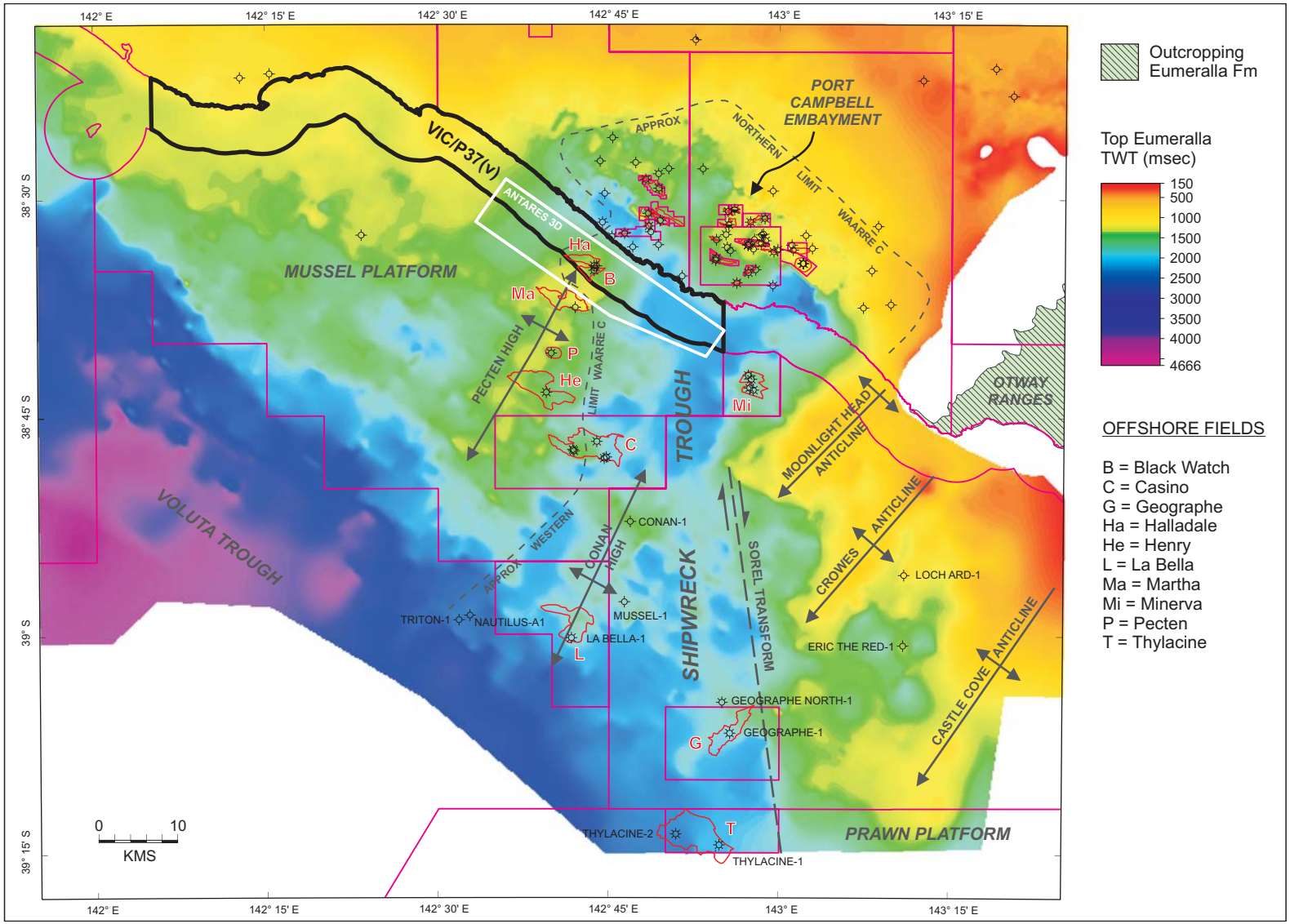

Figure 3. Late Cretaceous structural elements of the Eastern Otway Basin.

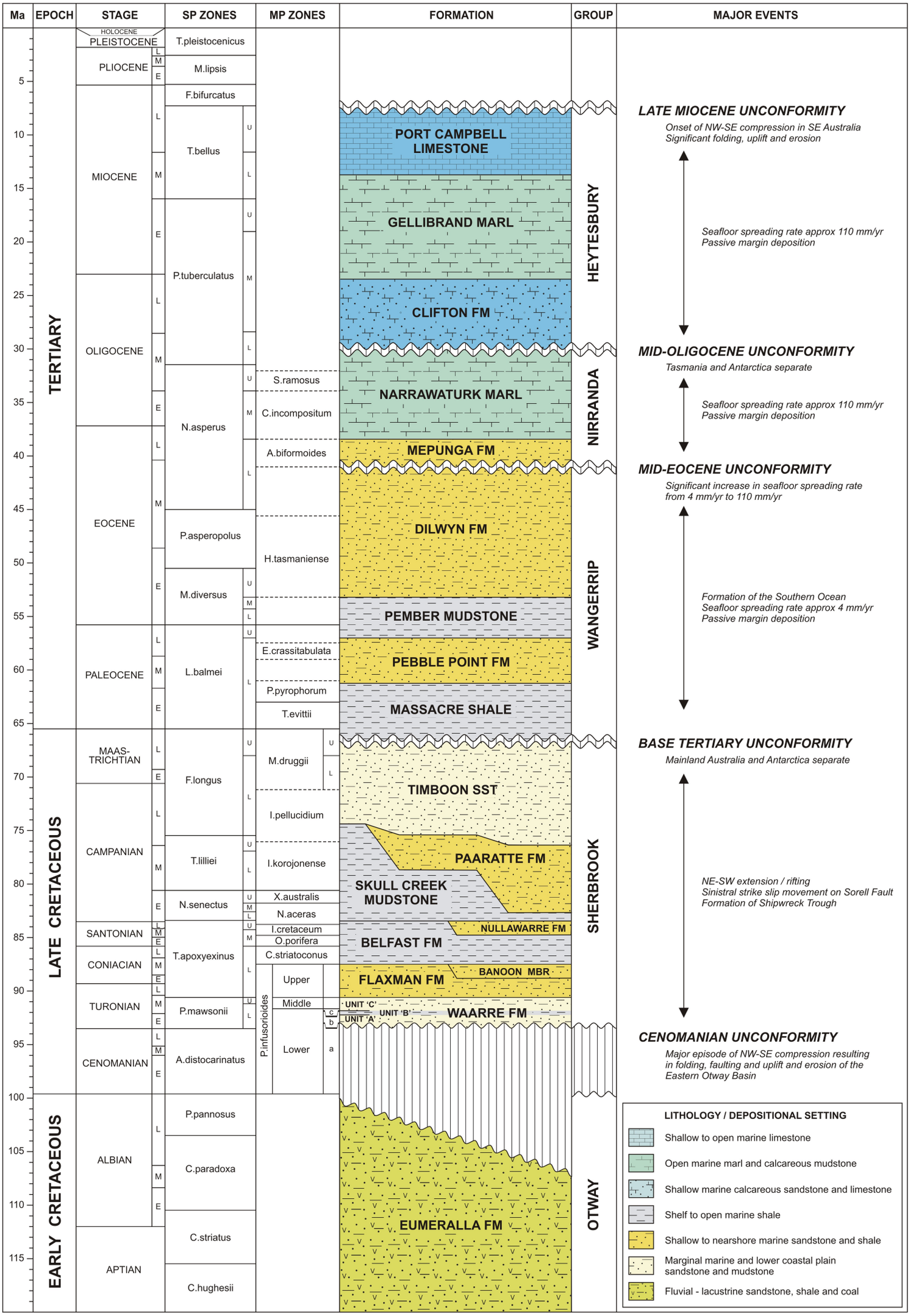

Figure 4. Generalised stratigraphy of the Port Campbell Embayment - Northern Shipreck Trough.

The Sherbrook Group, which contains the primary and secondary objectives, is divided into seven lithostratigraphic units called, from base to top, the Waarre Formation, FlaxmanFormation, Belfast Formation, Nullawarre Formation, Skull Creek Mudstone, Paaratte Formation and Timboon Sandstone.

In the Port Campbell Embayment, the Waarre Formation, the primary objective at Black Watch and Halladale, is divided into three units called (in ascending stratigraphic order) A, B and C. Unit A is sequence of interbedded estuarine to marginal marine shale and sandstone up to 43 m thick with a highly variable net to gross and moderate porosity and permeability. It is overlain by a very nearshore to offshore marine argillaceous shale up to 37 m thick (Unit B) which is in turn overlain by a fluvial to tidally-influenced marginal-marine medium- to coarse-grained quartz-rich sandstone up to 41 m thick with a high net to gross and excellent porosity and permeability (Unit C). The bulk of the gas discovered onshore occurs within Unit C, with Unit A at Boggy Creek, Wallaby Creek and Skull Creek also containing small volumes of gas. The sealing units for the Waarre C onshore are the Flaxman Formation (top seal) and Belfast Formation (cross-fault seal).

The Nullawarre Formation, the secondary objective in Halladale-1 DW1, is a shallow marine glauconitic sandstone. The formation is up to 100 m thick in the northern part of the Port Campbell Embayment and thins toward the south, pinching out just south of the present day coastline.

4. SEISMIC EVALUATION

4.1 Seismic Data Acquisition

The Antares 3D MSS was acquired by PGS on behalf of the VIC/P37(v) JV between 25 October and 11 November 2003. It was recorded over the eastern half of VIC/P37(v), with some ingress into adjacent permits VIC/P44, VIC/P38(v) and VIC/L22 to the south and east. The survey totalled 211 km^2 in area, with 134 km^2 of full-fold data acquired within VIC/P37(v).

4.2 Seismic Markers

Figure 5 is an Inline from the Antares 3D across the Black Watch and Halladale fields showing key seismic markers. Sixteen horizons were mapped in total from the Narrawaturk Marl down to the Eumeralla Formation, with strong amplitudes observed at the Upper Nullawarre, Lower Nullawarre, Waarre C and Waarre A levels.

The four parallel high amplitude seismic reflections at approximately 1.75 seconds in Figure 5 were interpreted to represent the tops of the Waarre C, Waarre B, Waarre A and Eumeralla Formation based on character ties into key onshore wells (ie. Croft-1, Naylor-1, Naylor South-1, Wallaby Creek-1, Grumby-1 and Langley-1) as it was not possible to get a direct seismic tie into the onshore 2D / 3D seismic due to the data gap along the coastal zone. An attempt was made to tie these events at Black Watch and Halladale directly into Minerva-1, Minerva-2A, Casino-1, Casino-2 and Pecten-1A offshore, but this proved difficult due to the distances between the wells and the high degree of faulting.

The four parallel high amplitude seismic reflections approximately 200 milliseconds above the Top Waarre C seismic event were interpreted to represent the top and base of two sandstone beds based on the seismic character of the Nullawarre Formation onshore in the vicinity of Curdie-1, 8.5 km to the ENE of Halladale-1 DW1, where the formation is represented by two sands, each approximately 14 m thick, separated by a 26 m thick shale. Again, an attempt was made to tie these events at Black Watch and Halladale directly into Minerva-1, Minerva-2A, Casino-1, Casino-2 and Pecten-1A offshore, but this too proved difficult.

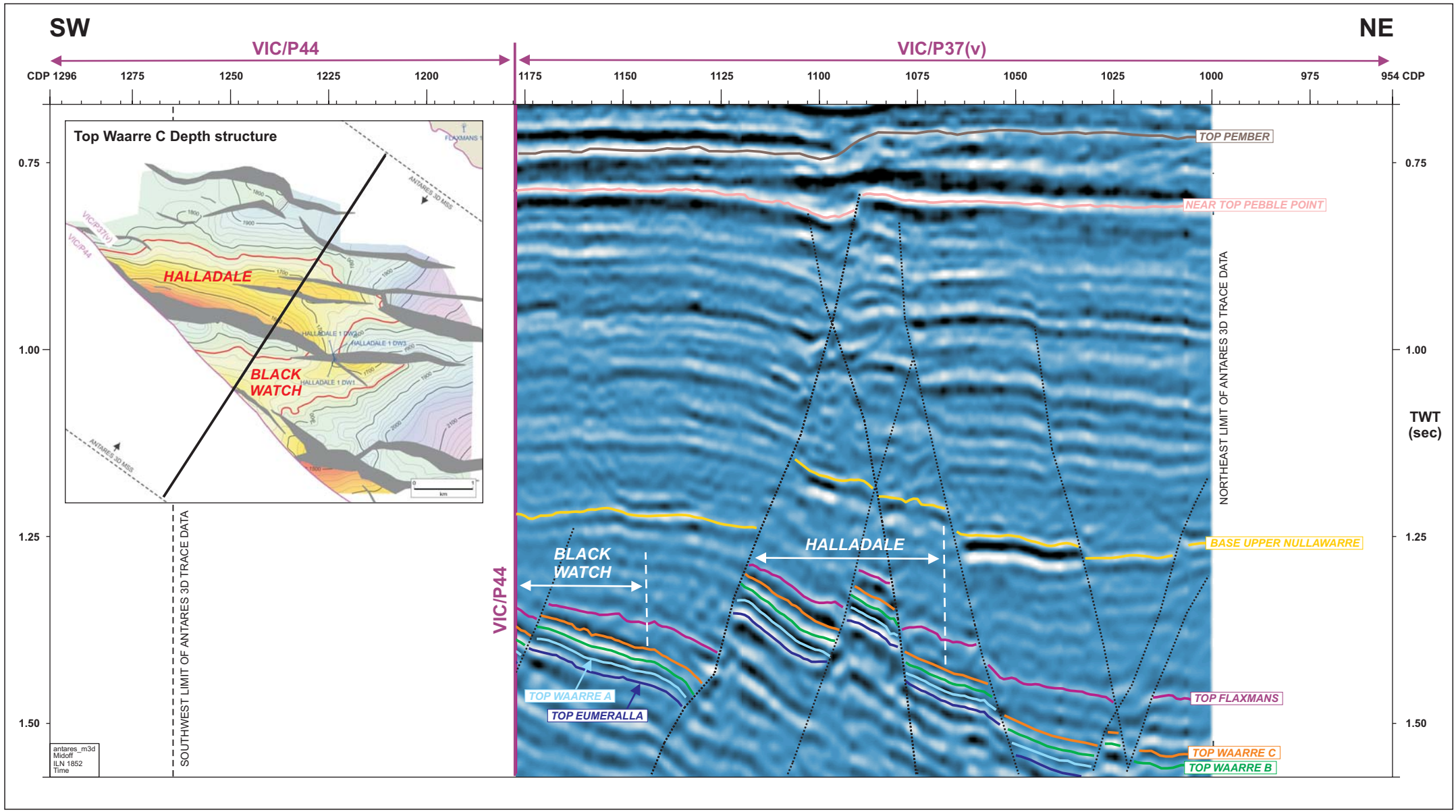

Figure 5. Antares 3D Inline 1852 across Black Watch and Halladale showing key seismic markers.

4.3 Depth Conversion

The seismic markers were converted to depth using a composite regional time-depth function based on check shot data and seismic times from nearby onshore wells. The upper part of the function down to approximately 1400 mSS was derived by fitting a best-fit line of regression through check shot data from Curdie-1, Grumby-1, Wallaby Creek-1, Langley-1, Port Campbell-2, Howmains-1 and Flaxmans-1, while the deeper part of the function was derived by passing a line of best fit through a cross-plot of well depths and seismic times for the tops of the Waarre C, Waarre B, Waarre A and Eumeralla in Boggy Creek-1, Croft-1, Dunbar-1, Dunbar East-1, Grumby-1, Naylor-1, Naylor South-1, Vaughan-1, Wallaby Creek-1, Wallaby Creek-2 and Langley-1.

4.4 Actual vs Predicted Depths

The pre- and post-drill stratigraphy of Halladale-1 DW3 is illustrated in Figure 6. Three tops came in high to prognosis by between 4.7 and 8.9 m, and three low to prognosis by between 1.6 and 28.5 m (see Table 2). The tops of the Waarre C and Waarre A both came in high to prognosis by 8.9 and 4.7 mTVD respectively, while the top of the Waarre B came in exactly on prognosis. The top of the Nullawarre Formation came in 1.6 m high to prognosis. The base of the Nullawarre Formation was faulted out.

Table 2. Halladale-1 DW3 actual vs predicted formation tops

FORMATION	PREDICTED DEPTH (mTVDSS)	ACTUAL DEPTH (mTVDSS)	Δ (m)	HIGH/LOW
Port Campbell Limestone				
Gellibrand Marl				
Clifton Formation				
Narrawaturk Marl				
Mepunga Formation				
Dilwyn Formation				
Pember Mudstone				
Pebble Point Formation				
Massacre Shale				
Paaratte Formation				
Skull Creek Mudstone	1341.0	1342.6	1.6	LOW
Nullawarre Formation	not prognosed	1487.0		
FAULT	1463.0	1491.5	28.5	LOW
Belfast Formation	1463.0	1491.5	28.5	LOW
Flaxman Formation	1712.0	1697.4	14.6	HIGH
Waarre C	1781.0	1772.1	8.9	HIGH
Waarre B	1804.0	1804.0	0	
Waarre A	1835.0	1830.3	4.7	HIGH

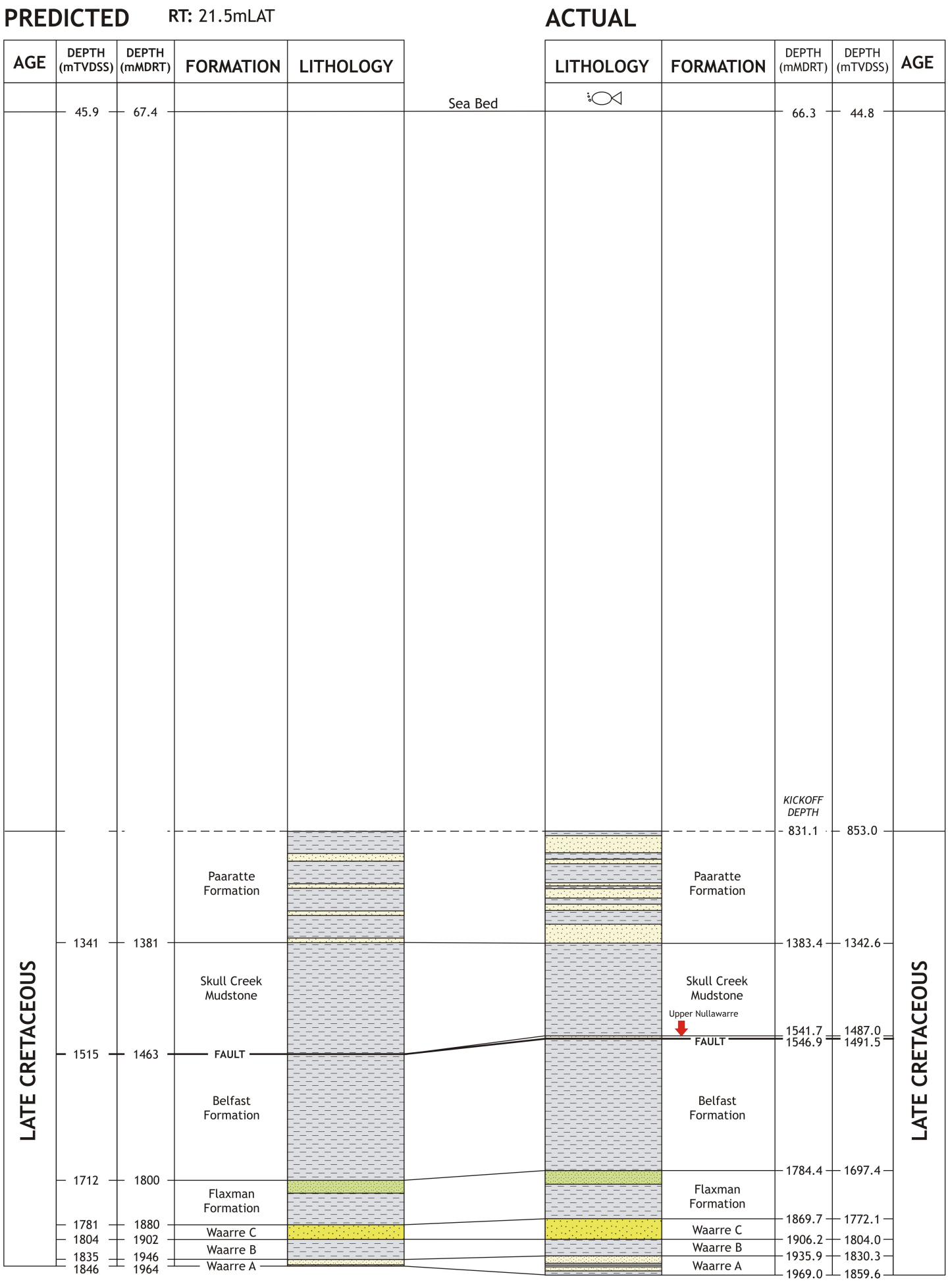

Figure 6. Halladale-1 DW3 predicted vs actual stratigraphy.

4.5 Well Tie

Figure 7 is a synthetic seismogram for Halladale-1 DW3 from the Skull Creek Formation down to the Eumeralla Formation generated using a wavelet extracted from the Antares 3D. A VSP was not recorded in Halladale-1 DW3 due to the proximity of the well to Halladale-1 DW1.

4.6 Structure

The structure of Black Watch and Halladale at the Top Waarre C and Top Waarre A levels inside VIC/P37(v) is illustrated in Figures 8 and 9 respectively. The interpreted GWCs for the two units, as determined from formation pressure data (see Section 8.1), are alsoshown along with the well paths for Halladale-1 DW1, DW2 and DW3. The Top Waarre C depth map is based on the post-drill corrected time interpretation converted to depth using the pre-drill time-depth function and then depth-shifted to tie with the top of the Waarre C in Halladale-1 DW1, DW2 and DW3. The Top Waarre A depth map is based on the pre-drill time interpretation.

The Black Watch Field at the Top Waarre C level is an ENE-WSW striking fault-dependent closure with up to 170 m of vertical relief relative to the interpreted GWC (1770 mSS). The closure straddles the VIC/P37(v) / VIC/P44 permit boundary and consists of two opposing tilted fault blocks that dip toward each other connected by a saddle located approximately 35 m above the GWC about 1 km east of the VIC/P37(v) / VIC/P44 permit boundary. The VIC/P37(v) portion of Black Watch is 2.3 sq km in area and widens to the west from approximately 500 m at the eastern end of the field to 2 km along the VIC/P37(v) / VIC/P44 permit boundary. The southern side of the field is down-faulted against Eumeralla Formation by an E-W striking normal fault with approximately 160 m of throw, while the northern side of the field at its eastern end is delineated by an ENE-WSW striking normal fault with up to 100 m of throw to the north.

The Halladale Field at the Top Waarre C level is a WNW-ESE striking fault-dependent three-way dip closure bounded to the south-southwest by a down-to-south normal fault. The closure, as defined by the interpreted GWC (1760 mSS), is approximately 5 km long and 1 km wide with a vertical relief of 240 m and area of 4 sq km. Pressure data indicates the gas column in the Waarre C at Halladale is not in pressure communication with gas column in the Waarre C at Black Watch (see Section 8.1) even though the two pools appear to be in fault contact where the tips of the two opposing normal faults bounding the north side of Black Watch and the south side of Halladale crossover.

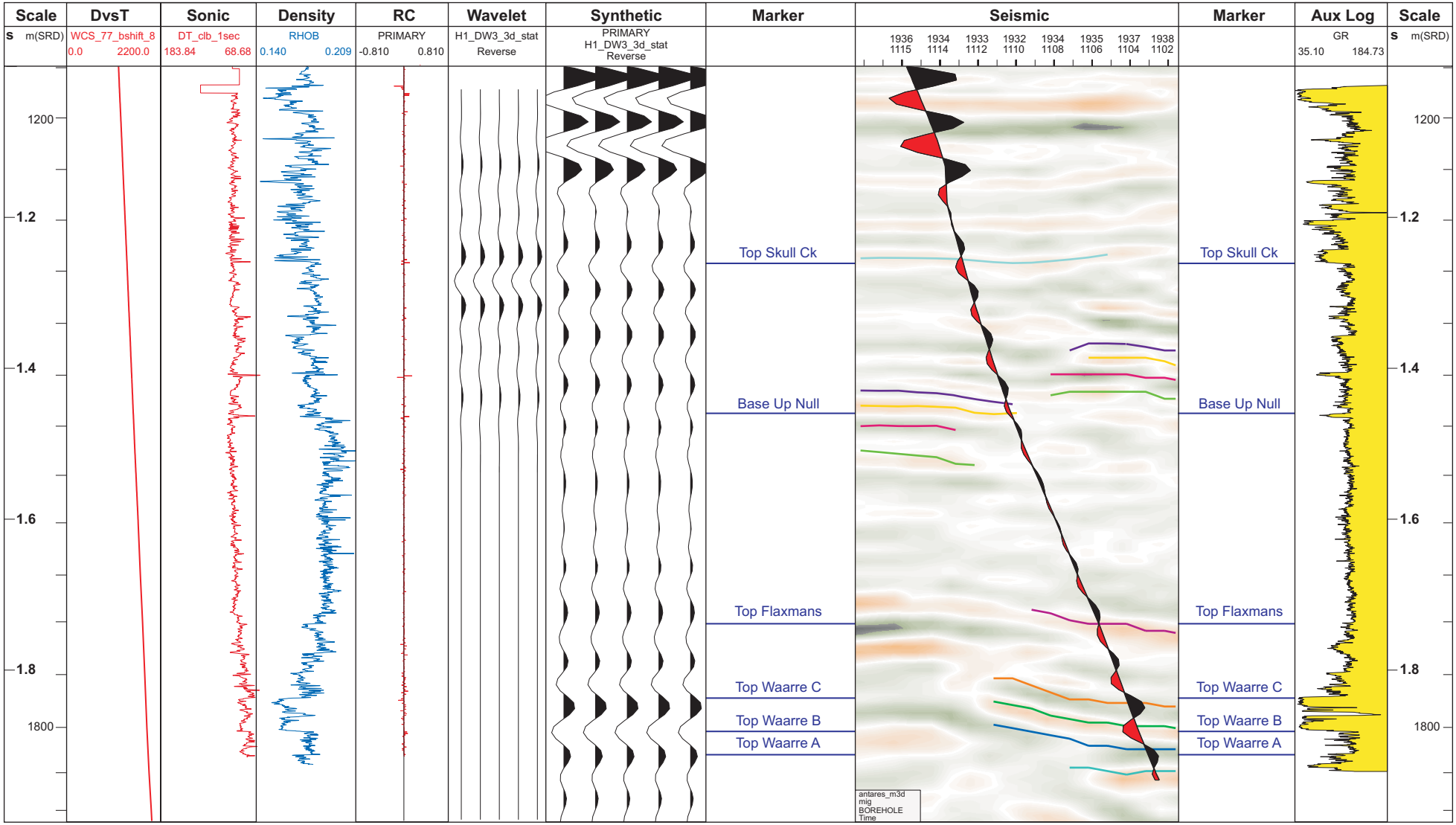

Figure 7. Halladale-1 DW3 synthetic seismogram (black wiggle trace) tied to seismic using VSP checkshot data from Halladale-1 DW1.

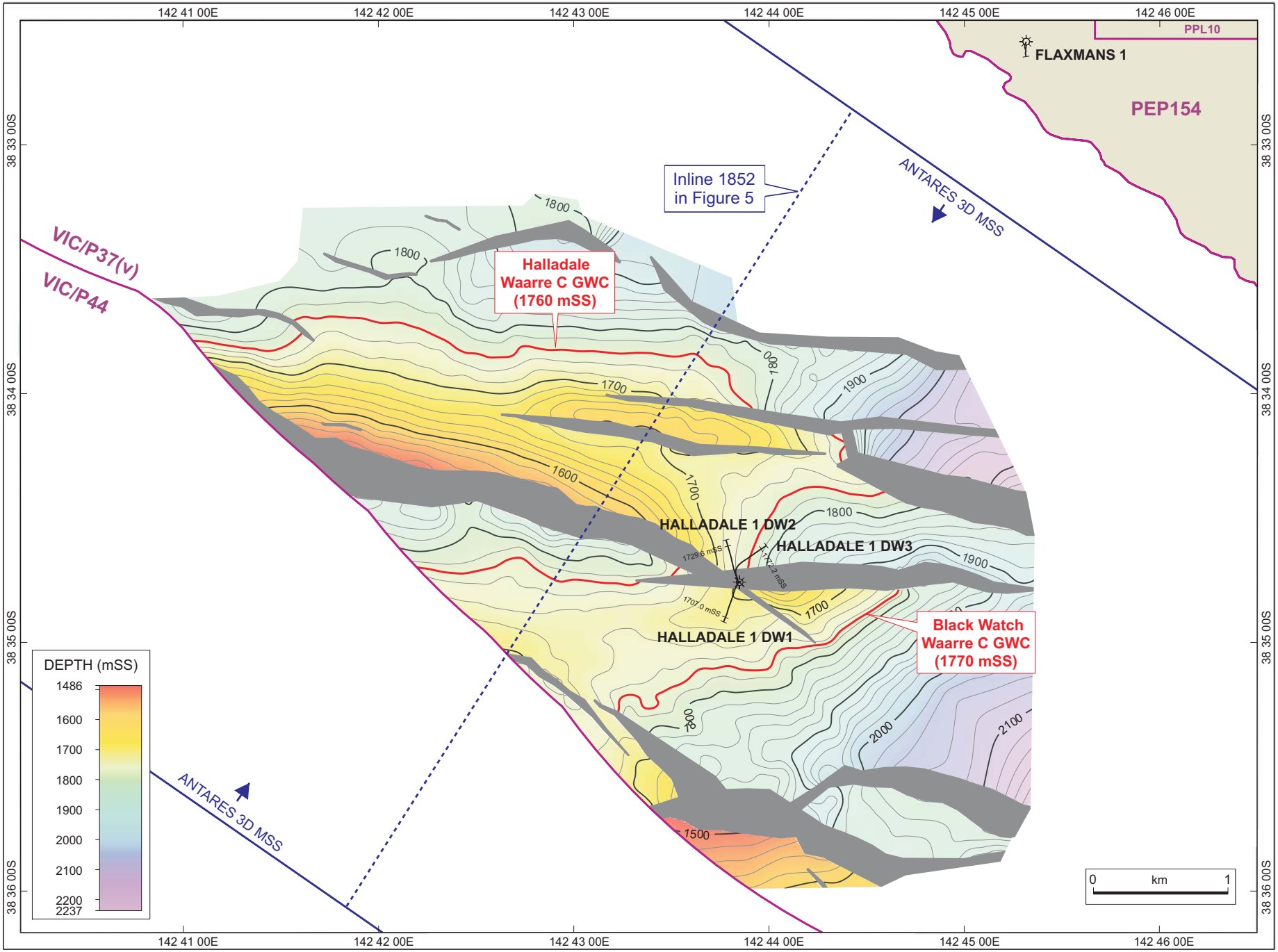

Figure 8. Top Waarre C depth structure map. Black Watch Waarre C GWC (1770 mSS) and Halladale Waarre C GWC (1760 mSS) shown in red.

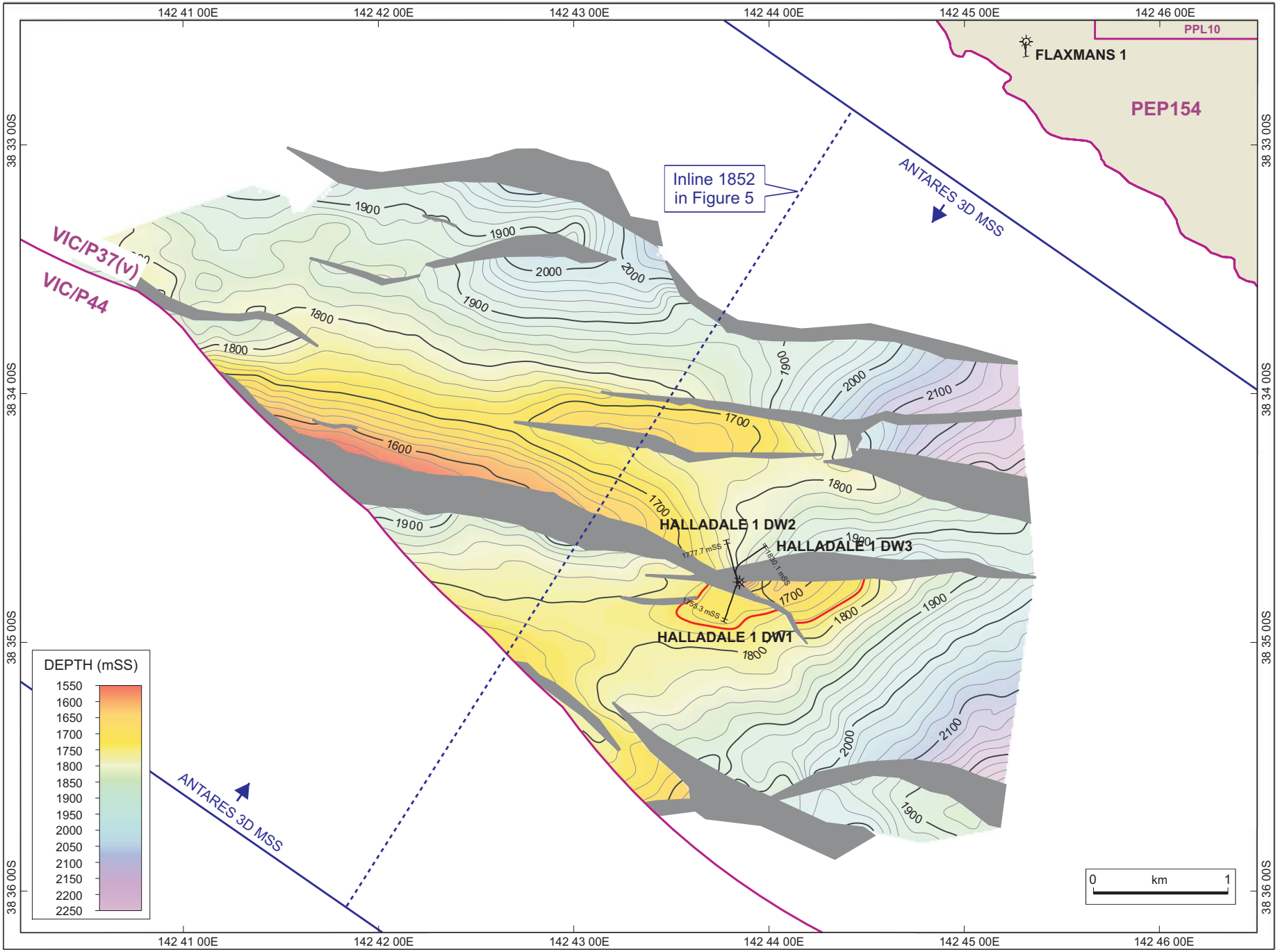

Figure 9. Top Waarre A depth structure map with Black Watch GWC (1766 mSS) shown in red.

The structure of Black Watch and Halladale at the Top Waarre A level inside VIC/P37(v) is almost identical in form to that of the Top Waarre C. The gas pool intersected in Halladale-1 DW1 at the top of the Waarre A is restricted to the small tilted fault block at the eastern end of Black Watch. The closure defined by the GWC (1766 mSS), as determined from pressure and log data, is very small (< 1 sq km) and has a vertical relief of about 90 m. The Waarre A in the adjacent Halladale fault block to the north was water wet in both in Halladale-1 DW2 and Halladale-1 DW3.

The structure of the Nullawarre Formation upstairs of Black Watch and Halladale at the Top Upper Nullawarre and Top Lower Nullawarre levels is illustrated in Figures 10 and 11 respectively. The two depth structure maps are based on the pre-drill time interpretation converted to depth using the pre-drill time-depth function and then depth-shifted to tie with the tops of the Upper Nullawarre and Lower Nullawarre in Halladale-1 DW1, DW2 and DW3. The interpreted GWCs for the two sands, 1481 mSS (Upper Nullawarre) and 1515 mSS (Lower Nullawarre), which are based on pressure data (see Section 8.1), are also shown in Figures 10 and 11 along with the well paths for Halladale-1 DW1, DW2 and DW3 and the outline of the Black Watch and Halladale fields at the Top Waarre C level (Figure 10 only). The two Nullawarre closures have an area of approximately 7 sq km and consist of small broad ENE-WSW striking faulted anticline approximately 3.2 km long and 1.2 km wide with 50 m of relief downthrown to the north against a prominent WNW-ESE striking horst-like feature approximately 4 km long, 1 km wide and 130 m in relief.

Figure 12 is a seismic traverse along the Halladale-1 DW1 and DW3 well paths. The top hole section is located in the middle of a small downthrown keystone block where the tips of the two opposing normal faults bounding the north side of Black Watch and the south side of Halladale crossover. Halladale-1 DW3 was designed as a sidetrack appraisal well off the Halladale-1 DW2 bore hole with a kick off point in the middle of the Paaratte Formation. The aim of the well was to obtain a water gradient from the Waarre C in order to calculate the GWCs for Black Watch and Halladale. The well was designed to intersect the top of the Waarre C approximately 250 m east of, and 52 m down-dip of, Halladale-1 DW2 approximately 2 mTVD below the seismic amplitude shutoff thought to represent the GWC (see Figure 13). The underlying Waarre A in Halladale-1 DW3 was not an objective based on the results of Halladale-1 DW2. The Nullawarre Formation in Halladale-1 DW3 was also expected to be faulted out.

After Halladale-1 DW3 had been successfully kicked-off, the well was directionally steered toward the east-northeast (056^{o}) at an inclination of 29^{o}, bottoming in Waarre A approximately 335 m NNE of the top hole location and 300 m east of the Halladale-1 DW2 bottom hole location. As expected, the Waarre C in the well was water wet but came in 8.9 mTVD (39%) thicker than the predrill prediction (23 mTVD). The well also tagged the top of

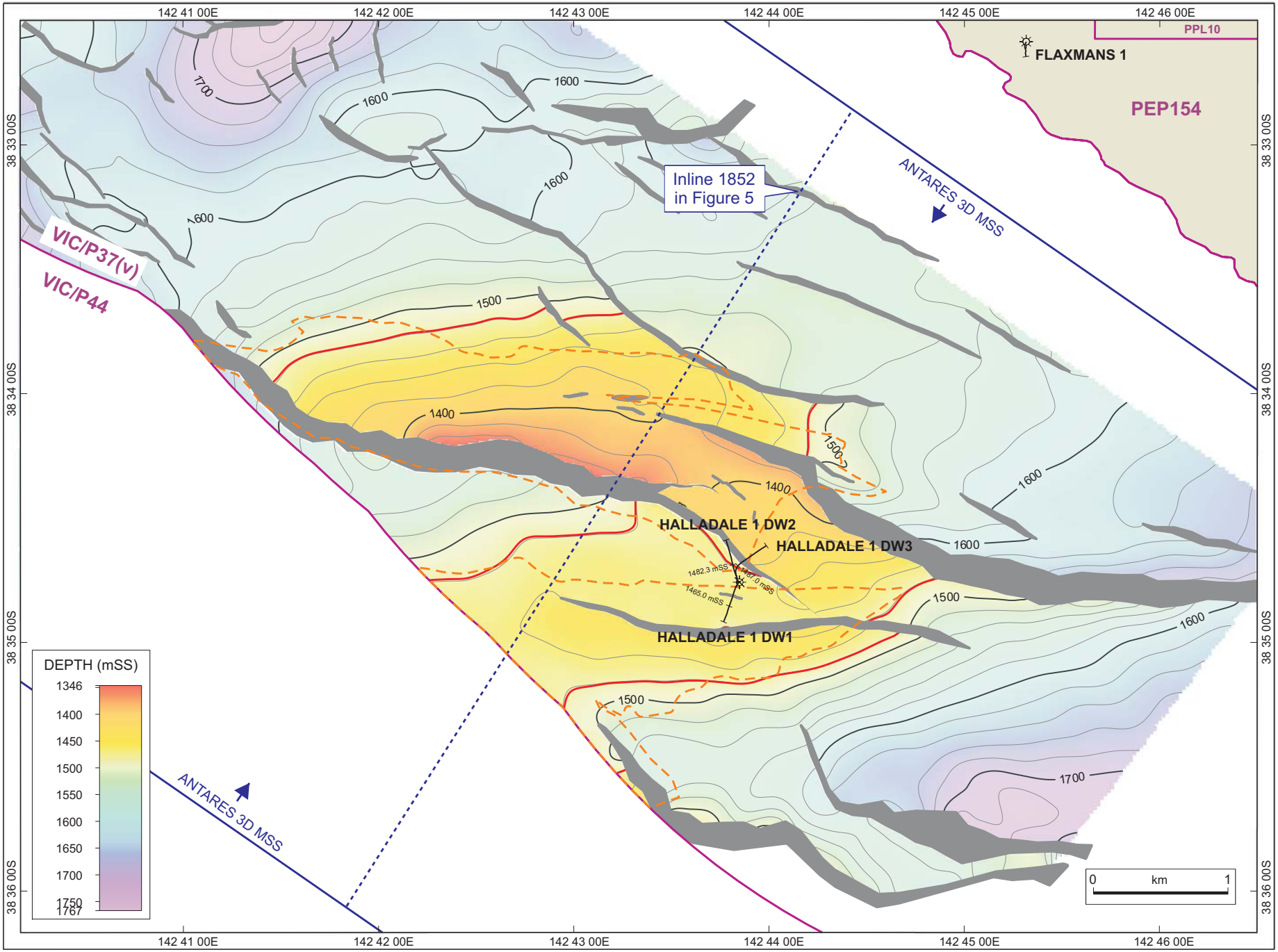

Figure 10. Top Upper Nullawaarre depth structure map with GWC (1481 mSS) shown in red. Outline of Black Watch and Halladale fields at Top Waarre C level shown in orange (dash).

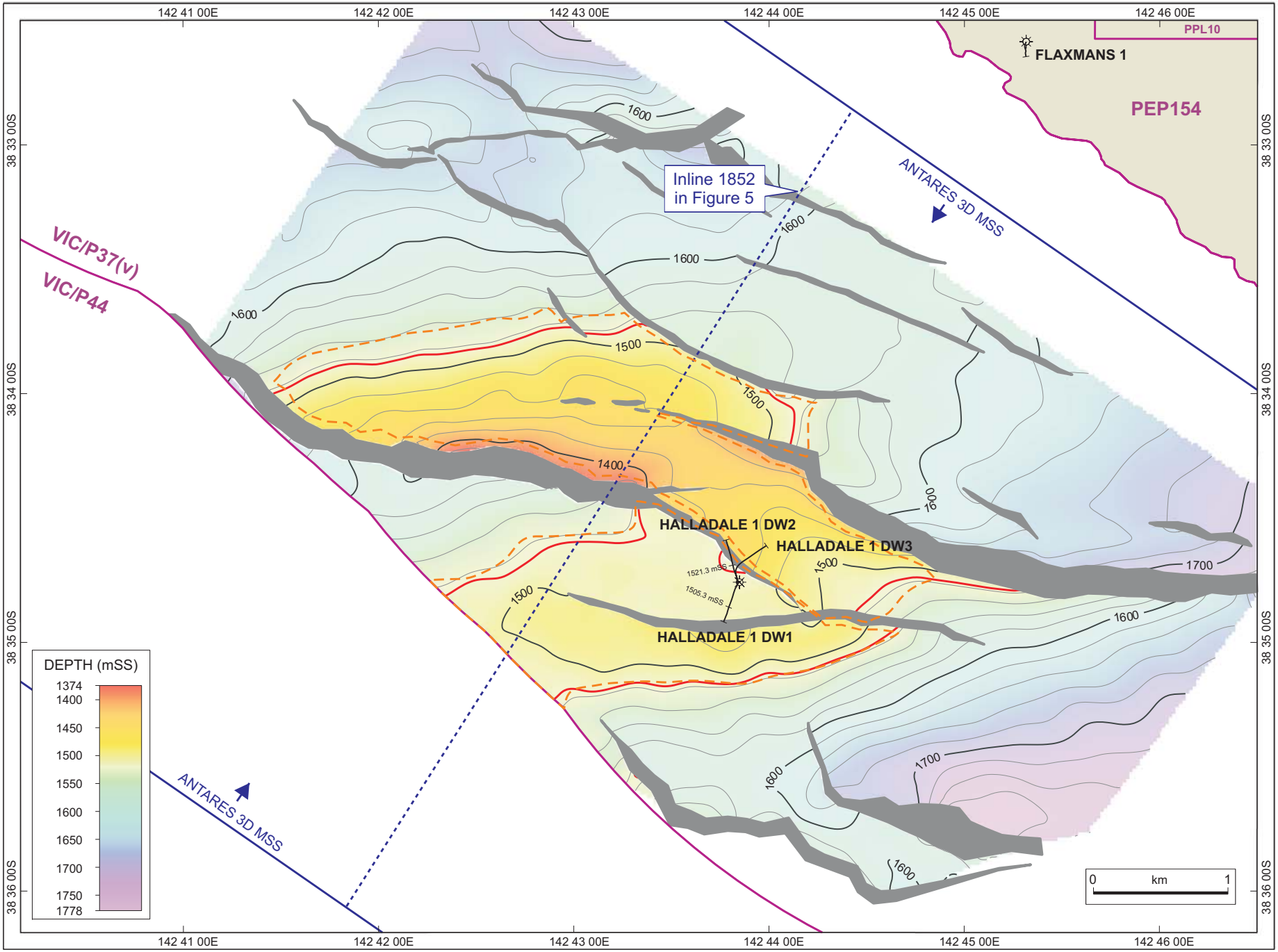

Figure 11. Top Lower Nullawaarre depth structure map. Lower Nullawarre GWC (1515 mSS) shown in red. Upper Nullawarre closure is shown in orange (dash). Note: Lower Nullawarre was not intersected in Halladale-1 DW3.

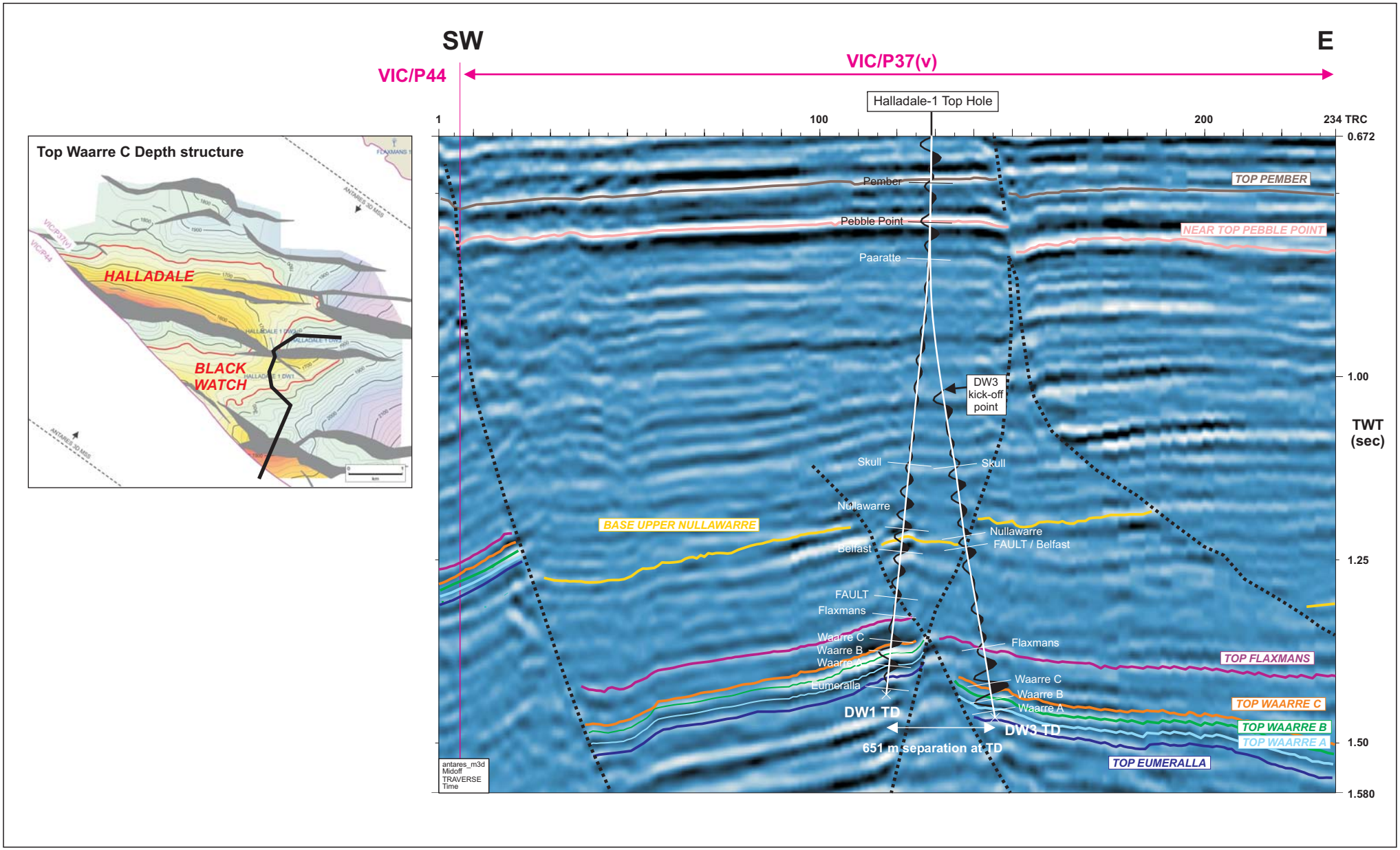

Figure 12. Seismic traverse along Halladale-1 DW1 and Halladale-1 DW3 well paths.

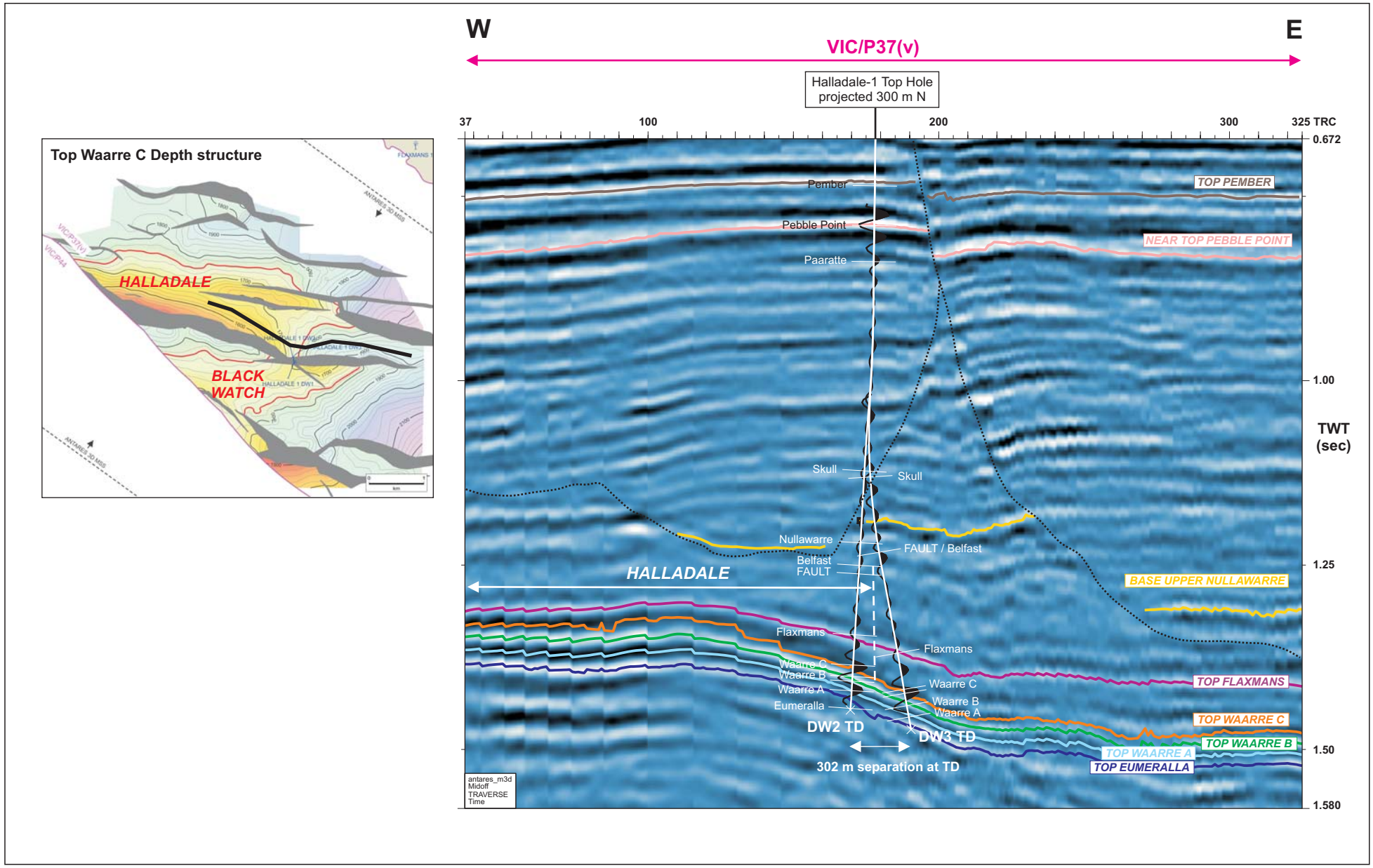

Figure 13. Seismic traverse down eastern flank of Halladale. Note: the well to seismic tie at the Nullawarre level is not accurate because the well paths for Halladale-1 DW1 and Halladale-1 DW3 are projected on to line of section at TD.

the Upper Nullawarre just before intersecting the fault bounding the south side of Halladale. Unsurprisingly, it too was also water wet, coming in approximately 5 m deeper than the top of the Upper Nullawarre in Halladale-1 DW2 approximately 80 m to the WNW.

5. WELL STRATIGRAPHY

The stratigraphic section intersected in Halladale-1 DW1 is illustrated in the Composite Well Log (Enclosure 1). Formation tops were picked based primarily on electric logs supported by cuttings lithologies and ROP breaks.

Cuttings in Halladale-1 DW3 were collected, washed and described at ten metre intervals from 1200 mMD down to 1830 mMD, then at five metre intervals down to TD (1969 mMD) The lithology and composition of the cuttings is summarised in Appendix 6 of the Halladale-1 DW3 Basic Data Report.

No samples were collected for biostratigraphic or petrological analysis.

SHERBROOK GROUP

Paaratte Formation
(1197.0 – 1383.4 mMD)

The Paaratte Formation in Halladale-1 DW3 is represented by 175.1 mTVD of interbedded sandstone and silty claystone with lesser argillaceous siltstone and claystone.

The sandstones are predominantly light grey, white, transparent to translucent in colour, becoming very light grey, light olive grey, light yellowish-grey and transparent and translucent toward the top. They are generally very-fine to medium-grained, loose, with subangular to subrounded (occasionally angular to subrounded), slightly elongate to slightly spherical (occasionally elongate to slightly spherical) framework grains and 10 to 20% visual porosity. Pyrite is often present as an accessory in trace amounts down to 1310 mMD and as a cement from 1320 mMD down to the base of the formation.

The silty claystones in the upper part of the formation down to 1320 mMD are predominantly brownish-grey to olive-grey, medium grey, medium dark-grey in colour, very soft to soft or soft to firm, amorphous to sub-blocky or amorphous to dispersive, with up to 5% glauconite, 5% pyrite, and trace carbonaceous matter and mica. Below 1320 mMD, the silty claystones are medium brownish-grey, light brown to medium grey in colour and contain trace amounts of carbonaceous matter and pyrite but no glauconite or mica.

The argillaceous siltstones range from medium grey, medium dark grey, olive grey, brownish-grey, light brown to speckled black in colour, very soft to soft or soft to firm,

amorphous to sub-blocky, blocky or dispersive, with trace carbonaceous matter and pyrite, and occasional trace glauconite and mica.

The claystones are off-white, very light grey, yellowish-grey, transparent to translucent in colour, very soft to soft, amorphous to dispersive. No accessories were observed.

Skull Creek Mudstone
(1383.4 – 1541.7 mMD)

The Skull Creek Mudstone in Halladale-1 DW3 is represented by 144.4 mTVD of silty claystone with minor interbedded sandstone. The silty claystone is predominantly light brownish-grey to medium brownish-grey in colour, occasionally light brown or light grey, and is generally very soft to soft and amorphous to dispersive. Carbonaceous matter and mica are ubiquitous throughout the formation but are only present in trace amounts. Pyrite is also present but is less common. Crinoid fragments are present in trace (0.1%) amounts near the base of the formation. The sandstones are light grey to white, transparent and translucent in colour, loose, predominantly fine-grained, moderate to well-sorted, with subangular to subrounded, slightly elongate to slightly spherical framework grains, trace pyrite and 20% visual porosity.

Nullawarre Formation
(1541.7 – 1546.9 mMD)

Halladale-1 DW3 intersected the fault bounding the south side of Halladale approximately 4.8 mMD below the top of the Nullawarre Formation, so only the top of the Upper Nullawarre sand was intersected in the well before it penetrated the underlying Belfast Formation (1546.9 – 1784.4 mMD). The sandstone is described as light-grey, white, translucent to transparent in colour, fine- to medium-grained, moderate to well-sorted, friable, with angular to subangular slightly elongate to slightly spherical framework grains, 20% visual porosity and trace lithic fragments.

Belfast Formation
(1546.9 – 1784.4 mMD)

The Belfast Formation in Halladale-1 DW3 is represented by 205.9 mTVD of silty claystone. The silty claystone is predominantly medium light grey to light brownish grey in colour, ranging from very soft to soft and amorphous to sub-blocky in the upper half of the

formation, to soft to firm and sub-blocky to blocky in the lower half. Glauconite is ubiquitous throughout the formation, typically ranging between 0.1 and 2 %, rising to 5% at 1750 and 1760 mMD, and 10% at 1780 mMD. Pyrite, carbonaceous matter and mica are present in trace amounts all through the formation as well.

Flaxman Formation
(1784.4 – 1869.7 mMD)

The Flaxman Formation in Halladale-1 DW3 is 74.7 mTVD thick. The upper two thirds of the formation consists of silty claystone that ranges from medium light grey to light brownish-grey, medium brownish-grey, medium grey, dark-grey, greenish-grey, medium greenish-grey, dark greenish-grey in colour, occasionally light yellow to light yellowish-grey. It is generally soft to firm and sub-blocky to blocky, with up to 2% glauconite and trace pyrite, carbonaceous matter and mica.

The lower third of the formation is composed of interbedded sandy claystone and sandstone with rare silty claystone at the base. The sandy claystone is predominantly light grey to medium-grey in colour, occasionally dark grey, brownish-grey, greenish grey, white or light green, very soft to soft, amorphous to dispersive, with trace glauconite, carbonaceous matter and mica. The sandstone is light-grey, white, translucent to transparent in colour, occasionally light yellow, ranging from very-fine- to fine-grained at the top to very-fine- to medium-grained at the base, loose, with subangular to subrounded, slightly elongate to slightly spherical framework grains, and 15 to 20% visual porosity. Sorting is high variable, ranging from very poor to poor, poor to moderate, and moderate to well sorted. The silty claystone is light grey to medium grey in colour, occasionally brownish grey to greenish grey, very soft to soft, amorphous to dispersive, with trace glauconite, carbonaceous matter and mica.

Waarre Formation
(1869.7 – 1969.0 mMD)

Waarre C
(1869.7 – 1906.2 mMD)

The Waarre C in Halladale-1 DW3 is 31.9 mTVD thick and consists largely of sandstone with two beds of silty claystone approximately 1.3 and 1.6 mTVD thick near the top and base of the unit respectively. The sandstone is light-grey, white, translucent to transparent in colour, occasionally pale yellow, predominantly medium-grained, loose, and very poorly to

poorly sorted, with angular to subrounded, elongate to slightly spherical or slightly elongate to spherical framework grains, trace pyrite, and 20% visual porosity. The silty claystone is light brownish-grey, brownish-grey to light grey in colour, occasionally dark grey, very soft to moderately hard, amorphous to sub-blocky, with trace mica, carbonaceous matter and pyrite.

Waarre B
(1906.2 – 1935.9 mMD)

The Waarre B in Halladale-1 DW3 is represented by 26.3 mTVD of silty claystone with minor interbedded sandstone. The silty claystone is light brownish-grey, light grey to medium grey in colour, occasionally dark grey or greenish-grey, very soft to soft, amorphous to dispersive, with trace pyrite, carbonaceous matter and mica. The sandstone is light-grey, white, translucent to transparent in colour, loose, very fine to fine-grained, with subangular to subrounded, moderate- to well-sorted, slightly elongate to slightly spherical framework grains, trace pyrite and 15 to 20% visual porosity.

Waarre A
(1935.9 – 1969.0 mMD TD)

The Waarre A in Halladale-1 DW3 is represented by 29.6 mTVD of interbedded silty claystone and sandstone. The silty claystone ranges from light brownish grey to medium brownish grey, light grey and medium grey in colour, and is generally very soft to soft (rarely firm), amorphous to dispersive (rarely sub-blocky), with trace pyrite and mica, and up to 2% carbonaceous matter. The sandstone is light-grey, white, translucent to transparent in colour, loose, very fine to fine-grained, generally moderate to well-sorted, with subangular to subrounded (occasionally rounded), slightly elongate to spherical framework grains, with trace pyrite and 15% visual porosity.

6. HYDROCARBON SHOWS

The recording of mud log gas data in Halladale-1 DW3 commenced at a depth of 1197 mMD in the lower half of the Paaratte Formation. From this point down to the base of the Paaratte Formation (1383.4 mMD), the total gas reading in the well remained at background levels except for a small peak (0.98 %) at 1254.5 mMD. No fluorescence was observed.

Immediately upon penetrating the Skull Creek Formation, the total gas reading in the well rose slightly, averaging approximately 0.5% down to the top of the Nullawarre Formation (1541.7 mMD), spiking at 3.24% at 1441.0 mMD. The total gas reading in the well then dropped back down to approximately 0.2% when the well penetrated the fault (1546.9 mMD) bounding the south side of Halladale and entered the Belfast Formation, and remained at this level all the way down to about 1812 mMD in the middle of the Flaxman Formation (1784.4 – 1869.7 mMD) where it jumped slightly, averaging approximately 0.25% down to the top of the Waarre C (1869.7 mMD).

When the well penetrated the top of the Waarre C, the total gas reading rose quickly peaking twice, firstly at 1.51% at 1875.0 mMD, and then at 1.80% at 1877.0 mMD, before dropping back down to background levels (0.4%) at 1880 mMD where it remained all the way down through the rest of the Waarre C, Waarre B and Waarre A until TD. No fluorescence observed over any of these intervals.

7. RESERVOIR EVALUATION

7.1 Petrophysical Analysis

A detailed petrophysical review of the Late Cretaceous section intersected in Halladale-1 DW3 was conducted to assess the reservoir quality and hydrocarbon saturation of all zones that displayed good hydrocarbon shows while drilling. A copy of the petrophysical report is included in Appendix 1 of this volume, with a summary of the net sand and net pay in the well provided below in Table 3.

Table 3: Halladale-1 DW3 petrophysical summary

FORMATION	GROSS THICKNESS			NET SAND				NET PAY				
	TOP (mMD)	BASE (mMD)	THICK (mMD)	THICK (mMD)	N:G (%)	PHIT (%)	K (mD)	THICK (mMD)	N:G (%)	PHIT (%)	K (mD)	Sw (%)
Nullawarre	1541.7	1487.0	4.5	2.4	4.8	23.3		0	0			
Belfast	1546.9	1491.5	205.9	0	0							
Flaxman	1784.4	1697.4	74.7	0.6	0.8	9.2		0	0			
Waarre C	1869.7	1772.1	31.9	30.3	82.3	25.9	2702	0	0			
Waarre B	1906.2	1804.0	26.3	0	0							
Waarre A	1935.9	1830.3	29.6	5.2	15.6	24.9	44.2	0	0			

Net Sand cut-offs: Vshale < 40%, K > 0.2 mD
Net Pay cut-offs: Net Sand = 1, Sw < 60%

Log analysis indicates the Upper Nullawarre, Waarre C and Waarre A in Halladale-1 DW3 are all water wet with no net pay calculated. The Waarre C, the primary objective, has a gross thickness of 31.9 mMD with a net sand thickness of 30.3 mMD (N:G = 82.3%) and average porosity of 25.9%.

8. FORMATION TESTING

8.1 Formation Pressure Testing

A single run was made with the Baker Atlas Reservoir Characterisation Instrument (RCI) in Halladale-1 DW3 (Suite 1 Run 1) to acquire formation pressure data from the Waarre C over the interval 1871.7 - 1904.2 mMD. The stratigraphic position of the pretest points in Halladale-1 DW3 is shown on the Composite Well Log (Enclosure 1). A total of ten pretests were performed during the RCI run, all of which were successful. The basic data from this survey is tabled in Appendix 7 of the Halladale-1 DW3 Basic Data Report, and a copy of the interpretive report included in Appendix 2 of this volume.

Figure 3 in Appendix 2 of this volume is a pressure versus depth plot for the Waarre C and Waarre A in Halladale-1 DW1, DW2 and DW3. The pressure data from the Waarre C in Halladale-1 DW3 yielded a water gradient approximately 4 psi lower than the Waarre A water gradient from Halladale-1 DW1 and Halladale-1 DW2, but 36 and 40 psi higher than the Waarre water gradients from the onshore Port Campbell Embayment and Minerva gas field respectively. The intersection of the Halladale-1 DW1 and Halladale-1 DW2 Waarre C gas gradients with the Halladale-1 DW3 Waarre C water gradient defines the gas water contacts for Black Watch and Halladale at 1770 and 1760 mSS respectively.

8.2 Fluid Sampling

No fluid samples were collected in Halladale-1 DW3.

8.3 Production Testing

No production tests were run in Halladale-1 DW3.

9. GEOCHEMICAL STUDIES

9.1 Mud Gas Isotope Analysis

To assess the vertical and lateral connectivity of Upper Nullawarre, Lower Nullawarre, Waarre C and Waarre A at Black Watch / Halladale, and whether the gas in the Upper Nullawarre and Lower Nullawarre is from the same source as the gas in the Waarre C and Waarre A, seventy-eight mud gas samples were collected from in Halladale-1 DW1, DW2 and DW3 for compositional and carbon isotope analysis. In Halladale-1 DW3, the cuttings (n = 18) were collected at regular intervals of approximately 50 mMD from just below the kick-off point in the middle of the Paaratte Formation down to TD, with additional samples collected at significant gas peaks. The basic data from this study is tabled in Appendix 10 of the Halladale-1 DW3 Basic Data Report, and a copy of the interpretive report included in Appendix 3 of this volume.

Figure 2 in Appendix 3 illustrates how the carbon isotope composition of methane, ethane and propane varies with depth in Halladale-1 DW1, DW2 and DW3. The isotope data indicates there is very little difference in the composition of methane both down hole in Halladale-1 DW3 and between Halladale-1 DW1, DW2 and DW3. As in Halladale-1 DW1 and DW2, the methane in Halladale-1 DW3 is isotopically heavy, with all of the samples except one from the Paarate Formation having $\delta^{13}C$ values between -35.4 and -32.5 ‰, indicating the gas in the bore hole is very mature. The anomalously light Paaratte Formation sample (-39.6 ‰) occurs at the same stratigraphic level as the two anomalously light Paarratte Formation samples in Halladale-1 DW2 (-39.3 ‰ & -38.9 ‰), which may be due to the gas in these sands coming into contact with artesian water.

9.2 Fluid Inclusion Screening

To understand the migration of hydrocarbons into Black Watch and Halladale, 174 cuttings samples were collected from Halladale-1 DW1, DW2 and DW3 for Fluid Inclusion Screening (FIS). In Halladale-1 DW3, sixty sets of cuttings were collected at intervals of 20 mMD from just below the kickoff point in the middle of the Paaratte Formation to the middle of the Flaxman Formation, then at 5 mMD intervals down to TD. A copy of the final report from Fluid Inclusion Technologies is included in Appendix 4. Analysis of the FIS data indicates there are no significant hydrocarbon indicator anomalies present in Halladale-1 DW3 except for a strong dry gas signal at 1885 mMD (1785.5 mSS) in the middle of the Waarre C (1869.7 – 1906.2 mMD / 1772.1 – 1804.0 mSS). No significant proximity-to-pay (PTP) anomalies were

detected either. The absence of a significant FIS response over the Waarre C interval in the well is probably not a sample interval related problem as in Halladale-1 DW1 or Halladale-1 DW2 because eight sets of cuttings were collected from the Waarre C interval in the well for fluid inclusion screening.

10. CONTRIBUTIONS TO GEOLOGICAL KNOWLEDGE

Halladale-1 DW3 reached TD in the Waarre A having met all of its technical objectives. Pressure data from the Waarre C yielded a water gradient 4 psi lower than the water gradient obtained from the Waarre A in Halladale-1 DW1 and Halladale-1 DW2, indicating the Waarre C and Waarre A aquifers at Black Watch / Halladale are not in hydraulic communication. The Waarre C water gradient at Black Watch / Halladale is also 36 psi higher than the Waarre C water gradient onshore in the Port Campbell Embayment, and 40 psi higher than the Warre C water gradient from the Minerva gas field, indicating the aquifers in the Port Campbell Embayment / North Shipwreck Trough are compartmentalised.

11. REFERENCES

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APPENDIX 1:
PETROPHYSICS REPORT

VIC/P37(v), OTWAY BASIN, VICTORIA

HALLADALE DW1, DW2 & DW3

PETROPHYSICAL INTERPRETATION

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339 Coronation Drive
MILTON QLD 4064

Andy Hall, September 2005

EXECUTIVE SUMMARY

The Halladale-1 DW1 and DW2 wells were drilled in Permit VIC/P37(v) as exploration wells targeting gas in the Waarre C and Waarre A Formations in the Black Watch and Halladale structures respectively. Halladale-1 DW3 was drilled as an appraisal well targeting the water column in the Waarre C sandstone beneath the Halladale gas column to obtain water gradient data to allow the GWC to be determined from pressure data.

These wells were drilled consecutively between 22nd March and 24th April 2005.

The wells were logged with LWD gamma – sonic – neutron- density – resistivity. Pressure measurements were also taken in the Waarre C Formation in all wells and in the Nullawarre and Waarre A in DW1 and DW2 to estimate fluid contacts.

The Waarre C Formation was cored in DW1, where only Sand II was cored, and DW2, where most of the Waarre C interval was cored. Routine and special core analysis has been carried out on these cores and is incorporated into the interpretations in this report.

No production tests were conducted in any of the Halladale-1 wells.

When DW1 was drilled, gas columns were encountered in the Nullawarre, the Waarre C and the Waarre A Formations. DW2 encountered a gas column only in the Waarre C Formation. DW3 was drilled below the GWC determined for all formations to allow the measurement of the pressure gradient in the water leg for the Waarre C Formation.

Petrophysical analysis, integrating the core and log data, has been conducted for each well from the Nullawarre to the Eumeralla Formation and applying consistent input parameters across the wells for each Formation. The results of this interpretation are presented in Tables 1 to 3.

Sandstones were encountered at the top and base of the Nullawarre Formation in each well with a shale section separating them. In DW1, these sands were both found to be gas bearing, but pressure data proved the columns were not in communication and only had a limited extent beneath the well penetration. The highest sand thickness was encountered in DW2, where the shallower Nullawarre sand is best developed. This well has 18 mMD of net sand with an average porosity of 25%, but the sands have only low gas saturation throughout. The sandstones are thinner and water bearing in DW3.

The Waarre C varied in thickness from 22.4 mMD in DW1 to 36.8 mMD in DW3. A stratigraphy for the Waarre C has been applied in this work based upon lithostratigraphy (Figure 1).

Average properties for the entire Formation are also presented. Gas columns were encountered in DW1 and DW2 with no contact encountered in the wells. Pressure data shows that these columns have GWC contacts at 1769 mTVDSS and 1760 mTVDSS respectively using the water gradient data from DW3. In all wells, the sandstones have excellent reservoir quality, with average porosity in excess of 20% and geometric average permeability greater than 900 mD.

The Waarre A was encountered at the GWC in DW1. Consequently the gas saturation is quite low and little net pay is calculated. The formation was encountered below the GWC in both DW2 and DW3, where the TD was within the Waarre A interval. Net sand thickness ranges up to 17.6 metres. The porosity is interpreted in DW1 and DW2 to be 20 – 21%. The porosity in DW3 is interpreted to be significantly higher (25%), but this is derived mainly from the resistivity log as no conventional porosity logs were acquired and should be considered less well constrained. Permeability was derived from the MDT mobility function and is low relative to the Waarre C.

In summary:

- Halladale-1 DW1 has a net pay thickness of 21.6 mMD, with an average porosity of 23% and permeability of 980 mD. The average water saturation is 25%. 18.4 mMD of this net pay is in the Waarre C Formation.
- Halladale-1 DW2 has a net pay thickness of 19.9 mMD, with an average porosity of 22% and permeability of 1522 mD. The average water saturation is 20%. 18.6 mMD of this net pay is in the Waarre C Formation.
- Halladale-1 DW3 has a no net pay thickness as it was drilled below the GWC at Waarre C and Waarre A level to measure the formation water gradient.

Figure 1: Waarre C Stratigraphy Used in this Report

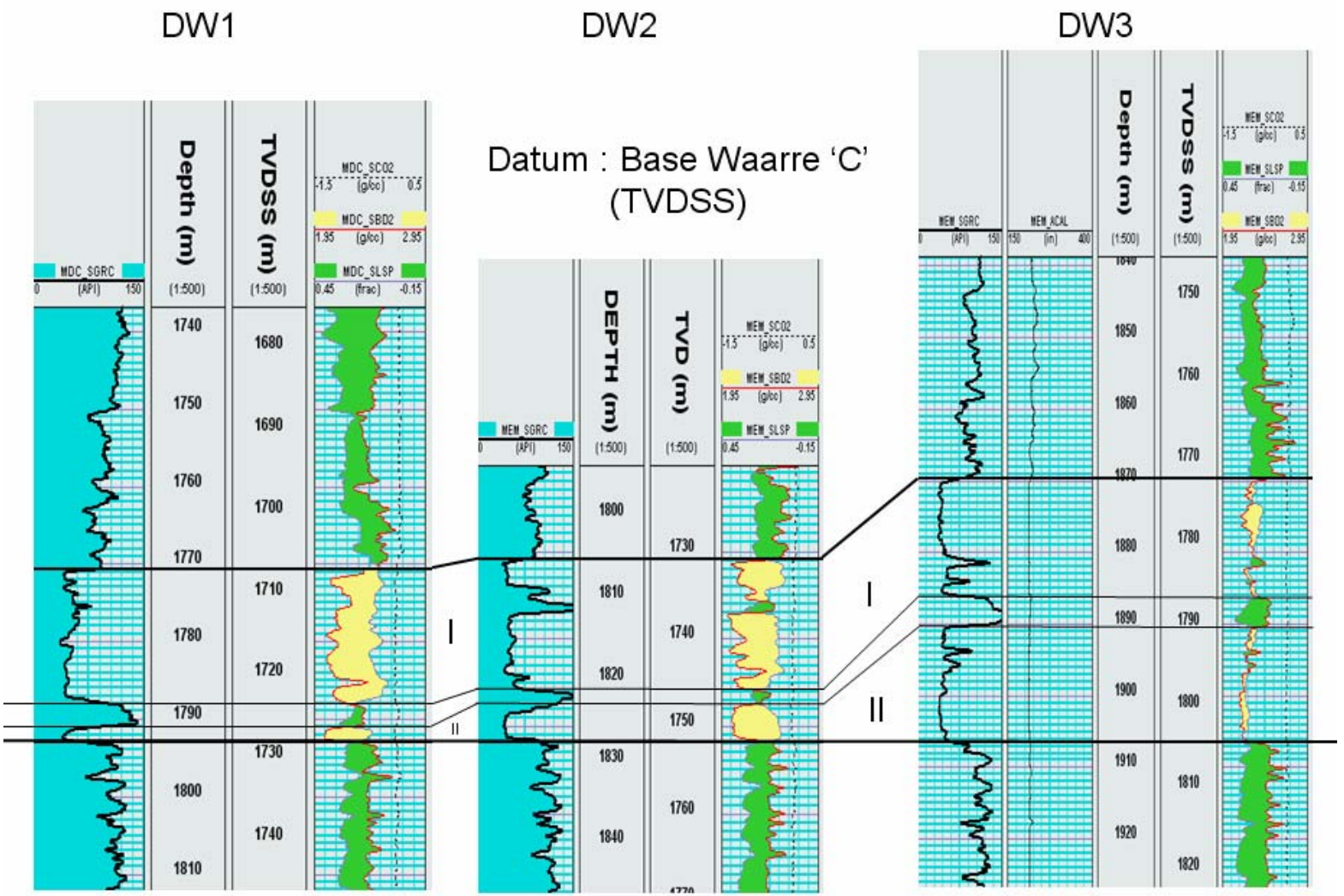


Table 1: Results of the Petrophysical Interpretation for Halladale-1 DW1

Halladale-1 DW-1														
	Gross Thickness			Net Sand					Net Pay					
	Top	Base	Thickness	Thickness	NTG	PHIT	PHIE	Perm	Thickness	NTG	PHIT	PHIE	Perm	Sw
Formation	(mRT)	(mRT)	(mMD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(Fraction)
Nullawarre	1515.5	1565.1	49.6	8.5	0.171	0.231	0.177		1.9	0.038	0.260	0.214	1.51	0.529
Belfast	1565.1	1723.1	158.0	0	0.000					0.000				
Flaxman	1723.1	1770.7	47.6	0	0.000					0.000				
Waarre C	1770.7	1793.1	22.4	18.4	0.821	0.228	0.207	1147	18.4	0.821	0.228	0.207	1147	0.196
WC I	*1770.7*	*1788.1*	*17.4*	*16.6*	*0.954*	*0.226*	*0.205*	*1185*	*16.6*	*0.954*	*0.226*	*0.205*	*1185*	*0.182*
IWCS	*1788.1*	*1791.0*	*2.9*	*0*	*0.000*				*0*	*0.000*				
WC II	*1791.0*	*1793.1*	*2.1*	*1.8*	*0.857*	*0.247*	*0.230*	*793*	*1.8*	*0.857*	*0.247*	*0.230*	*793*	*0.311*
Waarre B	1793.1	1821.6	28.5	0	0.000					0.000				
Waarre A	1821.6	1873.6	52.0	13.0	0.250	0.212	0.164	14.9	1.3	0.025	0.247	0.198	46.6	0.514
Eumeralla	1873.6	1918.0	> 44.4	6.1	0.137	0.186	0.135	5.8	0	0.000				
			402.5	**46**	**0.114**	**0.218**	**0.180**	**464**	**21.6**	**0.054**	**0.232**	**0.207**	**980**	**0.249**

Net Sand	Net Pay
Shale Volume < 40%	Net Sand = 1
Permeabiity > 0.20 mD	Water Saturation < 50%

Figure 2: Waarre C to Waarre A Sandstones in Halladale-1 DW1

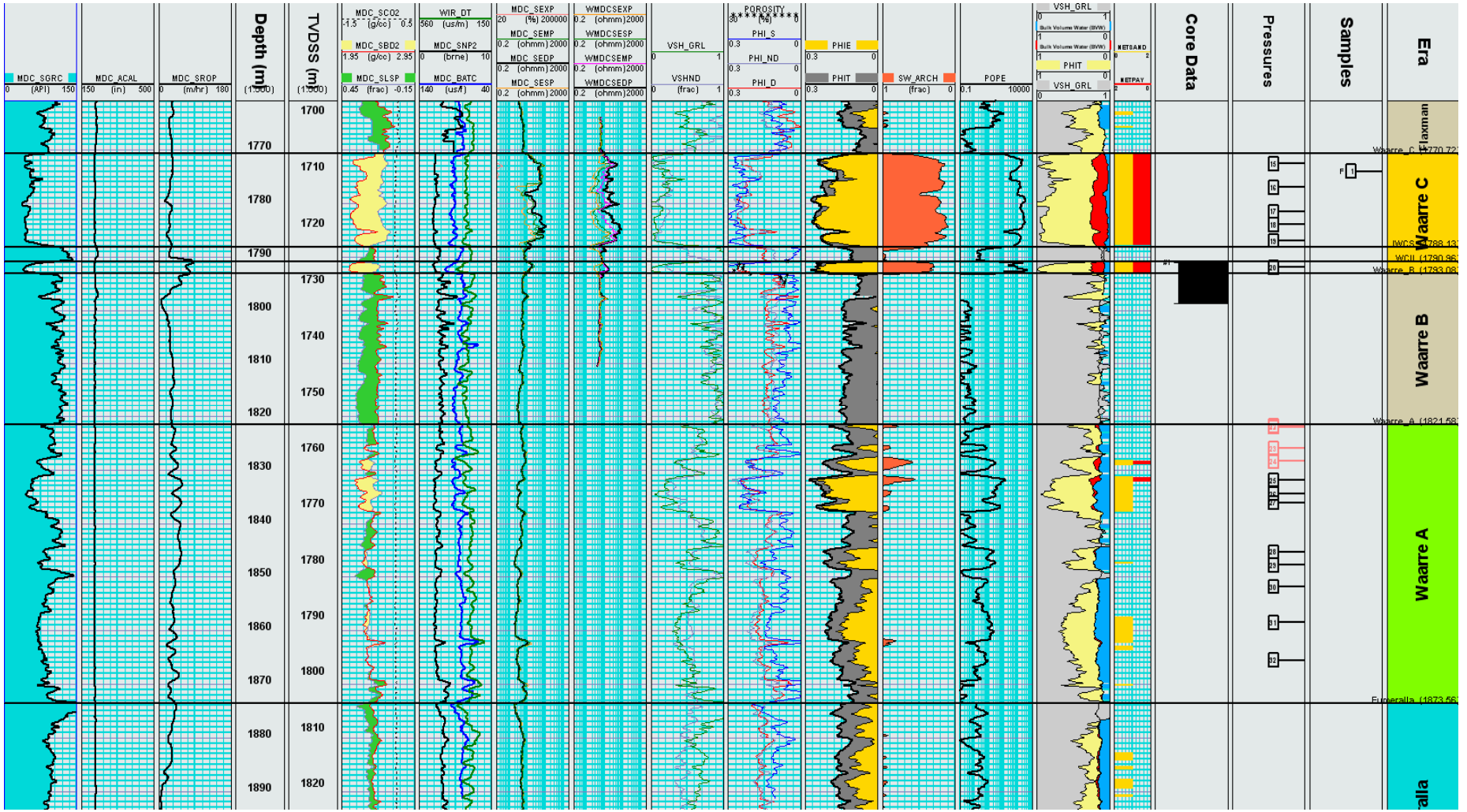


Table 2: Results of the Petrophysical Interpretation for Halladale-1 DW2

Halladale-1 DW-2														
	Gross Thickness			Net Sand					Net Pay					
	Top	Base	Thickness	Thickness	NTG	PHIT	PHIE	Perm	Thickness	NTG	PHIT	PHIE	Perm	Sw
Formation	(mRT)	(mRT)	(mMD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(Fraction)
Nullawarre	1538.5	1589.3	50.8	18.4	0.362	0.252	0.23	1.29	0	0.000				
Belfast	1589.3	1749.2	159.9	0	0.000				0	0.000				
Flaxman	1749.2	1803.7	54.5	3.2	0.059	0.222	0.180	2224	0	0.000				
Waarre C	1803.7	1827.2	23.5	18.6	0.791	0.223	0.208	1628	18.6	0.791	0.223	0.208	1628	0.185
WC I	*1803.7*	*1820.2*	*16.5*	*14.3*	*0.867*	*0.223*	*0.206*	*1181*	*14.3*	*0.867*	*0.223*	*0.206*	*1181*	*0.195*
/WCS	*1820.2*	*1821.9*	*1.7*	*0*	*0.000*				*0*	*0.000*				
WC II	*1821.9*	*1827.2*	*5.3*	*4.3*	*0.811*	*0.224*	*0.213*	*3115*	*4.3*	*0.811*	*0.224*	*0.213*	*3115*	*0.154*
Waarre B	1827.2	1855.1	27.9	0	0.000				0	0.000				
Waarre A	1855.1	1897.9	42.8	17.6	0.411	0.204	0.168	11.1	0	0.000				
Eumeralla	1897.9	1941.0	> 43.1	1.0	0.023	0.196	0.155	8.6	0	0.000				
			402.5	**58.8**	**0.146**	**0.226**	**0.200**	**640**	**18.6**	**0.046**	**0.223**	**0.208**	**1628**	**0.185**

Net Sand	Net Pay
Shale Volume < 40%	Net Sand = 1
Permeabiity > 0.20 mD	Water Saturation < 50%

Figure 3: Waarre C to Waarre A Sandstones in Halladale-1 DW2

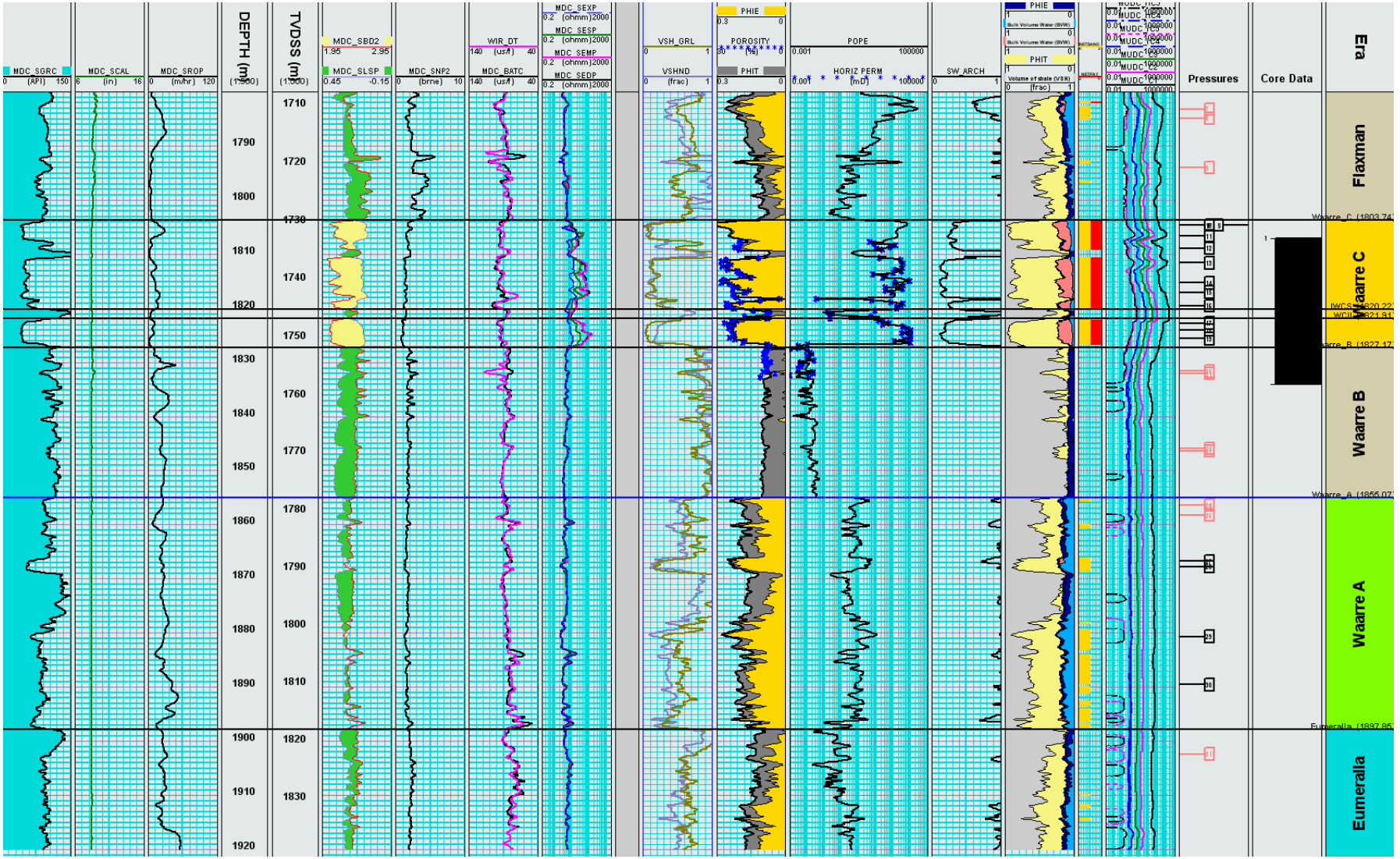
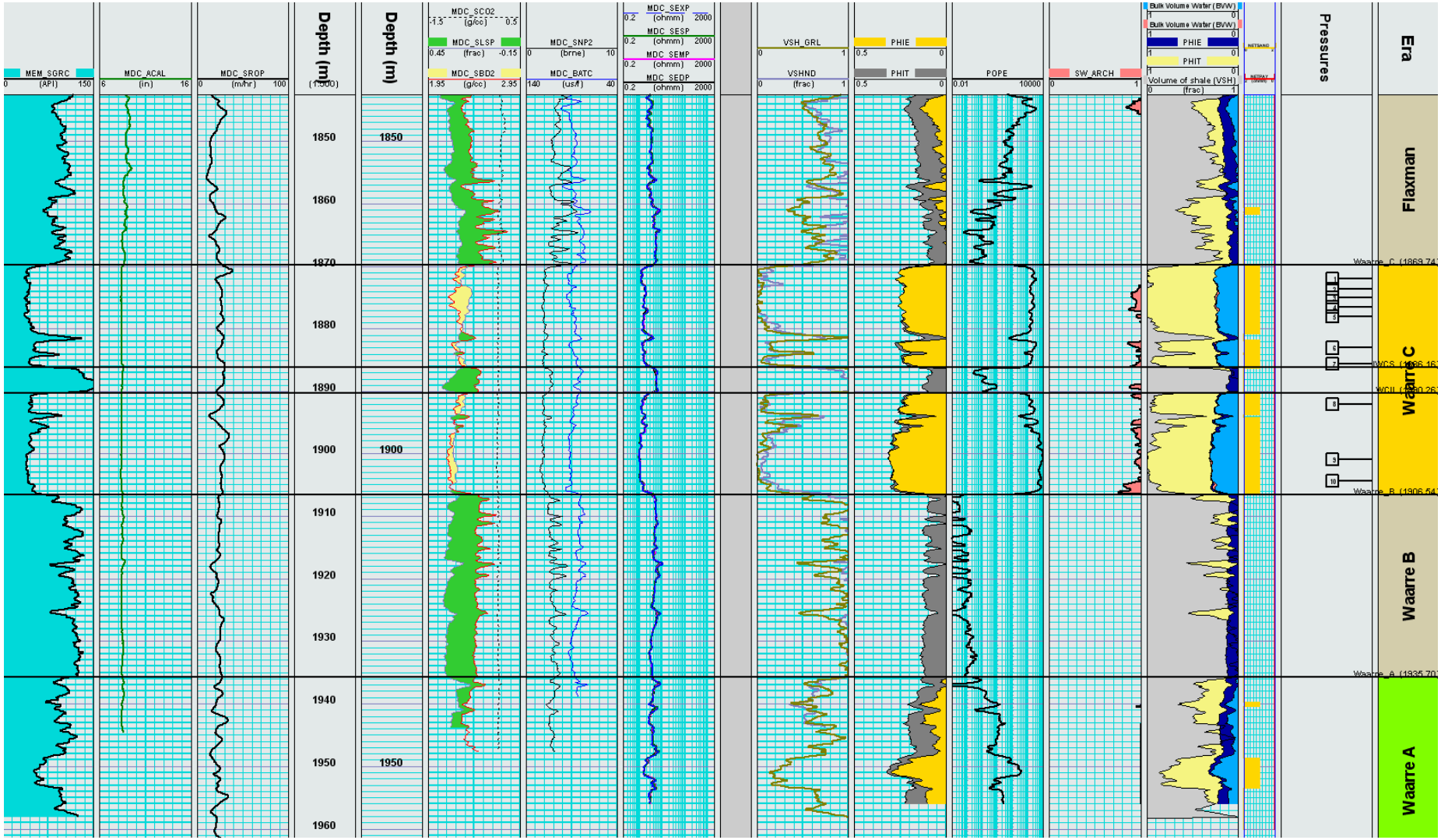


Table 3: Results of the Petrophysical Interpretation for Halladale-1 DW3

Halladale-1 DW-3														
	Gross Thickness			Net Sand					Net Pay					
	Top	Base	Thickness	Thickness	NTG	PHIT	PHIE	Perm	Thickness	NTG	PHIT	PHIE	Perm	Sw
Formation	(mRT)	(mRT)	(mMD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(mMD)	(Fraction)	(Fraction)	(Fraction)	(mD)	(Fraction)
Nullawarre	1497.6	1547.8	50.2	2.4	0.048	0.233	0.117		0	0.000				
Belfast	1547.8	1798.1	250.3	0	0.000				0	0.000				
Flaxman	1798.1	1869.7	71.6	0.6	0.008	0.092	0.033		0	0.000				
Waarre C	1869.7	1906.5	36.8	30.3	0.823	0.259	0.245	2702	0	0.000				
WC I	*1869.7*	*1886.2*	*16.5*	*14.9*	*0.903*	*0.240*	*0.228*	*1650*	0	*0.000*				
WCS	*1886.2*	*1890.3*	*4.1*	*0*	*0.000*				0	*0.000*				
WC II	*1890.3*	*1906.5*	*16.2*	*15.4*	*0.951*	*0.277*	*0.261*	*3720*	0	*0.000*				
Waarre B	1906.5	1935.7	29.2	0	0.000				0	0.000				
Waarre A	1935.7	1969.0	> 33.3	5.2	0.156	0.249	0.204	44.2	0	0.000				
Eumeralla	Not penetrated													
			471.4	**38.5**	**0.082**	**0.253**	**0.228**	**2133**	**0.0**	**0.000**				

Net Sand	Net Pay
Shale Volume < 40%	Net Sand = 1
Permeabiity > 0.20 mD	Water Saturation < 50%

Figure 4: Waarre C to Waarre A Sandstones in Halladale-1 DW3



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Enclosure 1: Interpreted Log and Core Section Over the Nullawarre to Eumeralla Formations for Halladale-1 DW1

Enclosure 2: Interpreted Log and Core Section Over the Nullawarre to Eumeralla Formations for Halladale-1 DW2

Enclosure 3: Interpreted Log and Core Section Over the Nullawarre to Eumeralla Formations for Halladale-1 DW3

WELL DETAILS

The Halladale-1 DW1 and DW2 wells were drilled in Permit VIC/P37(v) as exploration wells targeting gas in the Waarre C and Waarre A Formations in the Black Watch and Halladale structures respectively. Halladale-1 DW3 was drilled as an appraisal well targeting the water column in the Waarre C sandstone beneath the Halladale gas column to obtain water gradient data to allow the GWC to be determined from pressure data.

Latitude		**Longitude**	**Easting**		**Northing**
38° 34' 45.54" S		142° 43' 50.95" E	650,763		5,728,485
Drill Floor		21.5 m			
Water Depth		44.8 metres	**Rig**		Ocean Patriot
Borehole Record			**Casing Record**		
Inches	**mm**	**Base (mRT)**	**Inches**	**mm**	**Shoe Depth (mRT)**
36	914	101	30	762	99.5
17 ½	445	427	13 3/8	340	421
12 ¼	311	839	9 5/8	244	834
8 ½	216	See below			
Halladale-1 DW1					
Spud date		22 March 2005	**TD (mRT)**		1918
End Date		10 April 2005	**TD (mTVDRT)**		1869
Halladale-1 DW2					
Spud date		10 April 2005	**TD (mRT)**		1941
End Date		21 April 2005	**TD (mTVDRT)**		1875
Halladale-1 DW3					
Spud date		21 April 2005	**TD (mRT)**		1969
TD Date		24 April 2005	**TD (mTVDRT)**		1881

Borehole Deviation

All wells were drilled from the same surface location targeting different parts of the Halladale / Black Watch structure. The deviation and inclination plots for the wells are presented in Figure 5.

DW1 targeted the crest of the Black Watch structure to the southwest of the fault dividing the prospects. The well was drilled at an azimuth of approximately 200° and with a maximum inclination of 18.7° to a target 317 metres from the surface location.

DW2 targeted the gas column within the Halladale structure. The well kicked off from the DW1 borehole at approximately 800 metres and was drilled at an azimuth of 340° and with a maximum inclination of 23.7° to a target 328 metres from the surface location.

DW3 targeted the water column also within the Halladale structure to obtain pressure data for comparison with reservoir gas column pressures. The well kicked off from the DW2 borehole at approximately 1150 metres and was drilled at an azimuth of 55° and with a maximum inclination of 30.3° to a target 323 metres from the surface location.

Log Data

All wells were logged with the Sperry Sun FEWD (Formation Evaluation While Drilling) tools. Through the Nullawarre, Waarre C and Waarre A reservoir sections, the LWD logs[i] acquired were:

- GR-ACAL-SC02-SBD2-SLSP-SNP2-BATC-SEXP-SESP-SEMP-SEDP

Four additional wireline logging runs were conducted in Halladale-1 DW1 (Table 4). During Run 3, the RCI got stuck and had to be fished.

Three wireline logging runs were conducted in DW2 (Table 4). As the RCI became stuck in DW1, the sample acquisition RCI run was pipe conveyed.

The LWD neutron-density curves in DW3 did not reach the base of the Waarre A formation. This was, however, covered by the LWD gamma and resistivity logs. One wireline logging run (Table 4) was undertaken in DW3, with ten RCI pressure points being acquired in the Waarre C reservoir.

Four wireline logging runs were conducted in DW1. The temperatures from the logging runs had were at different depths and may be less reliable than other suites. These gave a corrected temperature at 1839 mTVDSS of 87.5°C, equivalent to a geothermal gradient of 43.2°Ckm^{-1}.

Three wireline logging runs were conducted in DW2. These gave a corrected temperature at 1849 mTVDSS of 90.7°C, equivalent to a geothermal gradient of 44.7°Ckm^{-1}.

Only one wireline logging run was conducted in DW3 and so no corrected temperature can be derived. The measured temperature (which will be an under-estimate) was 82.7^{o}C at 1938 mRT (1832.2 mTVDSS). This corresponds to a geothermal gradient of 40.7^{o}Ckm^{-1}.

The temperature gradient for DW2 appears to be the most reliable and this temperature data was used for all wells in the interpretation.

The depth datum for all wells was taken to be Run 1 of the wireline log data in each well. All LWD and mud logs were adjusted to fit this datum.

Table 4: Wireline Logging Runs Conducted in Wells Halladale-1 DW1, DW2 and DW3

Well	Run Number	Tools[ii]
Halladale-1 DW1	1	ORIT-STAR-XMAC-DSL
Halladale-1 DW1	2	GR-RCI (Pressures only)
Halladale-1 DW1	3	GR-RCI (Samples only)
Halladale-1 DW1	4	VSP
Halladale-1 DW2	1	ORIT-STAR-XMAC-DSL
Halladale-1 DW2	2	GR-RCI (Pressures only)
Halladale-1 DW2	3	PCL GR-RCI (Pressures and Samples)
Halladale-1 DW3	1	GR-RCI (Pressures only)

Core Data

Full diameter core was acquired in DW1 and DW2.

Core gamma logs were recorded in both wells and used to correct the logs to the wireline depth datum. In DW1, the core was 1.1 metres deep of the wireline depth datum. In DW2, the core was 0.4 metres deep of the wireline datum.

Core porosity and permeability were measured at 800 psi net overburden pressure (NOBP) and reservoir conditions, assumed to be 3100 psi NOBP. The data measured at reservoir conditions was used in the interpretation.

In DW1, the core was acquired through the Waarre C Sandstone II and upper interval of the Waarre B only. Porosity and permeability was measured on 25 plugs, with 21 plugs yielding valid data. The core in DW2 was acquired through the Waarre C Sand I, the IWC shale, Waarre C Sand II and into the Waarre B.

Grain Density was measured on 38 samples from the Waarre C Sand I, 10 samples from the IWC Shale, 24 samples from the Waarre C Sand II and 31 samples form the Waarre B (Figure 6). The average grain density applied to each reservoir is presented in Table 5.

The overburden corrected porosity / permeability relationships from the core data, along with the correlation line used in the interpretation is presented in Figure 7. The relationship between porosity and permeability is similar for all reservoirs except the Waarre C Sand II, where the trends are different, presumably due to facies variation. The trends presented were applied for the wells / intervals specified, whilst the average function was applied to Halladale-1 DW3.

Table 5: Grain Density by Reservoir from the Halladale-1 DW1 & DW2 Core Data

Reservoir	Grain Density (gcm^{-3})	Comments
Nullawarre	2.655	Not cored. Average property from Waarre C used
Waarre C Sand I	2.658	Cored only in Halladale-1 DW2
IWC Shale	2.644	Significant variation between DW1 and DW2, but all non-net
Waarre C Sand II	2.652	Average of DW1 and DW2 core data
Waarre B	2.670	Mode of distribution from DW1 and DW2 used
Waarre A	2.655	Not cored. Average property from Waarre C used

Eight plugs (four from each of the Waarre C Sand I and Sand II) from DW2 and one plug from the Waarre C Sand II in DW1 were submitted for electrical SCAL.

The cementation exponent ('m') was measured on the SCAL plugs (Figure 8). When plotted, assuming that 'a' = 1, m was determined to be 1.81. This was applied to all reservoirs in the Archie and Indonesia water saturation determinations. The shaly sand equivalent (m* = 1.88) was applied to the Waxman Smits derivation of water saturation.

The saturation exponent ('n') was also determined on the SCAL plugs (Figure 9). When plotted, 'n' can be seen to be different for the Waarre C I and II sandstones. In the Archie and Indonesia water saturation interpretations, n = 1.84 (n* = 2.04) was used in the Waarre C Sand I and n = 2.00 (n* = 2.19) in the Waarre C Sand II. n = 1.90 was applied to the Waarre A and Nullawarre reservoirs. The shaly sand equivalent was applied to the Waxman Smits derivation of water saturation.

The Cation Exchange Capacity (CEC) was measured on the SCAL plugs. Five measurements were available for the Waarre C Sand I (average 1.51 meq/100g, range 0.47 – 2.88 meq/100g) and four for Sand II (average 1.47 meq/100g, range 1.21 – 1.84 meq/100g) (Table 6). A comparison against various log properties (for instance, shale volume) was made without finding a significant trend. The effective concentration of exchange cations per unit volume of pore fluid (Qv) applied in the interpretation was a relationship to core porosity (Figure 10).

Capillary pressure measurements were made on five plugs in DW2 from the from the Waarre C Sand I, one plug in DW2 from the Intra-Waarre C Shale and one plug in DW1 and three plugs in DW2 from the from the Waarre C Sand II. Plots have been produced of the saturation plotted against calculated J Function (Figure 11) and the equations quoted on these plots were used to determine the capillary pressure derived water saturation in the Waarre C reservoir in all wells. No capillary pressure water saturation was derived for the Nullawarre or Waarre A reservoirs.

Table 6: Summary of the Cation Exchange Capacity Results

Summary of the cation exchange capacity (CEC) analysis results.								
Well	Reservoir	Sample no.	Core Depth (m)	Permeability to air (mD)	Porosity (Fraction)	Grain Density (g/cc)	CEC (meq/100gm)	QV (meq/cc pv)
DW-2	WC I	29	1809.05	649	0.223	2.67	2.88	0.27
DW-2	WC I	44	1813.50	3150	0.211	2.63	1.26	0.12
DW-2	WC I	57A	1817.50	3178	0.192	2.66	0.47	0.05
DW-2	WC I	62B	1818.84	392	0.127	2.68	2.06	0.38
DW-2	WC I	64	1819.50	3680	0.258	2.64	0.86	0.07
							1.51	**0.18**
DW-1	WC II	7	1793.00	899	0.260	2.65	1.33	0.10
DW-2	WC II	72	1821.90	51.1	0.180	2.67	1.84	0.22
DW-2	WC II	77A	1823.36	366	0.243	2.65	1.50	0.12
DW-2	WC II	84	1825.50	8230	0.224	2.65	1.21	0.11
							1.47	**0.14**

Formation Water Salinity

The formation water salinities for the Waarre C and Waarre A Formations were derived from the Pickett plots for the DW3 and DW2 wells respectively. The water resistivity for the Waarre A in DW3 could not be derived as the porosity logs do not extend across the interval, so the resistivity was been used (with an assumed water saturation of 100% and salinity) to derive porosity.

The formation water salinity (Figure 12) is derived to be 0.294 ohm.m at 25^{o}C (19,725 ppm NaCl equiv.) for the Waarre C and 0.517 ohm.m at 25^{o}C (10,710 ppm NaCl equiv.) for the Waarre A.

The formation water salinity for the Nullawarre was examined from the three wells (Figure 13). Only Halladale-1 DW1 shows any significant hydrocarbon signal. The formation water salinity was set to 0.403 ohm.m at 25^{o}C (13,990 ppm NaCl equiv) in each well.

Formation Fluid Density

Formation fluid density can be estimated by cross-plotting overburden corrected core porosity against log density and be used to derive a log porosity that, on average through the interval, honours the core data. The fluid density plots are presented in Figure 14.

In the WC II sandstone in DW1, the average grain density through the cored interval is 2.637 gcm^{-3}, which when cross-plotted against log density, yields a fluid density (to match the log to the core data) of 0.366 gcm^{-3}.

Figure 5: Well Bore Deviation for the Halladale-1 wells

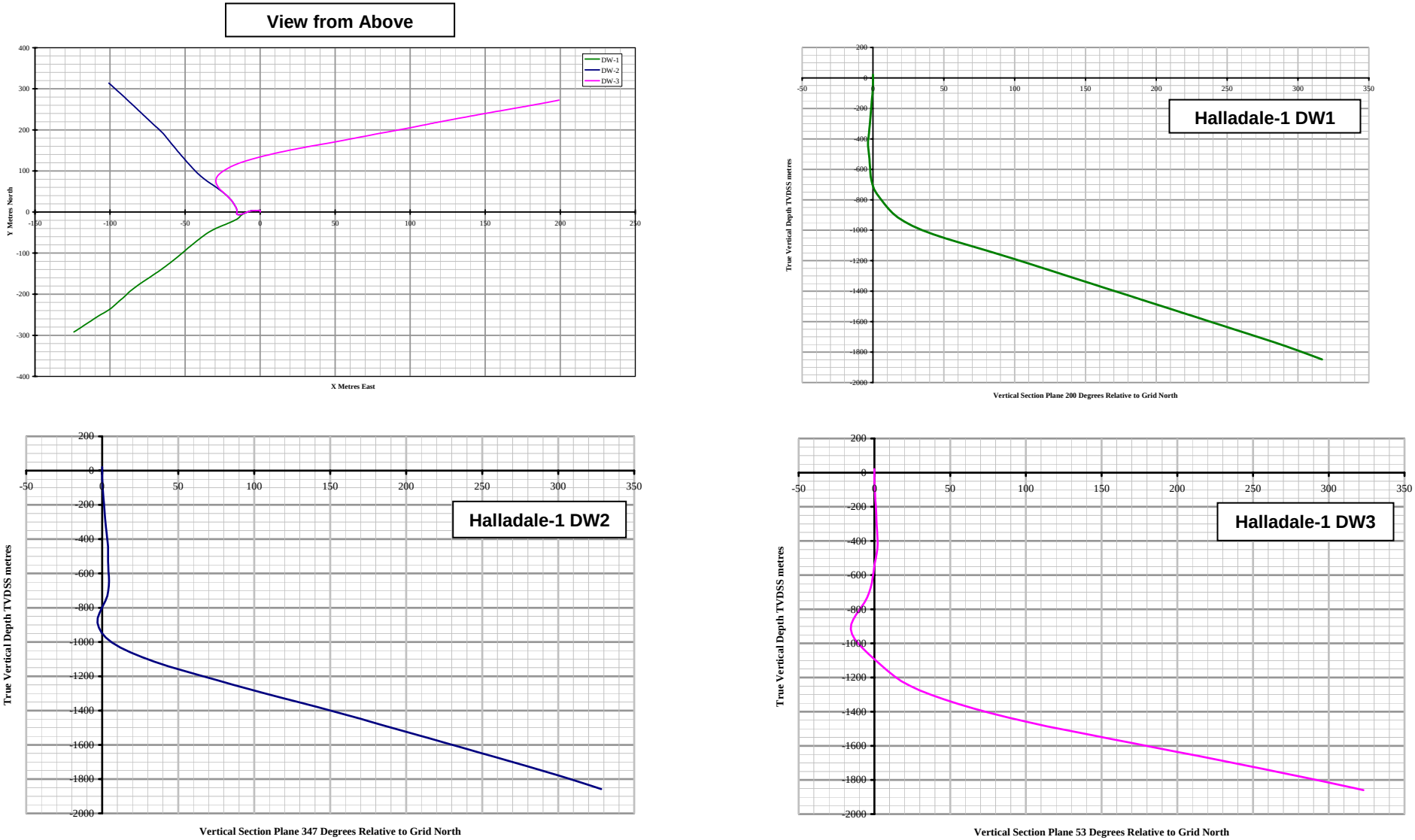
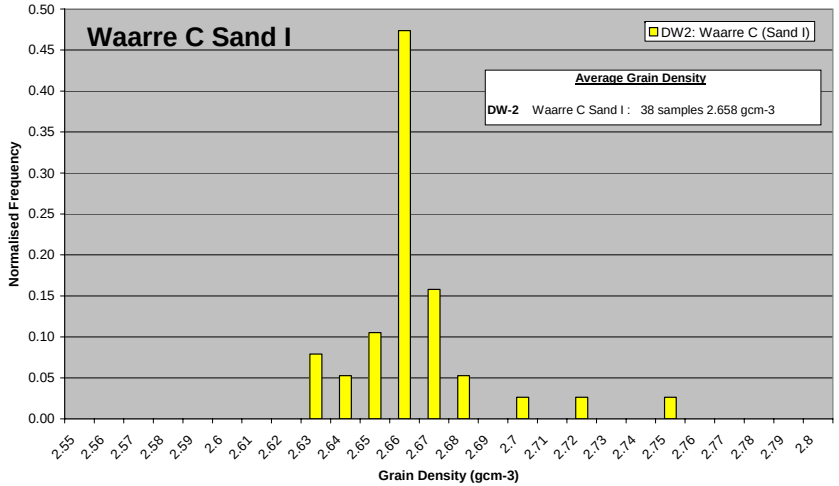
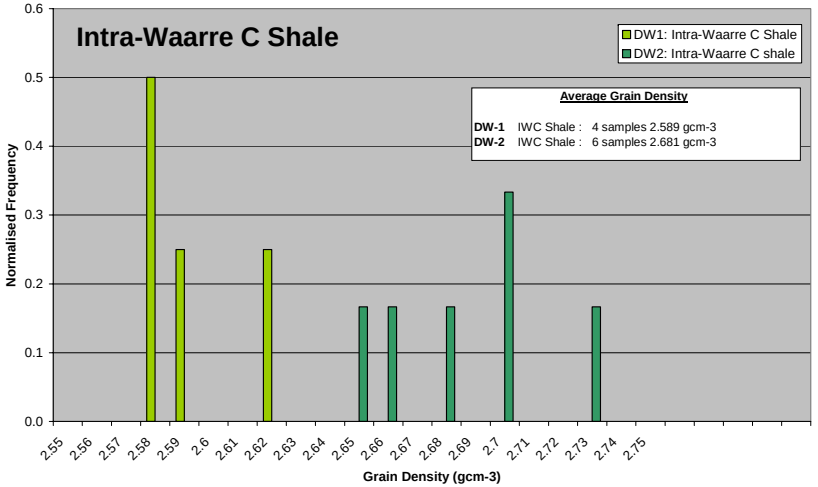
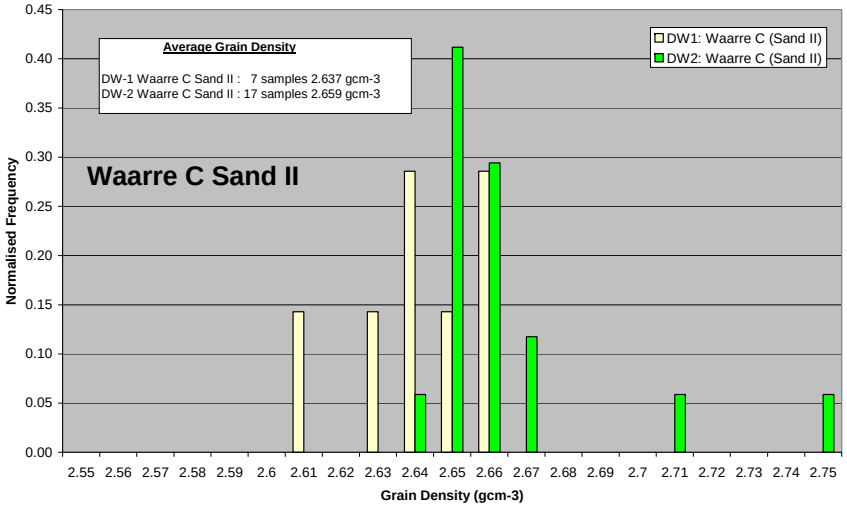


Figure 6: Grain Density Measurements from the Core Data







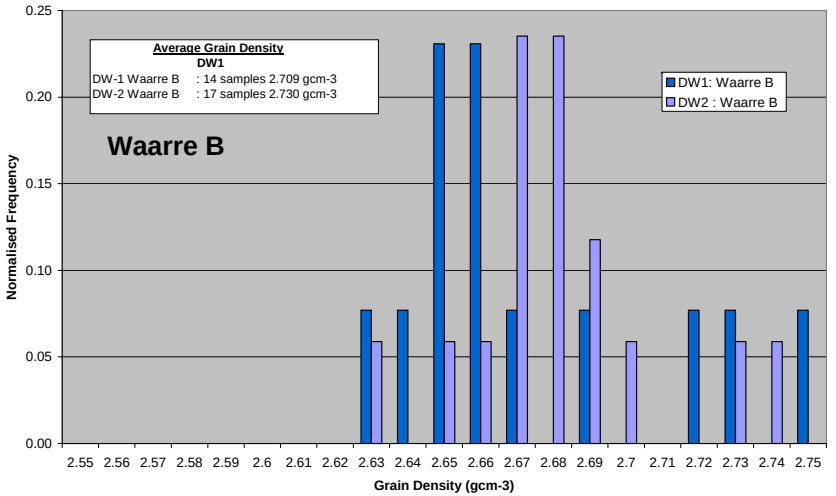
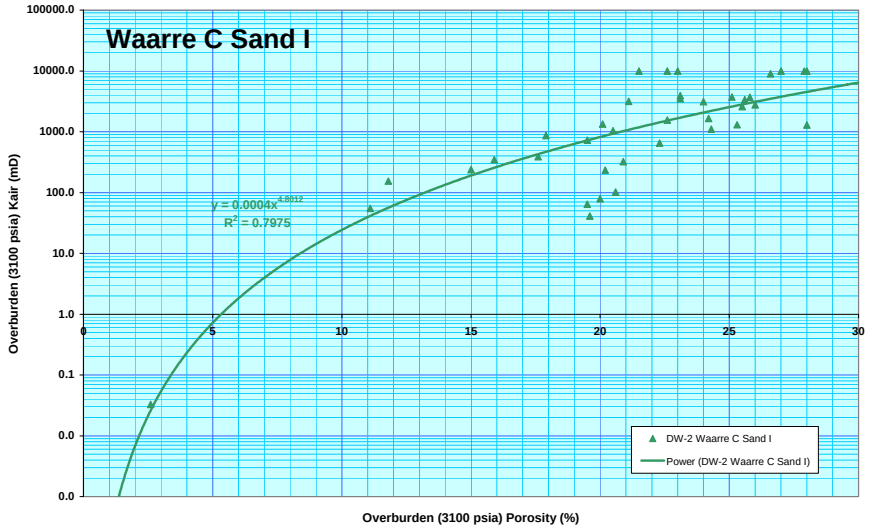
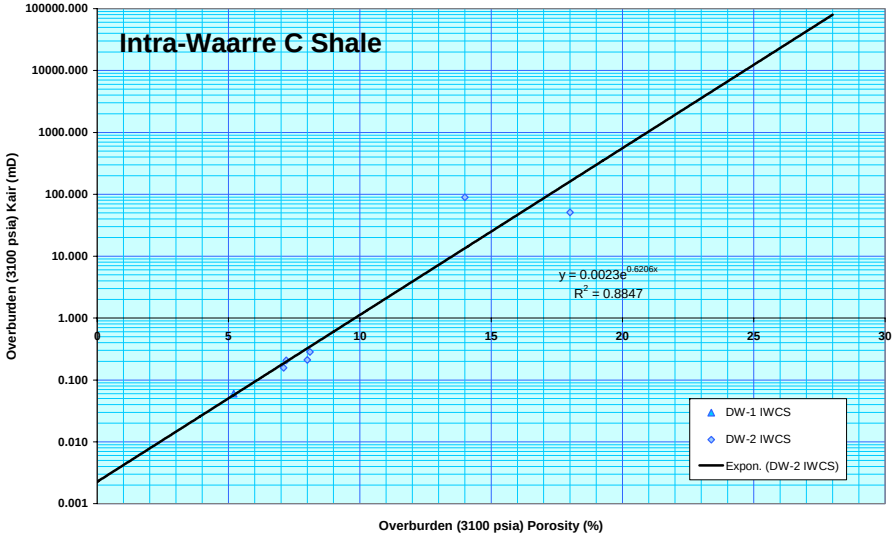
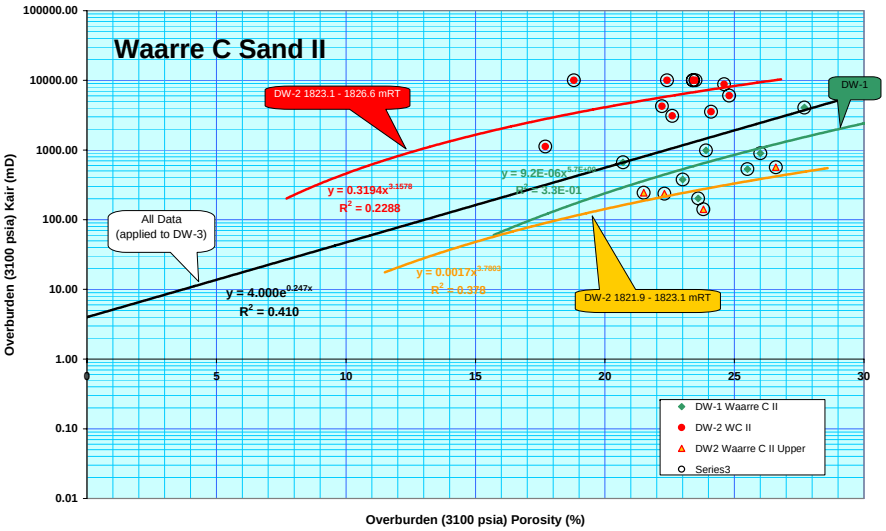


Figure 7: Porosity / Permeability Trends from the Core Data







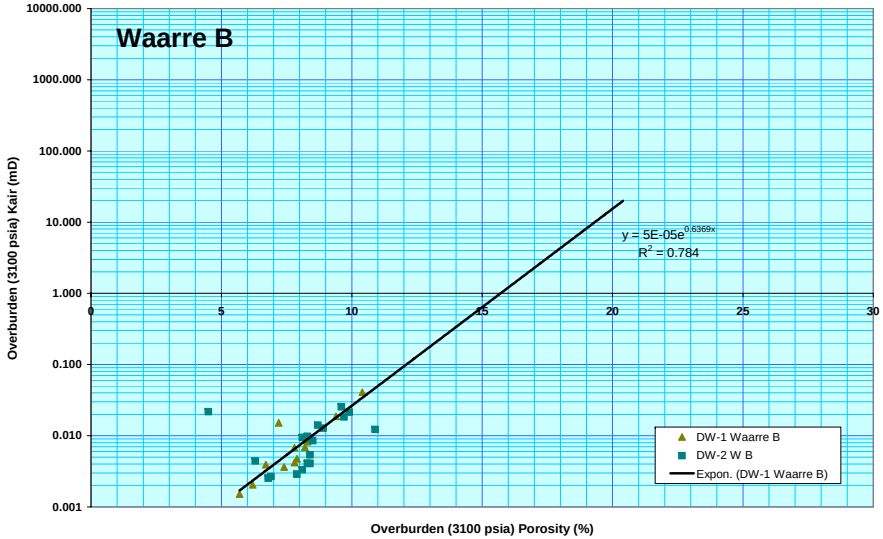
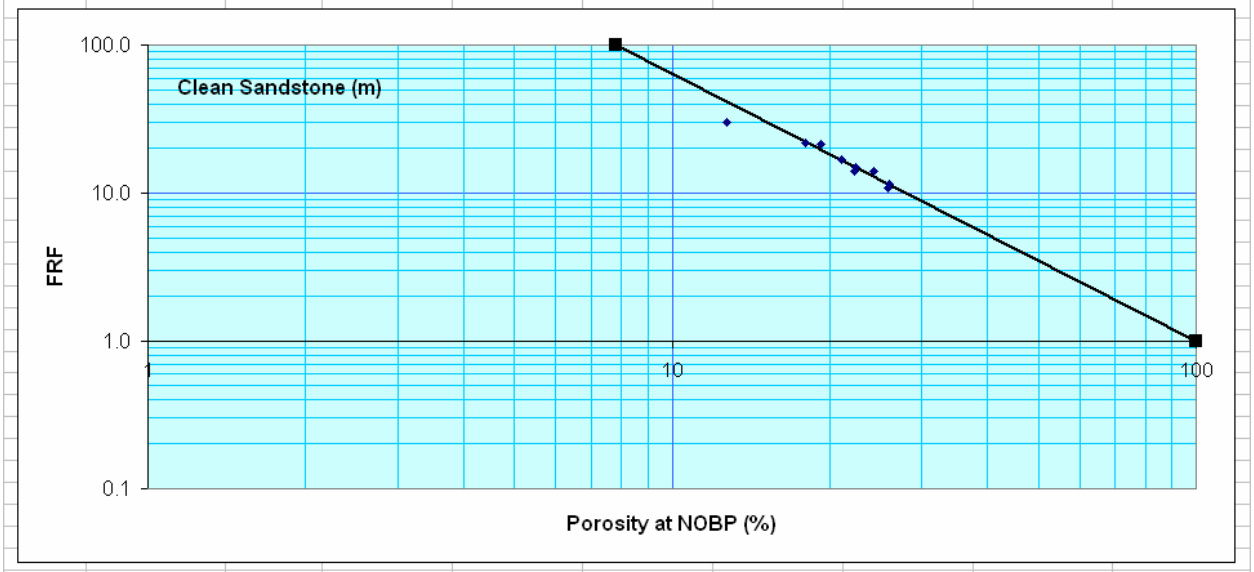


Figure 8: Formation Resistivity Factor for the Waarre C Reservoir

Cementation Exponent at a NOBP of 3100 psi

WELL	RESERVOIR	Sample no.	Core Depth (m)	K air at NOBP (md)	Porosity (%)	FRF (Clean)	FRF* (Shaly)	Cementation exponent m	Cementation exponent m*
DW-1	WC II	7	1793.00	899	26.0	11.5	12.7	1.82	1.88
DW-2	WC I	29	1809.05	649	22.3	14.2	17.9	1.77	1.92
DW-2	WC I	44	1813.50	3150	21.1	16.9	18.9	1.82	1.89
DW-2	WC I	57A	1817.50	2750	19.2	21.2	22.3	1.85	1.88
DW-2	WC I	62B	1818.84	392	12.7	30.1	41.3	1.65	1.80
DW-2	WC I	64	1819.50	3680	25.8	10.9	11.6	1.76	1.81
DW-2	WC II	72	1821.90	51.1	18.0	21.6	26.4	1.79	1.91
DW-2	WC II	77A	1823.36	366	24.3	14.0	15.7	1.87	1.95
DW-2	WC II	84	1825.50	8230	22.4	15.0	16.6	1.81	1.88
					Average m (forced regression with a = 1) =			1.81	1.88



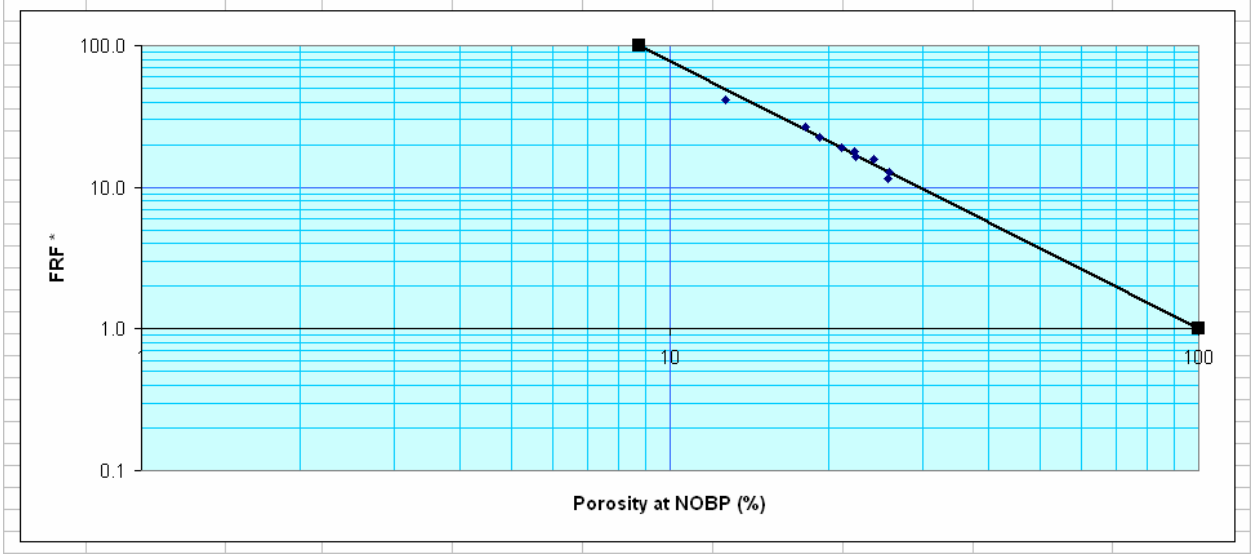
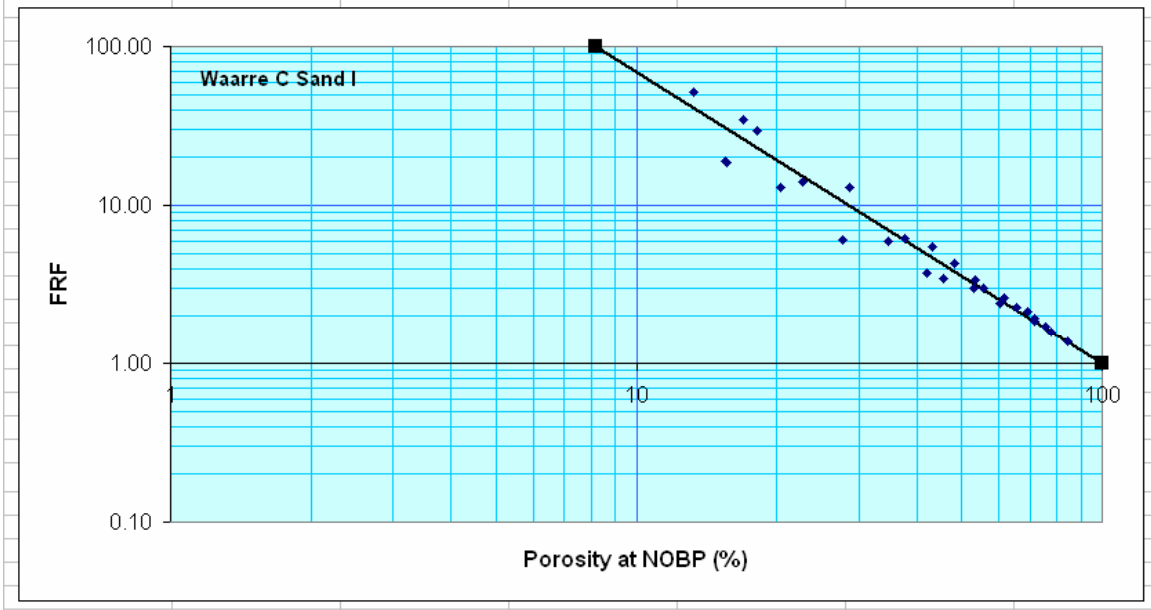


Figure 9: Saturation Exponent for the Waarre C Reservoirs

Saturation Exponent at a NOBP of 3100 psi

WELL	RESERVOIR	Sample no.	Core Depth (m)	K air at NOBP (md)	Porosity (%)	Saturation exponent "m"
DW-2	WC I	29	1809.05	649	22.3	2.03
DW-2	WC I	44	1813.50	3150	21.1	1.68
DW-2	WC I	57A	1817.50	2750	19.2	1.86
DW-2	WC I	62B	1818.84	392	12.7	1.66
DW-2	WC I	64	1819.50	3680	25.8	1.95
						1.84
DW-2	WC II	72	1821.90	51.1	18.0	2.06
DW-2	WC II	77A	1823.36	366	24.3	2.06
DW-2	WC II	84	1825.50	8230	22.4	1.84
DW-1	WC II	7	1793.00	899	26.0	2.05
						2.00



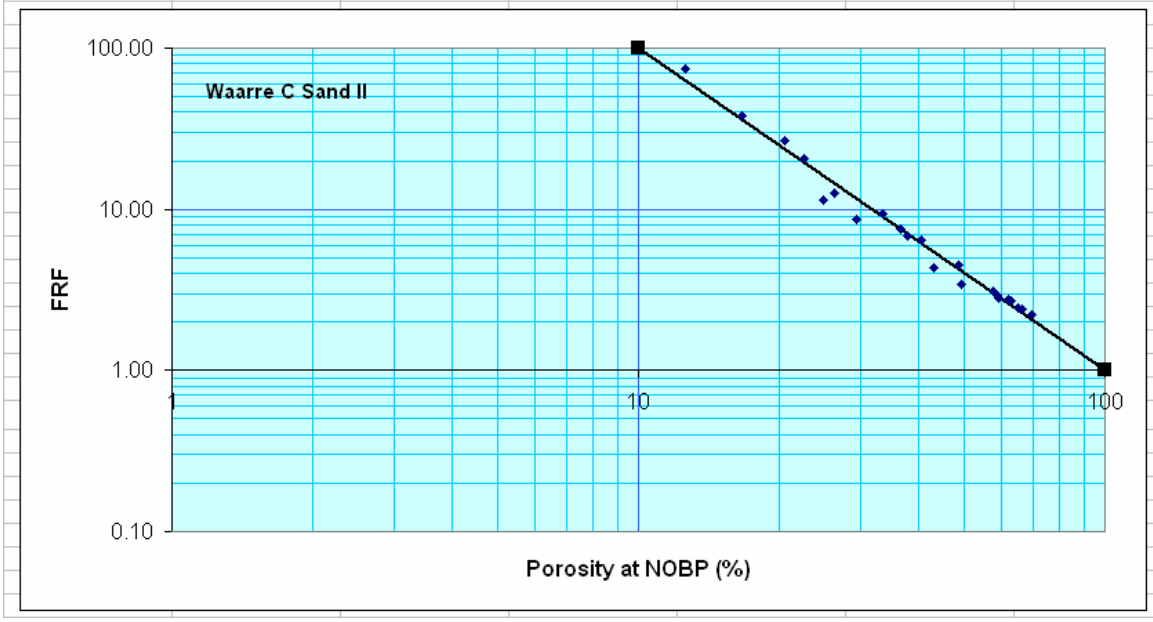


Figure 10: Relationship between Porosity and CEC from the SCAL Data

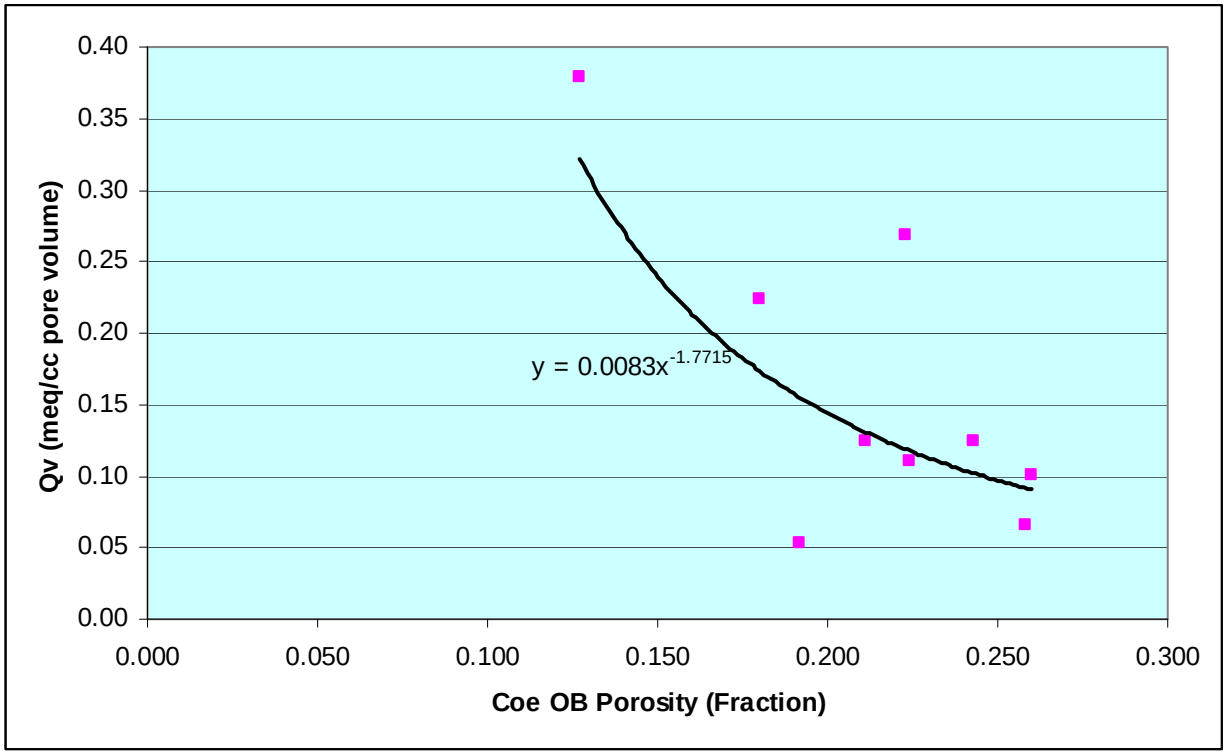


Figure 11: Saturation vs. J Function Relationships for the Waarre C Reservoirs

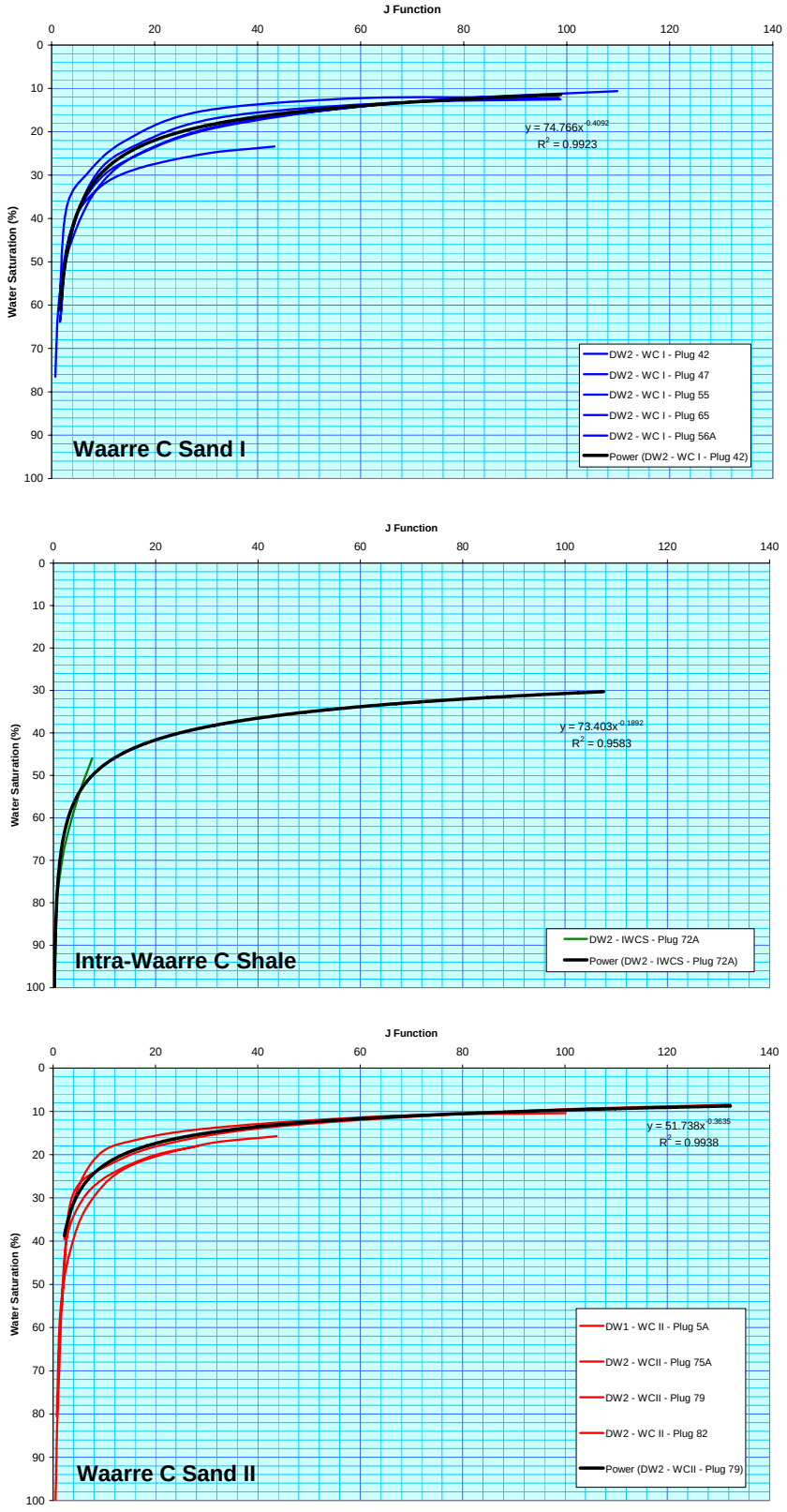
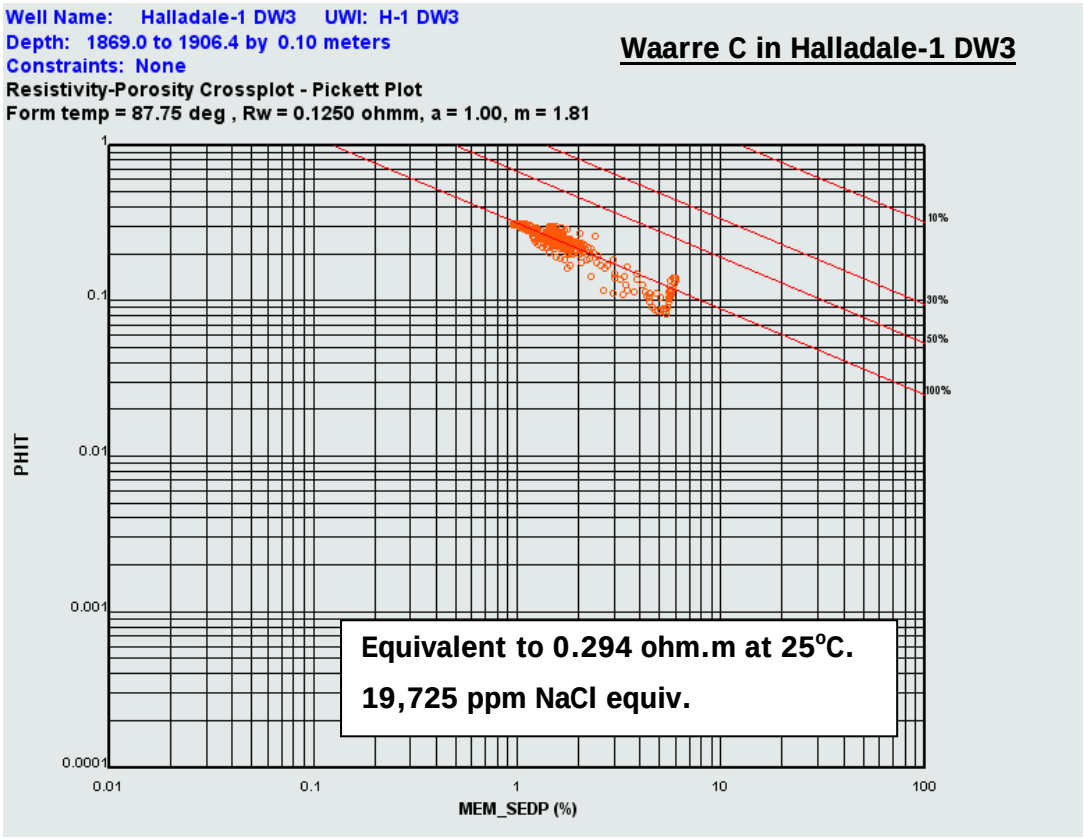


Figure 12: Formation Water Salinity for the Waarre C & Waarre A Formations



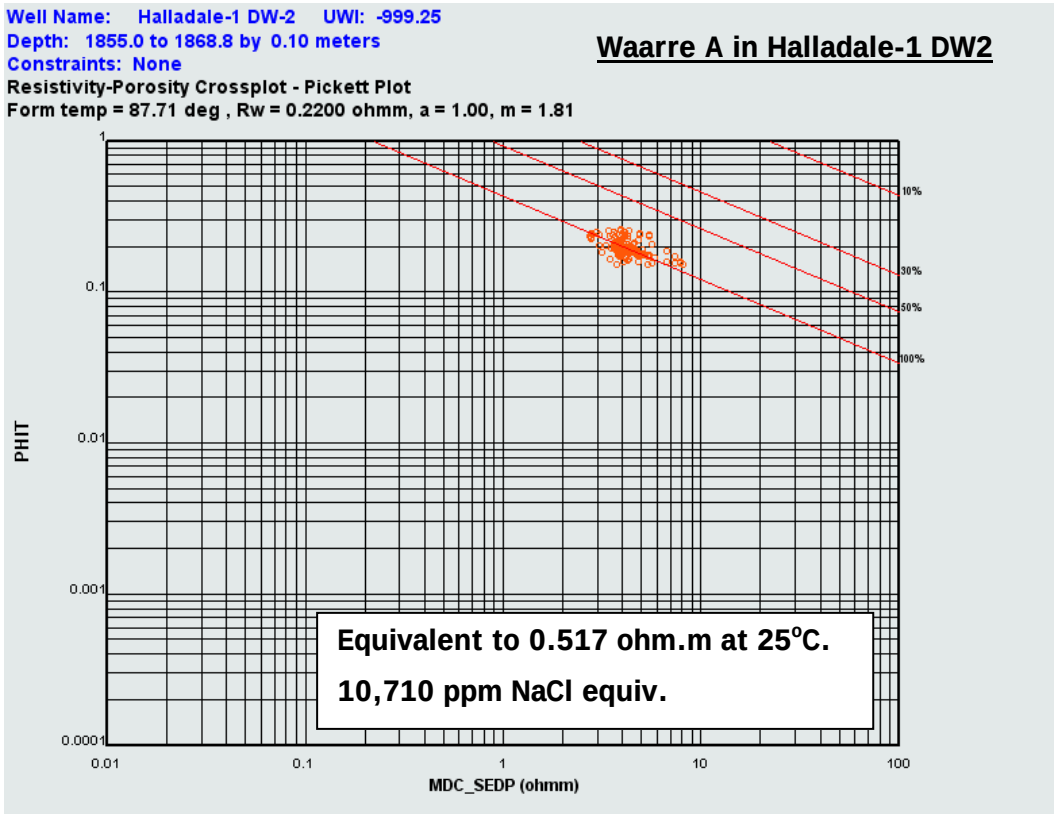
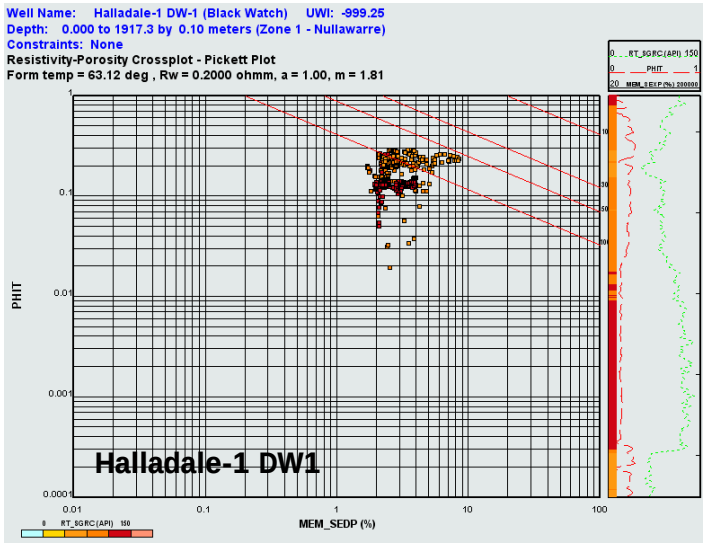
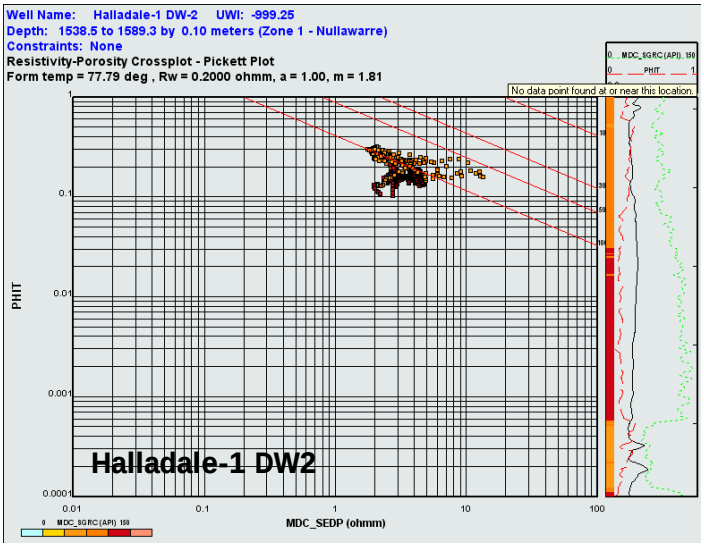


Figure 13: Formation Water Salinity for the Nullawarre Formation



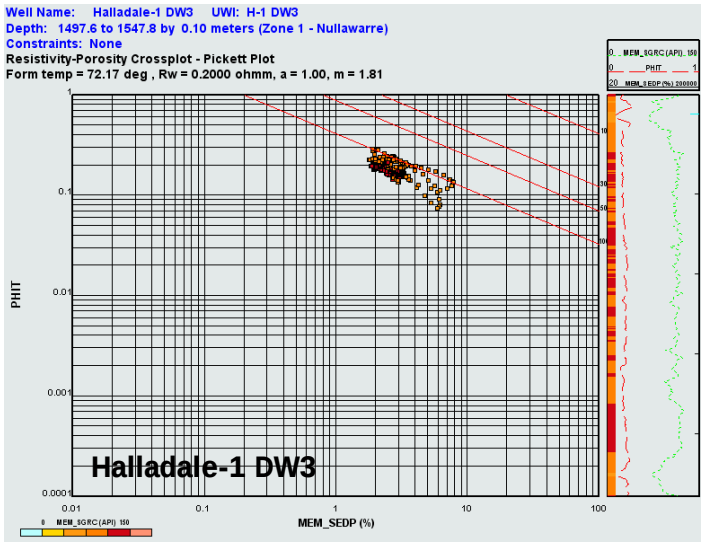
0.364 ohm.m at 25°C

15,600 ppm NaCl equiv



0.427 ohm.m at 25°C

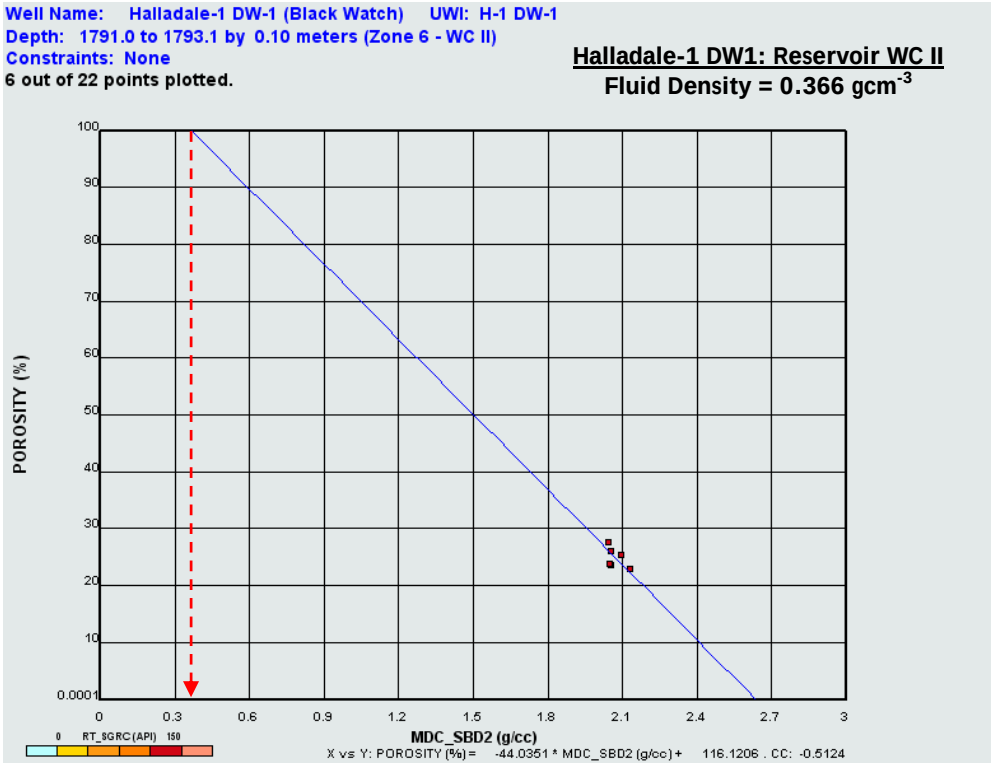
13,140 ppm NaCl equiv



0.403 ohm.m at 25°C

13,990 ppm NaCl equiv

Figure 14: Fluid density Determination for the Cored Intervals



INTERPRETATION METHODOLOGY

Shale Volume

Shale volume was calculated from the neutron-density cross-plot and the gamma ray logs. The fluid density and neutron response in the gas zones (DW1: Nullawarre, Waarre C and Waarre A and DW2: Waarre C) was adjusted so that the calculated shale volume from gamma and density / neutron was similar. The minimum calculated shale volume from the two methods was used in the ongoing interpretation.

Porosity

In the cored intervals (DW1 WCII and DW2 lower WC I, IWCS & WC II), total porosity was derived directly from the interpolated core data. In other zones in DW1 and DW2, the porosity was calculated from the neutron-density cross-plot.

In DW3, the porosity was derived from the neutron-density cross-plot for most of the section. At the base of the Waarre A, below 1930 mRT, porosity was calculated from the resistivity log using the Archie equation as no other porosity logs were acquired.

Permeability

In the cored intervals, the permeability was derived directly from the interpolated core data.

Elsewhere in the wells, permeability was calculated from the log derived porosity using the appropriate core-derived porosity / permeability transform.

Transform Derived in …	**Applied to …**		
Nullawarre (MDT mobility)	Nullawarre		
Waarre C Sand I	Waarre C Sand I		
Intra-Waarre C shale	Intra-Waarre C shale	Flaxman	
Waarre C Sand II	Waarre C Sand II	Waarre A	Nullawarre
Waarre B	Waarre B	Eumeralla	Belfast

The porosity / permeability transform for the Nullawarre Formation was derived by cross-plotting the MDT fluid mobility against the log derived porosity at the same depth (Figure 15). The scatter in the data probably represents differences in the fluid viscosity being tested.

Since no correction has been applied for this, the average curve on Figure 15 was used to determine permeability.

In a similar fashion, the permeability for the Waarre A and Eumeralla was determined from the MDT mobilities acquired in that interval (Figure 16).

Water Saturation

Water saturation was calculated in the Waarre C Sandstone using the Waxman Smits equation using the formation water and electric parameters determined from the core data.

The water saturation for all other intervals was calculated from the Indonesia equation, using surrounding shales as a guide to the clay conductivity in the formation. Whilst this is not ideal, the laminated shales may have different properties to the disseminated clays in the sandstones, it is considered better than simply applying electric properties from the Waarre C sandstone throughout the interpretation interval.

Water saturation was also calculated for the Waarre C from the capillary pressure data from the cores in DW1 and DW2 and used to estimate the Gas-Water-Contact (see Estimation of GWC below).

Water saturation in DW3 was simple calculated using the Archie equation as a screening exercise as the well was drilled below the GWC at all levels. No significant hydrocarbon saturation was calculated to be present.

Net Sand / Net Pay

Net sand was calculated to be present where the shale volume is less than 40% and the permeability is greater than 0.2 mD. No porosity cut-off was explicitly applied, although the determination of the permeability from the porosity / permeability core relationship implies one (that will vary by reservoir). Net Pay was calculated to be where Net Sand = 1 and water saturation is less than 50%.

Estimation of GWC

The gas-water contact can be estimated from pressure data provided that the pressure gradient for the hydrocarbon and water are known. Additionally, if capillary pressure is

available, the GWC can be estimated by comparing the calculated water saturation from the capillary pressure data to the water saturation calculated from the resistivity data.

Black Watch

The pressure data for the hydrocarbon legs in the Nullawarre Formation can be compared to one valid water pressure acquired in DW2 (Figure 17). Hence, there is some uncertainty in the water gradient that is applicable to the Nullawarre in Black Watch. The pressure data from DW1 does, however, confirm that the two gas columns are discrete and have fairly short (10 – 12 metres below the well) hydrocarbon columns.

The lowest known gas in the Waarre C in Black Watch is at 1728 mTVDSS (1793 mRT) in DW1. The pressure gradient data (Figure 18) gives a gas gradient that intersects the water gradient from the Waarre C Formation in DW3 at 1769 mTVDSS (1836 mRT in DW1). Coincidentally (or maybe not), the Waarre A gas pressures are on the same gradient as the Waarre C points. Should the Waarre A water gradient be applicable to the Waarre C Formation in Black Watch, therefore, the GWC would be coincident with the Waarre A GWC (at 1766 mTVDSS, 1832.8 mRT). When the capillary pressure water saturation is calculated with this contact, the values are equivalent to the resistivity derived water saturation in the better sands in the Waarre C Sand I (Figure 19). The derived capillary pressure water saturation is too high in the shalier intervals suggesting either that the capillary pressure plugs are not relevant in this facies. The capillary pressure derived water saturation is also too high in the thin Waarre C Sand II interval. As the porosity and permeability are derived from core and the capillary pressure relationship applied was derived from a core plug in the interval, the agreements should have been better. The discrepancy is probably due to the shoulder effects on the resistivity log in the thin bed. The effect could be a reduction is gas saturation in a transition zone, but this is considered unlikely as the Waarre C Sand I interval above would have lower gas saturation and the pressure gradient required to have a significantly shallower GWC in DW1 would be significantly outside the pressure gradient range from the other wells.

The Waarre A GWC in DW1 is defined by pressure data (Figure 18) to be at about 1766 mTVDSS (1833 mRT in DW1). This corresponds well with the gas-down-to (GDT) observed in the well. No capillary pressure data is available for comparison as no core was acquired in the Waarre A.

Halladale

DW2 has a gas accumulation in the Waarre C reservoir. An examination of the hydrocarbon gradient (Figure 16), along with the water gradient obtained in the same fault block from DW3, suggests a GWC at about 1760.5 mTVDSS (1837 mRT in DW2). The deepest known gas in

DW2 is at the base of the Waarre C formation at 1827 mRT (1751.3 mTVDSS). When the capillary pressure water saturation was calculated, the agreement with the resistivity data was very good across the cored interval (Figure 20). The agreement above the cored interval in the Waarre C is not so good suggesting either that the log derived porosity or, more likely, permeability is pessimistic or that the capillary pressure function has changed.

The Waarre A in DW2 is below the Waarre A GWC seen in Black Watch. Gas is assumed to be present up-dip of the well location in Halladale, but has not yet been proven. DW3 was intentionally drilled below the expected GWC at all levels to obtain aquifer pressures.

Figure 15 : Fluid Mobility vs. Log Porosity for the Nullawarre Formation

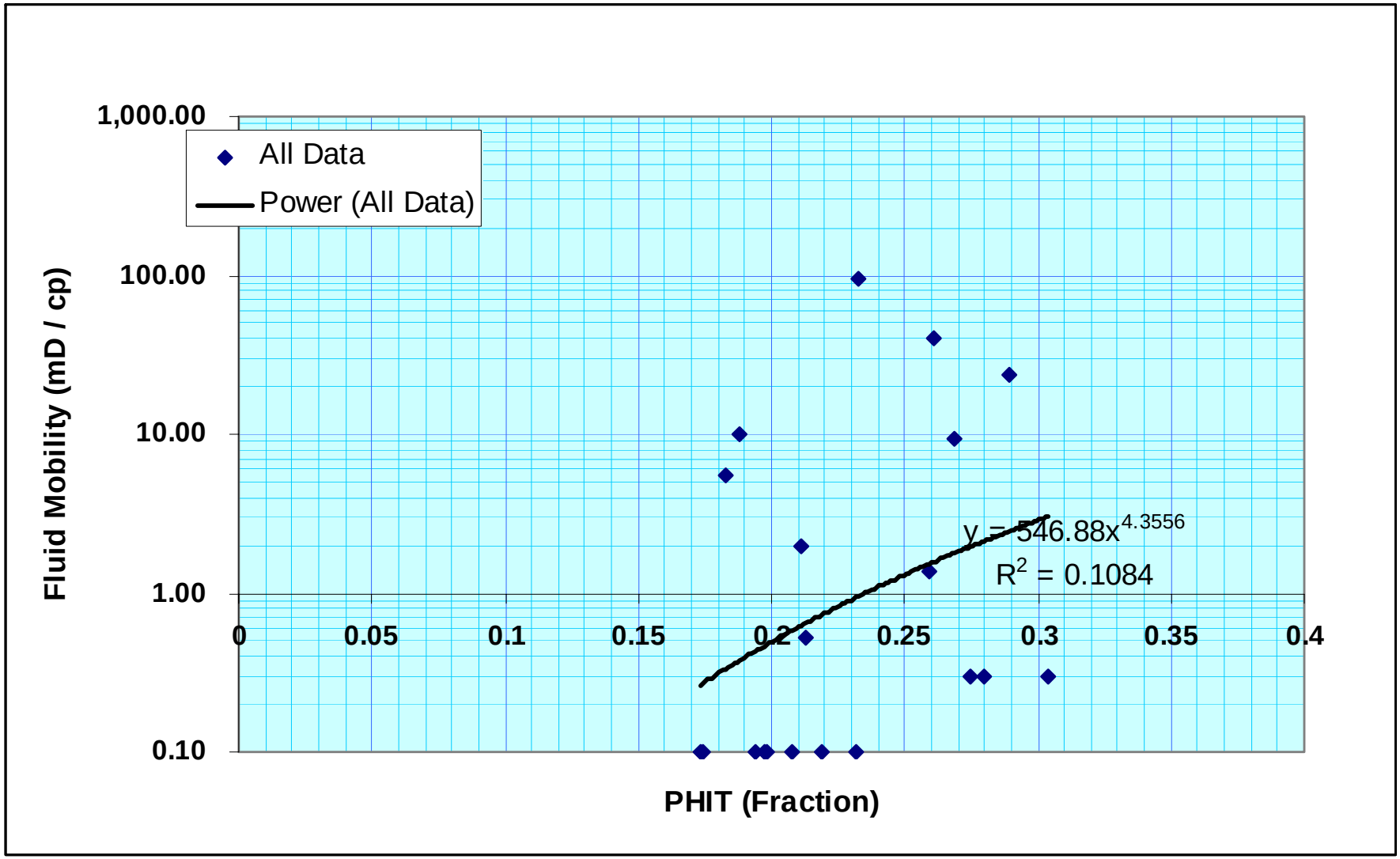


Figure 16 : Fluid Mobility vs. Log Porosity for the Waarre A and Eumeralla Formations

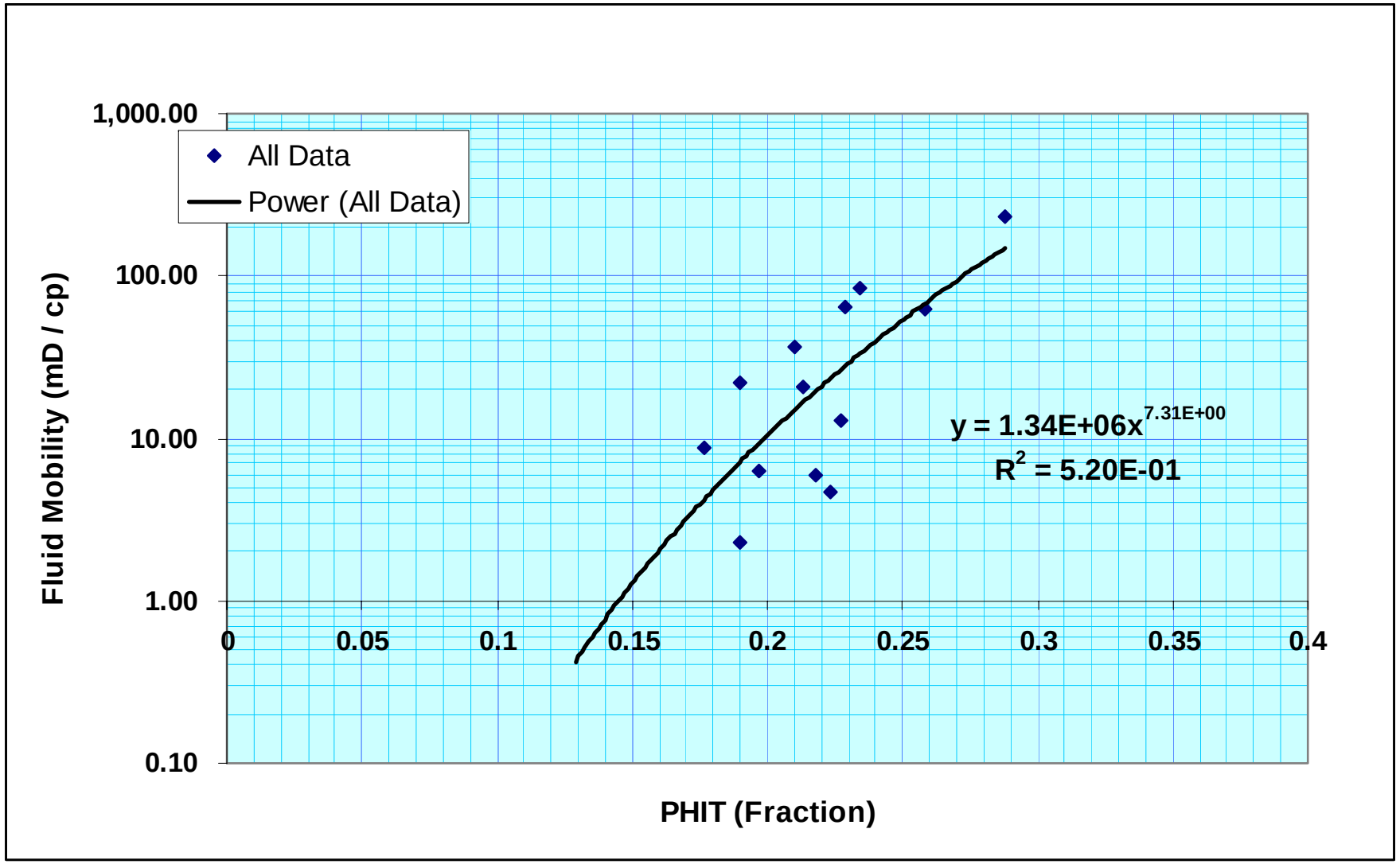


Figure 17: Nullawarre Fluid Pressure Gradient in DW1 and DW2

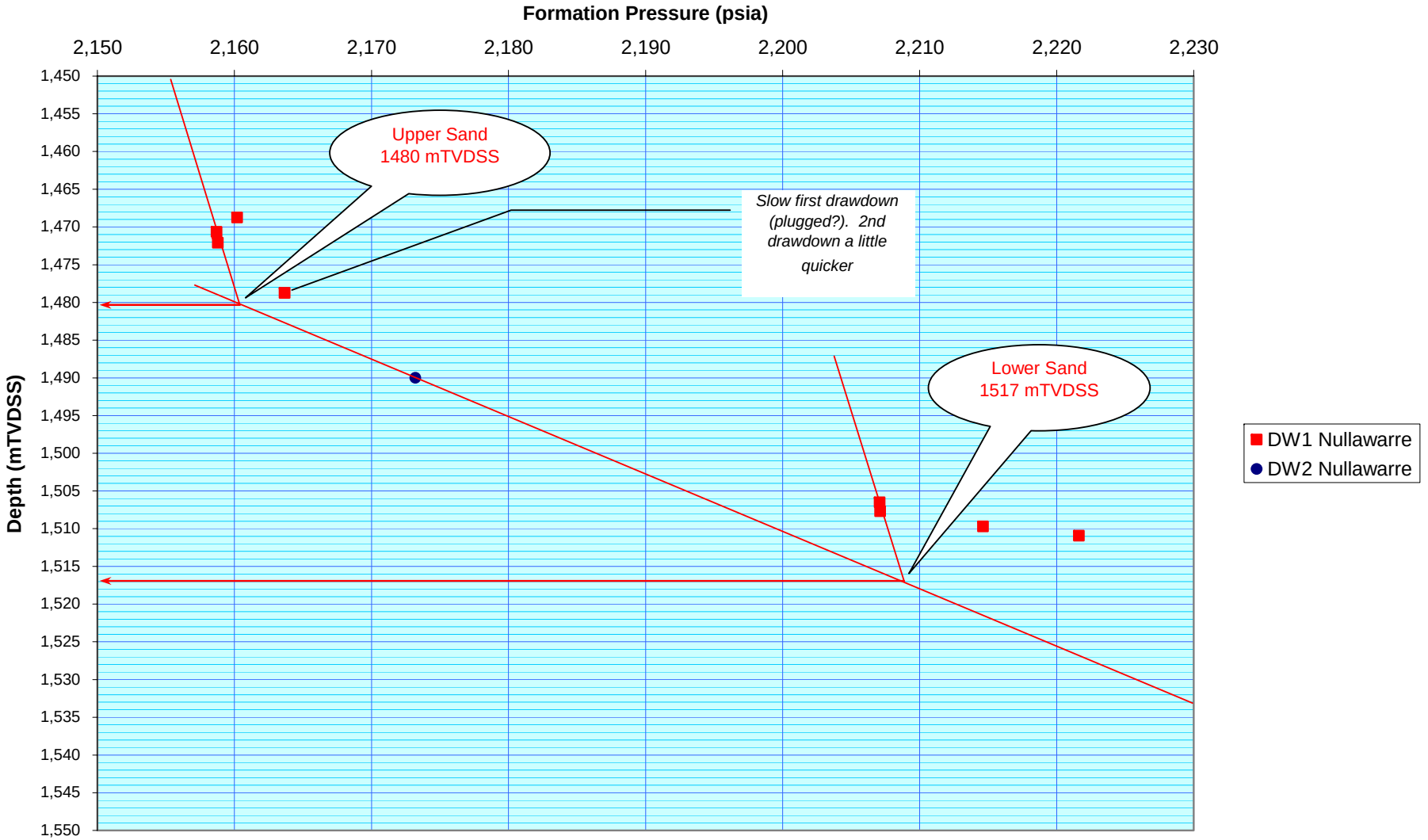


Figure 18: Waarre C and Waarre A Fluid Pressure Gradients

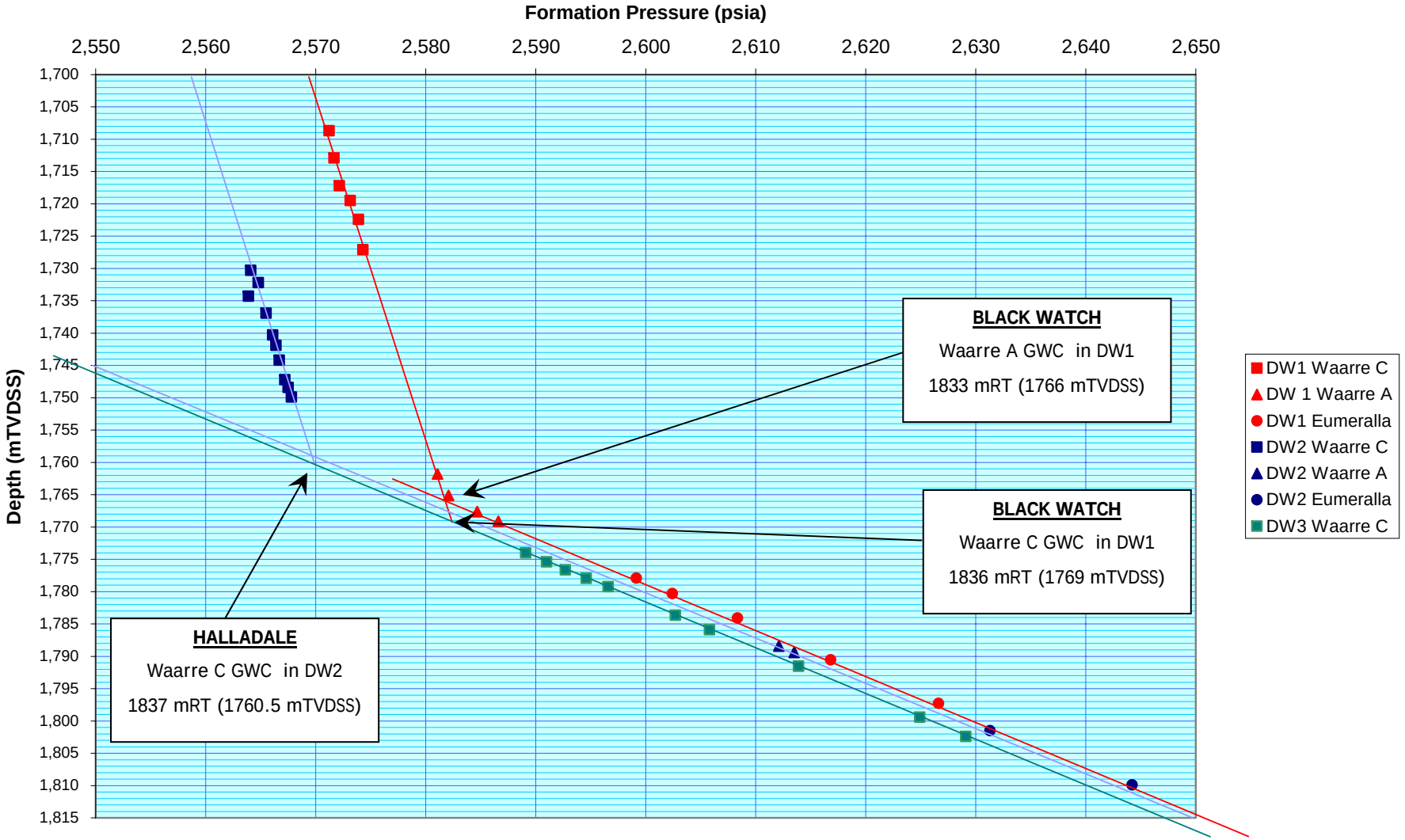


Figure 19: Waarre C Section in DW1 Showing the Agreement Between Capillary Pressure and Resistivity Calculated Water Saturation with a GWC at 1769 mTVDSS

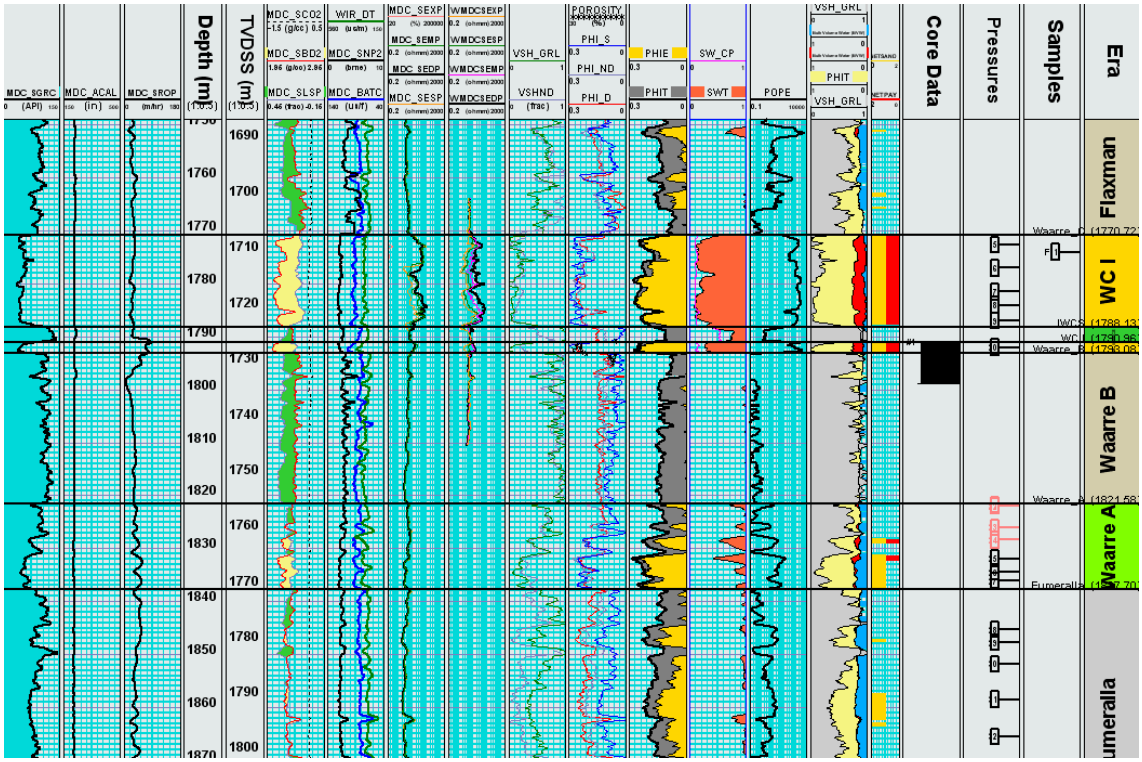
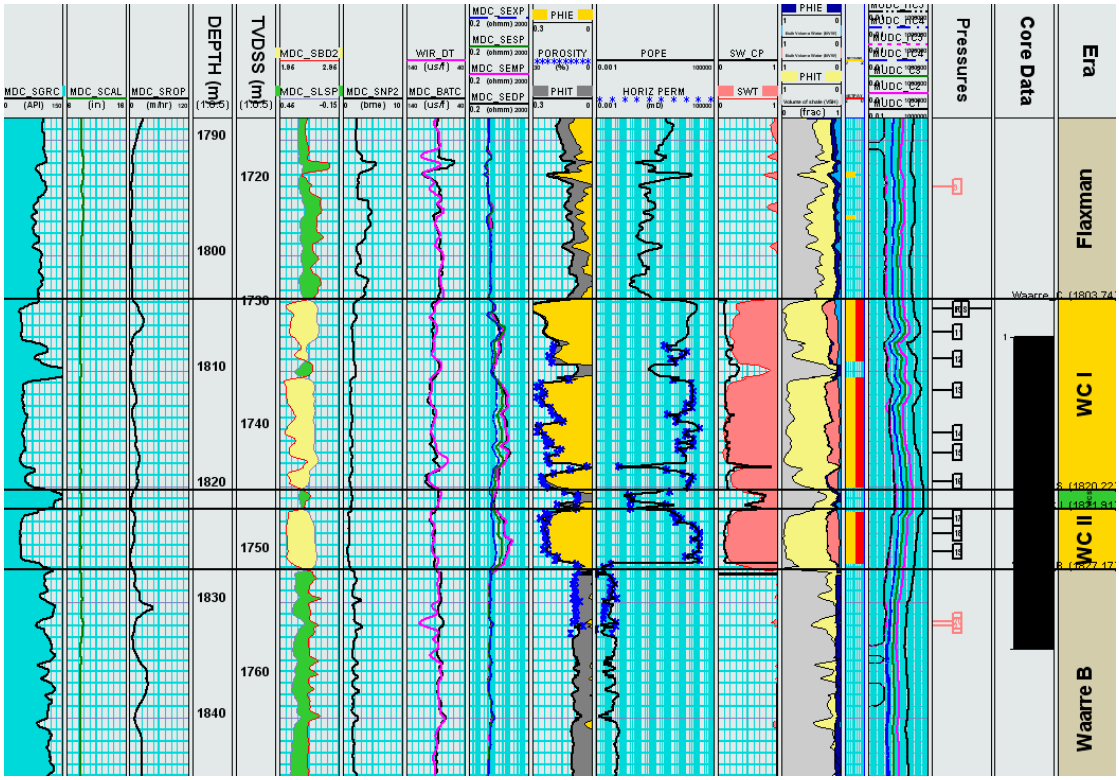


Figure 20: Waarre C Section in DW2 Showing the Agreement Between Capillary Pressure and Resistivity Calculated Water Saturation With a GWC at 1760.5 mTVDSS



INTERPRETATION BY FORMATION

Interpretation was conducted for the Nullawarre, Belfast, Flaxman, Waarre C, Waarre B, Waarre A and Eumeralla formations using the parameters described previously in this report.

Nullawarre Formation

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT[1])
Halladale-1 DW1	1515.1	1565.1	49.6	18.6	47.0
Halladale-1 DW2	1538.5	1589.3	50.8	21.9	47.1
Halladale-1 DW3	1497.6	1547.8	50.2	25.0	45.5

m AVT = metres apparent vertical thickness, taking no account of bed dip

The Nullawarre Formation in all wells in this study comprised a two very fine to medium grained sandstones separated by a silty claystone. No cores were taken in this formation, but the MDT mobilities suggest the flow potential is limited. These sandstones were found to be gas bearing in DW1 and water bearing in DW2 and DW3.

Analysis of the DW1 pressure data suggests that the sands have different GWC and that the gas columns do not extend significantly beneath the well. The high calculated water saturation in each sandstone in DW1 also suggests that the sands may be within the transition zone at DW1.

Log analysis suggests some limited pay thickness in DW1 which could be exploited if a significant section above the current well penetration is identified. At the current location, the well would probably cut water fairly quickly.

Belfast Formation

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1565.1	1723.1	158.0	18.5	149.8
Halladale-1 DW2	1589.3	1749.2	159.9	21.5	148.8
Halladale-1 DW3	1547.8	1798.1	250.3	29.0	218.5

The Belfast Formation is described as a massive silty claystone, with some glauconitic intervals.

No net sand or net pay was determined in this formation in any of the wells.

Flaxman Formation

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1723.1	1770.7	47.6	18.5	45.1
Halladale-1 DW2	1749.2	1803.7	54.5	21.3	50.8
Halladale-1 DW3	1798.1	1869.7	71.6	28.5	62.9

At the top of the Flaxman Formation in each well is an interval of dense, high neutron sandstone with a high (5 – 7 b/e) PEF response. In several nearby onshore wells, this interval is described as being an iron rich, goethitic cemented zone. As the neutron and density are both reacting to the unusual mineralogy, the porosity is difficult to determine. As there are, however, no gas shows, the interval is not expected to be net in any of the wells.

The Flaxman Formation is described as mainly a silty claystone interbedded with argillaceous siltstone and argillaceous sandstone. The sandstones are dominantly fine grained, but do have some medium grained intervals.

The net sand thickness ranges between 0 – 3 metres in the wells. No net pay is calculated to be present in any of the wells.

Waarre C

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1770.7	1793.1	22.4	18.4	21.3
Halladale-1 DW2	1803.7	1827.2	23.5	21.0	21.9
Halladale-1 DW3	1869.7	1906.5	36.8	28.7	32.3

The Waarre C was the primary target in the Halladale / Black Watch prospects.

In this study, the Waarre C Sandstone was sub-divided into three intervals, Waarre C Sand I (WC I), Intra-Waarre C Shale (IWCS) and the Waarre C Sand II (WC II), based upon correlation of the Halladale-1 DW1, DW2 and DW3 wells (Figure 1).

The Waarre C is described as generally medium grained sandstone; with some coarse grains and approximately 30% silt or fine sandstone. Some minor silica cement is noted.

The Waarre C was cored in two wells, DW1 and DW2. In DW1, only the Waarre C Sand II was cored. A thicker section, encompassing the WC I, IWCS and WC II was cored in DW2. Core porosity and permeability demonstrated very high quality reservoir porosity and permeability. Electrical and capillary pressure properties were also measured on the core and these are incorporated into this interpretation.

MDT pressure gradients demonstrated that the Waarre C sands in Black Watch and Halladale are not in pressure communication, with a pressure offset of approximately 10 psi. Using the water pressure gradient data from DW3, the gas-water contact was defined as 1760 mTVDSS in Halladale and 1769 mTVDSS in Black Watch. The contact in Halladale was confirmed by an excellent correlation between the capillary pressure and resistivity calculated water saturations. The correlation in DW1 was good in some sands, but poorer in others. The poorest correlation is in DW1 WCII, where the resistivity calculated water saturation is significantly lower than the capillary pressure calculated saturation. This could be due to the sand being within a transition zone, but is more likely to be a thin bed effect on the resistivity logs. More detailed resistivity modelling than conducted in this study should be undertaken to confirm this interpretation.

The net sand thickness varied between 18.4 mMD in DW1 and 30.3 mMD in DW3. The average porosity in DW1 and DW2 is 22 – 23%. In DW3, the average porosity is 26%. All wells are calculated to have a geometric average permeability over 1 Darcy. All the net sand is interpreted to be net pay in DW1 and DW2, with the average water saturation being approximately 20%. No net pay is calculated to be present in DW3 as it is significantly below the gas-water contact for the Halladale discovery.

Waarre B

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1793.1	1821.6	28.5	18.2	27.0
Halladale-1 DW2	1827.2	1855.1	27.9	20.8	26.1
Halladale-1 DW3	1906.5	1935.7	29.2	28.0	25.8

The Waarre B is described as a silty claystone with common carbonaceous specks, trace glauconite, trace pyrite nodules and occasionally grades to a siltstone.

No net sand or net pay is interpreted to be present in this well.

Waarre A

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1821.6	1873.6	52.0	17.3	49.6
Halladale-1 DW2	1855.1	1897.9	42.8	20.5	40.1
Halladale-1 DW3	1935.7	1969.0	> 33.3	27.0	> 29.7

The Waarre A was the secondary target in the Halladale / Black Watch prospects.

The Waarre A in each well has a shaly upper interval with the best, cleanest sandstone being at the base. In DW1 and DW2, the net sand thickness ranges from 13.0 – 17.6 mMD with an average porosity of 20 – 21%. Average porosity in DW3 was calculated to be much higher (25%), but as no porosity logs were acquired across this interval and the porosity is calculated from the resistivity, low confidence should be held in this interpretation. Permeability was calculated from the MDT mobility data and is low confidence, since the scatter on the mobility / log porosity chart is very high.

DW1 intersected the gas-water contact was drilled in the Waarre A, with pressure data and log analysis showing the upper, shaly, sandstones to be gas bearing and the lower, cleaner sands to be water-wet. Consequently, only 1.3 mMD of net pay is calculated to be present in DW1 with an average water saturation of 51%. The gas saturation is likely to increase significantly up-dip and the net pay / net sand ratio is likely to increase significantly.

Eumeralla Formation

Well	Top (mRT)	Base (mRT)	Gross Thickness (mMD)	Inclination Through Formation	Gross Thickness (m AVT)
Halladale-1 DW1	1873.6	1918.0	> 44.4	16.5	> 42.6
Halladale-1 DW2	1897.9	1941.0	> 43.1	19.5	> 40.6
Halladale-1 DW3	Not penetrated				

DW1 and DW2 were still in the Eumeralla Formation at TD and, hence, the quoted thicknesses refer to drilled thickness, rather than formation thickness at this location. DW3 reached TD in the Waarre A, above the Eumeralla Formation.

The Eumeralla Formation is an interbedded sequence of very fine to medium sandstones and silty claystones. The sandstones have some clay matrix, silica or calcite cement.

The net sand thickness is from 1.0 to 6.1 mMD in DW2 and DW1 respectively. The average net sand porosity in DW1 and DW2 is approximately 19% and this is correlated to the MDT mobility to correspond with a permeability of 6 – 9 mD. Although some gas shows were recorded during drilling, especially at DW1, the MDT gradients confirmed poor mobility sandstone throughout. No net pay is interpreted to be present at this location, although these sands may become net pay further up-dip if they have a common GWC with the Waarre A sandstones, as appears likely from the DW1 pressure data.

Appendix A : Terrastation TCL Routine For Halladale-1 DW1

```
 * Mud properties RM (C7), RMF (C9), RMC (C5), MW (C25)
* Temperatures RM (C8), RMF (C10), RMC (C6)
* MW
        C25= 1.26 * 8.34
* Rm
        C7 = 0.1025
        C8 = 21.93
* Rmf
        C9 = 0.0788
        C10 = 20.64
* Rmc
        C5 = 0.1662
        C6 = 21.85
PRINT Mud Properties entered
*-------------------------------------------------------------------
* Temperature Log
*
SET DEPTH INTERVAL 1500 1917
* SET BHT (C13) and Depth (C20), Surface Temp (C14) and Depth (C34)
        C13 = 90.7
        C20 = 1849
        C14 = 10
        C34 = 66.3
C47 = @KEY(TVDSS)
if (C47 > 0)
        C50 = @SETDEPTH (C20)
        C50 = @GETVALUE (TVDSS)
        BEGIN
                VT= C14 + (C13 - C14) * (VTVDSS - C34) / (C50 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mTVDSS
else
        BEGIN
                VT= C14 + (C13 - C14) * (VDEPTH - C34) / (C20 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mMD
endif
PRINT Temperature Log Created
*-------------------------------------------------------------------
* Set depth picks in constant tracks as too slow from mapping file
*
* Nullawarre
        C27 = 1515.55
* Belfast
        C28 = 1565.13
* Flaxman
        C29 = 1723.10
* WC I
        C30 = 1770.72
* IWCS
        C31 = 1788.13
* WC II
        C32 = 1790.96
* Waarre B
        C33 = 1793.08
* Waarre A
        C38 = 1821.58
* Eumeralla
        C21 = 1873.6
*
*********************************************************************
* INTERPRETATION LOOP
*********************************************************************
SET DEPTH INTERVAL 1500 1917
BEGIN
```

```
******************************
* Set Parameters by Reservoir*
******************************
* Matrix GR (C61), Density (C62), Sonic (C63), Neutron (C64)
            C61 = 40
            C62 = 2.637
            C63 = 55
            C64 = -0.05
*
* Shale GR (C65), Density (C66), Sonic (C67), Neutron (C68), CEC (C19)
* Shale compaction factor (C57), Cut-off (C41)
            C65 = 125
            C66 = 2.42
            C67 = 102
            C68 = 0.35
            C19 = 1.49
            C57 = 25
            C59 = 0.24
*
* Fluid GR (C69), Density (C70), Sonic (C71), Neutron (C72)
            C69 = 10
            C70 = 1.0
            C71 = 189
            C72 = 1.0
*
* Net sand and net pay cut-offs
* VSH (< C40), Porosity (> C41), Permeability (> C42), Sw (< C43)
            C40 = 0.40
            C41 = 0.01
            C42 = 0.20
            C43 = 0.60
*-------------------------------------------------------------------
* Grain Density (C62), Fluid density (C70) and Fluid neutron (C72)
* Nullawarre
            if (VDEPTH > C27 & VDEPTH < C28)
                        C62 = 2.655
                        C70 = 0.6
                        C72 = 0.6
            endif
* Belfast
            if (VDEPTH > C28 & VDEPTH < C29)
                        C62 = 2.670
            endif
* Flaxman
            if (VDEPTH > C29 & VDEPTH < C30)
                        C62 = 2.670
            endif
* Waarre C Sand I
            if (VDEPTH > C30 & VDEPTH < C31)
                        C62 = 2.658
                        C70 = 0.4
                        C72 = 0.4
            endif
* IWCS
            if (VDEPTH > C31 & VDEPTH < C32)
                        C62 = 2.644
            endif
* Waarre C Sand II
            if (VDEPTH > C32 & VDEPTH < C33)
                        C62 = 2.637
                        C70 = 0.366
                        C72 = 0.4
            endif
* Waarre B
            if (VDEPTH > C33 & VDEPTH < C38)
                        C62 = 2.670
            endif
```

```
* Waarre A
        if (VDEPTH > C38 & VDEPTH < C21)
                C62 = 2.655
                C70 = 0.5
                C72 = 0.5
        endif
* Eumeralla
        if (VDEPTH > C21 & VDEPTH < C2)
                C62 = 2.670
        endif
*-------------------------------------------------
* Archie Parameters
* Set a (C16), m (C17), n (C18)
        C16= 1
        C17= 1.81
*
* 'n' in Nullawarre & Waarre A Formations
                C18 = 1.90
* 'n' in WC I
        if (VDEPTH > C30 & VDEPTH < C31)
                C18 = 1.84
        endif
* 'n' in WC II
        if (VDEPTH > C32 & VDEPTH < C33)
                C18 = 2.00
        endif
*-------------------------------------------------
* Water Resistivity
* Set Rw (C11) and RWT (C12)
*
* Rw in Nullawarre, Belfast & Flaxman
        if (VDEPTH > C27 & VDEPTH < C30)
                C11 = 0.403
                C12 = 25
        endif
* Rw in Waarre C
        if (VDEPTH > C30 & VDEPTH < C33)
                C11 = 0.294
                C12 = 25
        endif
* 'n' in WC II
        if (VDEPTH > C33 & VDEPTH < C2)
                C11 = 0.517
                C12 = 25
        endif
*
        VRW_T = C11 * (C12 + 21.5) / (VT + 21.5)
        VRMF_T = C9 * (C10 + 21.5) / (VT + 21.5)
*******************************************************************************
*******************************************************************************
*
* Shale volume determination
*
        VVSH_GRL = (VMDC_SGRC-C61)/(C65 - C61)
        V1375 = (C62 - C70) * (C72 - VMDC_SLSP) - (VMDC_SBD2 - C70) * (C72 - C64)
        V1376 = (C62 - C70) * (C72 - C68) - (C66 - C70) * (C72 - C64)
        VVSHND=V1375 / V1376
*
                VVSH = VVSH_GRL
                if (VDEPTH > 1869)
                        if (VVSHND < VVSH_GRL)
                                VVSH = VVSHND
                        endif
                endif
*
        if (VVSH < 0)
                VVSH=0
```

```
            endif
            if (VVSH > 1)
                        VVSH=1
            endif
*-------------------------------------------------------------------
*
* Porosity
            VPHI_D = (C62 - VMDC_SBD2) / (C62 - C70)
            VPHI_DW = (C62 - VMDC_SBD2) / (C62 - 1.00)
*
            VNPSC = VSLSP_SS - VVSH * 0.28
            VPHI_ND = @SQT((VPHI_DW^2 + VNPSC^2) / 2)
*
            VDTSC = VMDC_BATC - VVSH * 25
            VPHI_S = (VDTSC - C63) / (C71 - C63)
*
            VPHIT = VPHI_ND
*
* Flaxman Formation
            if (VDEPTH > 1722 & VDEPTH < 1735)
                        VPHIT = VPHI_D
            endif
* Waarre B
            if (VDEPTH > C33 & VDEPTH < C38)
                        VPHIT = VPHI_D
            endif
*
* Waarre C Sand II
            if (VDEPTH > 1791.28 & VDEPTH < 1797.40)
                        VPHIT = VCOREPORO / 100
            endif
            VPHIE = VPHIT - VVSH * 0.17
*
* Lithology Determination ----------------------------------------------
*
            C71 = 189
            C70 = 1.00
            C72 = 1.00
*
            VM= ((C71 - VMDC_BATC) / (VMDC_SBD2 - C70))*0.01
            VN= (C72 - VMDC_SLSP) / (VMDC_SBD2 - C70)
*
            VRHOMAA = (VMDC_SBD2 - VPHIT * C70) / (1 - VPHIT)
            VDTMAA = (VMDC_BATC - VPHIT * C71) / (1 - VPHIT)
            VUMAA = (VMDC_SNP2*((VMDC_SBD2+0.1883)/1.0704)-VPHIT*C73)/(1-VPHIT)
*
*-------------------------------------------------------------------
* Permeability Transforms
* Nullawarre
            if (VDEPTH > C27 & VDEPTH < C28)
                        C55 = 546.88
                        C56 = 4.3556
                        VPOPE = C55*(VPHIT ^ C56)
            endif
* Belfast
            if (VDEPTH > C28 & VDEPTH < C29)
                        C55 = 5 * 10^-5
                        C56 = 0.6369
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Flaxman
            if (VDEPTH > C29 & VDEPTH < C30)
                        C55 = 0.0023
                        C56 = 0.6206
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Waarre C Sand I
```

```
        if (VDEPTH > C30 & VDEPTH < C31)
                C55 = 0.0004
                C56 = 4.8012
                VPOPE = C55*((VPHIT*100) ^ C56)
        endif
* IWCS
        if (VDEPTH > C31 & VDEPTH < C32)
                C55 = 0.0023
                C56 = 0.6206
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Waarre C Sand II
        if (VDEPTH > C32 & VDEPTH < C33)
                if (VDEPTH > 1791.28 & VDEPTH < 1797.40)
                        VPOPE = VCOREPERM
                else
                        C55 = 4.0
                        C56 = 0.247
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
                endif
        endif
* Waarre B
        if (VDEPTH > C33 & VDEPTH < C38)
                C55 = 5 * 10^-5
                C56 = 0.6369
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Waarre A
        if (VDEPTH > C38 & VDEPTH < C21)
                C55 = 1.34 * 10^6
                C56 = 7.31
                VPOPE = C55*(VPHIT ^ C56)
        endif
* Eumeralla
        if (VDEPTH > C21 & VDEPTH < C2)
                C55 = 1.34 * 10^6
                C56 = 7.31
                VPOPE = C55*(VPHIT ^ C56)
        endif
*******************************************************************************
* WATER SATURATION
*******************************************************************************
*------------------------------------------------------------------------------
* Capillary Pressure Sw calculation
* Gas Gradient (C74), Water Gradient (C75), Oil Gradient (C60)
* J functions related to SW (C44, C45) and GWC (C35)
*
        if (VDEPTH > C30 & VDEPTH < C33)
* Waarre C Sand I
                if (VDEPTH > C30 & VDEPTH < C31)
                        C74 = 0.10
                        C75 = 0.42
                        C60 = 0.295
                        C44 = 74.766
                        C45 = -0.4092
                        C35 = 1769
                endif
* IWCS
                if (VDEPTH > C31 & VDEPTH < C32)
                        C74 = 0.10
                        C75 = 0.42
                        C60 = 0.295
                        C44 = 73.403
                        C45 = -0.1892
                        C35 = 1769
                endif
* Waarre C Sand II
```

```
                    if (VDEPTH > C32 & VDEPTH < C33)
                        C74 = 0.10
                        C75 = 0.42
                        C60 = 0.295
                        C44 = 54.434
                        C45 = -0.3313
                        C35 = 1769
                    endif
*
*
                    VHEIGHT = C35 - VTVDSS
*
                    VLEV_J = (((VHEIGHT * 3.28084 * (C75 - C74))*1.44)/50) * (VPOPE / VPHIT)^0.5
                    VSW_CP = (C44 * VLEV_J^C45) / 100
:END_CP
        endif
*
*-------------------------------------------------------------------------
* Archie Water saturation
        VSW_ARCH = ((C16/VPHIT^C17)*(VRW_T/VMDC_SEDP))^(1/C18)
*
*-------------------------------------------------------------------------
* Indonesia
*
* Shale Resistivity
*       Nullawarre & Belfast
        if (VDEPTH > 1500 & VDEPTH < C29)
            C19 = 2.0
        endif
*       Flaxman and deeper
        if (VDEPTH > C29 & VDEPTH < C30)
            C19 = 3.0
        endif
*
        C54 = (C16*VRW_T)/(VPHIE^C17)
        VSW_IND= ((VVSH^(0.5*(2-VVSH)))/(C19/VMDC_SEDP)^0.5+(VMDC_SEDP/C54))^(-2/C18)
        C54 = (C16*VRMF_T)/(VPHIE^C17)
        VSXO_IND=((VVSH^(0.5*(2-VVSH)))/(C19/VMDC_SEXP)^0.5+(VMDC_SEXP/C54))^(-2/C18)
        VSW_IND = ((VSW_IND * VPHIE) + (VPHIT-VPHIE)) / VPHIT
        VSXO_IND = ((VSXO_IND * VPHIE) + (VPHIT-VPHIE)) / VPHIT
*
*-------------------------------------------------------------
* Waxman Smits Water Saturation
* QV = CEC * RHOG * (1 - PORO) / (100 * PORO)
        VQV= 0.0083 * VPHIT ^ -1.7715
*
* B = (0.225 * T  - 1.28 + 0.0004059*T^2) / 1+Rw^1.23*(0.045T-0.27)
        VB=(0.225*VT-1.28+0.0004059*VT^2)/(1+VRW_T^1.23*(0.045*VT-0.27))
*
        VM_STAR = 1.88
        VA_STAR = 1.00
*
        VTERM1=((VA_STAR*VRW_T)/(VMDC_SEDP*VPHIT^VM_STAR))
*
        VSW_TP=VSW_ARCH
        VNWS_T1=1+VRW_T*VB*VQV
        C47=0
:LOOP
        C47=C47+1
        if (C47>20)
            OUTPUT NUMBER 10 3 VDEPTH
            OUTPUT TEXT Did not converge
            PRINT OUTPUT
            GOTO ENDLOOP
        endif
*
        VN_STAR = 2.2
```

```
            if (VDEPTH > C30 & VDEPTH < C31)
                        VN_STAR = 2.04
            endif
            if (VDEPTH >C32 & VDEPTH < V33)
                        VN_STAR = 2.19
            endif
            VSW_WS = ( VTERM1 * (1/(1+((VRW_T*VB*VQV)/VSW_TP))))^(1/VN_STAR)
            VTEST=@ABS(VSW_WS-VSW_TP)
*
            if (VTEST < 0.01)
                        GOTO ENDLOOP
            else
                        VSW_TP=VSW_WS
                        GOTO LOOP
            endif
:ENDLOOP
*
*-----------------------------------------------------------------
* Calculate SWT
*
            VSWT = VSW_IND
            if (VDEPTH > C30 & VDEPTH < C33)
                        VSWT = VSW_WS
            endif
*
*-----------------------------------------------------------------
* Calculate BVW
            VBVW= VSWT * VPHIT
            if (VBVW > VPHIT)
                        VBVW = VPHIT
            endif
*
*-----------------------------------------------------------------
* Net Sand / Net Pay Flags
            if (VVSH < C40 & VPOPE > C42)
                        VNETSAND = 1
            else
                        VNETSAND = 0
            endif
            if (VNETSAND = 1 & VSWT < C43)
                        VNETPAY = 1
            else
                        VNETPAY = 0
            endif
*******************************************************************************
ENDBEGIN
*******************************************************************************
PRINT STARS
OUTPUT TEXT Well Name:
OUTPUT WELLNAME
PRINT OUTPUT
PRINT SPACES
OUTPUT TEXT RESERVOIR    GROSS INTERVAL        NET SAND            NET PAY
PRINT OUTPUT
OUTPUT TEXT GROSS Top, Base, Thickness
PRINT OUTPUT
OUTPUT TEXT NETSAND Thickness, NTG, PHIT, PHIE, PERMEABILITY
PRINT OUTPUT
OUTPUT TEXT NETPAY Thickness, NTG, PHIT, PHIE, PERMEABILITY, Sw
PRINT OUTPUT
SET CURRENT ZONE INullawarre
C26 = 1
:AVERAGES
IF (C26 = 1)
            OUTPUT TEXT Nullawarre
ENDIF
IF (C26 = 2)
```

```
            OUTPUT TEXT Belfast
ENDIF
IF (C26 = 3)
            OUTPUT TEXT Flaxman
ENDIF
IF (C26 = 4)
            OUTPUT TEXT Waarre C Sand I
ENDIF
IF (C26 = 5)
            OUTPUT TEXT IWCS
ENDIF
IF (C26 = 6)
            OUTPUT TEXT Waarre C Sand II
ENDIF
IF (C26 = 7)
            OUTPUT TEXT Waarre B
ENDIF
IF (C26 = 8)
            OUTPUT TEXT Waarre A
ENDIF
IF (C26 = 9)
            OUTPUT TEXT Eumeralla
ENDIF
C37 = 0
C36 = 0
C54 = 0
C74 = 0
PRINT SPACES
BEGIN
            C36 = C36 + 1
            if (C36 = 1)
                        C75 = VDEPTH
            endif
            if (VNETSAND = 1)
                        C37 = C37 + 1
                        VVSH_NS = VVSH
                        VPHIT_NS = VPHIT
                        VPHIE_NS = VPHIE
                        VPOPE_NS = VPOPE
            endif
            if (VNETPAY = 1)
                        C54 = C54 + 1
                        VVSH_NP = VVSH
                        VPHIT_NP = VPHIT
                        VPHIE_NP = VPHIE
                        VPOPE_NP = VPOPE
                        VSW_NP = VSWT
            endif
            C47 = VDEPTH
ENDBEGIN
                        C48 = C47 - C75
                        C49 = C37 / C36
                        C50 = C49 * C48
                        C51 = C54 / C36
                        C52 = C51 * C48
                        C38 = @AMEAN(VSH_NS)
                        C39 = @AMEAN(PHIT_NS)
                        C40 = @AMEAN(PHIE_NS)
                        C41 = @GMEAN(POPE_NS)
                        C42 = @AMEAN(VSH_NP)
                        C43 = @AMEAN(PHIT_NP)
                        C44 = @AMEAN(PHIE_NP)
                        C45 = @GMEAN(POPE_NP)
                        C46 = @AMEAN(SW_NP)
*
* Gross Interval
OUTPUT NUMBER  7 1 C75
```

```
OUTPUT NUMBER  7 1 C47
OUTPUT NUMBER  6 1 C48
* Net Sand Parameters
OUTPUT NUMBER  6 1 C50
OUTPUT NUMBER  6 3 C49
OUTPUT NUMBER  6 3 C39
OUTPUT NUMBER  6 3 C40
OUTPUT NUMBER  8 2 C41
* Net Pay Parameters
OUTPUT NUMBER 6 1 C52
OUTPUT NUMBER 6 3 C51
OUTPUT NUMBER 6 3 C43
OUTPUT NUMBER 6 3 C44
OUTPUT NUMBER 8 2 C45
OUTPUT NUMBER 6 3 C46
PRINT OUTPUT
SET NEXT ZONE
        if (C26 = 9)
                PRINT STARS
                STOP
        else
                C26 = C26+1
        endif
GOTO AVERAGES
```

Appendix B : Terrastation TCL Routine For Halladale-1 DW2

```
**************************************************
* Mud properties RM (C7), RMF (C9), RMC (C5), MW (C25)
* Temperatures RM (C8), RMF (C10), RMC (C6)
* MW
        C25= 1.26 * 8.34
* Rm
        C7 = 0.078
        C8 = 20.6
* Rmf
        C9 = 0.075
        C10 = 19.9
* Rmc
        C5 = 0.091
        C6 = 21.0
PRINT Mud Properties entered
*-------------------------------------------------------------------
* Temperature Log
*
SET DEPTH INTERVAL 1500 1940
* SET BHT (C13) and Depth (C20), Surface Temp (C14) and Depth (C34)
        C13 = 90.7
        C20 = 1849
        C14 = 10
        C34 = 66.3
C47 = @KEY(TVDSS)
if (C47 > 0)
        C50 = @SETDEPTH (C20)
        C50 = @GETVALUE (TVDSS)
        BEGIN
                VT= C14 + (C13 - C14) * (VTVDSS - C34) / (C50 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mTVDSS
else
        BEGIN
                VT= C14 + (C13 - C14) * (VDEPTH - C34) / (C20 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mMD
endif
PRINT Temperature Log Created
*-------------------------------------------------------------------
* Set depth picks in constant tracks as too slow from mapping file
*
* Nullawarre
        C27 = 1538.48
* Belfast
        C28 = 1589.33
* Flaxman
        C29 = 1749.18
* WC I
        C30 = 1803.74
* IWCS
        C31 = 1820.22
* WC II
        C32 = 1821.91
* Waarre B
        C33 = 1827.17
* Waarre A
        C38 = 1855.07
* Eumeralla
        C21 = 1897.9
*
**********************************************************************
* INTERPRETATION LOOP
**********************************************************************
```

```
SET DEPTH INTERVAL 1500 1920
BEGIN
*******************************
* Set Parameters by Reservoir*
*******************************
* Matrix GR (C61), Density (C62), Sonic (C63), Neutron (C64)
            C61 = 40
            C63 = 55
            C64 = -0.05
*
* Shale GR (C65), Density (C66), Sonic (C67), Neutron (C68), CEC (C19)
* Shale compaction factor (C57), Cut-off (C41)
            C65 = 125
            C66 = 2.42
            C67 = 102
            C68 = 0.35
            C19 = 1.49
            C57 = 25
            C59 = 0.24
*
* Fluid GR (C69), Density (C70), Sonic (C71), Neutron (C72)
            C69 = 10
            C70 = 1.0
            C71 = 189
            C72 = 1.0
*
*-----------------------------------------------------------------
* Net Sand and Net Pay Cut-offs
* VSH (< C40), Porosity (> C41), Permeability (> C42), Sw (< C43)
            C40 = 0.40
            C41 = 0.01
            C42 = 0.20
            C43 = 0.50
*
*-----------------------------------------------------
* Archie Parameters
* Set a (C16), m (C17), n (C18)
            C16= 1
            C17= 1.81
*
* 'n' in Nullawarre & Waarre A Formations
                        C18 = 1.90
* 'n' in WC I
            if (VDEPTH > C30 & VDEPTH < C31)
                        C18 = 1.84
            endif
* 'n' in WC II
            if (VDEPTH > C32 & VDEPTH < C33)
                        C18 = 2.00
            endif
*-----------------------------------------------------
* Water Resistivity
* Set Rw (C11) and RWT (C12)
*
* Rw in Nullawarre, Belfast & Flaxman
            if (VDEPTH > C27 & VDEPTH < C30)
                        C11 = 0.403
                        C12 = 25
            endif
* Rw in Waarre C
            if (VDEPTH > C30 & VDEPTH < C33)
                        C11 = 0.294
                        C12 = 25
            endif
* 'n' in WC II
            if (VDEPTH > C33 & VDEPTH < C2)
                        C11 = 0.517
```

```
                C12 = 25
        endif
*
        VRW_T = C11 * (C12 + 21.5) / (VT + 21.5)
        VRMF_T = C9 * (C10 + 21.5) / (VT + 21.5)
*-------------------------------------------------------------------
* Grain Density (C62), 'n' (C18), Rw (C11)
*
* Nullawarre
        if (VDEPTH > C27 & VDEPTH < C28)
                C62 = 2.655
        endif
* Belfast
        if (VDEPTH > C28 & VDEPTH < C29)
                C62 = 2.670
        endif
* Flaxman
        if (VDEPTH > C29 & VDEPTH < C30)
                C62 = 2.670
        endif
* Waarre C Sand I
        if (VDEPTH > C30 & VDEPTH < C31)
                C62 = 2.658
        endif
* IWCS
        if (VDEPTH > C31 & VDEPTH < C32)
                C62 = 2.644
                C11 = 0.294
        endif
* Waarre C Sand II
        if (VDEPTH > C32 & VDEPTH < C33)
                C62 = 2.652
        endif
* Waarre B
        if (VDEPTH > C33 & VDEPTH < C38)
                C62 = 2.670
        endif
* Waarre A
        if (VDEPTH > C38 & VDEPTH < C21)
                C62 = 2.655
        endif
* Eumeralla
        if (VDEPTH > C21 & VDEPTH < C2)
                C62 = 2.670
        endif
*********************************************************************************
*
* Shale volume determination
*
*       Waarre C Unit Ia
        if (VDEPTH >= 1803 & VDEPTH < 1807.7)
                C62 = 2.659
                C70 = 0.7
                C72 = 0.27
        endif
*       Waarre C Unit Iaa
        if (VDEPTH >= 1807.7 & VDEPTH < 1809)
                C62 = 2.684
                C70 = 0.632
                C72 = 0.6
        endif
*       Waarre C Unit Ib
        if (VDEPTH >= 1809 & VDEPTH < 1810.4)
                C62 = 2.659
                C70 = 0.301
                C72 = 0.8
        endif
```

```
*       Waarre C Unit Ic i
        if (VDEPTH >= 1810.5 & VDEPTH < 1820.4)
                C62 = 2.659
                C70 = 0.301
                C72 = 0.4
        endif
*       Waarre C Unit Ic ii
        if (VDEPTH >= 1810.5 & VDEPTH < 1820.4)
                C62 = 2.659
                C70 = 0.301
                C72 = 0.4
        endif
*       Waarre C Unit Ic iii
        if (VDEPTH >= 1810.5 & VDEPTH < 1820.4)
                C62 = 2.659
                C70 = 0.301
                C72 = 0.4
        endif
*       Waarre C Unit Ic iv
        if (VDEPTH >= 1810.5 & VDEPTH < 1820.4)
                C62 = 2.659
                C70 = 0.301
                C72 = 0.4
        endif
*       Waarre C IWCS
        if (VDEPTH >= 1820.4 & VDEPTH < 1821.9)
                C62 = 2.679
                C70 = 0.056
                C72 = 1.0
        endif
*       Waarre C Unit II Upper
        if (VDEPTH >= 1821.9 & VDEPTH < 1823.2)
                C62 = 2.656
                C70 = 0.219
                C72 = 0.25
        endif
*       Waarre C Unit II Lower A
        if (VDEPTH >= 1823.2 & VDEPTH < 1827.0)
                C62 = 2.648
                C70 = 0.182
                C72 = 0.25
        endif
*       Waarre B PT2
        if (VDEPTH >= 1827.0 & VDEPTH < 1855.0)
                        C62 = 2.730
                        C72 = 1.00
                if (VMDC_SBD2 < 2.55)
                        C70 = -0.367
                else
                        C70 = 0.739
                endif
        endif
*
*
        VVSH_GRL = (VMDC_SGRC-C61)/(C65 - C61)
        V1375 = (C62 - C70) * (C72 - VMDC_SLSP) - (VMDC_SBD2 - C70) * (C72 - C64)
        V1376 = (C62 - C70) * (C72 - C68) - (C66 - C70) * (C72 - C64)
        VVSHND=V1375 / V1376
*
        if (VVSH_GRL <= VVSHND)
                VVSH = VVSH_GRL
        else
                VVSH = VVSHND
        endif
*
:ENDVSHCALC
        if (VVSH < 0)
```

```
                VVSH=0
        endif
        if (VVSH > 1)
                VVSH=1
        endif
*-------------------------------------------------------------------
*
* Porosity
*
        VPHI_D = (C62 - VMDC_SBD2) / (C62 - C70)
        VPHI_DW = (C62 - VMDC_SBD2) / (C62 - 1.00)
        VNPSC = VSLSP_SS - VVSH * 0.25
        VPHI_ND = @SQT((VPHI_DW^2 + VNPSC^2) / 2)
        VDTSC = VMDC_BATC - VVSH * 15
        VPHI_S = (VDTSC - C63) / (C71 - C63)
*
        VPHIT = VPHI_ND
*
        if (VDEPTH > 1749 & VDEPTH < 1766)
                VPHIT = VPHI_D
        endif
*
        if (VDEPTH > 1807.7 & VDEPTH < 1809.3)
                VPHIT = VCOREPORO / 100
                GOTO ENDPHI
        endif
        if (VDEPTH > 1810.5 & VDEPTH < 1832.0)
                VPHIT = VCOREPORO / 100
        endif
* Waarre B
        if (VDEPTH > 1831.9 & VDEPTH < C38)
                VPHIT = VPHI_D
        endif
:ENDPHI
        VPHIE = VPHIT - VVSH * 0.12
*
* Lithology Determination ----------------------------------------------
*
        C71 = 189
        C70 = 1.00
        C72 = 1.00
*
        VM= ((C71 - VMDC_BATC) / (VMDC_SBD2 - C70))*0.01
        VN= (C72 - VMDC_SLSP) / (VMDC_SBD2 - C70)
*
        VRHOMAA = (VMDC_SBD2 - VPHIT * C70) / (1 - VPHIT)
        VDTMAA = (VMDC_BATC - VPHIT * C71) / (1 - VPHIT)
        VUMAA = (VMDC_SNP2*((VMDC_SBD2+0.1883)/1.0704)-VPHIT*C73)/(1-VPHIT)
*
*-------------------------------------------------------------------
* Permeability Transforms
* Above Nullawarre
        if (VDEPTH > 1500 & VDEPTH < C27)
                        C55 = 5 * 10^-5
                        C56 = 0.6369
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Nullawarre
        if (VDEPTH > C27 & VDEPTH < C28)
                C55 = 546.88
                C56 = 4.3556
                VPOPE = C55*(VPHIT ^ C56)
        endif
* Belfast
        if (VDEPTH > C28 & VDEPTH < C29)
                C55 = 5 * 10^-5
                C56 = 0.6369
```

```
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Flaxman
        if (VDEPTH > C29 & VDEPTH < C30)
                C55 = 0.0023
                C56 = 0.6206
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Waarre C Sand I
        if (VDEPTH > C30 & VDEPTH < C31)
                C55 = 0.0004
                C56 = 4.8012
                VPOPE = C55*((VPHIT*100) ^ C56)
*
                if (VDEPTH > 1807.7 & VDEPTH < 1809.3)
                        VPOPE = VCOREPERM
                endif
                if (VDEPTH > 1810.5 & VDEPTH < 1817.2)
                        VPOPE = VCOREPERM
                endif
                if (VDEPTH > 1818.1)
                        VPOPE = VCOREPERM
                endif
        endif
* IWCS
        if (VDEPTH > C31 & VDEPTH < C32)
                C55 = 0.0023
                C56 = 0.6206
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Waarre C Sand II
        if (VDEPTH > C32 & VDEPTH < C33)
                VPOPE = VCOREPERM
        endif
* Waarre B
        if (VDEPTH > C33 & VDEPTH < C38)
                C55 = 5 * 10^-5
                C56 = 0.6369
                VPOPE = C55*@EXP((VPHIT*100) * C56)
        endif
* Waarre A
        if (VDEPTH > C38 & VDEPTH < C21)
                C55 = 1.34 * 10^6
                C56 = 7.31
                VPOPE = C55*(VPHIT ^ C56)
        endif
* Eumeralla
        if (VDEPTH > C21 & VDEPTH < C2)
                C55 = 1.34 * 10^6
                C56 = 7.31
                VPOPE = C55*(VPHIT ^ C56)
        endif
*
*************************************************************************
* WATER SATURATION
*************************************************************************
*------------------------------------------------------------------------
* Capillary Pressure Sw calculation
* Gas Gradient (C74), Water Gradient (C75), Oil Gradient (C60)
* J functions related to SW (C44, C45) and GWC (C35)
*
* Waarre C Sand I
        if (VDEPTH > C30 & VDEPTH < C31)
        C74 = 0.10
        C75 = 0.45
        C60 = 0.295
        C44 = 74.766
```

```
            C45 = -0.4092
            C35 = 1760.5
            endif
* IWCS
            if (VDEPTH > C31 & VDEPTH < C32)
            C74 = 0.10
            C75 = 0.45
            C60 = 0.295
            C44 = 73.403
            C45 = -0.1892
            C35 = 1760.5
            endif
* Waarre C Sand II
            if (VDEPTH > C32 & VDEPTH < C33)
            C74 = 0.10
            C75 = 0.45
            C60 = 0.295
            C44 = 51.738
            C45 = -0.3635
            C35 = 1760.5
            endif
*
*
            VHEIGHT = C35 - VTVDSS
            if (VHEIGHT < 0)
                        VSW_CP = 1
                        GOTO END_CP
            endif
            VLEV_J = (((VHEIGHT * 3.28084 * (C75 - C74))*1.44)/50) * (VPOPE / VPHIT)^0.5
            VSW_CP = (C44 * VLEV_J^C45) / 100
:END_CP
*
*-------------------------------------------------------------------------
* Archie Water saturation
            VSW_ARCH = ((C16/VPHIT^C17)*(VRW_T/VMDC_SEDP))^(1/C18)
*
*-------------------------------------------------------------------------
* Indonesia
*
* Shale Resistivity
*           Nullawarre & Belfast
            if (VDEPTH > 1500 & VDEPTH < C29)
                        C19 = 2.0
            endif
*           Flaxman and deeper
            if (VDEPTH > C29 & VDEPTH < C30)
                        C19 = 3.0
            endif
*
            C54 = (C16*VRW_T)/(VPHIE^C17)
            VSW_IND= ((VVSH^(0.5*(2-VVSH)))/(C19/VMDC_SEDP)^0.5+(VMDC_SEDP/C54))^(-2/C18)
            C54 = (C16*VRMF_T)/(VPHIE^C17)
            VSXO_IND=((VVSH^(0.5*(2-VVSH)))/(C19/VMDC_SEXP)^0.5+(VMDC_SEXP/C54))^(-2/C18)
            VSW_IND = ((VSW_IND * VPHIE) + (VPHIT-VPHIE)) / VPHIT
            VSXO_IND = ((VSXO_IND * VPHIE) + (VPHIT-VPHIE)) / VPHIT
*
*-------------------------------------------------------------
* Waxman Smits Water Saturation
* QV = CEC * RHOG * (1 - PORO) / (100 * PORO)
            VQV= 0.0083 * VPHIT ^ -1.7715
*
* B = (0.225 * T  - 1.28 + 0.0004059*T^2) / 1+Rw^1.23*(0.045T-0.27)
            VB=(0.225*VT-1.28+0.0004059*VT^2)/(1+VRW_T^1.23*(0.045*VT-0.27))
*
            VM_STAR = 1.88
            VA_STAR = 1.00
*
```

```
            VTERM1=((VA_STAR*VRW_T)/(VMDC_SEDP*VPHIT^VM_STAR))
*
            VSW_TP=VSW_ARCH
            VNWS_T1=1+VRW_T*VB*VQV
            C47=0
:LOOP
            C47=C47+1
            if (C47>20)
                        OUTPUT NUMBER 10 3 VDEPTH
                        OUTPUT TEXT Did not converge
                        PRINT OUTPUT
                        GOTO ENDLOOP
            endif
*
            VN_STAR = 2.2
            if (VDEPTH > C30 & VDEPTH < C31)
                        VN_STAR = 2.04
            endif
            if (VDEPTH >C32 & VDEPTH < V33)
                        VN_STAR = 2.19
            endif
            VSW_WS = ( VTERM1 * (1/(1+((VRW_T*VB*VQV)/VSW_TP))))^(1/VN_STAR)
            VTEST=@ABS(VSW_WS-VSW_TP)
*
            if (VTEST < 0.01)
                        GOTO ENDLOOP
            else
                        VSW_TP=VSW_WS
                        GOTO LOOP
            endif
:ENDLOOP
*
*-------------------------------------------------------------
* Calculate SWT
*
            VSWT = VSW_IND
            if (VDEPTH > C30 & VDEPTH < C33)
                        VSWT = VSW_WS
            endif
*
*-------------------------------------------------------------
* Calculate BVW
            VBVW= VSWT * VPHIT
            if (VBVW > VPHIT)
                        VBVW = VPHIT
            endif
*
*-------------------------------------------------------------
* Net Sand / Net Pay Flags
            if (VVSH < C40 & VPOPE > C42)
                        VNETSAND = 1
            else
                        VNETSAND = 0
            endif
            if (VNETSAND = 1 & VSWT < C43)
                        VNETPAY = 1
            else
                        VNETPAY = 0
            endif
*
            if (VDEPTH > 1920)
                        VNETSAND = 0
                        VNETPAY = 0
            endif
*****************************************************************************
ENDBEGIN
*****************************************************************************
```

```
PRINT STARS
OUTPUT TEXT Well Name:
OUTPUT WELLNAME
PRINT OUTPUT
PRINT SPACES
OUTPUT TEXT RESERVOIR    GROSS INTERVAL        NET SAND            NET PAY
PRINT OUTPUT
OUTPUT TEXT GROSS Top, Base, Thickness
PRINT OUTPUT
OUTPUT TEXT NETSAND Thickness, NTG, PHIT, PHIE, PERMEABILITY
PRINT OUTPUT
OUTPUT TEXT NETPAY Thickness, NTG, PHIT, PHIE, PERMEABILITY, Sw
PRINT OUTPUT
SET CURRENT ZONE INullawarre
C26 = 1
:AVERAGES
IF (C26 = 1)
        OUTPUT TEXT Nullawarre
ENDIF
IF (C26 = 2)
        OUTPUT TEXT Belfast
ENDIF
IF (C26 = 3)
        OUTPUT TEXT Flaxman
ENDIF
IF (C26 = 4)
        OUTPUT TEXT Waarre C Sand I
ENDIF
IF (C26 = 5)
        OUTPUT TEXT IWCS
ENDIF
IF (C26 = 6)
        OUTPUT TEXT Waarre C Sand II
ENDIF
IF (C26 = 7)
        OUTPUT TEXT Waarre B
ENDIF
IF (C26 = 8)
        OUTPUT TEXT Waarre A
ENDIF
IF (C26 = 9)
        OUTPUT TEXT Eumeralla
ENDIF
C37 = 0
C36 = 0
C54 = 0
C74 = 0
PRINT SPACES
BEGIN
        C36 = C36 + 1
        if (C36 = 1)
                C75 = VDEPTH
        endif
        if (VNETSAND = 1)
                C37 = C37 + 1
                VVSH_NS = VVSH
                VPHIT_NS = VPHIT
                VPHIE_NS = VPHIE
                VPOPE_NS = VPOPE
        endif
        if (VNETPAY = 1)
                C54 = C54 + 1
                VVSH_NP = VVSH
                VPHIT_NP = VPHIT
                VPHIE_NP = VPHIE
                VPOPE_NP = VPOPE
                VSW_NP = VSWT
```

```
        endif
        C47 = VDEPTH
ENDBEGIN
                C48 = C47 - C75
                C49 = C37 / C36
                C50 = C49 * C48
                C51 = C54 / C36
                C52 = C51 * C48
                C38 = @AMEAN(VSH_NS)
                C39 = @AMEAN(PHIT_NS)
                C40 = @AMEAN(PHIE_NS)
                C41 = @GMEAN(POPE_NS)
                C42 = @AMEAN(VSH_NP)
                C43 = @AMEAN(PHIT_NP)
                C44 = @AMEAN(PHIE_NP)
                C45 = @GMEAN(POPE_NP)
                C46 = @AMEAN(SW_NP)
*
* Gross Interval
OUTPUT NUMBER  7 1 C75
OUTPUT NUMBER  7 1 C47
OUTPUT NUMBER  6 1 C48
* Net Sand Parameters
OUTPUT NUMBER  6 1 C50
OUTPUT NUMBER  6 3 C49
OUTPUT NUMBER  6 3 C39
OUTPUT NUMBER  6 3 C40
OUTPUT NUMBER  8 2 C41
* Net Pay Parameters
OUTPUT NUMBER 6 1 C52
OUTPUT NUMBER 6 3 C51
OUTPUT NUMBER 6 3 C43
OUTPUT NUMBER 6 3 C44
OUTPUT NUMBER 8 2 C45
OUTPUT NUMBER 6 3 C46
PRINT OUTPUT
SET NEXT ZONE
        if (C26 = 9)
                PRINT STARS
                STOP
        else
                C26 = C26+1
        endif
GOTO AVERAGES
```

Appendix C : Terrastation TCL Routine For Halladale-1 DW3

```
**********************************************
* Mud properties RM (C7), RMF (C9), RMC (C5), MW (C25)
* Temperatures RM (C8), RMF (C10), RMC (C6)
* MW
        C25= 1.26 * 8.34
* Rm
        C7 = 0.078
        C8 = 20.6
* Rmf
        C9 = 0.075
        C10 = 19.9
* Rmc
        C5 = 0.091
        C6 = 21.0
PRINT Mud Properties entered
*-------------------------------------------------------------------
* Temperature Log
*
SET DEPTH INTERVAL 1450 1960
* SET BHT (C13) and Depth (C20), Surface Temp (C14) and Depth (C34)
        C13 = 90.7
        C20 = 1849
        C14 = 10
        C34 = 66.3
C47 = @KEY(TVDSS)
if (C47 > 0)
        C50 = @SETDEPTH (C20)
        C50 = @GETVALUE (TVDSS)
        BEGIN
                VT= C14 + (C13 - C14) * (VTVDSS - C34) / (C50 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mTVDSS
else
        BEGIN
                VT= C14 + (C13 - C14) * (VDEPTH - C34) / (C20 - C34)
        ENDBEGIN
        PRINT Temperature calculated in mMD
endif
PRINT Temperature Log Created
**********************************************************************
* INTERPRETATION LOOP ***********************************************
**********************************************************************
* Set depth picks in constant tracks as too slow from mapping file
*
* Nullawarre
        C27 = 1497.62
* Belfast
        C28 = 1547.77
* Flaxman
        C29 = 1798.11
* WC I
        C30 = 1869.74
* IWCS
        C31 = 1886.16
* WC II
        C32 = 1890.26
* Waarre B
        C33 = 1906.54
* Waarre A
        C38 = 1935.70
* Eumeralla
        C21 = 1969.0
*
* Set Parameters by Reservoir*
*****************************
```

```
* Matrix GR (C61), Density (C62), Sonic (C63), Neutron (C64)
        C61 = 40
        C63 = 55
        C64 = -0.05
*
* Shale GR (C65), Density (C66), Sonic (C67), Neutron (C68), Res (C19)
* Shale compaction factor (C57), Cut-off (C41)
        C65 = 125
        C66 = 2.42
        C67 = 102
        C68 = 0.35
        C19 = 1.6
        C57 = 25
        C59 = 0.24
*
* Fluid GR (C69), Density (C70), Sonic (C71), Neutron (C72)
        C69 = 10
        C70 = 1.0
        C71 = 189
        C72 = 1.0
*-----------------------------------------------------------------
* Net sand and net pay cut-offs
* VSH (< C40), Porosity (> C41), Permeability (> C42), Sw (< C43)
        C40 = 0.40
        C41 = 0.01
        C42 = 0.20
        C43 = 0.60
*-----------------------------------------------------------------
BEGIN
* Grain Density
* Nullawarre
        if (VDEPTH > C27 & VDEPTH < C28)
                C62 = 2.655
        endif
* Belfast
        if (VDEPTH > C28 & VDEPTH < C29)
                C62 = 2.670
        endif
* Flaxman
        if (VDEPTH > C29 & VDEPTH < C30)
                C62 = 2.670
        endif
* Waarre C Sand I
        if (VDEPTH > C30 & VDEPTH < C31)
                C62 = 2.658
        endif
* IWCS
        if (VDEPTH > C31 & VDEPTH < C32)
                C62 = 2.644
        endif
* Waarre C Sand II
        if (VDEPTH > C32 & VDEPTH < C33)
                C62 = 2.652
        endif
* Waarre B
        if (VDEPTH > C33 & VDEPTH < C38)
                C62 = 2.670
        endif
* Waarre A
        if (VDEPTH > C38 & VDEPTH < C21)
                C62 = 2.655
        endif
* Eumeralla
        if (VDEPTH > C21 & VDEPTH < C2)
                C62 = 2.670
        endif
*-----------------------------------------------------
```

```
* Archie Parameters
* Set a (C16), m (C17), n (C18)
        C16= 1
        C17= 1.81
*
* 'n' in Nullawarre & Waarre A Formations
                C18 = 1.90
* 'n' in WC I
        if (VDEPTH > C30 & VDEPTH < C31)
                C18 = 1.84
        endif
* 'n' in WC II
        if (VDEPTH > C32 & VDEPTH < C33)
                C18 = 2.00
        endif
*-------------------------------------------------
* Water Resistivity
* Set Rw (C11) and RWT (C12)
*
* Rw in Nullawarre, Belfast & Flaxman
        if (VDEPTH > C27 & VDEPTH < C30)
                C11 = 0.403
                C12 = 25
        endif
* Rw in Waarre C
        if (VDEPTH > C30 & VDEPTH < C33)
                C11 = 0.294
                C12 = 25
        endif
* 'n' in WC II
        if (VDEPTH > C33 & VDEPTH < C2)
                C11 = 0.517
                C12 = 25
        endif
*
        VRW_T = C11 * (C12 + 21.5) / (VT + 21.5)
        VRMF_T = C9 * (C10 + 21.5) / (VT + 21.5)
*
*******************************************************************************
*******************************************************************************
*
* Shale volume determination
*
        VVSH_GRL = (VMDC_SGRC-C61)/(C65 - C61)
        V1375 = (C62 - C70)*(C72 - VMDC_SLSP)-(VMDC_SBD2 - C70)*(C72 - C64)
        V1376 = (C62 - C70)*(C72 - C68)-(C66 - C70)*(C72 - C64)
        VVSHND=V1375 / V1376
*
        if (VVSH_GRL < VVSHND)
                VVSH = VVSH_GRL
        else
                VVSH = VVSHND
        endif
        if (VDEPTH > 1943)
                VVSH = VVSH_GRL
        endif
*
        if (VVSH < 0)
                VVSH=0
        endif
        if (VVSH > 1)
                VVSH=1
        endif
*-------------------------------------------------------------------------
*
* Porosity
        VPHI_D = (C62 - VMDC_SBD2) / (C62 - C70)
```

```
            VPHI_DW = (C62 - VMDC_SBD2) / (C62 - 1.00)
*
            VNPSC = VSLSP_SS - VVSH * 0.25
            VPHI_ND = (VPHI_DW + VNPSC) / 2
*
            VDTSC = VMDC_BATC - VVSH * 15
            VPHI_S = (VDTSC - C63) / (C71 - C63)
*
            VPHI_R = ((C16 * VRW_T) / (VMDC_SEDP)) ^ (1 / C17)
*
            VPHIT = VPHI_ND
*
* Waarre B
            if (VDEPTH > C33 & VDEPTH < C38)
                        VPHIT = VPHI_D
            endif
*
            if (VDEPTH > 1943)
                        VPHIT = VPHI_R
            endif
*
            VPHIE = VPHIT - VVSH * 0.17
*
* Lithology Determination ----------------------------------------------
*
            C71 = 189
            C70 = 1.00
            C72 = 1.00
*
            VM= ((C71 - VMDC_BATC) / (VMDC_SBD2 - C70))*0.01
            VN= (C72 - VMDC_SLSP) / (VMDC_SBD2 - C70)
*
            VRHOMAA = (VMDC_SBD2 - VPHIT * C70) / (1 - VPHIT)
            VDTMAA = (VMDC_BATC - VPHIT * C71) / (1 - VPHIT)
            VUMAA = (VMDC_SNP2*((VMDC_SBD2+0.1883)/1.0704)-VPHIT*C73)/(1-VPHIT)
*
*-------------------------------------------------------------------------
* Permeability Transforms
* Nullawarre
            if (VDEPTH > C27 & VDEPTH < C28)
                        C55 = 546.88
                        C56 = 4.3556
                        VPOPE = C55*(VPHIT ^ C56)
            endif
* Belfast
            if (VDEPTH > C28 & VDEPTH < C29)
                        C55 = 5 * 10^-5
                        C56 = 0.6369
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Flaxman
            if (VDEPTH > C29 & VDEPTH < C30)
                        C55 = 0.0023
                        C56 = 0.6206
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Waarre C Sand I
            if (VDEPTH > C30 & VDEPTH < C31)
                        C55 = 0.0004
                        C56 = 4.8012
                        VPOPE = C55*((VPHIT*100) ^ C56)
            endif
* IWCS
            if (VDEPTH > C31 & VDEPTH < C32)
                        C55 = 0.0023
                        C56 = 0.6206
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
```

```
            endif
* Waarre C Sand II
            if (VDEPTH > C32 & VDEPTH < C33)
                        C55 = 4.0
                        C56 = 0.247
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Waarre B
            if (VDEPTH > C33 & VDEPTH < C38)
                        C55 = 5 * 10^-5
                        C56 = 0.6369
                        VPOPE = C55*@EXP((VPHIT*100) * C56)
            endif
* Waarre A
            if (VDEPTH > C38 & VDEPTH < C21)
                        C55 = 1.34 * 10^6
                        C56 = 7.31
                        VPOPE = C55*(VPHIT ^ C56)
            endif
* Eumeralla
            if (VDEPTH > C21 & VDEPTH < C2)
                        C55 = 1.34 * 10^6
                        C56 = 7.31
                        VPOPE = C55*(VPHIT ^ C56)
            endif
*-------------------------------------------------------------------
*
* Archie Water saturation
            VSW_ARCH = ((C16/VPHIT^C17)*(VRW_T/VMDC_SEDP))^(1/C18)
*
*
* Calculate BVW
            VBVW=VSW_ARCH*VPHIT
            if (VBVW > VPHIE)
                        VBVW = VPHIE
            endif
*
* Net Sand / Net Pay Flags
            if (VVSH < C40 & VPOPE > C42)
                        VNETSAND = 1
            else
                        VNETSAND = 0
            endif
            if (VNETSAND = 1 & VSW_ARCH < C43)
                        VNETPAY = 1
            else
                        VNETPAY = 0
            endif
ENDBEGIN
*
*-------------------------------------------------------------------
PRINT STARS
OUTPUT TEXT Well Name:
OUTPUT WELLNAME
PRINT OUTPUT
PRINT SPACES
OUTPUT TEXT RESERVOIR    GROSS INTERVAL        NET SAND            NET PAY
PRINT OUTPUT
OUTPUT TEXT GROSS Top, Base, Thickness
PRINT OUTPUT
OUTPUT TEXT NETSAND Thickness, NTG, PHIT, PHIE, PERMEABILITY
PRINT OUTPUT
OUTPUT TEXT NETPAY Thickness, NTG, PHIT, PHIE, PERMEABILITY, Sw
PRINT OUTPUT
SET CURRENT ZONE INullawarre
C26 = 1
:AVERAGES
```

```
IF (C26 = 1)
        OUTPUT TEXT Nullawarre
ENDIF
IF (C26 = 2)
        OUTPUT TEXT Belfast
ENDIF
IF (C26 = 3)
        OUTPUT TEXT Flaxman
ENDIF
IF (C26 = 4)
        OUTPUT TEXT Waarre C Sand I
ENDIF
IF (C26 = 5)
        OUTPUT TEXT IWCS
ENDIF
IF (C26 = 6)
        OUTPUT TEXT Waarre C Sand II
ENDIF
IF (C26 = 7)
        OUTPUT TEXT Waarre B
ENDIF
IF (C26 = 8)
        OUTPUT TEXT Waarre A
ENDIF
IF (C26 = 9)
        OUTPUT TEXT Eumeralla
ENDIF
*
C37 = 0
C36 = 0
C54 = 0
C74 = 0
PRINT SPACES
BEGIN
        C36 = C36 + 1
        if (C36 = 1)
                C75 = VDEPTH
        endif
        if (VNETSAND = 1)
                C37 = C37 + 1
                VVSH_NS = VVSH
                VPHIT_NS = VPHIT
                VPHIE_NS = VPHIE
                VPOPE_NS = VPOPE
        endif
        if (VNETPAY = 1)
                C54 = C54 + 1
                VVSH_NP = VVSH
                VPHIT_NP = VPHIT
                VPHIE_NP = VPHIE
                VPOPE_NP = VPOPE
                VSW_NP = VSW_ARCH
        endif
        C47 = VDEPTH
ENDBEGIN
                C48 = C47 - C75
                C49 = C37 / C36
                C50 = C49 * C48
                C51 = C54 / C36
                C52 = C51 * C48
                C38 = @AMEAN(VSH_NS)
                C39 = @AMEAN(PHIT_NS)
                C40 = @AMEAN(PHIE_NS)
                C41 = @GMEAN(POPE_NS)
                C42 = @AMEAN(VSH_NP)
                C43 = @AMEAN(PHIT_NP)
                C44 = @AMEAN(PHIE_NP)
```

```
                    C45 = @GMEAN(POPE_NP)
                    C46 = @AMEAN(SW_NP)
*
* Gross Interval
OUTPUT NUMBER  7 1 C75
OUTPUT NUMBER  7 1 C47
OUTPUT NUMBER  6 1 C48
* Net Sand Parameters
OUTPUT NUMBER  6 1 C50
OUTPUT NUMBER  6 3 C49
OUTPUT NUMBER  6 3 C39
OUTPUT NUMBER  6 3 C40
OUTPUT NUMBER  8 2 C41
* Net Pay Parameters
OUTPUT NUMBER 6 1 C52
OUTPUT NUMBER 6 3 C51
OUTPUT NUMBER 6 3 C43
OUTPUT NUMBER 6 3 C44
OUTPUT NUMBER 8 2 C45
OUTPUT NUMBER 6 3 C46
PRINT OUTPUT
SET NEXT ZONE
        if (C26 = 9)
                    PRINT STARS
                    STOP
        else
                    C26 = C26+1
        endif
GOTO AVERAGES
```

[i] Sperry Sun LWD Tool Nomenclature

GR = Gamma Ray,

ACAL = Acoustic caliper,

SCO2 = Density standoff correction,

SBD2 = Density,

SLSP = limestone neutron porosity,

SNP2 = PEF

BATC = acoustic sonic tool

SEXP = micro-resistivity

SESP = shallow resistivity

SEMP = Medium resistivity

SEDP = Deep resistivity

[ii] Baker Hughes Wireline Tool Nomenclature

ORIT = Orientation tool

STAR =

XMAC = Cross Multi-pole Array Acoustilog

DSL =

RCI = Reservoir Characterisation Instrument (similar to the Schlumberger MDT)

PCL = Pipe conveyed logging

Halladale-1 DW-1 (Black Watch)

Permit: Exploration	**RTE:** 21.5 m	**TD (logs):** 1917.3 m
Latitude : 38° 34’ 45.54’ S	**Bit Size:** 216.0 mm	**BHT:** 90.7 degC
Longtitude : 142° 43’ 50.95’ E	**Rm:** 0.102 ohmm at: 21.9 degC	**Vertical Scale** 1:500 m
Easting :	**Rmf:** 0.079 ohmm at: 20.6 degC	**Interpreter :** Andy Hall
Northing :	**Rmc:** 0.166 ohmm at: 21.9 degC	
Datum :	**Plot created on:** 24/Oct/05 at: 15:48: 3	

MDC_SGRC 0 (API) 150 | MDC_ACAL 150 (in) 500 | MDC_SROP 0 (m/hr) 180 | Depth (m) (1:500) | TVDSS (m) (1:500)

MDC_SCO2 -1.5 (g/cc) 0.5 | MDC_SBD2 1.95 (g/cc) 2.95 | MDC_SLSP 0.45 (frac) -0.15 | WIR_DT 560 (us/m) 150 | MDC_SNP2 0 (brne) 10 | MDC_BATC 140 (us/f) 40

MDC_SEXP 20 (%) 200000 | MDC_SEMP 0.2 (ohmm) 2000 | MDC_SEDP 0.2 (ohmm) 2000 | MDC_SESP 0.2 (ohmm) 2000

WMDCSEXP 0.2 (ohmm) 2000 | WMDCSESP 0.2 (ohmm) 2000 | WMDCSEMP 0.2 (ohmm) 2000 | WMDCSEDP 0.2 (ohmm) 2000

VSH_GRL 0 (frac) 1 | VSHND 0 (frac) 1

POROSITY 30 (%) 0 | PHI_S 0.3 0 | PHI_ND 0.3 0 | PHI_D 0.3 0

PHIE 0.3 0 | PHIT 0.3 0

SW_ARCH 1 (frac) 0

POPE 0.1 10000

VSH_GRL 0 1 | Bulk Volume Water (BVW) 1 0 | Bulk Volume Water (BVW) 1 0 | PHIT 1 0 | VSH_GRL 0 1

NETSAND 0 2 | NETPAY 2 0

Core Data

Pressures

Samples

Era

Skull Creek

Nullawarre (1515.55)

Nullawarre

Belfast (1565.13)

Belfast

Flaxman (1723.10)

Flaxman

Waarre_C (1770.72)

Waarre C

IWCS (1788.13)

WCII (1790.96)

Waarre_B (1793.08)

Waarre B

Waarre_A (1821.58)

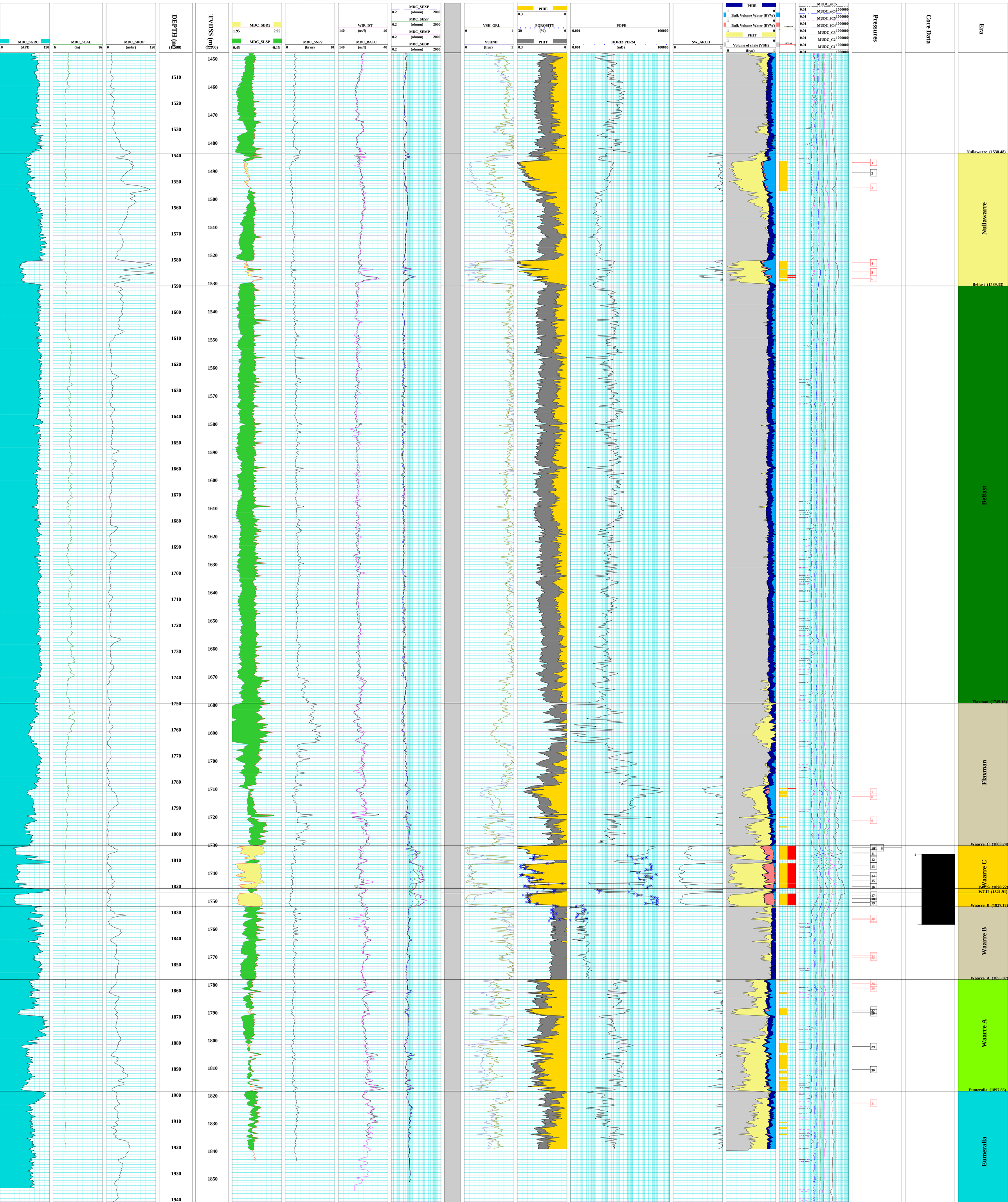
Waarre A

Eumeralla (1873.56)

Eumeralla

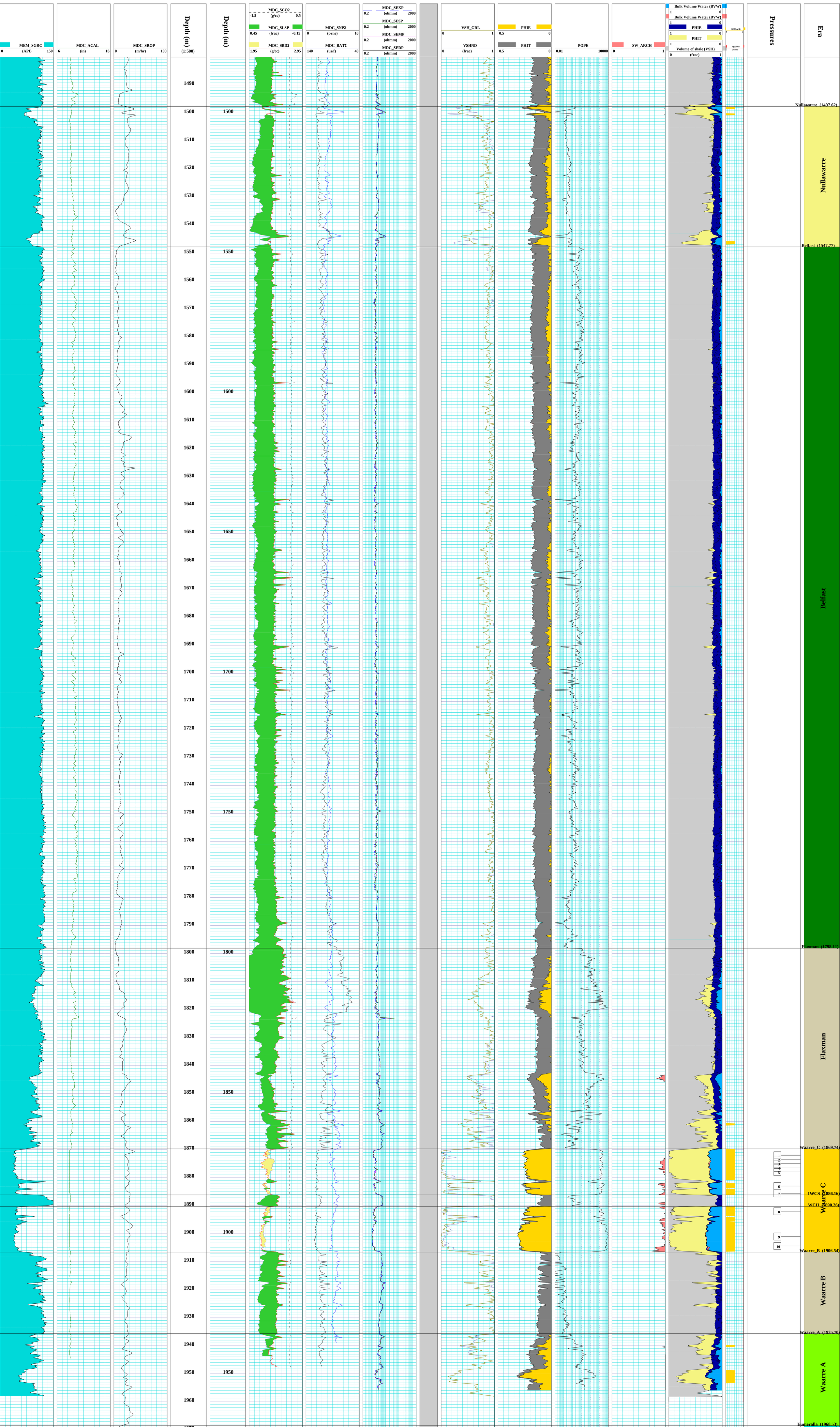
Halladale-1 DW-2

Permit: Exploration	**RTE:** 21.5 m	**TD (logs):** 1945.1 m
Latitude : 38° 34’ 45.67’ S	**Bit Size:** 216.0 mm	**BHT:** 90.7 degC
Longtitude : 148° 43’ 50.82’ E	**Rm:** 0.078 UNKN at: 20.6 degC	**Vertical Scale** 1:500 m
Easting :	**Rmf:** 0.075 UNKN at: 19.9 degC	**Interpreter :** Andy Hall
Northing :	**Rmc:** 0.091 UNKN at: 21.0 degC	
Datum :	**Plot created on:** 24/Oct/05 **at:** 15:46:37	



Halladale-1 DW3

Permit: Exploration	**RTE:** 21.5 m	**TD (logs):** 1969.0 m
Latitude : 38° 34' 45.67' S	**Bit Size:** 216.0 mm	**BHT:** 90.7 degC
Longtitude : 148° 43' 50.82' E	**Rm:** 0.078 UNKN at: 20.6 degC	**Vertical Scale** 1:500 m
Easting :	**Rmf:** 0.075 UNKN at: 19.9 degC	**Interpreter :** Andy Hall
Northing :	**Rmc:** 0.091 UNKN at: 21.0 degC	
Datum :	**Plot created on:** 24/Oct/05 at: 15:49: 9	



APPENDIX 2:
RCI INTERPRETATION REPORT

Halladale-1 DW1,DW2 & DW3

INTERPRETATION OF RESERVOIR CHARACTERIZATION INSTRUMENT (RCI)

OCTOBER 2005

DATE OF SURVEYS:
06/4/2005(DW1)
18/4/2005(DW2)
25/4/2005(DW3)

Origin Energy Resources Limited
Second Floor, South Tower, John Oxley Centre
339 Coronation Drive
MILTON QLD 4064

Joe Parver, April 2007

Baker Atlas RCI tool was used to obtain pressure data and collect reservoir fluid samples from Halladale-1 DW1, DW2 and DW3.

DW1 RCI Program (06/04/2005):

The DW1 first RCI program (logging run #2-pressure only) had pre-tests taken from 1519.5mMD to 1865.5mMD covering Nullawarre, Waarre C and Waarre A sands. During the first RCI program a total of 34 pre-tests were attempted of which 25 were successful and 9 were tight. A second RCI run (logging run#3-sample only) was carried out to collect fluid samples. The RCI tool got stuck after performing a fall off test at the first sample point (1772.6 mMD). Several attempts made to free the tool were unsuccessful. Finally two 840 cc fluid samples were collected at this point before a fishing operation being carried out. Eventually drill pipe was run to free the RCI tool. No more attempts were made to collect more samples.

DW2 RCI Program (18/04/2005):

The DW2 first RCI Program (logging run #2-pressure only) had pre-test taken from 1542.0mMD down to 1846.0mMD covering the Nullawarre and Waarre C sands. The RCI tool got stuck at 1852.0mMD after 23 pre-tests were taken. The tool eventually came free and was pulled out of the hole. A second RCI run (logging run#3-pressure and sample) was carried out using pipe convey logging (PCL) operation in order to perform additional pre-tests (8 pre-tests within Waarre A) and collect fluid samples (3 fluid samples from Waarre C). During the DW2 first and second RCI programs a total of 31 pre-tests were attempted of which 15 were successful and 16 were tight. Three RCI fluid samples (gas) were also taken at 1804.6mMD.

DW3 RCI Program (24/04/2005):

Halladale-1 DW-3 was drilled as an appraisal well targeting the water zone in Waarre C in order to define a water line. The DW3 RCI program (logging run #1-pressure only) had pre-tests taken from 1872.0mMD to 1904.4mMD covering Waarre C water zone. During the RCI program a total of 10 pre-tests were attempted which all were successful. No attempts were made to collect fluid samples.

A summary of the pre-test data for DW1, DW2 and DW3 are included in Appendix 8 of Halladale-1 WCR Basic Data.

During the DW1 and DW2 RCI programs a total of 5 samples were collected from Waarre C. The descriptions of these samples are shown below while the fluid composition and PVT analysis of the collected samples are included in Appendix 8 of the Halladale-1 WCR Basic Data.

Halladale-1 DW1

2x840 CC Gas sample from Waarre C at 1772.6 mMD
(CO2=0.5%, N2=2.0%, C1+C2=92.9%, C3+C4=2.7% & C5+=1.9%)

Halladale-1 DW2

3x 840 CC Gas sample from Waarre C at 1804.6 mMD
(CO2=0.4%, N2=1.4%, C1+C2=94.8%, C3+C4=1.9% & C5+=1.5%)

The interpretation of the RCI data is presented in Figures 3 to 5 while Figures 1 and 2 demonstrate data validation and quality check.

Figure 1 shows the initial mud hydrostatic pressure recorded by Baker Hughes RCI gauges for DW1, DW2 and DW3. The data indicates a gradient of 0.549 psi/ft equivalent to a mud density of 1.266 g/cc at the downhole conditions which is also consistent with the reported drilling data (1.26 g/cc).

Figure 2 illustrates the difference between the initial and final mud hydrostatic pressures recorded by Baker Hughes RCI gauges for DW1, DW2 and DW3. As shown in this plot the difference between these measurements is mainly close to zero (+/- 1.0 psi).

Figure3 shows all the RCI points from DW1, DW2 and DW3 recorded in the Waarre C and Waarre A. The DW1 Waarre C pre-test points lie on a gas trend with a gradient of 0.059 psi/ft equivalent to a gas density of 0.136 g/cc at the reservoir conditions and consistent with compositional analysis of the collected gas samples at this level (SG=0.66). Meanwhile, most of the DW1 Waarre A pre-test points are within the water zone except two points which seem to fit the aforementioned Waarre C gas line.

The DW2 Waarre C pre-test points also lie on a gas trend with similar gradient as DW1. Meanwhile, all of the DW2 Waarre A pre-test points appear to be within the water zone.

The DW-3 RCI data, which were measured to define a water line for the Waarre C sand, is also shown in this plot. The DW3 Waarre C pre-test points fit a water line with a gradient of 0.429 psi/ft equivalent to a water salinity of 18,000 ppm.

The intersects of the DW1 and DW2 Waarre C gas lines with DW3 Waarre C water line define gas water contacts for Black Watch (DW1) and Halladale (DW2) at 1770.0 and 1760.0 mss respectively. Meanwhile, a water line with a gradient of 0.429 psi/ft (similar to the DW3 Waarre C gradient) drawn through DW1 and DW2 Waarre A water points intersects the DW1 Waarre A gas line (which are superimposed by the Waarre C gas line) at 1766.0 mss as shown in this plot.

The trends of regional water line (based on the onshore RFT data) and Minerva water line are also shown in this plot.

Figure 4 shows the RFT pre-test points from some of the onshore and offshore wells and the position of Halladale-1 (DW1, DW2 and DW3) profile with respect to these data.

Figure 5 shows the DW1 and DW2 RCI data recorded in Nullawarre Formation. Most of the DW1 pre-tests appear to be supercharged. However a few limited valid RCI points together with the information from other hydrocarbon indicators (gas shows and density/neutron crossovers) indicate a potential for two separate gas columns which have been referred to Nullawarre upper and lower sands in this plot. On the basis of this assumption two gas lines with similar gradient as the Waarre C were drawn through the valid RCI points to represent these two gas columns. No water line can be interpreted from the DW1 pre-tests.

Almost all the DW2 Nullawarre RCI pre-tests are tight except one point which appears to be permeable. The mud log data does not indicate high gas reading for DW2 Nullawarre sand in this well. It was also assumed that the aforementioned single permeable RCI point in DW2 is a valid water point. Based on those assumptions a water line (with similar gradient as the Waarre C) was drawn through the DW2 only RCI point to represent Nullawarre water line.

On the basis of the above assumptions the estimated gas water contacts for the Nullawarre upper and lower sands are 1481.0 and 1515.0 mss.

The trend of a water line fitted through McIntee Nullawarre RFT points is also shown in this plot.

A summary of the results are shown in the following table.

Formation	RCI Profile	Fluid	Black Watch GWC (mss)	Halladale GWC (mss)
Waarre C	**Figure 4**	**Gas**	**1770.0**	**1760.0**
Waarre A	**Figure 4**	**Gas**	**1766.0**	**-**
Upper Nullawarre	**Figure 6**	**Gas**	**1481.0 (Est.)**	**-**

Lower Nullawarre	**Figure 6**	**Gas**	**1515.0 (Est.)**	**-**

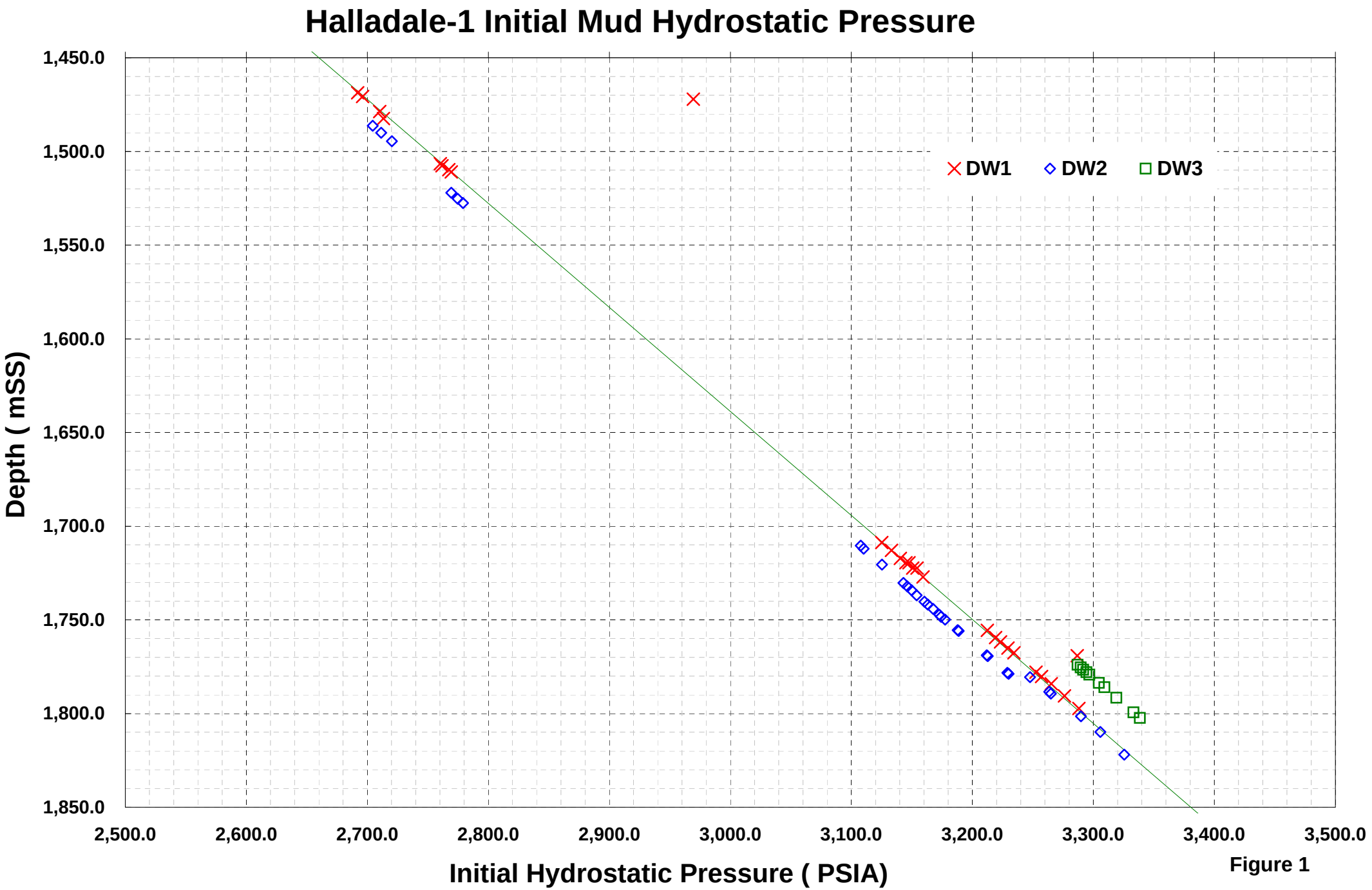

Halladale-1 Initial Mud Hydrostatic Pressure
1,450.0
1,500.0
1,550.0
1,600.0
1,650.0
1,700.0
1,750.0
1,800.0
1,850.0
Depth (mSS)
DW1
DW2
DW3
2,500.0
2,600.0
2,700.0
2,800.0
2,900.0
3,000.0
3,100.0
3,200.0
3,300.0
3,400.0
3,500.0
Initial Hydrostatic Pressure (PSIA)

Figure 1

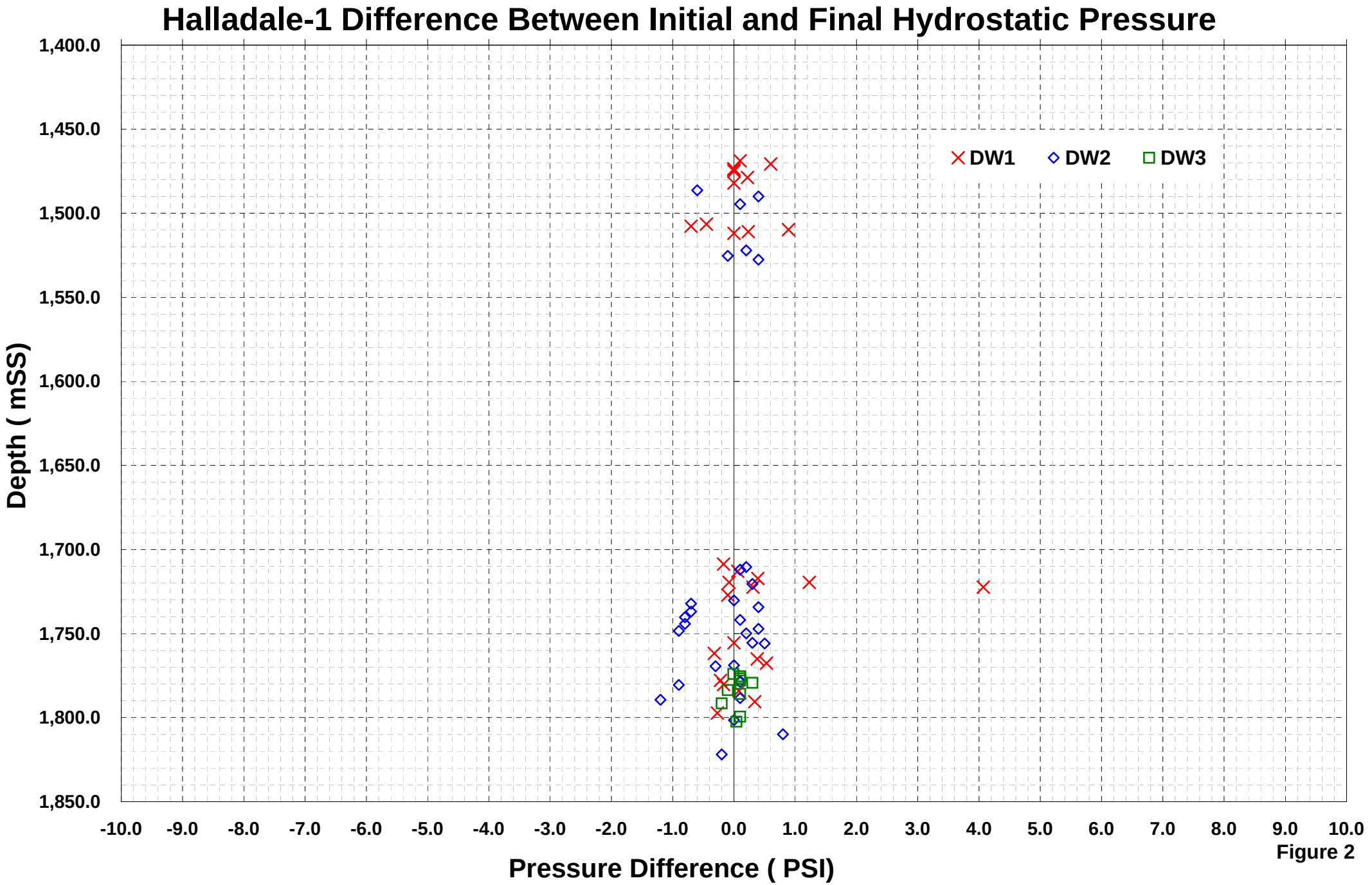

Halladale-1 Difference Between Initial and Final Hydrostatic Pressure
1,400.0
1,450.0
1,500.0
1,550.0
1,600.0
1,650.0
1,700.0
1,750.0
1,800.0
1,850.0
Depth (mSS)
DW1
DW2
DW3
-10.0
-9.0
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Pressure Difference (PSI)

Figure 2

Halladale-1 DW1,DW2 &DW3 Waarre Pressure v.s. Depth Profile

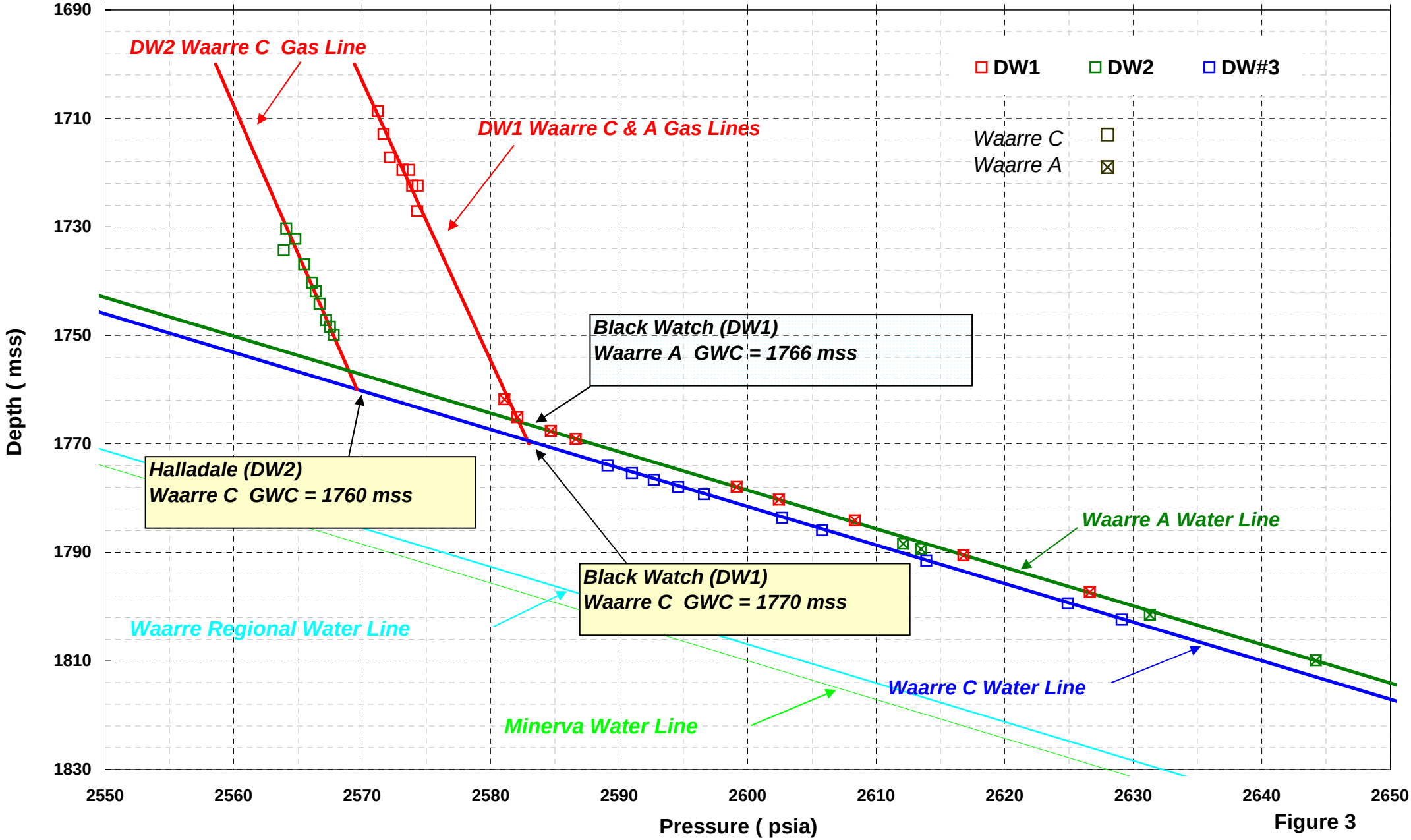


Figure 3

WAARRE FORMATION RFT PLOT

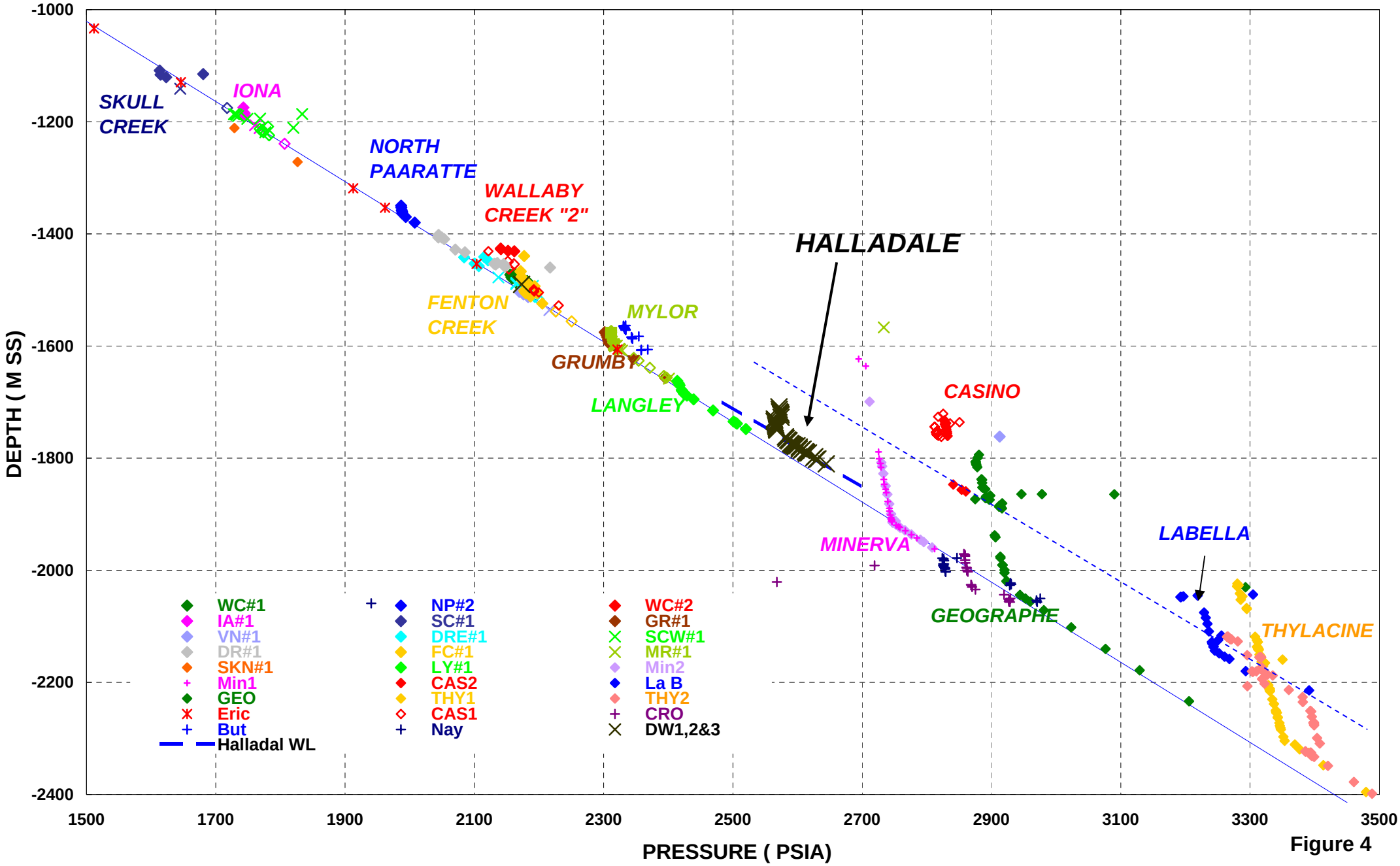


Figure 4

DW1&DW2 Nullawarre Pressure v.s. Depth Profile

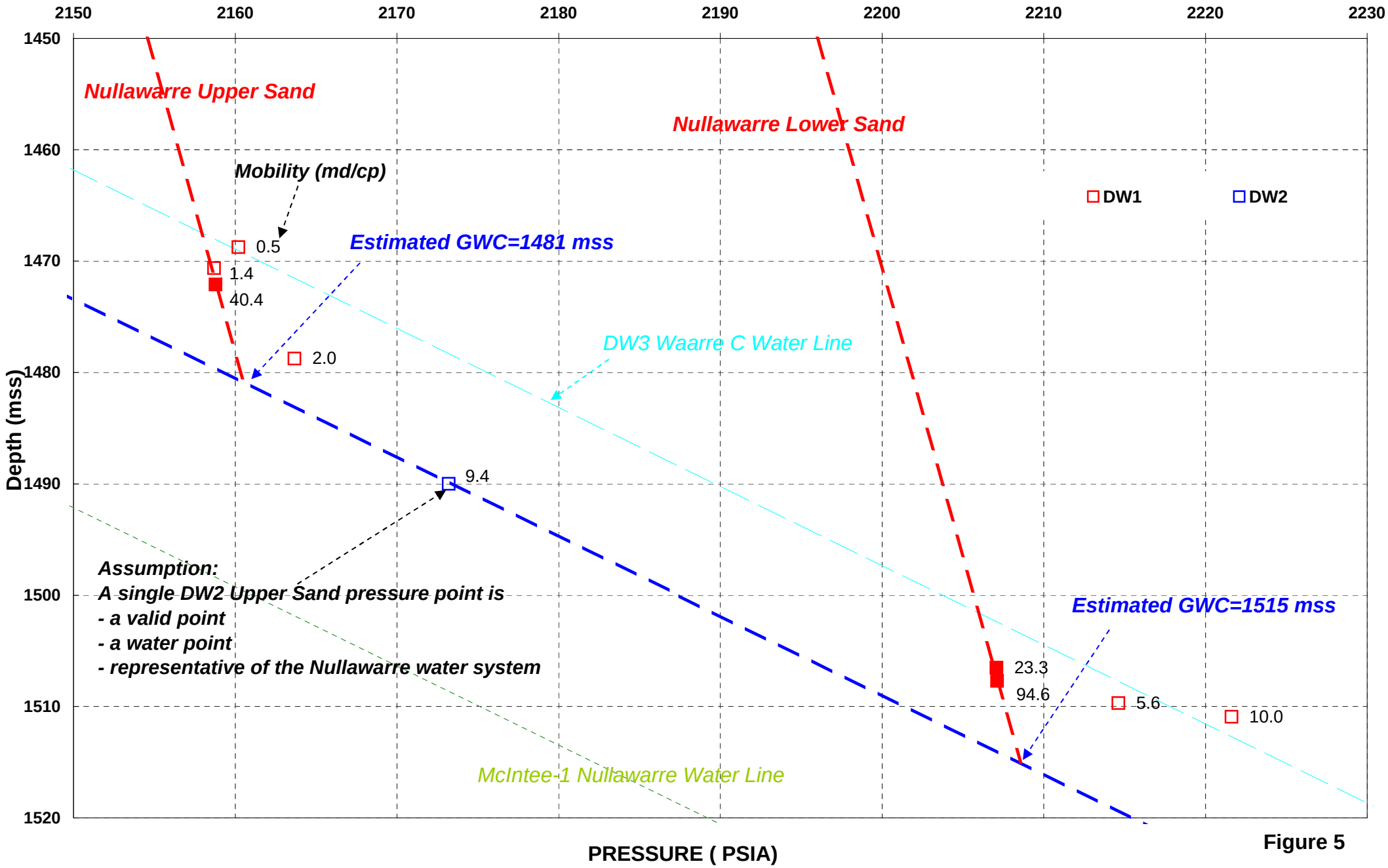


Figure 5

APPENDIX 3:
MUD GAS ISOTOPE REPORT

Geochemical Interpretation of Halladale Gas, VIC/P37(V), Otway Basin

Bob Davis

Petroleum Systems Analysis Team
GeoSolutions, Exploration and New Ventures

February 2006

ABN 63 005 482 986

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EXECUTIVE SUMMARY

A suite of isotubes and MDT gases from Halladale-1 DW-1 (Black Watch), DW-2 (Halladale) and DW-3 were subjected to compositional and isotopic analysis. Halladale gas is fairly dry, and was probably expelled from isotopically heavy humic or mixed humic/lacustrine organic matter within the early to peak gas window. The low concentration of carbon dioxide in these gases most likely derives from low maturity Type III organic matter. Gases from Waarre C sands in DW-1 and DW-2 are isotopically distinctive, suggesting they are in separate compartments. This is supported by pressure profiles, which display an offset of c. 10 psi. There is no convincing evidence of flow barriers between the Waarre A and C sands in Halladale-1 DW-1, and Waarre C sands in DW-2 and DW-3 although significant variability within isotope values hints at poor communication.

At least three families of gases are present in the Shipwreck Trough. Family 1 includes Halladale, Boggy Creek, Casino, Fenton Creek, Lavers and Mylor. Family 2 consists of Geographe, Thylacine and La Bella, whereas Family 3 contains Minerva and (the unrelated accumulation) Port Fairy. There is evidence of multiple source rocks or multiple charge events contributing to the Halladale accumulation.

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1 Business Case

With the discovery of gas at Halladale in April 2005, a need to characterise the gas for integration with existing data, and further calibration of the charge model was identified. This report summarises the state of our knowledge of the chemistry of Otway gases to date.

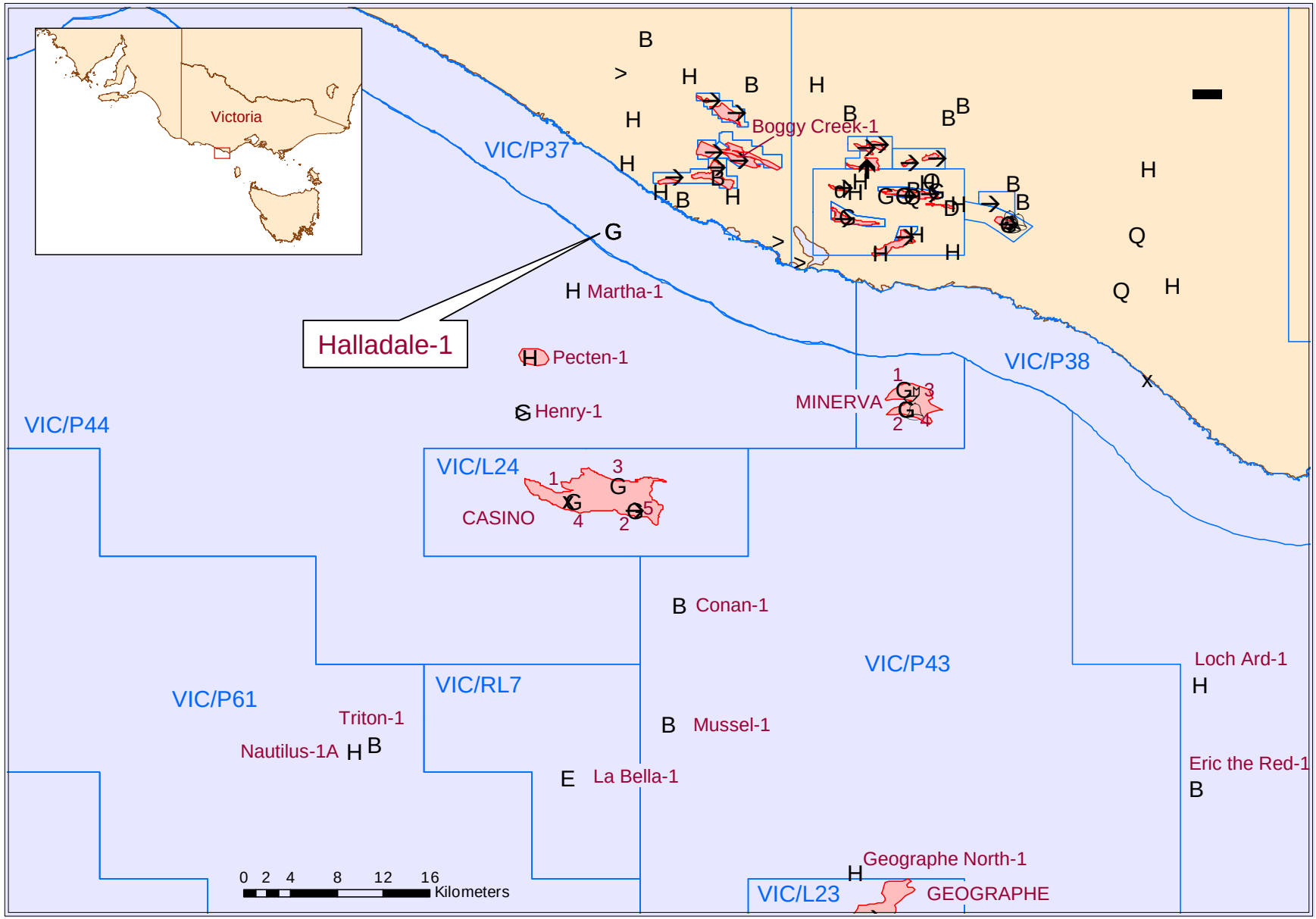

Figure 1: Location map

2 Introduction

2.1 Background

Halladale-1 (38°34'45.54"S, 142°43'50.95"E) was spudded on 22nd April 2005 in 45 m (LAT) of water, on the western flank of the Shipwreck Trough, VIC/P37(V), some 4 km from the coast of Victoria (Figure 1). Drilling operations were managed by Woodside Energy Ltd (62.5% equity) under an agreement with the operator, Origin Energy (37.5% equity). Three wells were drilled in succession from the Halladale-1 location. Halladale-1 DW-1 (Black Watch prospect) deviated to the south and intersected a gross gas-bearing interval of 59m TVT in the Waarre Formation. Halladale-1 DW-2 (Halladale prospect) deviated to the north and intersected a gross gas-bearing interval of 21m TVT in the Waarre Formation. Halladale-1 DW-3 was deviated down-flank from the Halladale gas to the northeast, to obtain aquifer pressures in the Waarre Formation.

2.2 Mud Gas Isotopes

A total of 78 isotubes were collected from the three Halladale wells, comprising 33 from DW-1, 27 from DW-2 and 18 from DW-3. Compositional analyses were performed on all samples, followed by isotope analysis of selected mud gases. The results of mud gas analysis are presented in Table 1 and plotted in Figure 2.

The majority of the well section, from c. 1210m to c. 1860m TVDSS, yields isotopically heavy methane, with $\delta^{13}C$ values ranging from -35‰ to -32‰. This is characteristic of very mature gas - much more so than attained by the sediments penetrated by the well, suggesting pervasive migration of high maturity gas throughout the sedimentary column. Almost all samples cluster tightly on methane vs. ethane and ethane vs. propane plots in Figure 3 and Figure 4, suggesting gas of similar provenance pervades the entire section. An exception is thin sands within the Paaratte Formation, which in DW-2 yield isotopically lighter methane ($\delta^{13}C$ of -40‰). This is confirmed by a similar result in DW-3, though no isotope results were obtained for this interval in DW-1 (Figure 2). Isotopically lighter methane suggests these sands have been charged with gas of lower average maturity, however substantially heavier ethane ($\delta^{13}C$ of -18‰) suggests higher maturity. Both of these observations may be accounted for by another mechanism – biodegradation and methanogenesis – suggesting the Paaratte gas may be in contact with artesian water.

Well	Isotech Lab No.	Sample Date	Sample Time	MDKB Meters	TVDSS Meters	Gas Units %	GC Date	O_2 + Ar ppm	CO_2 ppm	N_2 ppm	CO ppm	C_1 ppm	C_2 ppm	C_2H_4 ppm	C_3 ppm	C_3H_6 ppm	iC_4 ppm	nC_4 ppm	iC_5 ppm	nC_5 ppm	C_6+ ppm	$\delta^{13}C_1$ per mil	$\delta^{13}C_2$ per mil	$\delta^{13}C_3$ per mil	Comments
DW-1	89606	3/30/2005	12:45	850	827	0.0203	9/29/2005	219600	660	779700	0	4	0	0	0	0	0	0	0	0	1				
DW-1	89607	3/31/2005	3:01	908.8	886.6	0.011	9/29/2005	219700	430	779900	0	4	0	0	0	0	0	0	0	0	2				
DW-1	89608	3/31/2005	4:03	951.7	929.1	0.052	9/29/2005	209900	4300	785700	0	68	3	0	1	1	1	0	3	1	57				
DW-1	89609	3/31/2005	5:21	1003	979.4	0.052	9/29/2005	207200	5300	787400	0	58	3	1	1	1	1	0	2	1	67				
DW-1	89610	3/31/2005	6:07	1050.7	1025.3	0.119	9/29/2005	204600	4800	790100	0	428	6	3	1	1	1	0	2	1	65				
DW-1	89611	3/31/2005	7:22	1101	1072.9	0.152	9/29/2005	200300	6100	793100	0	404	11	7	1	1	1	0	2	1	69				
DW-1	89612	3/31/2005	8:34	1150	1118.9	0.092	9/29/2005	207000	6900	785800	0	213	9	6	1	1	1	0	1	0	33				
DW-1	89613	3/31/2005	10:04	1200	1166.6	0.104	9/29/2005	203300	4800	791500	0	292	10	3	10	1	12	10	5	3	62				
DW-1	89614	3/31/2005	11:58	1248.6	1211.9	1.376	9/29/2005	201600	6300	787700	140	3950	174	40	21	6	19	11	6	4	71	-34.9	-19.2		
DW-1	89615	3/31/2005	12:01	1250.3	1213.6	0.508	9/29/2005	201300	6800	787900	30	3610	175	10	22	2	22	12	7	4	67				
DW-1	89616	3/31/2005	14:08	1300	1260.6	0.04	9/29/2005	219800	690	779500	0	28	1	0	0	0	0	0	0	0	4				
DW-1	89617	3/31/2005	16:01	1350.3	1308.3	0.1	9/29/2005	214800	4800	779600	0	720	24	1	3	0	6	2	2	1	19				
DW-1	89618	3/31/2005	18:02	1400	1355.5	0.59	9/29/2005	210700	6200	777100	0	5450	336	1	102	1	20	20	5	3	16	-34.5			
DW-1	89619	3/31/2005	20:58	1436.4	1390	2	9/29/2005	199700	6200	749100	0	42600	1630	0	489	1	72	83	19	14	45				
DW-1	89620	3/31/2005	21:00	1436.6	1390.2	4.1	9/29/2005	193300	6400	731500	0	65200	2500	0	737	1	107	121	28	21	67	-32.6	-23.5	-22.8	
DW-1	89621	3/31/2005	21:37	1450.2	1403.1	1.17	9/29/2005	207600	6900	774300	0	10300	586	0	219	0	35	45	10	8	34	-33.1			
DW-1	89622	4/01/2005	12:22	1500	1450.3	1.07	9/29/2005	204200	9000	775600	0	10200	601	0	255	1	45	58	14	11	47	-33.0			
DW-1	89623	4/01/2005	1:27	1521.4	1470.6	5.881	9/29/2005	195800	8600	745700	0	47600	1570	0	467	1	70	85	19	15	50	-32.9	-23.6	-22.9	
DW-1	89624	4/01/2005	1:33	1522.2	1471.3	5.838	9/29/2005	199400	7900	747600	0	43000	1420	0	423	1	63	77	17	14	41				
DW-1	89625	4/01/2005	1:48	1535.3	1483.7	23.015	9/29/2005	159600	9100	629100	0	193000	6700	0	1810	1	234	265	56	43	99	-33.0	-23.3	-23.1	
DW-1	89626	4/01/2005	2:27	1550	1497.7	1.181	9/29/2005	212500	5200	775100	0	6620	349	0	129	0	20	27	6	5	22	-32.4			
DW-1	89627	4/01/2005	3:04	1566.1	1512.9	11.56	9/29/2005	187000	7100	699400	0	101700	3420	1	958	1	130	149	32	25	58				
DW-1	89628	4/01/2005	3:06	1567.5	1514.3	22.495	9/29/2005	167400	8000	636600	0	179500	6190	0	1690	1	220	248	53	40	93	-33.1	-23.4	-22.3	
DW-1	89629	4/01/2005	4:19	1600	1545	1.307	9/29/2005	209500	8100	773300	0	8420	419	0	130	0	22	31	8	7	33	-33.0	-23.5	-23.4	
DW-1	89630	4/01/2005	6:31	1650	1592.4	1.202	9/29/2005	208100	8600	774200	0	8640	338	0	61	1	14	19	7	6	32	-33.6			
DW-1	89631	4/01/2005	8:25	1700	1639.9	1.038	9/29/2005	197100	6400	788400	0	7470	449	2	134	1	19	23	8	7	37	-32.9	-24.0	-23.5	
DW-1	89632	4/01/2005	10:35	1750	1687.3	0.437	9/29/2005	216600	3400	777900	0	1910	104	0	36	0	5	7	2	2	10	-32.7			
DW-1	89633	4/01/2005	11:52	1778.9	1714.6	31.91	9/29/2005	142200	9900	548200	0	282200	12400	0	3750	3	493	495	102	75	149	-33.9	-23.8	-23.4	
DW-1	89634	4/01/2005	12:27	1785.5	1721	41.02	9/30/2005	127300	10500	516500	0	325000	14500	0	4560	3	620	624	130	96	173	-33.3	-22.9	-22.3	
DW-1	89635	4/04/2005	6:18	1800.4	1735.1	0.1	9/30/2005	218100	760	780300	0	749	50	0	16	0	2	3	1	1	6				
DW-1	89636	4/04/2005	8:14	1852.5	1784.8	0.31	9/30/2005	217000	1100	777800	0	3800	189	0	56	0	7	9	2	2	7	-33.3	-23.7	-22.6	cryo-enrichment
DW-1	89637	4/04/2005	14:05	1900	1830.4	0.05	9/30/2005	216600	2000	780700	0	596	26	0	13	0	3	5	1	1	8				
DW-1	89638	4/04/2005	16:44	1918	1847.7	0.09	9/30/2005	215700	2600	781100	0	566	21	0	9	0	3	4	2	1	9				
DW-2	89639	4/11/2005	12:50	901.5	879.4	0.021	9/30/2005	216000	110	783800	0	23	2	0	2	0	1	1	2	1	23				
DW-2	89640	4/11/2005	2:41	950.2	928.1	0.028	9/30/2005	212400	100	787300	0	143	5	0	2	0	2	1	3	2	50				
DW-2	89641	4/11/2005	4:22	1001.9	979.5	0.028	9/30/2005	209200	80	790600	0	92	3	0	1	0	1	1	3	1	49				
DW-2	89642	4/11/2005	6:06	1056.3	1033.2	0.047	9/30/2005	215000	110	784700	0	186	4	0	2	0	1	1	1	1	35				
DW-2	89643	4/11/2005	8:01	1107.1	1082.3	0.03	9/30/2005	212800	130	786800	0	187	4	0	1	0	1	1	1	1	26				
DW-2	89644	4/11/2005	10:02	1150.1	1123.6	0.041	9/30/2005	212900	110	786900	0	64	2	0	1	0	1	1	1	0	18				
DW-2	89645	4/11/2005	13:45	1200	1170.3	0.06	9/30/2005	212200	150	787400	0	195	4	1	2	0	3	2	2	1	25				
DW-2	89646	4/11/2005	16:30	1250	1216.7	0.71	9/30/2005	211500	130	782300	0	5710	256	1	56	0	12	10	4	3	36	-35.0			
DW-2	89647	4/11/2005	19:00	1300	1262.9	0.34	9/30/2005	210700	110	786300	0	2590	131	2	43	1	16	12	7	4	48	-39.3			
DW-2	89648	4/11/2005	21:24	1350	1309	0.21	9/30/2005	211200	110	787400	0	1100	56	3	20	1	12	7	5	3	35	-38.9			
DW-2	89649	4/12/2005	2:35	1400	1354.9	0.202	9/30/2005	211700	110	786900	0	1160	80	0	25	0	9	8	5	3	37	-33.6			
DW-2	89650	4/12/2005	9:20	1450	1400.9	0.51	9/30/2005	213400	130	781700	0	4280	289	1	116	0	19	26	7	6	41	-32.4	-23.5	-22.9	
DW-2	89651	4/12/2005	16:30	1500	1447.3	0.35	9/30/2005	215100	170	781900	0	2560	112	1	51	0	12	17	6	5	36	-32.4			
DW-2	89652	4/13/2005	19:00	1550	1493.8	0.79	9/30/2005	211200	320	779800	0	8320	258	0	59	1	7	9	3	3	22	-32.7	-23.7	-22.8	
DW-2	89653	4/13/2005	20:30	1600	1540.2	0.78	9/30/2005	210800	330	780800	0	7640	322	0	71	1	8	10	3	3	21	-33.1	-24.2	-23.5	
DW-2	89654	4/14/2005	0:32	1650	1586.6	0.53	9/30/2005	213500	560	782100	0	3590	149	6	25	1	5	5	2	2	19	-33.0			
DW-2	89655	4/14/2005	5:38	1700	1633	0.59	9/30/2005	210700	810	783800	0	4480	183	1	37	1	5	4	2	1	10	-33.0			
DW-2	89656	4/14/2005	17:30	1750	1679.5	0.26	9/30/2005	210400	220	787300	0	1900	86	1	28	0	4	6	2	2	8	-32.3			
DW-2	89657	4/14/2005	21:10	1783	1710.2	3.52	9/30/2005	199600	290	748700	0	49500	1450	0	346	1	40	44	9	7	21	-32.3	-23.1	-22.8	
DW-2	89658	4/15/2005	0:37	1800	1726.1	0.99	9/30/2005	210900	290	780600	0	7770	273	2	87	1	13	16	4	4	16	-32.2			
DW-2	89659	4/15/2005	1:50	1805.8	1731.4	4.32	9/30/2005	198200	270	744200	0	54900	1750	1	473	1	62	68	15	12	35				
DW-2	89660	4/15/2005	3:17	1807.9	1733.4	12.623	9/30/2005	154400	280	600300	0	234700	7630	2	2000	2	242	258	51	39	81	-32.2	-23.1	-22.5	
DW-2	89661	4/16/2005	2:25	1809.7	1735.1	7.13	9/30/2005	200200	270	738400	0	58600	1830	1	473	1	59	66	14	12	37				
DW-2	89662	4/16/2005	2:50	1812.5	1737.7	28.3	9/30/2005	162200	270	599700	0	226700	8120	3	2210	3	264	286	59	45	100	-32.1	-23.1	-22.4	
DW-2	89663	4/17/2005	17:15	1850	1772.6	0.52	9/30/2005	216100	310	779200	0	4170	161	1	42	0	5	7	2	1	8	-32.2			
DW-2	89664	4/17/2005	15:30	1900	1819.7	0.6	9/30/2005	215800	370	778800	0	4820	147	0	41	0	5	7	2	2	10	-32.1			
DW-2	89665	4/17/2005	18:30	1941.7	1859.1	0.27	9/30/2005	216900	330	781100	0	1590	51	0	19	0	3	4	1	1	7	-31.9			
DW-3	89666	4/22/2005	5:40	1250.2	1217.4	0.57	9/30/2005	216000	240	780400	0	3160	142	0	30	0	7	5	2	1	9	-35.4			
DW-3	89667	4/22/2005	7:21	1300	1264.4	0.142	9/30/2005	216700	310	781700	0	1210	53	1	13	0	4	3	2	1	6	-39.6			
DW-3	89668	4/22/2005	9:22	1350	1311.3	0.06	9/30/2005	208300	330	790700	0	582	27	1	9	0	6	3	3	1	8				
DW-3	89669	4/22/2005	11:17	1400	1358.2	0.32	9/30/2005	216100	1700	780000	0	2060	106	0	24	0	4	4	2	1	5	-33.9			
DW-3	89670	4/22/2005	13:50	1450	1404.3	0.65	9/30/2005	216100	2400	778600	0	2600	162	0	56	0	9	13	4	3	13	-32.8			
DW-3	89671	4/22/2005	16:20	1500	1449.7	0.35	9/30/2005	215700	3000	779000	0	2060	142	0	66	0	12	16	4	4	15	-32.5			
DW-3	89672	4/22/2005	20:23	1550	1494.3	0.16	9/30/2005	216800	1700	780400	0	988	60	0	22	0	4	5	2	1	7				
DW-3	89673	4/23/2005	4:45	1600	1537.7	0.17	9/30/2005	217400	830	780800	0	877	35	0	5	0	1	1	0	0	2				
DW-3	89674	4/23/2005	9:38	1650	1581	0.19	9/30/2005	217300	1200	780400	0	1090	36	0	4	0	1	1	0	0	2	-34.2			
DW-3	89675	4/23/2005	15:25	1700	1624.3	0.19	9/30/2005	216800	1500	780500	0	1100	45	0	6	0	1	1	1	0	2	-33.6			
DW-3	89676	4/23/2005	21:30	1750	1667.6	0.21	9/30/2005	217000	1900	779800	0	1270	62	0	12	0	1	1	0	0	2	-33.3			
DW-3	89677	4/24/2005	4:09	1800	1710.9	0.06	9/30/2005	217200	1900	780300	0	567	24	0	8	0	1	2	0	0	1				
DW-3	89678	4/24/2005	8:03	1836.6	1742.9	0.21	9/30/2005	216900	2000	779600	0	1390	59	0	15	0	2	3	1	1	2	-32.9			
DW-3	89679	4/24/2005	9:21	1855.9	1759.9	0.2	9/30/2005	217100	1900	779300	0	1650	67	0	19	0	2	4	1	1	4	-32.5			
DW-3	89680	4/24/2005	10:49	1883.8	1784.5	0.37	9/30/2005	216900	2000	778800	0	2190	96	0	27	0	3	5	1	1	8	-32.7	-23.7	-22.9	cryo-enrichment
DW-3	89681	4/24/2005	14:30	1900	1798.6	0.32	9/30/2005	217000	1900	778800	0	2180	91	0	29	0	4	6	2	2	10	-32.6	-23.6	-22.7	cryo-enrichment
DW-3	89682	4/24/2005	14:30	1950	1842.9	0.31	9/30/2005	216200	2500	778500	0	2660	111	1	35	0	5	6	2	2	10	-32.7			
DW-3	89683	4/24/2005	16:20	1969	1859.9	0.25	9/30/2005	217100	2100	778600	0	2030	100	1	29	0	3	4	1	1	4	-33.2			

Table 1: Isotube data, Halladale-1

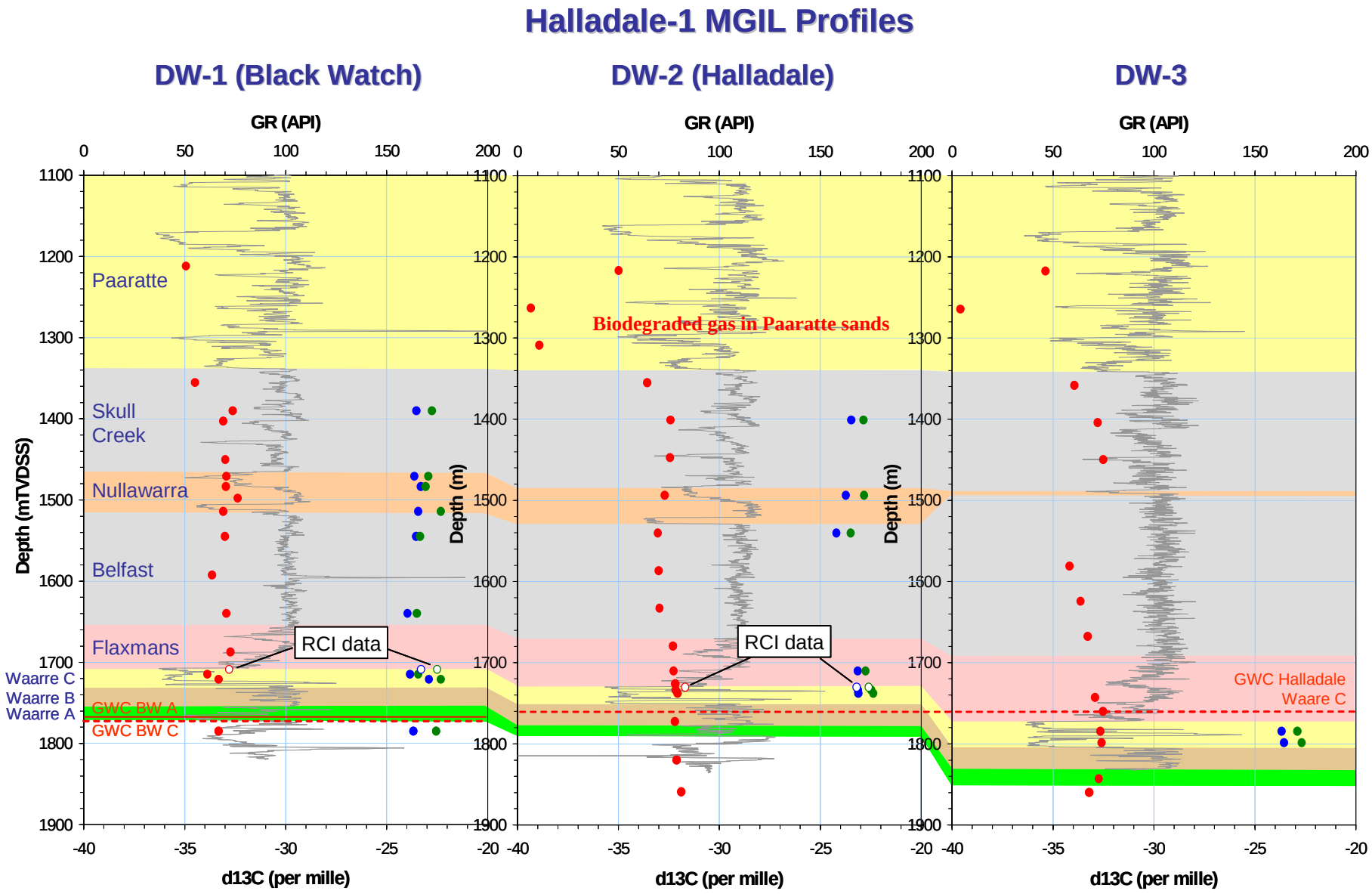

Figure 2: Halladale mud gas isotope profiles (TVDSS)

If available, propane values would have helped to clarify whether biodegradation was indeed the cause of the anomalous isotopic composition of Paarratte gas, as propane is highly sensitive to biodegradation and would be even heavier (less negative) than ethane. Unfortunately, none were obtained within the Paaratte Formation in any of the wells.

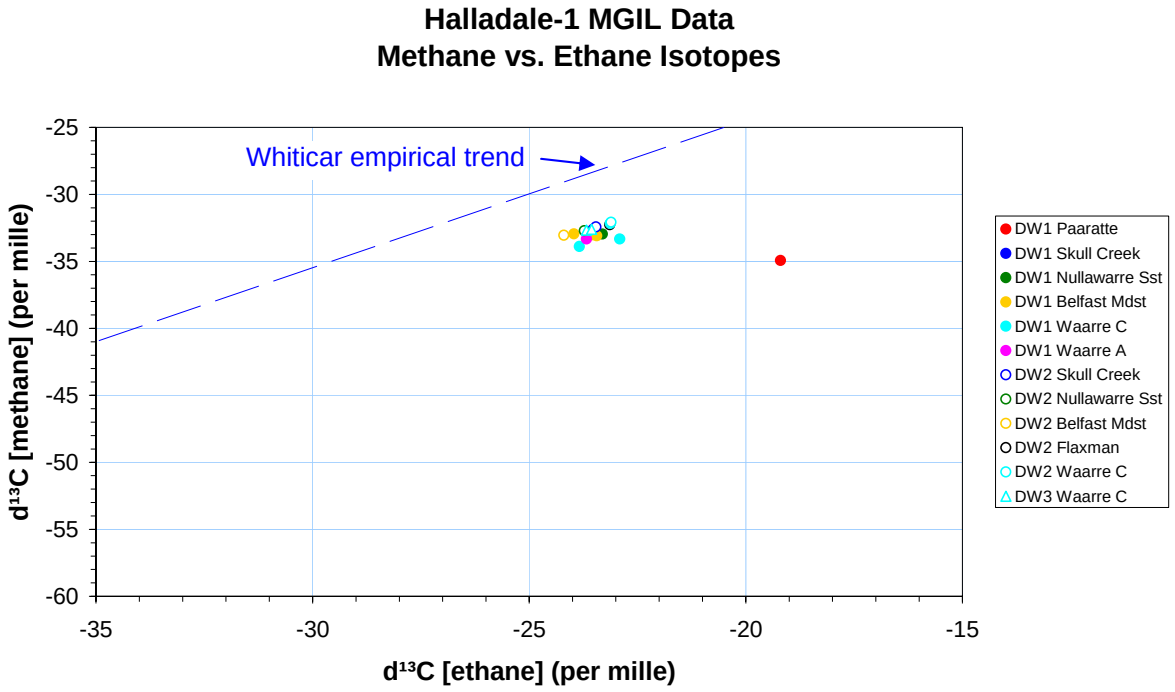

Figure 3: Methane vs ethane isotopes (all isotubes)

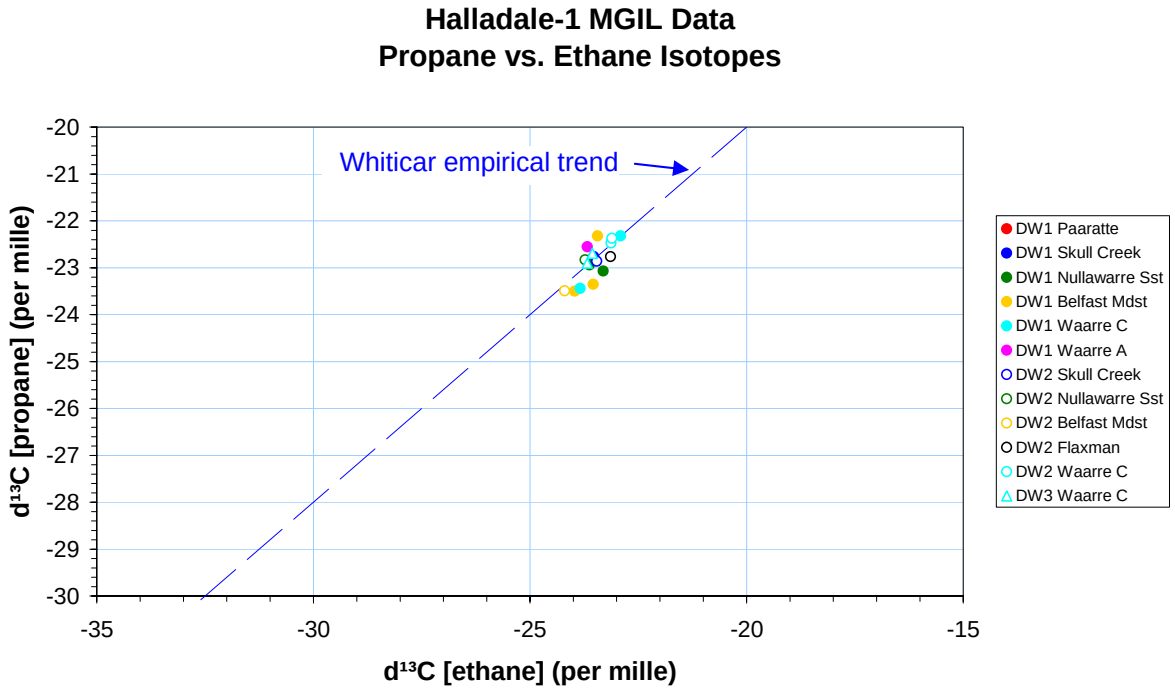

Figure 4: Propane vs ethane isotopes (all isotubes)

As gases are the most mobile of fluids in the subsurface, they are anticipated to reach thermodynamic equilibrium more readily than heavier components of petroleum. Gas isotope data can be measured to a precision of ± 0.1‰ on recovered fluids, and to about ± 0.5‰ in isotube samples. Differences larger than combined sampling and analytical error can therefore be used in a reservoir geochemical context to indicate flow barriers.

The spread in isotope data of c. 2‰ methane and c. 1‰ ethane and propane between the Waarre A and C sands in Halladale-1 DW-1, and Waarre C sands in DW-2 and DW-3 (Figure 5 and Figure 6) hints at compartmentalisation, but given the modest precision of mud gas isotope analysis, it is insufficient to definitively indicate flow barriers between the wells.

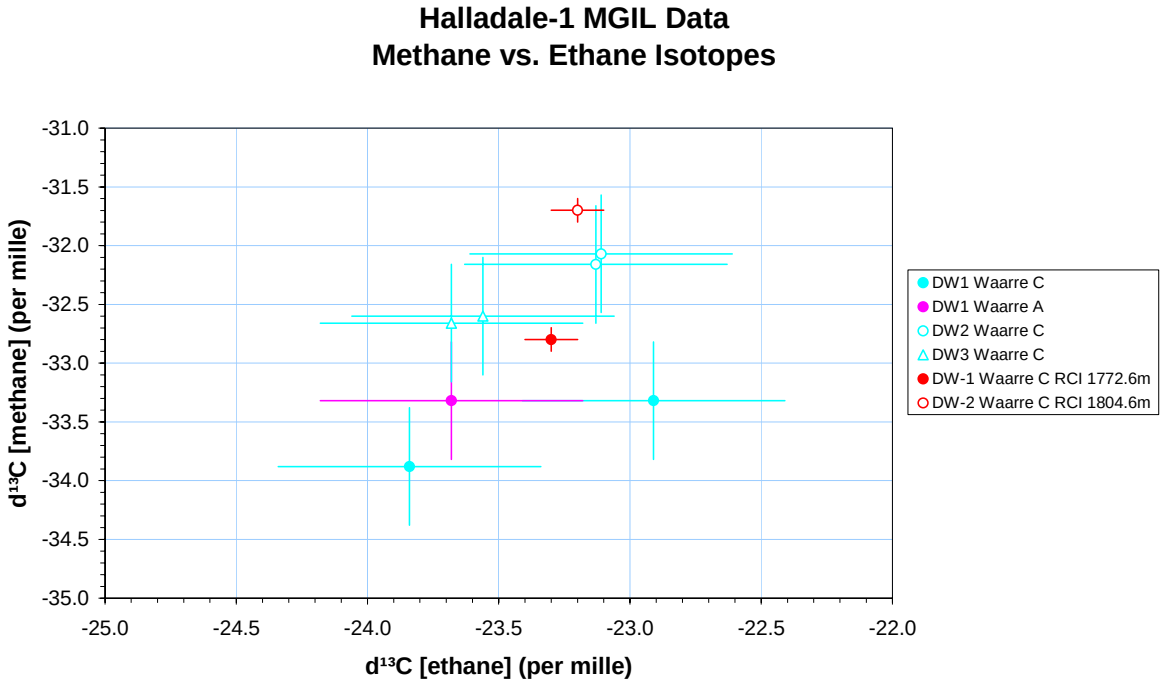

Figure 5: Methane vs ethane isotopes (Waarre isotubes and RCI)

RCI samples collected in Waarre C sands in DW-1 and DW-2 display very similar wet gas isotopes, but differ in methane isotopes by 1.1‰. This is five times the analytical precision, suggesting that Waarre C gas in DW-1 is not in thermodynamic equilibrium with Waarre C gas in DW-2, implying they are in separate compartments. This is supported by pressure profiles, which display an offset of c. 10 psi between gas legs in DW-1 and DW-2 (Figure 7).

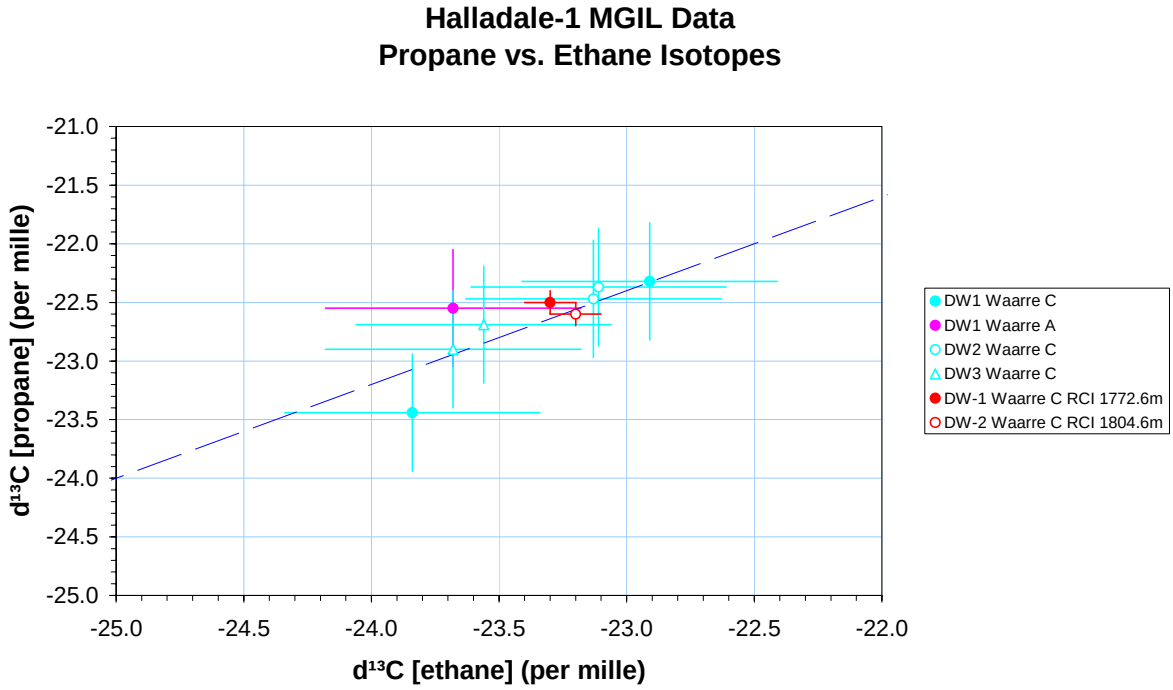

Figure 6: Propane vs ethane isotopes (Waarre isotubes and RCI)

2.3 RCI Gas Inventory

Five 840 cc wireline RCI samples were acquired from the gas columns in Halladale DW-1 (Blackwatch) and Halladale DW-2 (Halladale) (Table 2).

Well	*Date*	*Suite/Run*	*Depth (mKB)*	*Depth (TVDSS)*	*Serial #*	*Transferred into*	*Phase*
DW-1	06/04/05	1/3	1772.6	1708.7	369197		Gas
DW-1	06/04/05	1/3	1772.6	1708.7	369106	L-128	Gas
DW-2	19/04/05	1/3	1804.6	1730.3	189727	L-332	Gas
DW-2	19/04/05	1/3	1804.6	1730.3	189732	L-188	Gas
DW-2	19/04/05	1/3	1804.6	1730.3	189768	L-076	Gas

Table 2: RCI fluid inventory Halladale-1

2.4 Gas Composition

PVT analysis of the Halladale gases was performed at Petrolab (Australia) Pty Ltd., Magill, South Australia. The gases proved to be methane-rich (88-91%) with small amounts of nitrogen (1.4-1.9%) and carbon dioxide (0.4-0.5%) (Table 3). CGR is negligible at < 2

bbl/mmscf gas. PVT analyses suggest that Halladale-1 DW1 is wetter than gases from DW2, raising the possibility of a separate compartment. Compartmentalisation is supported by RCI data, which indicate a pressure offset of c. 10 psi between DW1 and DW2 gas legs. Differences in composition between DW1 and DW2 are not, however, supported by the pressure data. If anything, DW2 displays a slightly higher gradient than DW1, implying a denser (more liquids-rich) gas, although the difference between 0.19 psi/m and 0.206 psi/m is likely to be within measurement error.

Well	***DW-1***	***DW-2***	***DW-2***	***DW-2***
Depth (TVDSS)	1708.7	1730.3	1730.3	1730.3
Cylinder #	L-128	L-332	L-188	L-076
CO2	0.46	0.47	0.39	0.50
N2	1.88	1.36	1.36	1.38
C1	87.88	90.74	90.50	90.91
C2	5.30	4.17	4.26	4.20
C3	2.19	1.62	1.59	1.61
iC4	0.56	0.30	0.38	0.32
nC4	0.59	0.38	0.42	0.35
iC5	0.19	0.12	0.13	0.11
nC5	0.15	0.10	0.11	0.09
C6	0.26	0.18	0.20	0.15
C7	0.34	0.27	0.30	0.21
C8	0.12	0.10	0.16	0.07
C9	0.08	0.09	0.12	0.05
C10	0.03	0.06	0.07	0.02
C11	0.00	0.03	0.01	0.03
C12	0.00	0.01	0.00	0.00
Calculated CGR (bbl/MMSCF @ STP)	-	1.4	0.4	0.3
Wetness (C2-C4/C1-C4)	9.0%	6.7%	6.8%	6.7%

Table 3: Gas compositions from PVT analysis (Petrolab)

Gases from DW1 and DW2 were subjected to compositional and isotope analysis by Isolab in the Netherlands. Gas compositions were found to be extremely similar between the PVT and geochemistry labs (Figure 8).

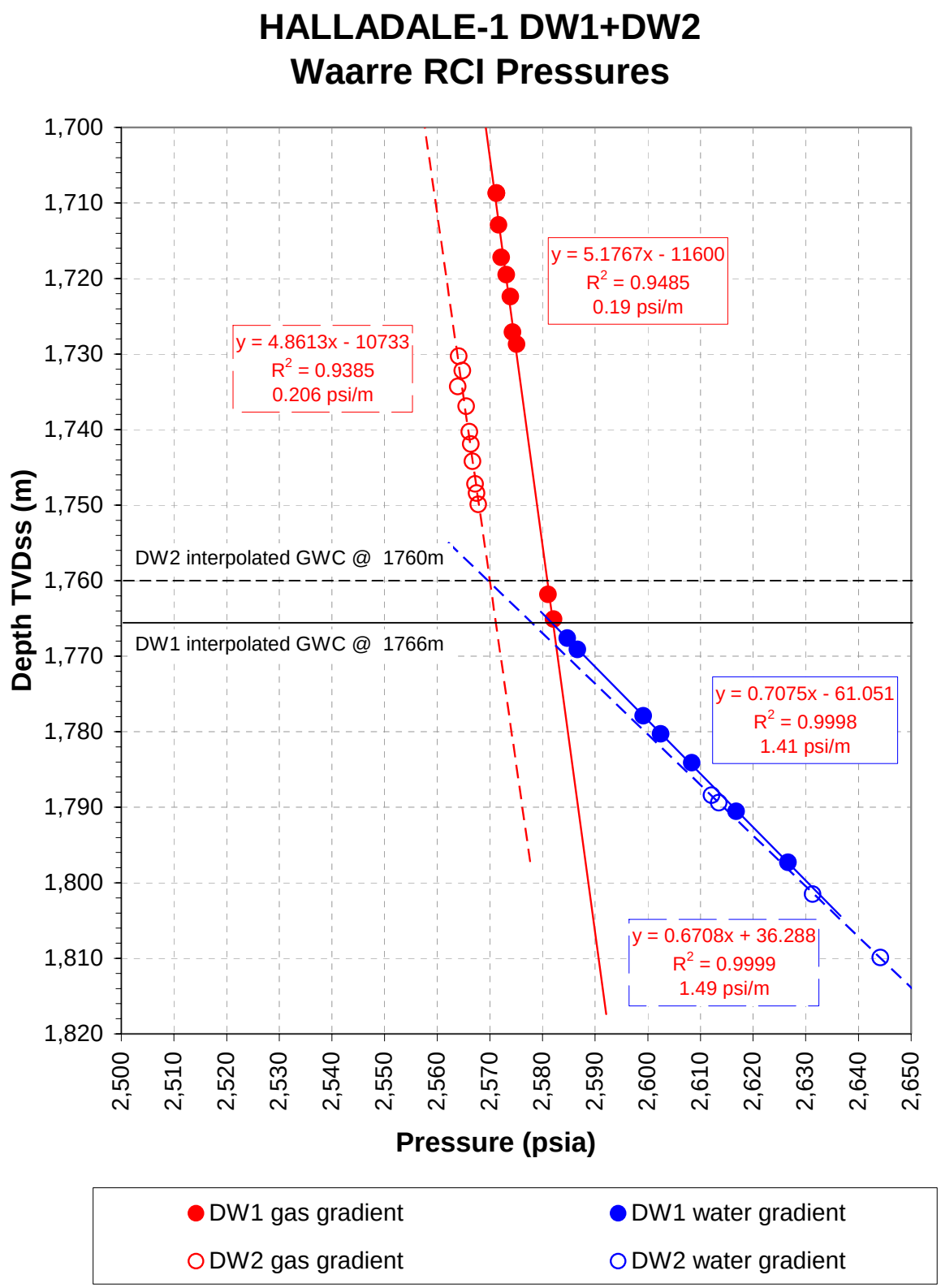

Figure 7: Comparison of Halladale-1 DW1 and DW2 RCI pressure gradients

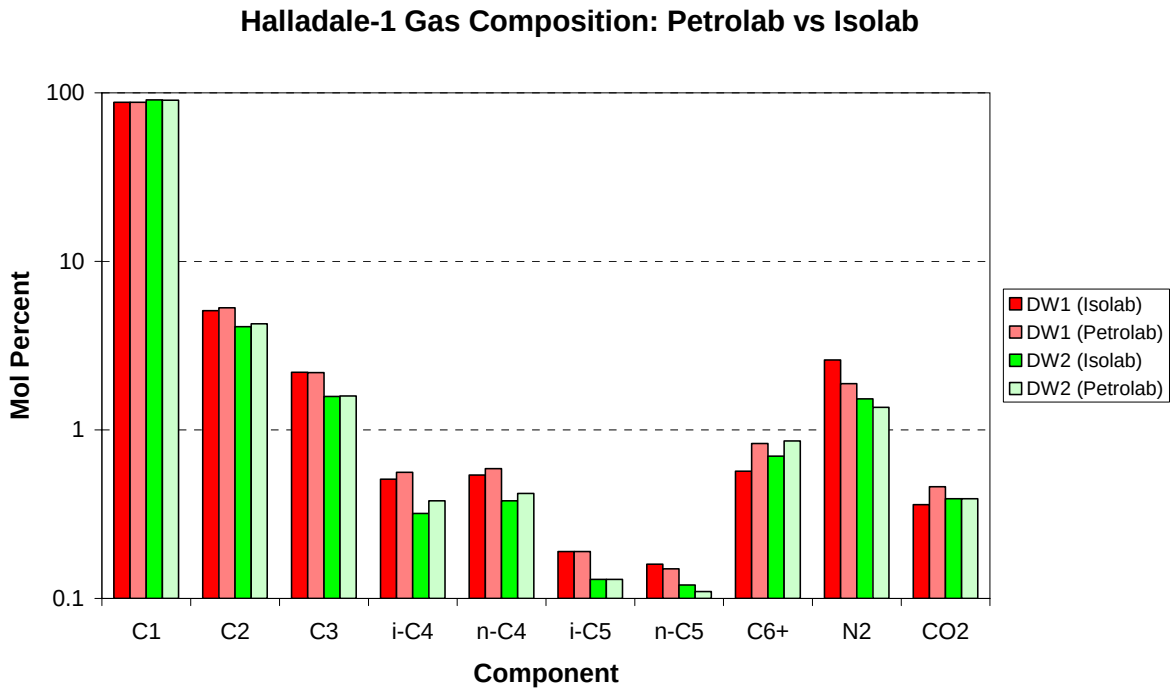

Figure 8: Gas compositions, DW1 and DW2 (Petrolab vs Isolab)

Pixler ratios show that the distribution of gaseous hydrocarbons in Halladale is comparable to Thylacine and La Bella, but somewhat drier (more mature) than Geographe and wetter (less mature) than Minerva. Pine Lodge and Boggy Creek gases are very dry, suggesting they are either highly mature, primarily biogenic of severely biodegraded. The anomalously high C1/C3 ratio of the former suggests it has been biodegraded, as propane is the earliest wet gas component to be removed by bacterial action, whereas the latter does not display anomalous C1/C3 ratio, so is likely to be either highly mature, or mixed with a large proportion of biogenic methane. Boggy Creek methane is in fact isotopically heavy (-35.5‰) suggesting it is dry due to expulsion from a high maturity source.

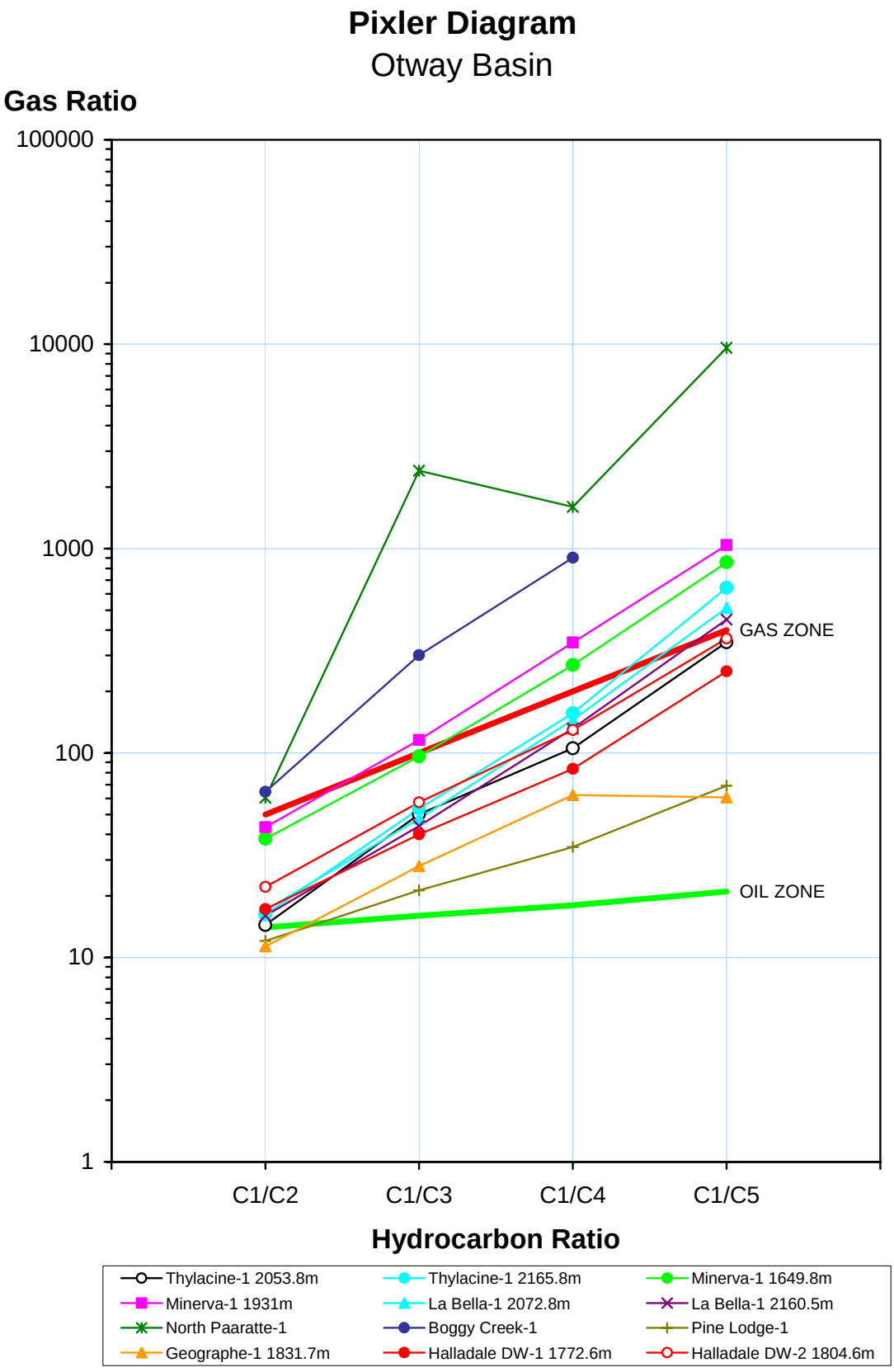

Figure 9: Pixler plot of Otway Basin gases

2.5 Isotope Analyses

The objectives of isotopic analysis of petroleum gases are threefold - firstly to establish the maturity and provenance of the gas; secondly to corroborate the modelled maturity of the proposed source rock in the basin model, and thirdly to provide an indication of communication between reservoirs. Gases, particularly methane, are highly mobile and may be expected to reach thermodynamic equilibrium rapidly in the subsurface. Differences in composition, particularly isotopic composition, may be interpreted in conjunction with the fill-spill history, to infer connectivity or compartmentalisation between adjacent wells.

The isotopic composition of the Halladale gases was determined by Isolab in Neerijnen, Holland and results are presented in Table 4. As previously observed, methane differs by about 1‰ between the two gases, which is significantly greater than experimental error (± 0.1‰), supporting the contention that DW1 and DW2 are in separate compartments.

Sample ID	$\delta^{13}C$ C_1	$\delta^{13}C$ C_2	$\delta^{13}C$ C_3	$\delta^{13}C$ i-C_4	$\delta^{13}C$ n-C_4	$\delta^{13}C$ i-C_5	$\delta^{13}C$ n-C_5	δD C_1	$\delta^{13}C$ CO_2	$\delta^{15}N$ N_2
DW1 1772.6 mKB	-32.8	-23.3	-22.5	-22.0	-21.6	-22.5	-22.2	-166.0	-12.9	-4.3
DW2 1804.6 mKB	-31.7	-23.2	-22.6	-22.1	-21.9	-22.9	-22.8	-163.0	-12.2	+4.1

Table 4: Isotopic composition of Halladale gas

Halladale-1 gas contains almost the most isotopically heavy (least negative) methane values encountered in the Otway basin to date. Conventional interpretation using a Schoell diagram suggests they were expelled toward the base of the conventional gas window for marine (labile) source rocks (Figure 10).

A Whiticar plot of methane versus ethane and propane isotope data reveals that methane is highly discordant with wet gases and therefore is probably not co-genetic. Halladale methane-ethane and methane-propane pairs lie far from the empirical trends observed by Whiticar, suggesting mixing with a proportion of bacterial methane (Figure 11). Whiticar's ethane-propane plot, however, suggests that the wet gases are concordant, and on account of their extremely heavy (less negative) isotopic composition, could have been generated at very high maturity (c. 2.5% Ro. vit.).

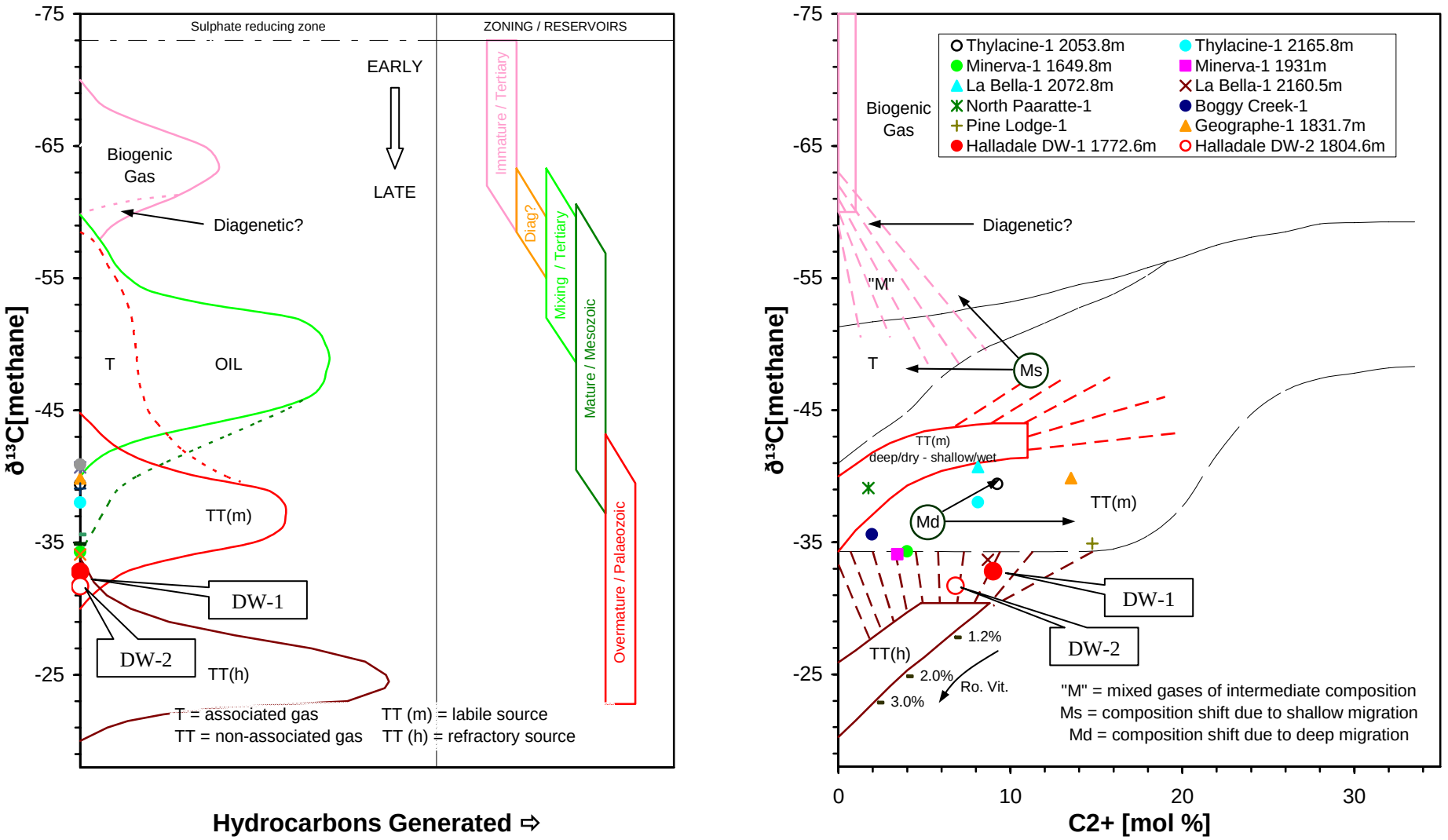

Figure 10: Schoell's genetic classification of natural gases

The proportion of wet gas components makes it unlikely that Halladale gas is highly mature, and is it more probable that the source kerogen is either humic (terrestrial), and/or isotopically heavy (e.g. lacustrine).

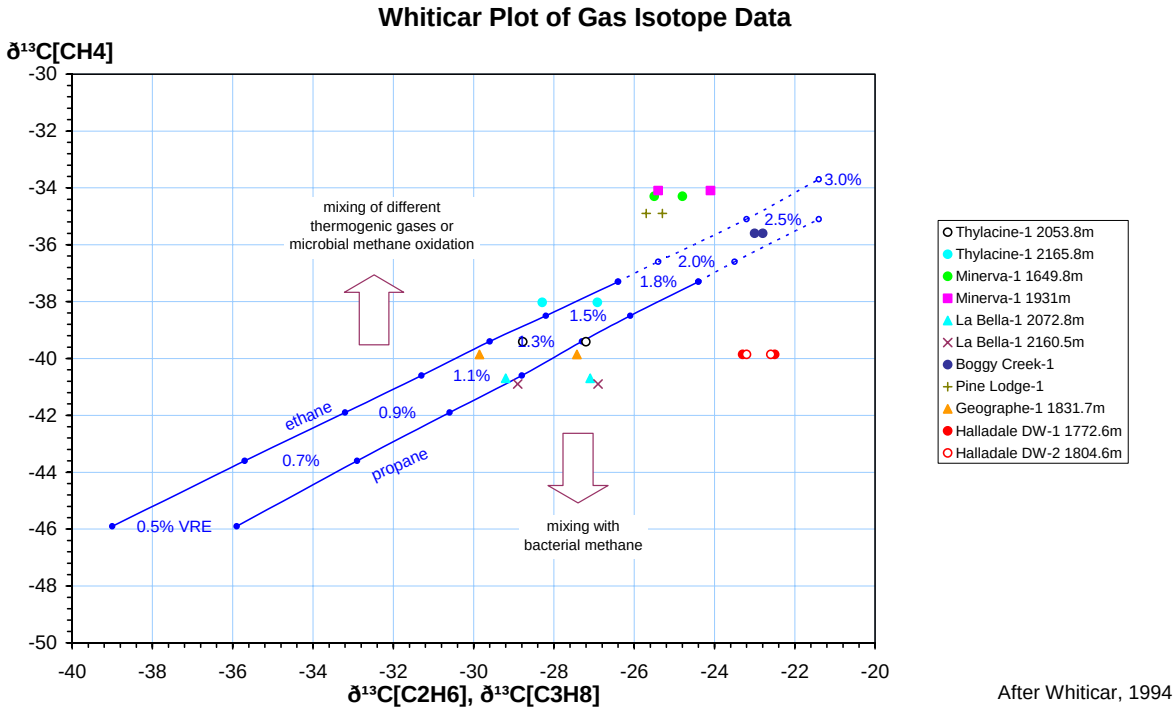

Figure 11: Whiticar plot of methane vs. ethane and propane isotopes

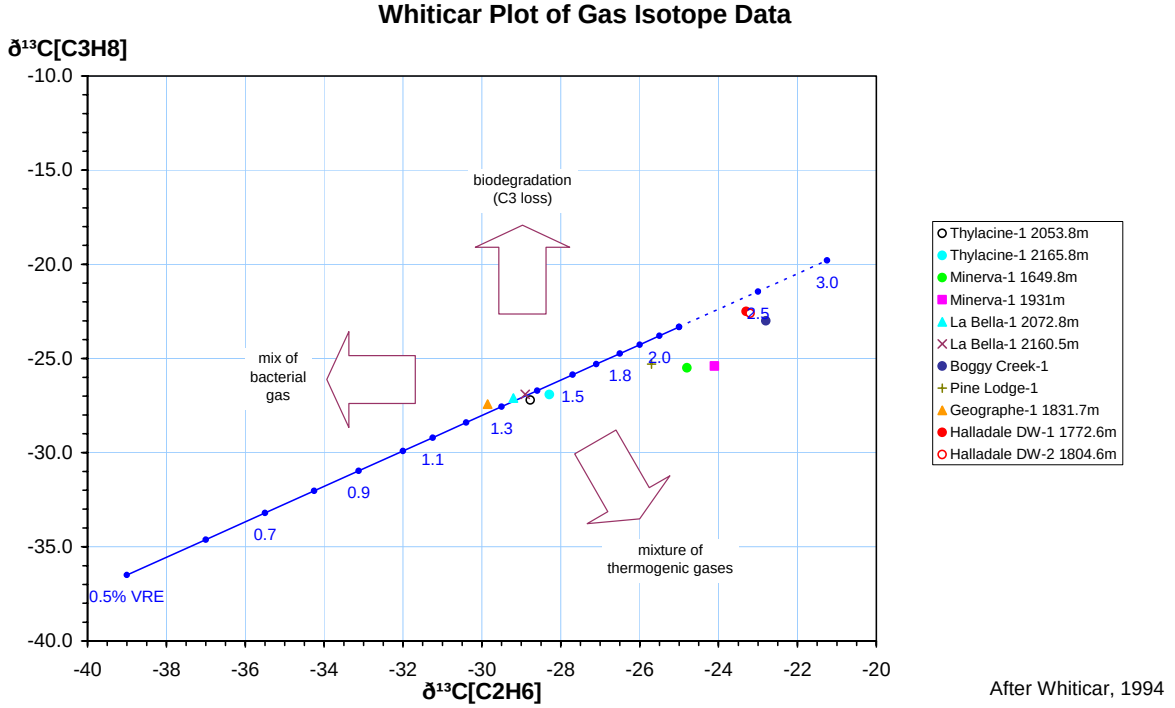

Figure 12: Whiticar plot of propane vs. ethane isotopes

Halladale wet gas is isotopically very similar to Boggy Creek, suggesting it may be genetically related (Figure 12). This is reinforced by the proximity of the two fields (Figure 1). Open file isotope data from the Shipwreck Trough suggest there are three families of fluids. Halladale gas has an affinity with the Casino Field to the south, and onshore Fenton Creek, Lavers and Mylor discoveries to the north, but not with Minerva to the southeast (Figure 13).

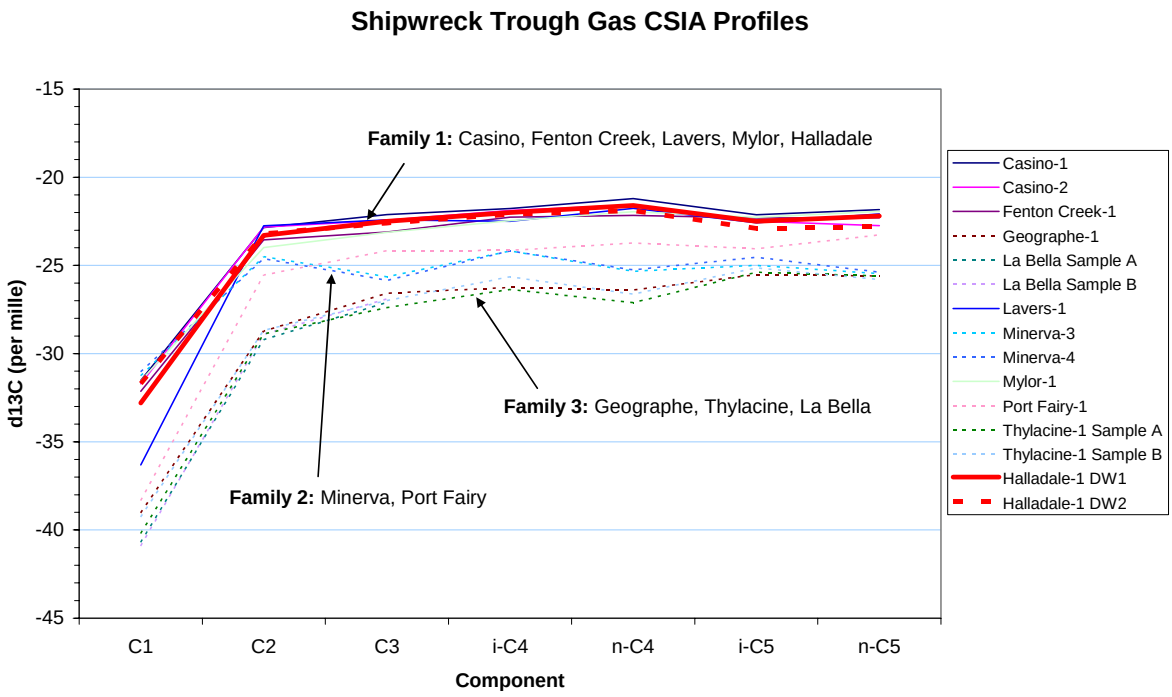

Figure 13: Shipwreck Trough Gas CSIA Profiles

2.6 Condensate CSIA

Combining the isotopic composition of the gas with the delta-^{13}C isotopic composition of the condensate yields a whole fluid CSIA profile. This is plotted together with paraffin concentration in normalised mole percent in Figure 14. Oil range paraffins become increasingly isotopically light (i.e. more negative) with increasing carbon number. This is characteristic of a high maturity (isotopically heavy) gas mixing with a less mature (isotopically light) liquids fraction, and suggests either multiple source rocks or multiple charge events have resulted in a mixed fluid in the Halladale structure.

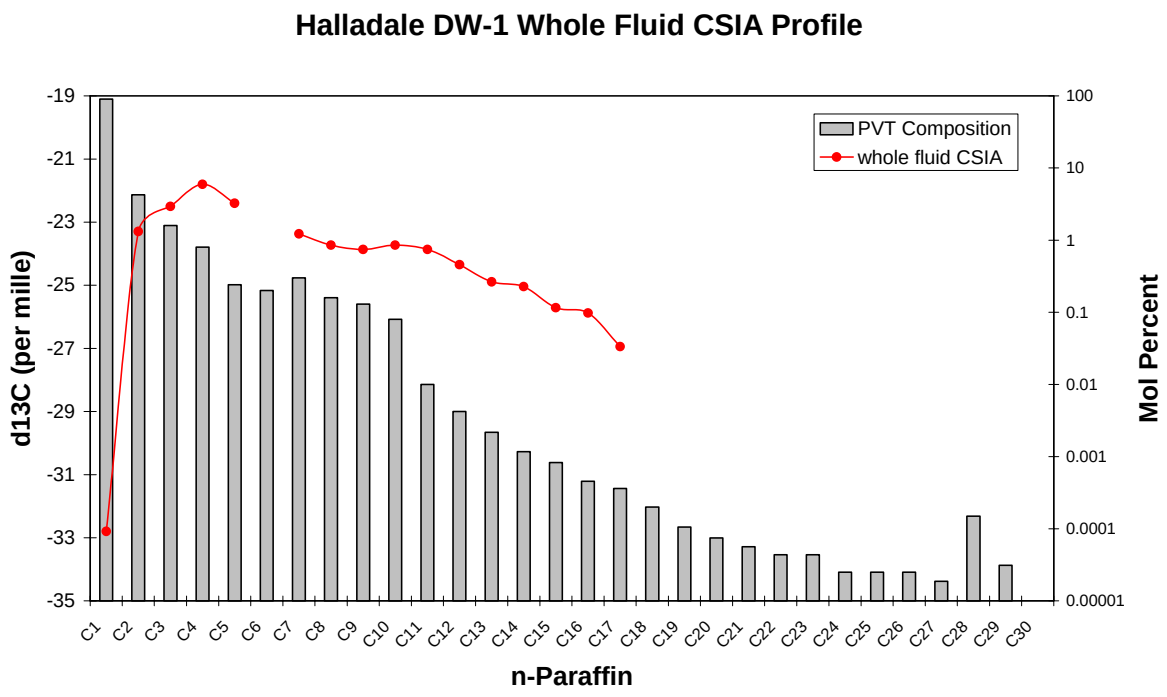

Figure 14: Halladale DW-1 whole fluid CSIA Profile

2.7 Non-Hydrocarbon Gases

Halladale gas contains 0.4-0.5% CO_2 and 1.4-1.9% nitrogen (Table 3). Stable carbon isotope analysis of the carbon dioxide yielded $\delta^{13}C$ values of -12.2 to -12.9‰. This is typical of CO_2 generated as a by product of marine or freshwater methanogenesis (Figure 15). It is also close to the range of isotope values observed in CO_2 expelled from Type III organic matter during diagenesis, and is therefore unlikely to be related to the high levels of CO_2 seen in onshore fields such as Caroline, which are of a magmatic or juvenile origin.

Nitrogen unexpectedly yielded quite different isotopic composition between DW-1 and DW-2 gas. The former displays $\delta^{15}N$ of -4.3‰ (relative to air, with $\delta^{15}N$ of 0‰) whereas the latter contained $\delta^{15}N$ of +4.1‰. This was queried with Isolab and the values confirmed. The gases were measured consecutively, followed by a standard, and there is no obvious reason why they should differ by more than 8‰.

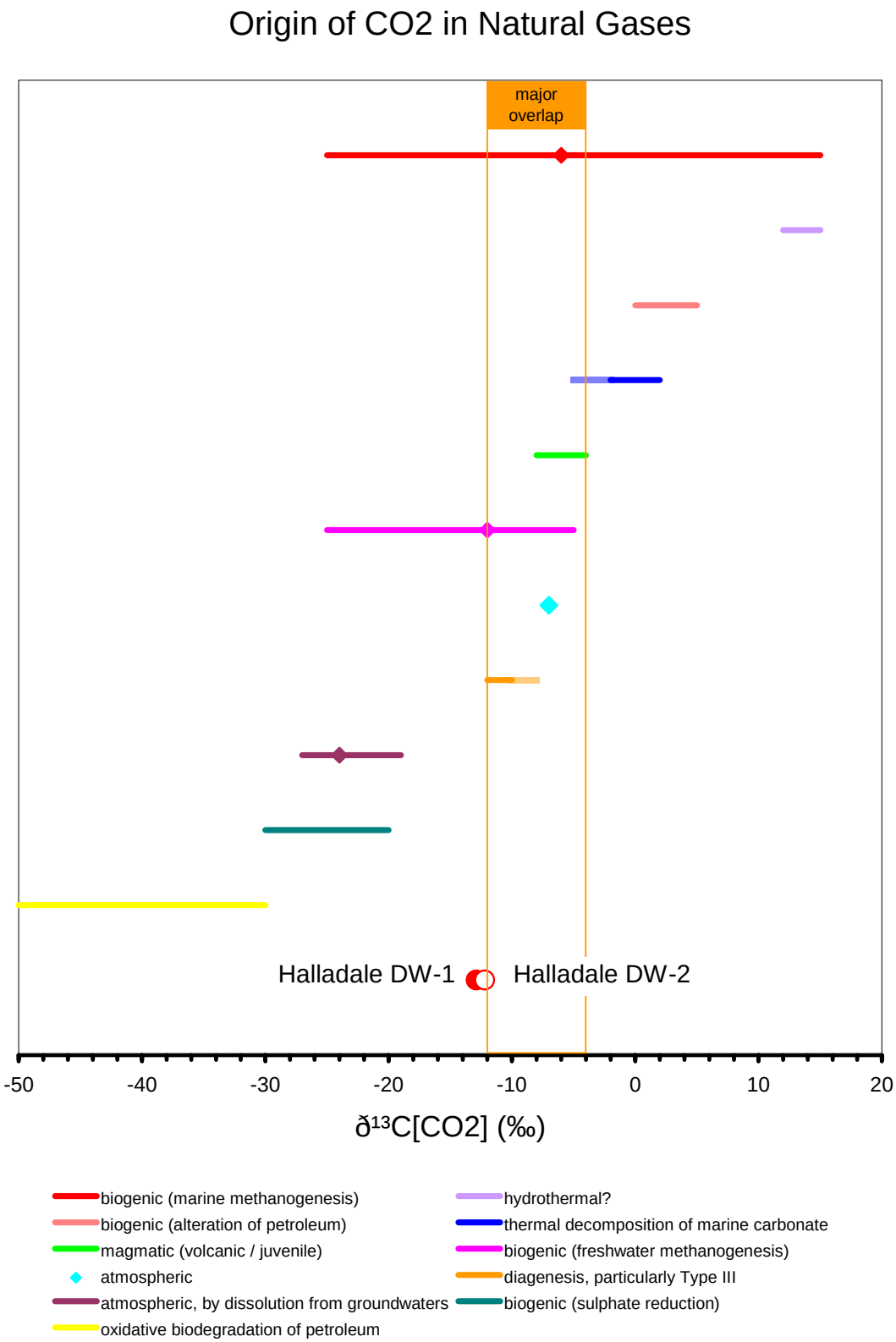

Figure 15: Genetic origin of CO_2 in natural gases

3 Conclusions

- Halladale gases are fairly dry, consisting of 88-91% methane and 7-9% wet gas, with 0.4-0.5% CO_2 and 1.4-1.9% nitrogen. Pixler ratios are consistent with a gas expelled within the early to peak gas window.

- Stable carbon isotope ratios are suggestive of a highly mature gas, expelled towards the base of the conventional gas window, but it is more probable that the origin of these isotope ratios is an isotopically heavy humic or lacustrine source kerogen at a much lower level of thermal maturity.

- Isotope data from isotubes are insufficiently distinctive to definitively indicate flow barriers between the Waarre A and C sands in Halladale-1 DW-1, and Waarre C sands in DW-2 and DW-3. RCI samples from Waarre C sands in DW-1 and DW-2 are isotopically distinctive, suggesting they are in separate compartments. This is supported by pressure profiles, which display an offset of c. 10 psi.

- On the basis of isotope profiles, three families of gases are identified in the Shipwreck Trough. Halladale has an affinity with other Family 1 gases, Boggy Creek, Casino, Fenton Creek, Lavers and Mylor. It is unrelated to Family 2 (Geographe, Thylacine, La Bella) or Family 3 (Minerva, Port Fairy).

- A strongly inclined paraffin CSIA (compound specific isotope) profile suggests mixing of a high maturity isotopically heavy gas, with a less mature isotopically light gas. This may be the result of either multiple source rocks or multiple charge events contributing to the Halladale accumulation.

- Carbon dioxide is isotopically light and was most likely expelled from Type III organic matter during diagenesis.

Isotech Mudgas Data (Isotubes)

Halladale-1

Well Name	Isotech Lab No.	Sample Date	Sample Time	Depth 1 Meters	TVDSS Meters	Gas Units %	GC Date	O_2 + Ar ppm	CO_2 ppm	N_2 ppm	CO ppm	C_1 ppm	C_2 ppm	C_2H_4 ppm	C_3 ppm	C_3H_6 ppm	iC_4 ppm	nC_4 ppm	iC_5 ppm	nC_5 ppm	C_6+ ppm	$\delta^{13}C_1$ per mil	$\delta^{13}C_2$ per mil	$\delta^{13}C_3$ per mil	Comments	Formation
DW-1	89606	3/30/2005	12:45	850	827	0.0203	9/29/2005	219600	660	779700	0	4	0	0	0	0	0	0	0	0	1					Pember Mdst
DW-1	89607	3/31/2005	3:01	908.8	886.6	0.011	9/29/2005	219700	430	779900	0	4	0	0	0	0	0	0	0	0	2					Pebble Point
DW-1	89608	3/31/2005	4:03	951.7	929.1	0.052	9/29/2005	209900	4300	785700	0	68	3	0	1	1	1	0	3	1	57					Paaratte
DW-1	89609	3/31/2005	5:21	1003	979.4	0.052	9/29/2005	207200	5300	787400	0	58	3	1	1	1	1	0	2	1	67					Paaratte
DW-1	89610	3/31/2005	6:07	1050.7	1025.3	0.119	9/29/2005	204600	4800	790100	0	428	6	3	1	1	1	0	2	1	65					Paaratte
DW-1	89611	3/31/2005	7:22	1101	1072.9	0.152	9/29/2005	200300	6100	793100	0	404	11	7	1	1	1	0	2	1	69					Paaratte
DW-1	89612	3/31/2005	8:34	1150	1118.9	0.092	9/29/2005	207000	6900	785800	0	213	9	6	1	1	1	0	1	0	33					Paaratte
DW-1	89613	3/31/2005	10:04	1200	1166.6	0.104	9/29/2005	203300	4800	791500	0	292	10	3	10	1	12	10	5	3	62					Paaratte
DW-1	89614	3/31/2005	11:58	1248.6	1211.9	1.376	9/29/2005	201600	6300	787700	140	3950	174	40	21	6	19	11	6	4	71	-34.9	-19.2			Paaratte
DW-1	89615	3/31/2005	12:01	1250.3	1213.6	0.508	9/29/2005	201300	6800	787900	30	3610	175	10	22	2	22	12	7	4	67					Paaratte
DW-1	89616	3/31/2005	14:08	1300	1260.6	0.04	9/29/2005	219800	690	779500	0	28	1	0	0	0	0	0	0	0	4					Paaratte
DW-1	89617	3/31/2005	16:01	1350.3	1308.3	0.1	9/29/2005	214800	4800	779600	0	720	24	1	3	0	6	2	2	1	19					Paaratte
DW-1	89618	3/31/2005	18:02	1400	1355.5	0.59	9/29/2005	210700	6200	777100	0	5450	336	1	102	1	20	20	5	3	16	-34.5				Skull Creek
DW-1	89619	3/31/2005	20:58	1436.4	1390	2	9/29/2005	199700	6200	749100	0	42600	1630	0	489	1	72	83	19	14	45					Skull Creek
DW-1	89620	3/31/2005	21:00	1436.6	1390.2	4.1	9/29/2005	193300	6400	731500	0	65200	2500	0	737	1	107	121	28	21	67	-32.6	-23.5	-22.8		Skull Creek
DW-1	89621	3/31/2005	21:37	1450.2	1403.1	1.17	9/29/2005	207600	6900	774300	0	10300	586	0	219	0	35	45	10	8	34	-33.1				Skull Creek
DW-1	89622	4/01/2005	12:22	1500	1450.3	1.07	9/29/2005	204200	9000	775600	0	10200	601	0	255	1	45	58	14	11	47	-33.0				Skull Creek
DW-1	89623	4/01/2005	1:27	1521.4	1470.6	5.881	9/29/2005	195800	8600	745700	0	47600	1570	0	467	1	70	85	19	15	50	-32.9	-23.6	-22.9		Nullawarre Sst
DW-1	89624	4/01/2005	1:33	1522.2	1471.3	5.838	9/29/2005	199400	7900	747600	0	43000	1420	0	423	1	63	77	17	14	41					Nullawarre Sst
DW-1	89625	4/01/2005	1:48	1535.3	1483.7	23.015	9/29/2005	159600	9100	629100	0	193000	6700	0	1810	1	234	265	56	43	99	-33.0	-23.3	-23.1		Nullawarre Sst
DW-1	89626	4/01/2005	2:27	1550	1497.7	1.181	9/29/2005	212500	5200	775100	0	6620	349	0	129	0	20	27	6	5	22	-32.4				Nullawarre Sst
DW-1	89627	4/01/2005	3:04	1566.1	1512.9	11.56	9/29/2005	187000	7100	699400	0	101700	3420	1	958	1	130	149	32	25	58					Belfast Mdst
DW-1	89628	4/01/2005	3:06	1567.5	1514.3	22.495	9/29/2005	167400	8000	636600	0	179500	6190	0	1690	1	220	248	53	40	93	-33.1	-23.4	-22.3		Belfast Mdst
DW-1	89629	4/01/2005	4:19	1600	1545	1.307	9/29/2005	209500	8100	773300	0	8420	419	0	130	0	22	31	8	7	33	-33.0	-23.5	-23.4		Belfast Mdst
DW-1	89630	4/01/2005	6:31	1650	1592.4	1.202	9/29/2005	208100	8600	774200	0	8640	338	0	61	1	14	19	7	6	32	-33.6				Belfast Mdst
DW-1	89631	4/01/2005	8:25	1700	1639.9	1.038	9/29/2005	197100	6400	788400	0	7470	449	2	134	1	19	23	8	7	37	-32.9	-24.0	-23.5		Belfast Mdst
DW-1	89632	4/01/2005	10:35	1750	1687.3	0.437	9/29/2005	216600	3400	777900	0	1910	104	0	36	0	5	7	2	2	10	-32.7				Flaxman
DW-1	89633	4/01/2005	11:52	1778.9	1714.6	31.91	9/29/2005	142200	9900	548200	0	282200	12400	0	3750	3	493	495	102	75	149	-33.9	-23.8	-23.4		Waarre C
DW-1	89634	4/01/2005	12:27	1785.5	1721	41.02	9/30/2005	127300	10500	516500	0	325000	14500	0	4560	3	620	624	130	96	173	-33.3	-22.9	-22.3		Waarre C
DW-1	89635	4/04/2005	6:18	1800.4	1735.1	0.1	9/30/2005	218100	760	780300	0	749	50	0	16	0	2	3	1	1	6					Waarre B
DW-1	89636	4/04/2005	8:14	1852.5	1784.8	0.31	9/30/2005	217000	1100	777800	0	3800	189	0	56	0	7	9	2	2	7	-33.3	-23.7	-22.6	**	Waarre A
DW-1	89637	4/04/2005	14:05	1900	1830.4	0.05	9/30/2005	216600	2000	780700	0	596	26	0	13	0	3	5	1	1	8					Eumarella
DW-1	89638	4/04/2005	16:44	1918	1847.7	0.09	9/30/2005	215700	2600	781100	0	566	21	0	9	0	3	4	2	1	9					Eumarella

Isotech Mudgas Data (Isotubes)

Halladale-1

Well Name	Isotech Lab No.	Sample Date	Sample Time	Depth 1 Meters	TVDSS Meters	Gas Units %	GC Date	O_2 + Ar ppm	CO_2 ppm	N_2 ppm	CO ppm	C_1 ppm	C_2 ppm	C_2H_4 ppm	C_3 ppm	C_3H_6 ppm	iC_4 ppm	nC_4 ppm	iC_5 ppm	nC_5 ppm	C_6+ ppm	$\delta^{13}C_1$ per mil	$\delta^{13}C_2$ per mil	$\delta^{13}C_3$ per mil	Comments	Formation
DW-2	89639	4/11/2005	12:50	901.5	879.4	0.021	9/30/2005	216000	110	783800	0	23	2	0	2	0	1	1	2	1	23					Pebble Point
DW-2	89640	4/11/2005	2:41	950.2	928.1	0.028	9/30/2005	212400	100	787300	0	143	5	0	2	0	2	1	3	2	50					Paaratte
DW-2	89641	4/11/2005	4:22	1001.9	979.5	0.028	9/30/2005	209200	80	790600	0	92	3	0	1	0	1	1	3	1	49					Paaratte
DW-2	89642	4/11/2005	6:06	1056.3	1033.2	0.047	9/30/2005	215000	110	784700	0	186	4	0	2	0	1	1	1	1	35					Paaratte
DW-2	89643	4/11/2005	8:01	1107.1	1082.3	0.03	9/30/2005	212800	130	786800	0	187	4	0	1	0	1	1	1	1	26					Paaratte
DW-2	89644	4/11/2005	10:02	1150.1	1123.6	0.041	9/30/2005	212900	110	786900	0	64	2	0	1	0	1	1	1	0	18					Paaratte
DW-2	89645	4/11/2005	13:45	1200	1170.3	0.06	9/30/2005	212200	150	787400	0	195	4	1	2	0	3	2	2	1	25					Paaratte
DW-2	89646	4/11/2005	16:30	1250	1216.7	0.71	9/30/2005	211500	130	782300	0	5710	256	1	56	0	12	10	4	3	36	-35.0				Paaratte
DW-2	89647	4/11/2005	19:00	1300	1262.9	0.34	9/30/2005	210700	110	786300	0	2590	131	2	43	1	16	12	7	4	48	-39.3				Paaratte
DW-2	89648	4/11/2005	21:24	1350	1309	0.21	9/30/2005	211200	110	787400	0	1100	56	3	20	1	12	7	5	3	35	-38.9				Paaratte
DW-2	89649	4/12/2005	2:35	1400	1354.9	0.202	9/30/2005	211700	110	786900	0	1160	80	0	25	0	9	8	5	3	37	-33.6				Skull Creek
DW-2	89650	4/12/2005	9:20	1450	1400.9	0.51	9/30/2005	213400	130	781700	0	4280	289	1	116	0	19	26	7	6	41	-32.4	-23.5	-22.9		Skull Creek
DW-2	89651	4/12/2005	16:30	1500	1447.3	0.35	9/30/2005	215100	170	781900	0	2560	112	1	51	0	12	17	6	5	36	-32.4				Skull Creek
DW-2	89652	4/13/2005	19:00	1550	1493.8	0.79	9/30/2005	211200	320	779800	0	8320	258	0	59	1	7	9	3	3	22	-32.7	-23.7	-22.8		Nullawarre Sst
DW-2	89653	4/13/2005	20:30	1600	1540.2	0.78	9/30/2005	210800	330	780800	0	7640	322	0	71	1	8	10	3	3	21	-33.1	-24.2	-23.5		Belfast Mdst
DW-2	89654	4/14/2005	0:32	1650	1586.6	0.53	9/30/2005	213500	560	782100	0	3590	149	6	25	1	5	5	2	2	19	-33.0				Belfast Mdst
DW-2	89655	4/14/2005	5:38	1700	1633	0.59	9/30/2005	210700	810	783800	0	4480	183	1	37	1	5	4	2	1	10	-33.0				Belfast Mdst
DW-2	89656	4/14/2005	17:30	1750	1679.5	0.26	9/30/2005	210400	220	787300	0	1900	86	1	28	0	4	6	2	2	8	-32.3				Flaxman
DW-2	89657	4/14/2005	21:10	1783	1710.2	3.52	9/30/2005	199600	290	748700	0	49500	1450	0	346	1	40	44	9	7	21	-32.3	-23.1	-22.8		Flaxman
DW-2	89658	4/15/2005	0:37	1800	1726.1	0.99	9/30/2005	210900	290	780600	0	7770	273	2	87	1	13	16	4	4	16	-32.2				Flaxman
DW-2	89659	4/15/2005	1:50	1805.8	1731.4	4.32	9/30/2005	198200	270	744200	0	54900	1750	1	473	1	62	68	15	12	35					Waarre C
DW-2	89660	4/15/2005	3:17	1807.9	1733.4	12.623	9/30/2005	154400	280	600300	0	234700	7630	2	2000	2	242	258	51	39	81	-32.2	-23.1	-22.5		Waarre C
DW-2	89661	4/16/2005	2:25	1809.7	1735.1	7.13	9/30/2005	200200	270	738400	0	58600	1830	1	473	1	59	66	14	12	37					Waarre C
DW-2	89662	4/16/2005	2:50	1812.5	1737.7	28.3	9/30/2005	162200	270	599700	0	226700	8120	3	2210	3	264	286	59	45	100	-32.1	-23.1	-22.4		Waarre C
DW-2	89663	4/17/2005	17:15	1850	1772.6	0.52	9/30/2005	216100	310	779200	0	4170	161	1	42	0	5	7	2	1	8	-32.2				Waarre B
DW-2	89664	4/17/2005	15:30	1900	1819.7	0.6	9/30/2005	215800	370	778800	0	4820	147	0	41	0	5	7	2	2	10	-32.1				Eumarella
DW-2	89665	4/17/2005	18:30	1941.7	1859.1	0.27	9/30/2005	216900	330	781100	0	1590	51	0	19	0	3	4	1	1	7	-31.9				Eumarella

Isotech Mudgas Data (Isotubes)

Halladale-1

Well Name	Isotech Lab No.	Sample Date	Sample Time	Depth 1 Meters	TVDSS Meters	Gas Units %	GC Date	O_2 + Ar ppm	CO_2 ppm	N_2 ppm	CO ppm	C_1 ppm	C_2 ppm	C_2H_4 ppm	C_3 ppm	C_3H_6 ppm	iC_4 ppm	nC_4 ppm	iC_5 ppm	nC_5 ppm	C_6+ ppm	$\delta^{13}C_1$ per mil	$\delta^{13}C_2$ per mil	$\delta^{13}C_3$ per mil	Comments	Formation
DW-3	89666	4/22/2005	5:40	1250.2	1217.4	0.57	9/30/2005	216000	240	780400	0	3160	142	0	30	0	7	5	2	1	9	-35.4				Paaratte
DW-3	89667	4/22/2005	7:21	1300	1264.4	0.142	9/30/2005	216700	310	781700	0	1210	53	1	13	0	4	3	2	1	6	-39.6				Paaratte
DW-3	89668	4/22/2005	9:22	1350	1311.3	0.06	9/30/2005	208300	330	790700	0	582	27	1	9	0	6	3	3	1	8					Paaratte
DW-3	89669	4/22/2005	11:17	1400	1358.2	0.32	9/30/2005	216100	1700	780000	0	2060	106	0	24	0	4	4	2	1	5	-33.9				Skull Creek
DW-3	89670	4/22/2005	13:50	1450	1404.3	0.65	9/30/2005	216100	2400	778600	0	2600	162	0	56	0	9	13	4	3	13	-32.8				Skull Creek
DW-3	89671	4/22/2005	16:20	1500	1449.7	0.35	9/30/2005	215700	3000	779000	0	2060	142	0	66	0	12	16	4	4	15	-32.5				Skull Creek
DW-3	89672	4/22/2005	20:23	1550	1494.3	0.16	9/30/2005	216800	1700	780400	0	988	60	0	22	0	4	5	2	1	7					Belfast Mdst
DW-3	89673	4/23/2005	4:45	1600	1537.7	0.17	9/30/2005	217400	830	780800	0	877	35	0	5	0	1	1	0	0	2					Belfast Mdst
DW-3	89674	4/23/2005	9:38	1650	1581	0.19	9/30/2005	217300	1200	780400	0	1090	36	0	4	0	1	1	0	0	2	-34.2				Belfast Mdst
DW-3	89675	4/23/2005	15:25	1700	1624.3	0.19	9/30/2005	216800	1500	780500	0	1100	45	0	6	0	1	1	1	0	2	-33.6				Belfast Mdst
DW-3	89676	4/23/2005	21:30	1750	1667.6	0.21	9/30/2005	217000	1900	779800	0	1270	62	0	12	0	1	1	0	0	2	-33.3				Belfast Mdst
DW-3	89677	4/24/2005	4:09	1800	1710.9	0.06	9/30/2005	217200	1900	780300	0	567	24	0	8	0	1	2	0	0	1					Flaxman
DW-3	89678	4/24/2005	8:03	1836.6	1742.9	0.21	9/30/2005	216900	2000	779600	0	1390	59	0	15	0	2	3	1	1	2	-32.9				Flaxman
DW-3	89679	4/24/2005	9:21	1855.9	1759.9	0.2	9/30/2005	217100	1900	779300	0	1650	67	0	19	0	2	4	1	1	4	-32.5				Flaxman
DW-3	89680	4/24/2005	10:49	1883.8	1784.5	0.37	9/30/2005	216900	2000	778800	0	2190	96	0	27	0	3	5	1	1	8	-32.7	-23.7	-22.9	**	Waarre C
DW-3	89681	4/24/2005	14:30	1900.04	1798.6	0.32	9/30/2005	217000	1900	778800	0	2180	91	0	29	0	4	6	2	2	10	-32.6	-23.6	-22.7	**	Waarre C
DW-3	89682	4/24/2005	14:30	1950	1842.9	0.31	9/30/2005	216200	2500	778500	0	2660	111	1	35	0	5	6	2	2	10	-32.7				Waarre A
DW-3	89683	4/24/2005	16:20	1969	1859.9	0.25	9/30/2005	217100	2100	778600	0	2030	100	1	29	0	3	4	1	1	4	-33.2				Waarre A

Chemical analysis based on standards accurate to within 2%

**Ethane and propane isotope data obtained via cryo-enrichment

APPENDIX 4:
FIS REPORT

UWI# 999999999999
FIS# FI050074a

Fluid Inclusion Technologies, Inc.
Innovations in Petroleum Risk Management

A Stratigraphic Reconstruction of Bulk Volatile Chemistry from Fluid Inclusions in:

HALLADALE 1

Prepared October 18, 2005 for

Origin

Fluid Inclusion Technologies, Inc.
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A Stratigraphic Reconstruction of Bulk Volatile Chemistry from Fluid Inclusions in:

HALLADALE 1

Prepared October 18, 2005
by
Fluid Inclusion Technologies, Inc.

Executive Summary for well: HALLADALE 1

Petroleum Indications, Type and Quality: The section above approximately 1390 m contains dry gas species and sulfur compounds suggestive of an FIS microseep. These features are considered encouraging for deeper liquid petroleum exploration in the area. Thin sections from 920 m, 1010 m and 1260 m consist largely of sandstone and contain no visible liquid petroleum inclusions. Benzene anomalies at 1030 m, 1210 m and 1290 m may be sensing nearby charge, although the interpretation is complicated somewhat by the co-occurrence of sulfur compounds.

The section below 1785 m contains gas and intermittent liquid-range petroleum indications. The latter are recorded at 1795 m, 1840 m, 1870 m, 1885 m and 1905 m. Thin sections reveal rare, yellow-fluorescent, moderate gravity oil inclusions at 1840 m and rare, yellow-fluorescent moderate and white-fluorescent upper-moderate gravity petroleum inclusions at 1905 m. Lithologies are dominated by sandstone and shale. Shale contains appreciable gas-prone and minor mature(?) oil-prone kerogen. Mature source rock can contribute to FIS responses, and may do so here.

Proximal Pay Indications: Benzene anomalies (possibly with associated acetic acid but unclear due to co-elution effects from sulfur compounds) are documented at 1030 m, 1210 m and 1290 m. These species (benzene and organic acid) generally indicate the nearby presence of reservoired hydrocarbons; however, in this case the interpretation is not nearly as definitive due to possible interference from bacterial species (see below).

Potential Seals: Possible seals are identified at 900 m, 1200 m, 1770 m, 1840 m and 1940 m.

Evidence for Bacterial or Thermal Alteration: Evidence for a bacterial microseep is documented above 1390 m. FIS microseeps often occur above or near deeper charge. The features are generated by microseepage of light thermogenic hydrocarbons from depth followed by bacterial sulfate reduction at temperatures below about 65 C. The presence of these shallow features is considered encouraging for finding deeper oil or condensate bearing reservoirs in the area.

Other: Nothing of note.

Summary of Results for well: HALLADALE 1

This report contains Fluid Inclusion Stratigraphy and Fluid Inclusion Petrography results for HALLADALE 1 and was prepared for Origin by *Fluid Inclusion Technologies, 2217 N. Yellowood Ave., Broken Arrow, OK 74133; ph: (918) 461-8984; fax: (918) 461-2085; www.fittulsa.com.*

Table I: Logistical Information

Client:	**Origin**	Analyzed Depth:	**805 - 1969 Meters**
Well:	**HALLADALE 1**	Sample Spacing:	**See Individual Spectra**
		Sample Total:	**174**

Table II: Fluid Inclusion Petrography from HALLADALE 1

Well Name: Halladale 1																				
Sample Depth	**Rock Type**	**Petroleum Fluid Inclusion Populations**												**Kerogen (possible source rk)**					**Bitumen**	
		Population 1				**Population 2**				**Population 3**										
***Units:* (Meters)**	***Dominant / Subordinate***	***Fluorescence Color***	***API Gravity (estimated)***	***Host Mineral & occurrence***	***Abundance***	***Fluorescence Color***	***API Gravity (estimated)***	***Host Mineral & occurrence***	***Abundance***	***Fluorescence Color***	***API Gravity (estimated)***	***Host Mineral & occurrence***	***Abundance***	***Host Rock***	***Type***	***OP Fluor Color***	***GP Abundance***	***OP Abundance***	***Type***	***Abundance***
920	ss																			
1010	ss																			
1260	ss,sh													sh	go	yl	c	r		
1795	ss,sh													sh	go	or	c	r		
1840	shly ss	yl	m	dq	r									sh	gp		c			
1905	sh,ss	yl	m	dq	r	wt	um	dq	r					sh	go	or	a	sv		

ss: sandstone	mt: metamorphic rock	m: moderate	r: rare	ds: dead petroleum stain
si: siltstone	no: none	um: upper-moderate	sv: several	po: pore-occluding bitmn
sh: shale	br: brown	h: high	c: common	pb: pyrobitumen
cb: carbonate	or: orange	dq: frac in detrital quartz	a: abundant	
sa: salt	yl: yellow	dr: quartz dust rim	xa: very abundant	Notes:
an: anhydrite	wt: white	qc: quartz cement	go: oil and gas prone	
ch: chert	bl: blue	df: frac detrital feldspar	op: oil prone	
co: coal	l: low	cm: matrix carbonate	gp: gas prone	
ig: igneous rock	ul: upper-low	cc: carbonate cement	ls: live petroleum stain	

Table III: FIS Terminology: Abbreviations and Acronyms

HC Type & Quality		Anomalous HC Zones		Fluid Contacts	
NHC	non-hydrocarbon	**MP**	migration pathway	**OWC**	oil-water contact
DG	dry gas	**PC**	present day ptrlm column	**GWC**	gas-water contact
WG	wet gas	**PPC**	paleo-ptrlm column	**GOC**	gas-oil contact
GC	gas condensate	**RI**	recycled ptrlm inclusions	**POWC**	paleo-oil-water contact
VO	volatile oil	**SR**	source rock	**PGWC**	paleo-gas-water contact
O	oil	**GP**	gas prone kerogen	**PGOC**	paleo-gas-oil contact
BD	biodegraded	**OP**	oil prone kerogen		
TA	thermally altered	**OGP**	oil and gas prone kerogen		
		CNT	contamination		

Water-Soluble Anomalies		Miscellaneous	
WS	undifferentiated water-soluble anomaly	**SL**	seal
WSSR	source rock related water-soluble anomaly	**MS**	microseep
WSTA	water-soluble anomaly sourced from thermal alteration		
PTPL	proximity to oil or gas-condensate		
PTPG	proximity to gas		

Petrographic Observations					
A	abundant	**IG**	igneous rock	**SA**	salt
AN	anhydite	**L**	low	**SH**	shale
BL	blue	**LG**	large	**SI**	siltstone
BR	brown	**M**	moderate	**SM**	small
C	common	**MD**	medium	**SS**	sandstone
CB	carbonate	**MT**	metamorphic rock	**ST**	petroleum stain
CC	carbonate cement	**NO**	none	**SV**	several
CH	chert	**OR**	orange	**UL**	upper-low
CM	matrix carbonate	**PB**	pyrobitumen	**UM**	upper-moderate
CO	coal	**PF**	pore filling bitumen	**V**	variable
DF	detrital feldspar	**PR**	pore rimming bitumen	**W**	weak
DQ	detrital quartz	**QC**	quartz cement	**WT**	white
DR	quartz dust rim	**R**	rare	**XA**	extremely abundant
H	high	**S**	strong	**YL**	yellow

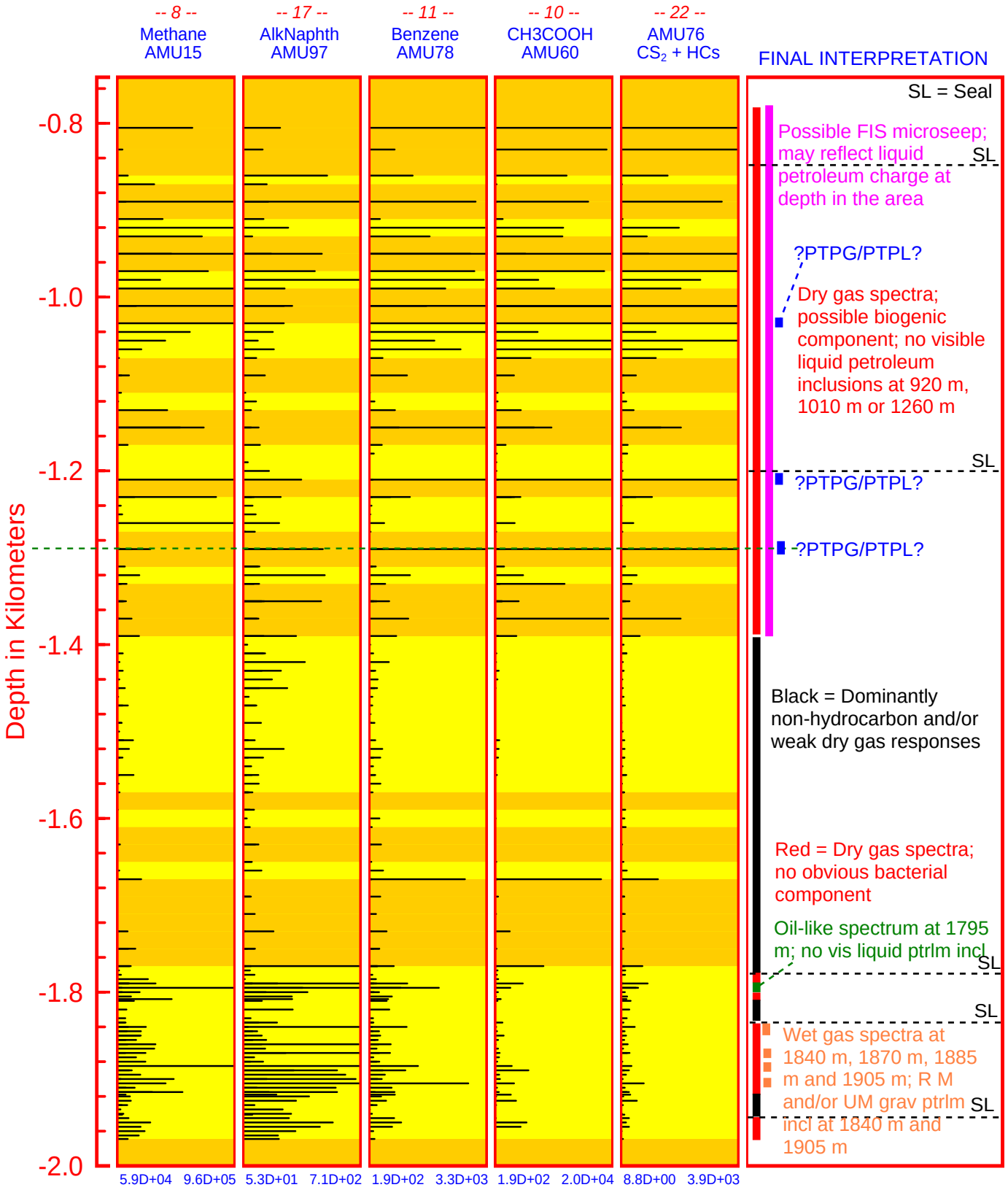
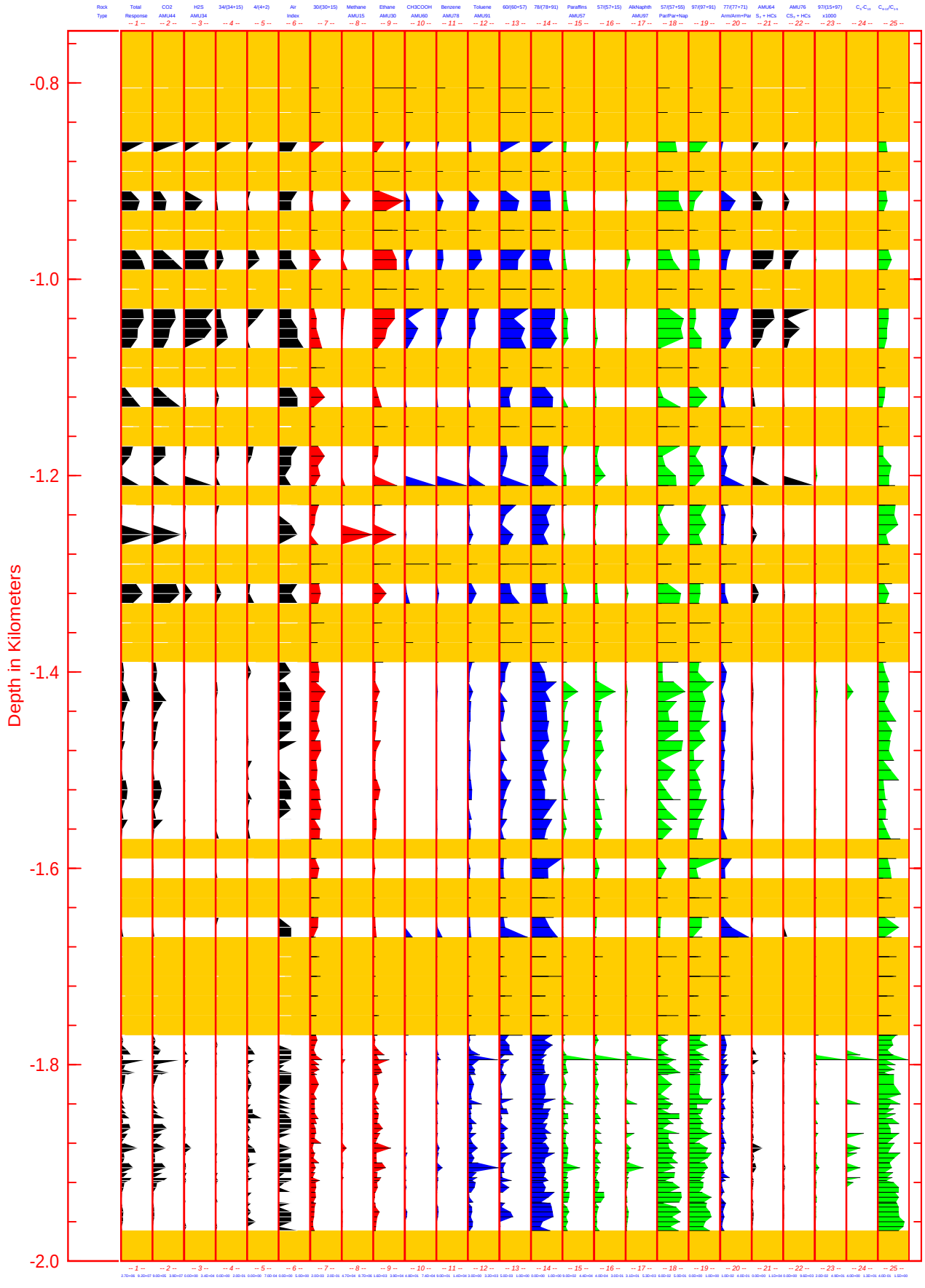


Figure 1: FIS Summary Tracks (see Sect. A for further explanation)

HALLADALE 1 : All FIS Data



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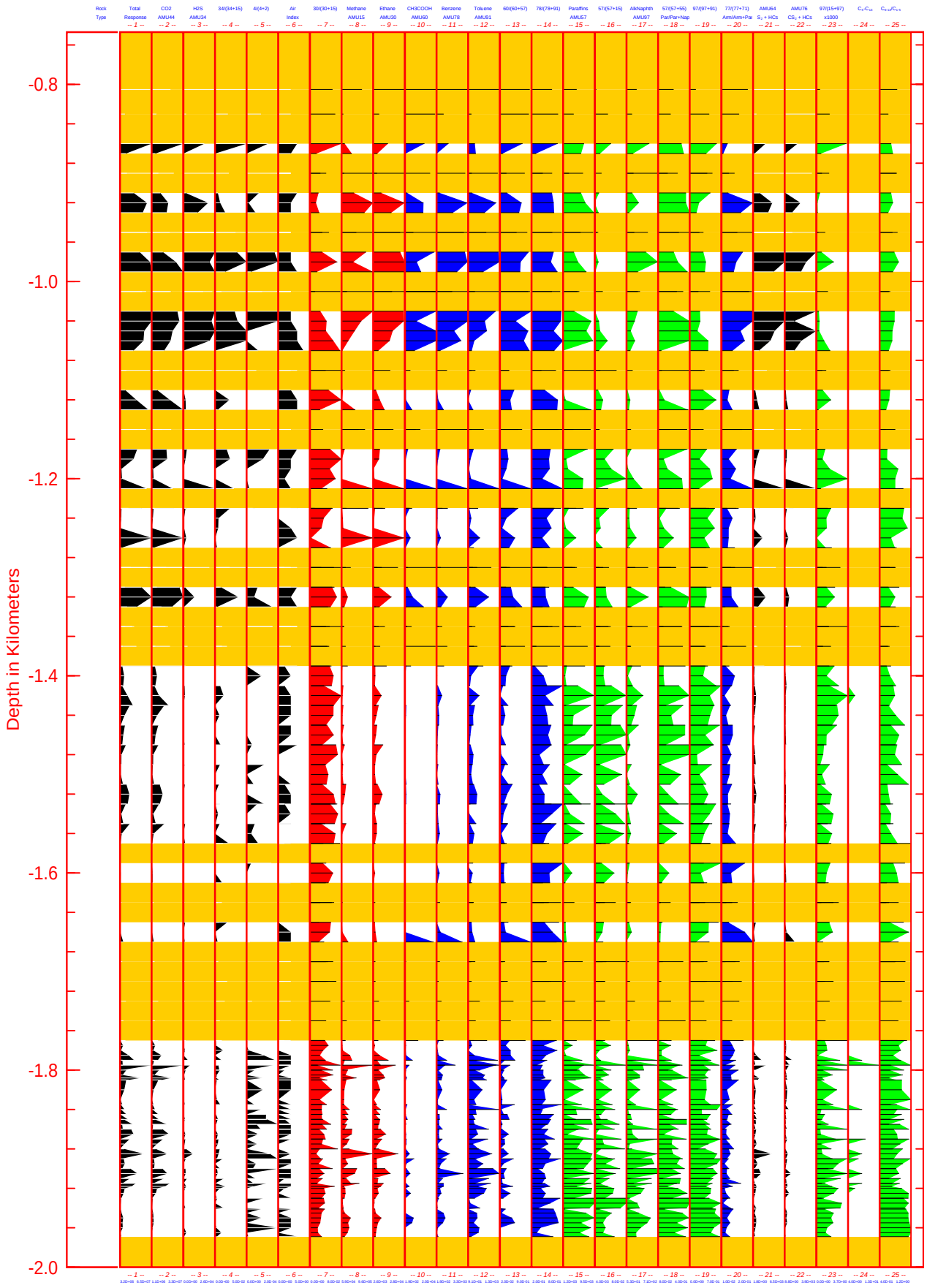
FIT

UWI# 999999999999
FIS# *FI*050074a

HALLADALE 1 : 90% of all FIS Data



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FIS#FI050074a

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1 Overview of FIT, Inc. and Fluid Inclusion Stratigraphy

Fluid Inclusion Technologies (FIT), Inc., is a laboratory-based petroleum service organization established in 1997 and offering a variety of analytical services including some previously proprietary technologies. **Fluid Inclusion Stratigraphy (FIS)**, the most widely applicable of these technologies is a rapid analytical technique that involves the automated analysis of volatile compounds trapped within micron-sized cavities in rock material taken from well cuttings, core or outcrop samples. These "fluid inclusions" are representative samples of subsurface fluids, and are not subject to fractionation during sampling or evaporative loss during sample storage for any length of time. The procedure has major impact in the areas of **both Petroleum Production and Exploration Applications** providing information unattainable via more traditional methods and, has been instrumental in the discovery of significant petroleum reserves, influenced exploration and acreage acquisition decisions and provided innovative options for resource estimation, petroleum production and enhanced oil recovery operations. **Fluid Inclusion Stratigraphic Analysis**, often in combination with other patented techniques, emerging geochemical methodologies and standard microscopic methods, all available through Fluid Inclusion Technologies, Inc., provides a unique and unequaled industry product boasting an impressive list of proven applications including determination of **Product Type**, **Hydrocarbon Migration**, **Seals and Seal Integrity**, **Fluid Contacts**, **Proximity to Reservoired Petroleum**, **Pay Zone/By Passed Pay Delimitation**, **Reservoir-Scale Compartmentallization** and **Fluid Pressure Compartments**. Further information regarding the application of **FIS Analysis** and the other technical services we provide to problems in petroleum exploration and production is available elsewhere in this report and on our website:"www.fittulsa.com".

1.1 General Logistics of Initiating an FIS Analysis

To Initiate an FIS Analysis: contact FIT[1] directly to discuss goals of the study, sample requirements, turnaround time, pricing, and other related aspects. New clients are particularly encouraged to consult with our staff during the early stages of project development to optimize sample selection, preparation and shipment. Rock materials for FIS Analysis are shipped directly to C&M Storage[2], our sample handling facility, for sample preparation including any necessary crushing/sieving, subsampling and washing. The turnaround time for a typical FIS Analysis is preliminary data in 1-2 weeks time following receipt of samples by C&M and final report 1-2 weeks following preliminary analysis. These times are approximate and depend on the amount of sample preparation required, job size and analytical backlog. At the time of issue of this report, the cost for obtaining an FIS Analysis was $5,500 U.S. for a full-well analysis (up to 575 samples) and $3,000 U.S. for a short-well analysis (up to 180 samples). The cost includes the automated mass spectrometric analysis, preparation of and fluid inclusion petrography on selected thin-sections sampled throughout the well, and interpretation in the form of annotated depth plots (see Figure 1).

When sampling for FIS Analysis: the technique is equally applicable to cuttings, core and outcrop samples, but all samples will ultimately be reduced to cuttings-sized rock material. Wells drilled with any mud system can be analyzed (including oil-based systems),

[1]Fluid Inclusion Technologies, 2217 N. Yellowood Ave., Broken Arrow, 74012, USA., phone (918) 461-8984
[2]Attn: FIS Analysis, C&M Storage, 3311 Hwy, 77 South, Schulenburg, TX 78956, USA

as can samples of any age (i.e., fresh cuttings or those warehoused for many years). Our suggested sampling interval for general well studies is 30 ft (10 m). Pay-delineation studies, reservoir-scale studies or other applications involving rapidly changing fluid chemistries should be sampled at the tightest possible spacing, depending on sample availability (e.g., 1-3 ft). A maximum of 575 samples can be analyzed for a given well. Approximately 1 gm of clean rock material is needed for each sample. In most cases, some amount of additional washing is required - even for "washed samples", thus, it is best to send enough to ensure ample material after a final wash. It is further recommended that "clean lith cuts" be provided to minimize costs associated with additional sample preparation as all sample washing and preparation costs will be charged back to the client. The quoted price for an FIS Analysis is exclusive of sample preparation, handling and shipping; estimates for these project-specific services are available upon request.

1.2 Organization of this Report

Analytical results of the FIS analysis of HALLADALE 1 are presented graphically in Sections 2.1 and 2.2 as a series of profiles each illustrating the variation of a particular atomic mass (m/z) or ratio of two masses with measured depth. A general discussion of the interpretation of FIS data including the significance of particular features and trends (or their absence) is provided in Appendix A. The remaining information provided in subsequent sections includes: 1) reference spectra, collected on internal standards and used to monitor inter- and intra-analytical consistency of the quadrupole analyses which are presented and discussed in Appendix B; and 2) mass spectra from all samples which are listed individually by depth in Appendix C.

1.3 Output Formats

Analytical results of the present study are available in electronic format as described below. The first five items are included on the 3.5" floppy diskette provided with each color hard-copy of the final report. The remaining file, FI050074a-1.pdf, is available upon request for a nominal fee.

1. FI050074a-1.las – LAS-format, 26-column file containing recorded depth and Tracks 1-25 from the *FIT Analysis* of HALLADALE 1
2. FI050074a-1.txt – TXT-format, 26-column file containing recorded depth and Tracks 1-25 from the *FIT Analysis* of HALLADALE 1
3. FI050074a-2.las.Z – LAS-format (compressed), 181-column file containing recorded depth and background corrected, normalized, standardized individual mass spectra (m/z 2-180) from the *FIT Analysis* of HALLADALE 1
4. FI050074a-s.pdf – PDF format, electronic file of the summary tracks and annotations from the *FIT Analysis* of HALLADALE 1
5. FI050074a-c.pdf – PDF format, electronic file of the poster containing *90% of all FIS Data* from the *FIT Analysis* of HALLADALE 1
6. FI050074a-1.pdf – PDF format, electronic file of the final report (entire document) of the *FIT Analysis* of HALLADALE 1

2 Analytical Results

2.1 FIS Depth Profiles Showing all Data

Millivolt responses for selected ionic species or species ratios resulting from FIS mass spectrometric analysis are displayed in Figures 2-6 (trackplots one through twenty-five). The identity of the individual ions involved in construction of the trackplots are listed in Table IV below. The tracks are organized into groups of related compounds; tracks 1-6 representing inorganic gases, tracks 7-9 representing dry organic gases, tracks 8-14 representing water soluble organic species or ratios of "more soluble" to "less soluble" species, and tracks 15-20 and 21-25 representing petroleum components of higher molecular weight and two sulfur compounds. The general interpretation of *FIS* data shown in the trackplots is discussed in Appendix A.

Table IV: Identification of Organic and Inorganic Species Represented in Track Plots

Mass #	Description
2	hydrogen (H_2^+)
4	helium ($^4He^+$)
15	C_1 fragment (CH_3^+); largely methane
30	C_2 fragment ($C_2H_6^+$); largely ethane
34	hydrogen sulfide (H_2S^+)
44	dominantly carbon dioxide (CO_2^+); possible C_3 fragment overlap
55	contribution from C_4 and greater naphthenes
57	contribution from C_4 and greater paraffins
60	dominantly acetic acid (CH_3COOH^+); possible dominance by carbonyl sulfide (COS^+) in some cases
64	S_2 or SO_2 plus hydrocarbons
71	contribution from C_5 and greater paraffins
76	CS_2 plus hydrocarbons
77	contribution from aromatic species
78	benzene ($C_6H_6^+$) with possible contribution by carbon disulfide (CS_2^+)
91	toluene ($C_7H_7^+$)
97	C_7 alkylated naphthene fragment

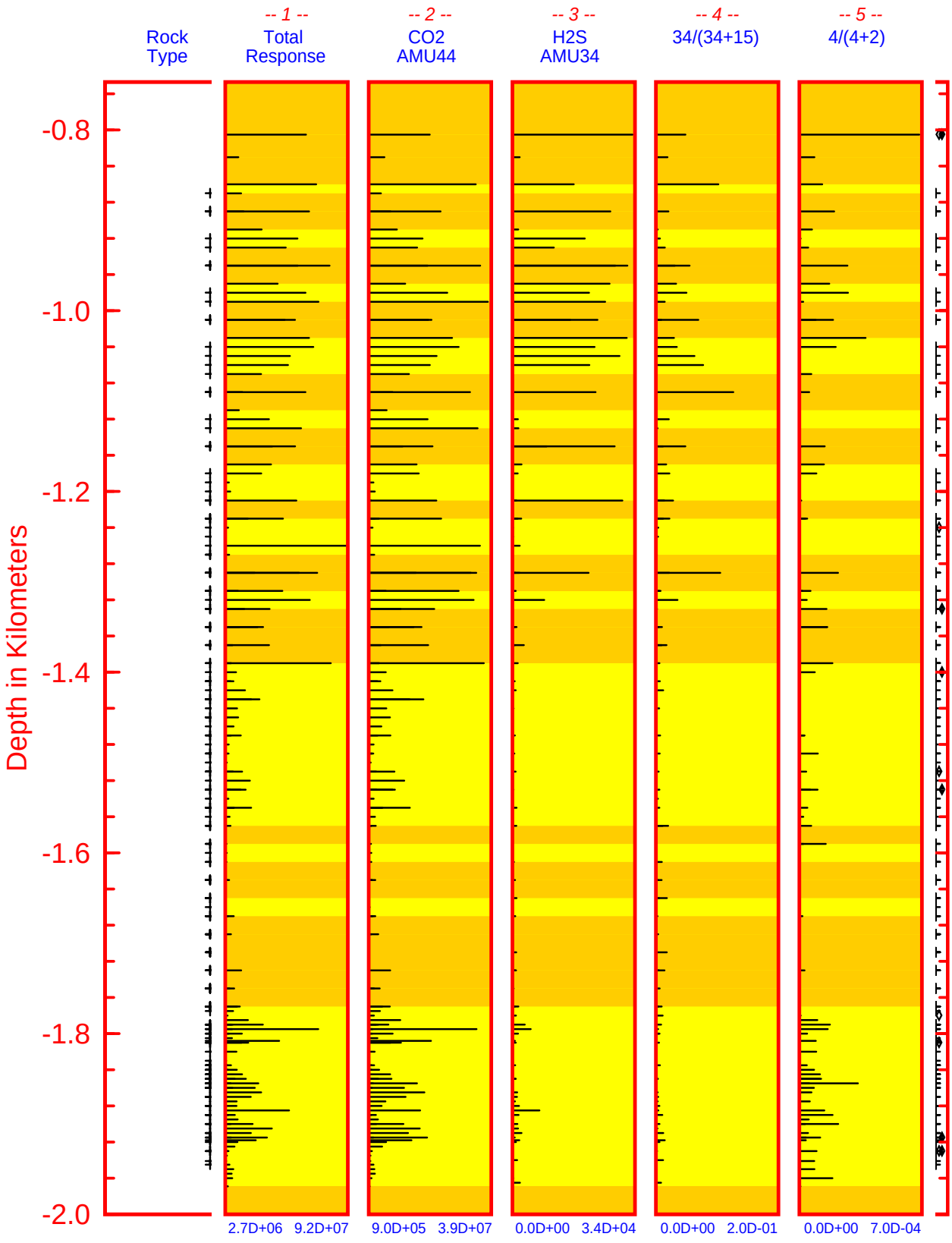


Figure 2: All FIS Data: Tracks 1 – 5 (see Sect. A.3 for explanation)

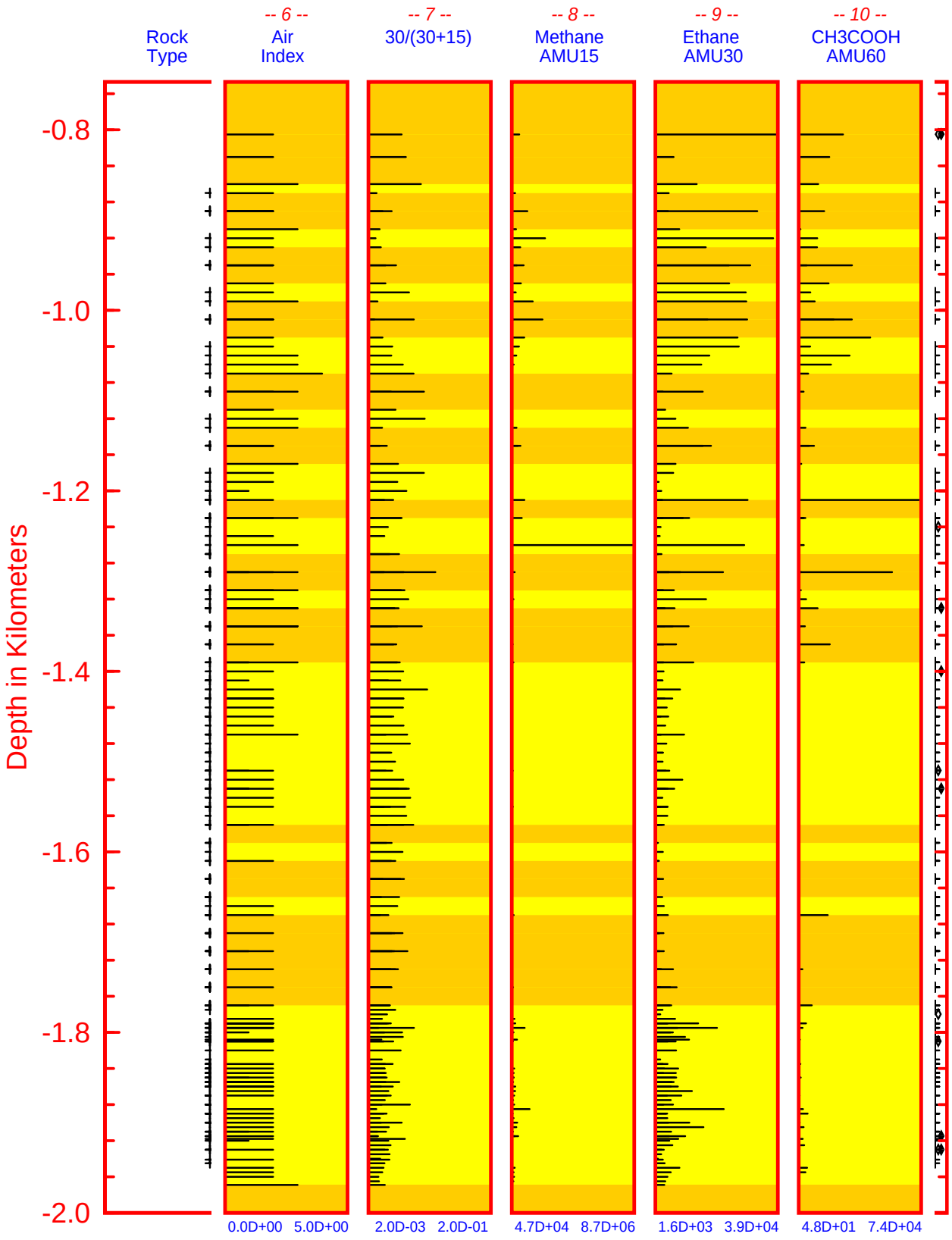


Figure 3: All FIS Data: Tracks 6 – 10 (see Sect. A.3 for explanation)

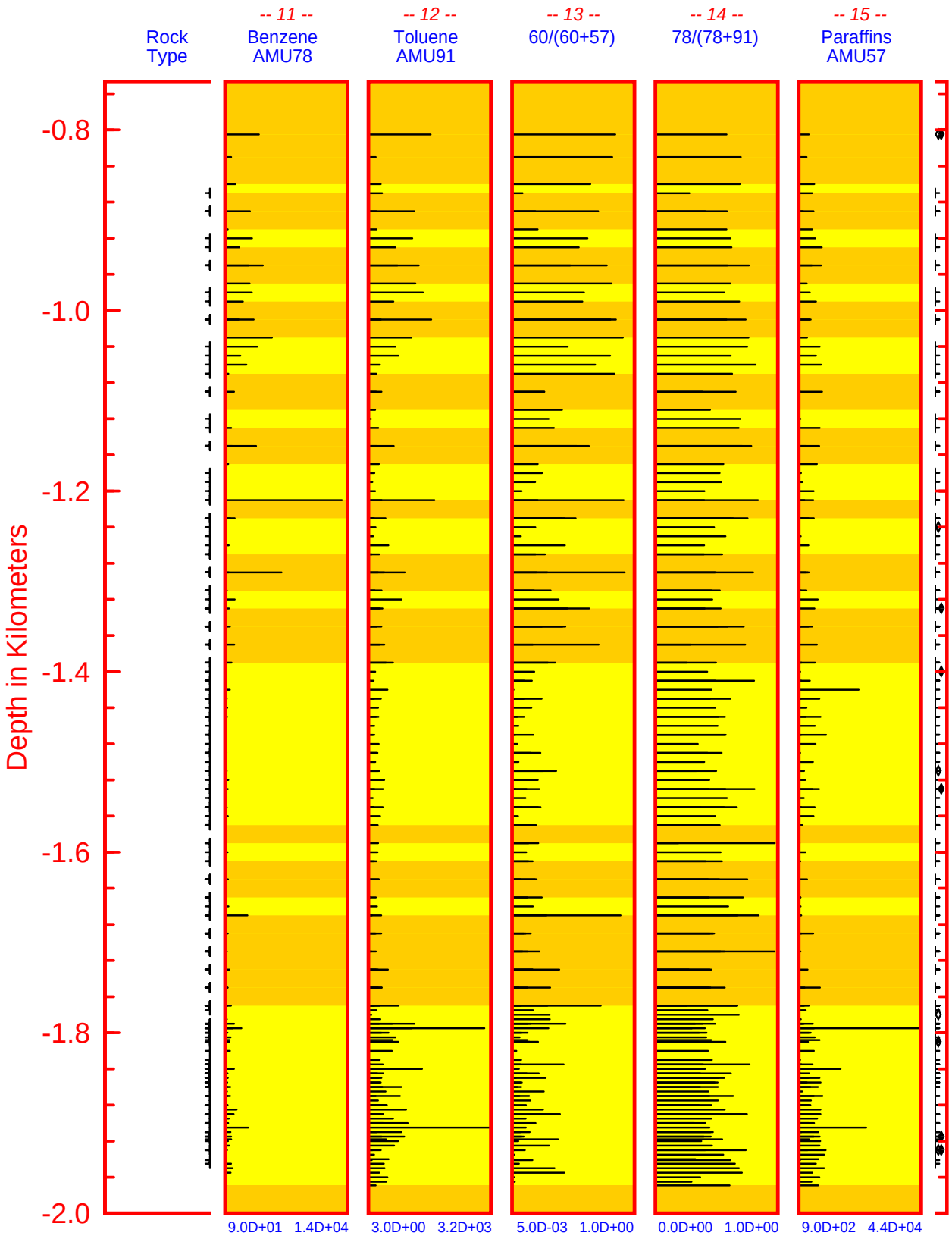


Figure 4: All FIS Data: Tracks 11 – 15 (see Sect. A.3 for explanation)

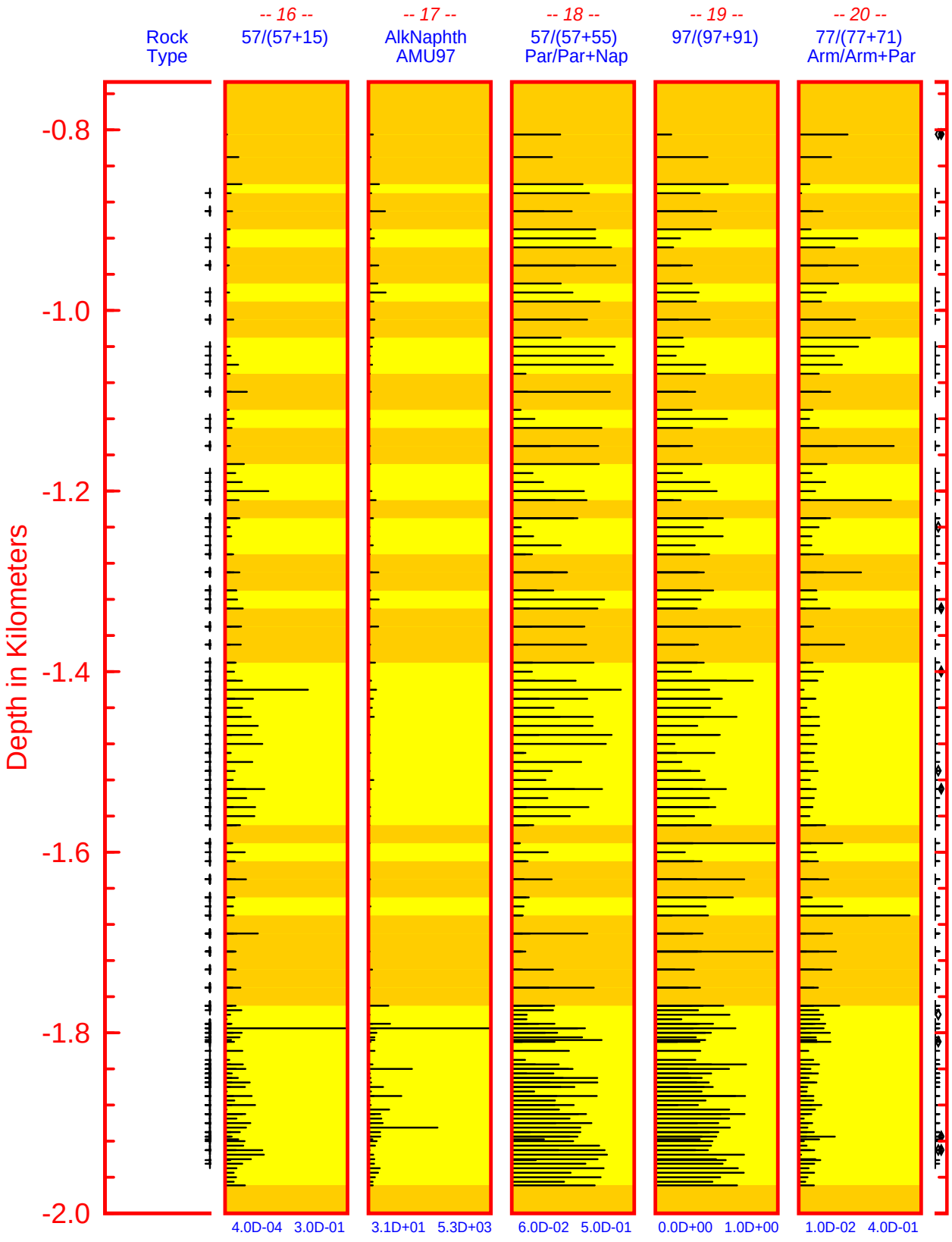


Figure 5: All FIS Data: Tracks 16 – 20 (see Sect. A.3 for explanation)

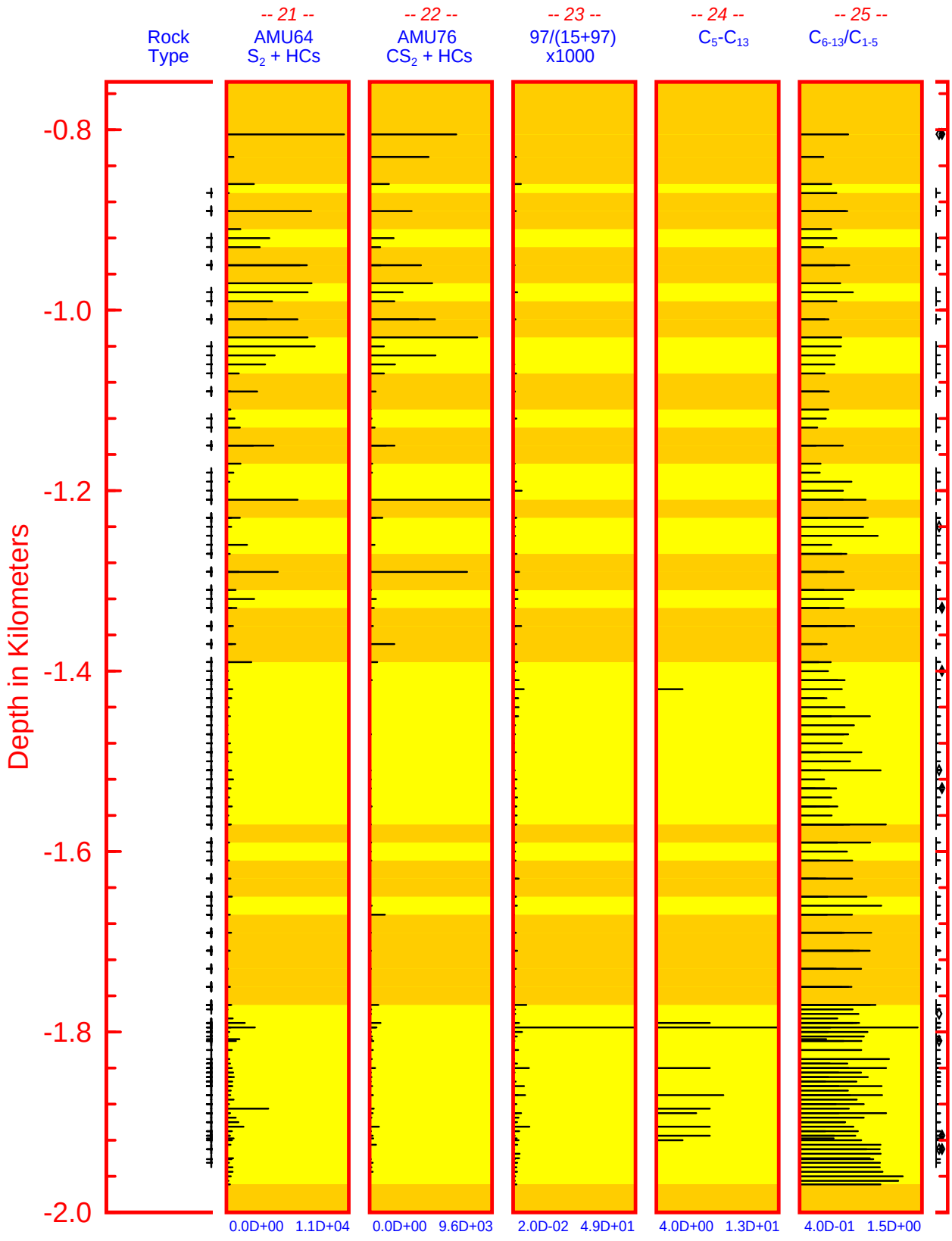


Figure 6: All FIS Data: Tracks 21 – 25 (see Sect. A.3 for explanation)

2.2 FIS Depth Profiles Showing 90% of all Data

Figures 7-11 show the same data as that given in Figures 2-6 of Section 2.1 *except* the upper and lower 5% of the data have been removed in each track and the scale along the abscissa adjusted accordingly in order to accentuate small deviations from background and reduce attenuation effects associated with scale-dominating responses. The identity of the individual ions involved in construction of the trackplots are listed in Table IV. The tracks are organized into groups of related compounds; tracks 1-6 representing inorganic gases, tracks 7-9 representing dry organic gases, tracks 8-14 representing water soluble organic species or ratios of "more soluble" to "less soluble" species, and tracks 15-20 and 21-25 representing petroleum components of higher molecular weight and two sulfur compounds. The general interpretation of *FIS* data shown in the trackplots is discussed in Appendix A.

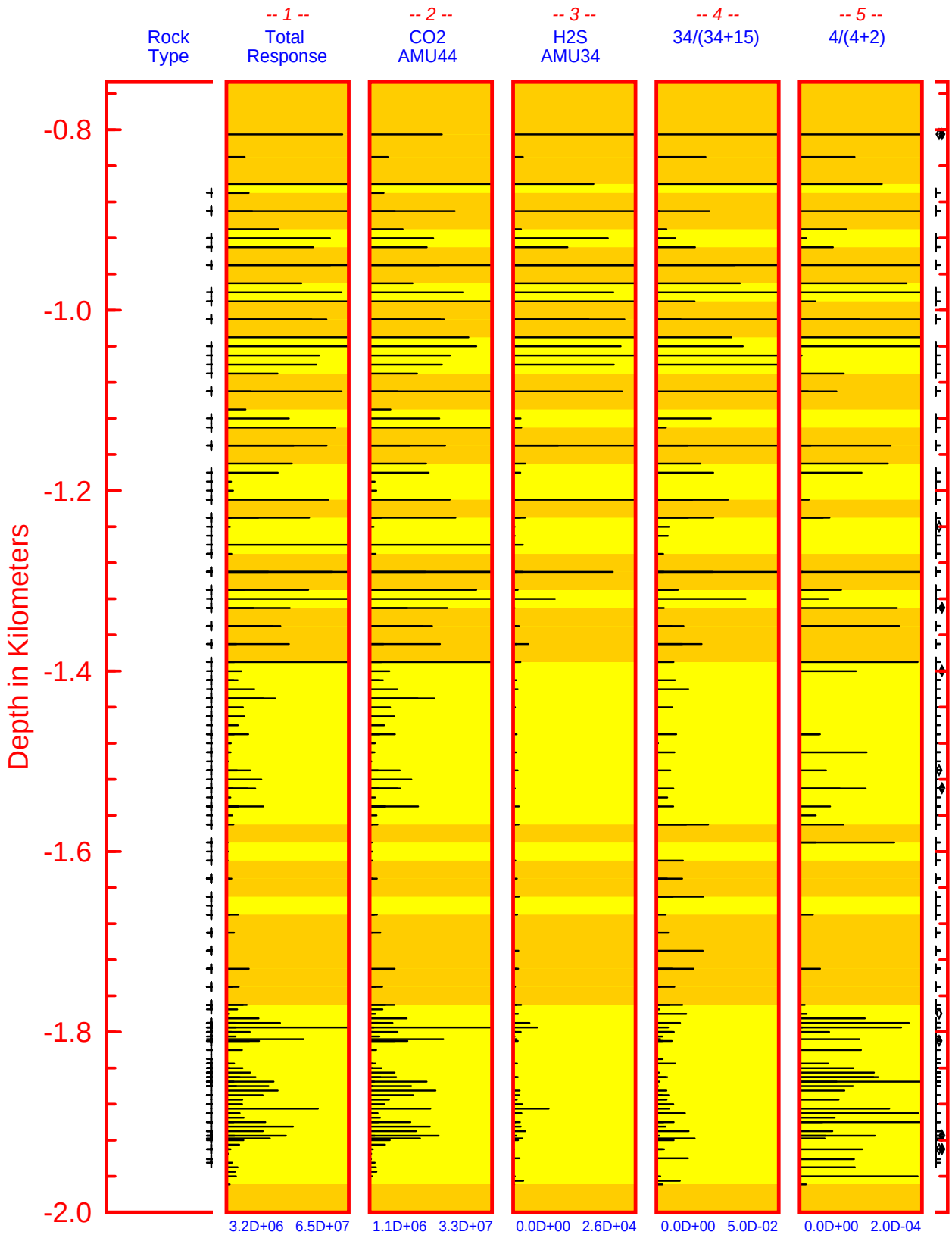


Figure 7: 90% of all FIS Data: Tracks 1 – 5 (see Sect. A.3 for explanation)

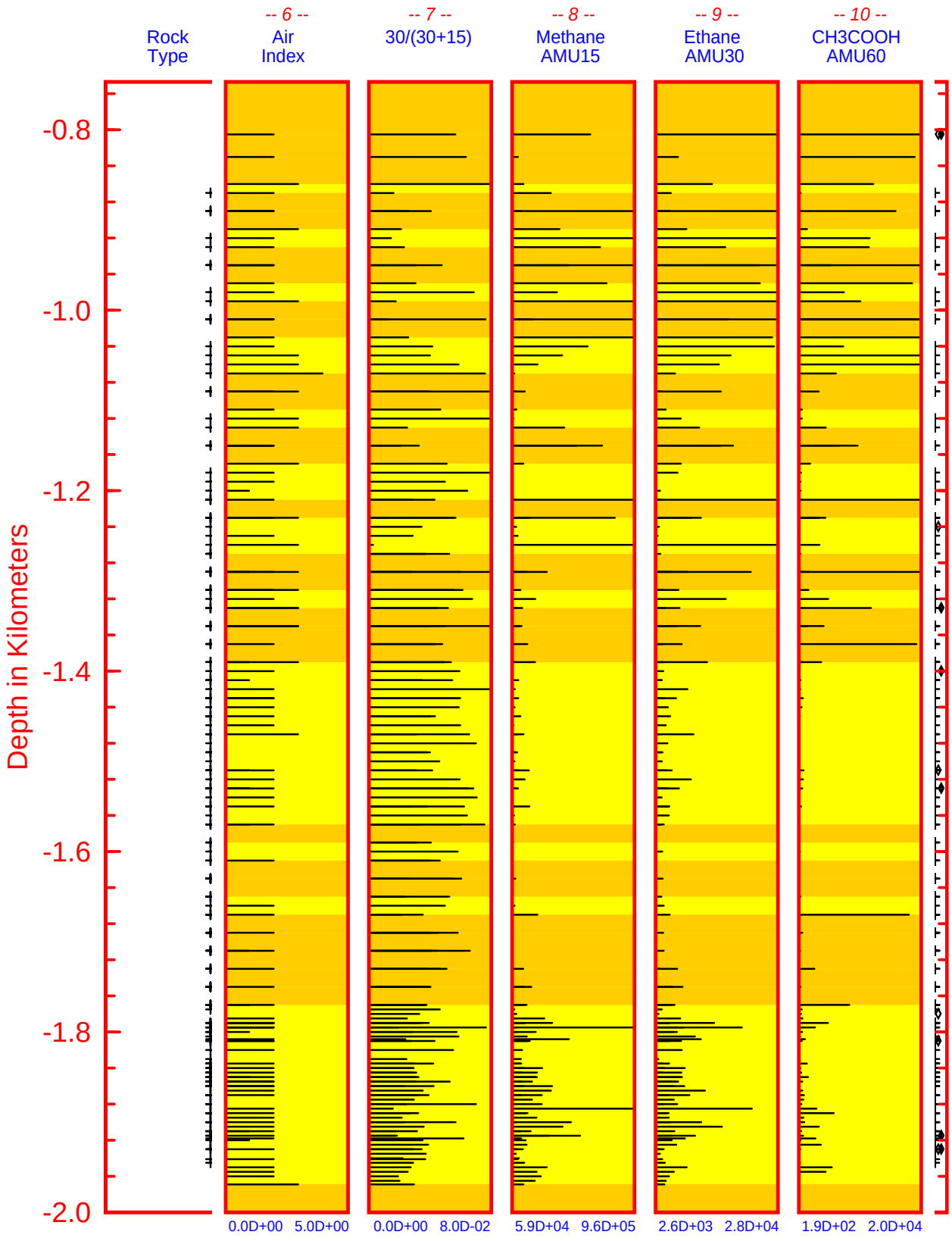


Figure 8: 90% of all FIS Data: Tracks 6 – 10 (see Sect. A.3 for explanation)

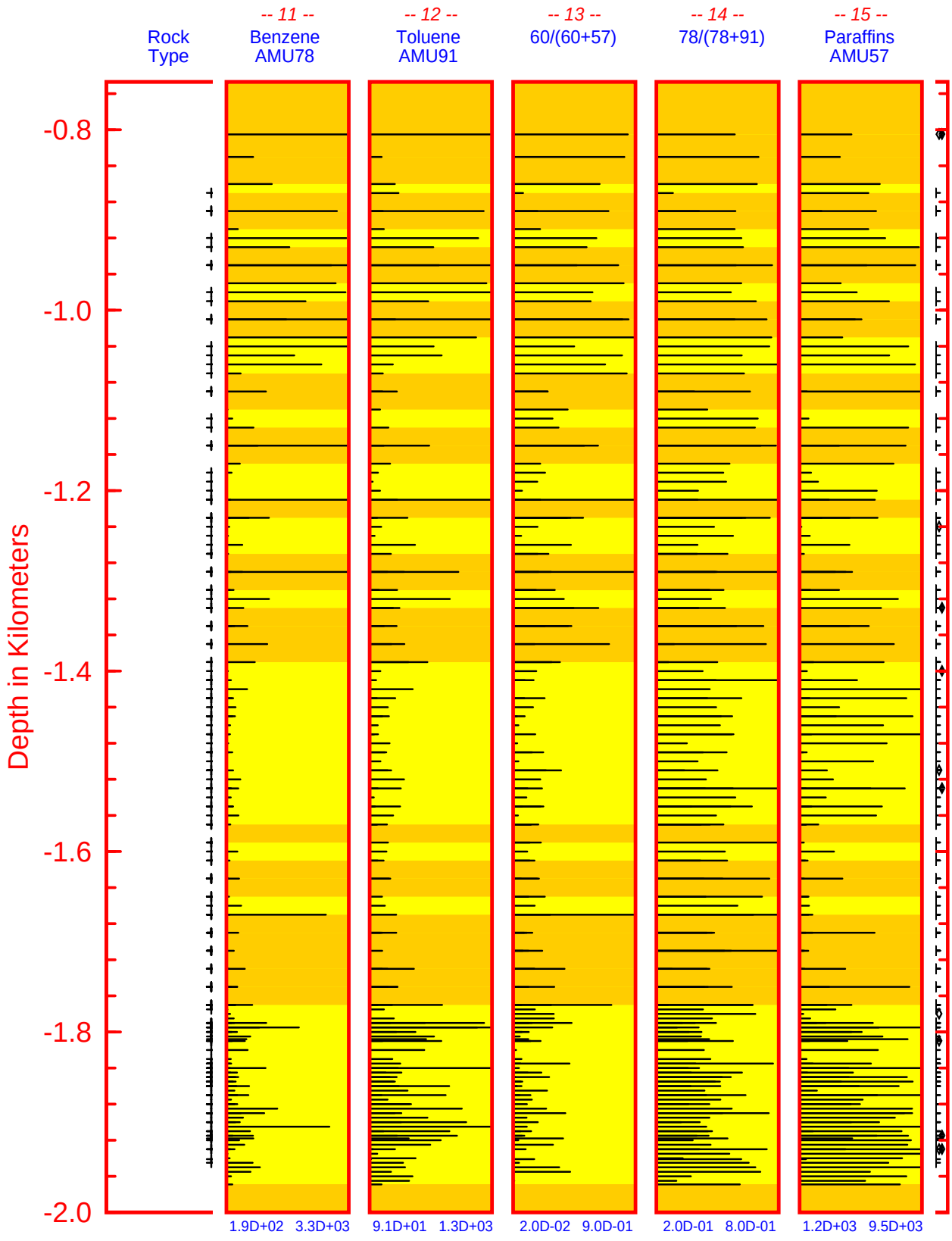


Figure 9: 90% of all FIS Data: Tracks 11 – 15 (see Sect. A.3 for explanation)

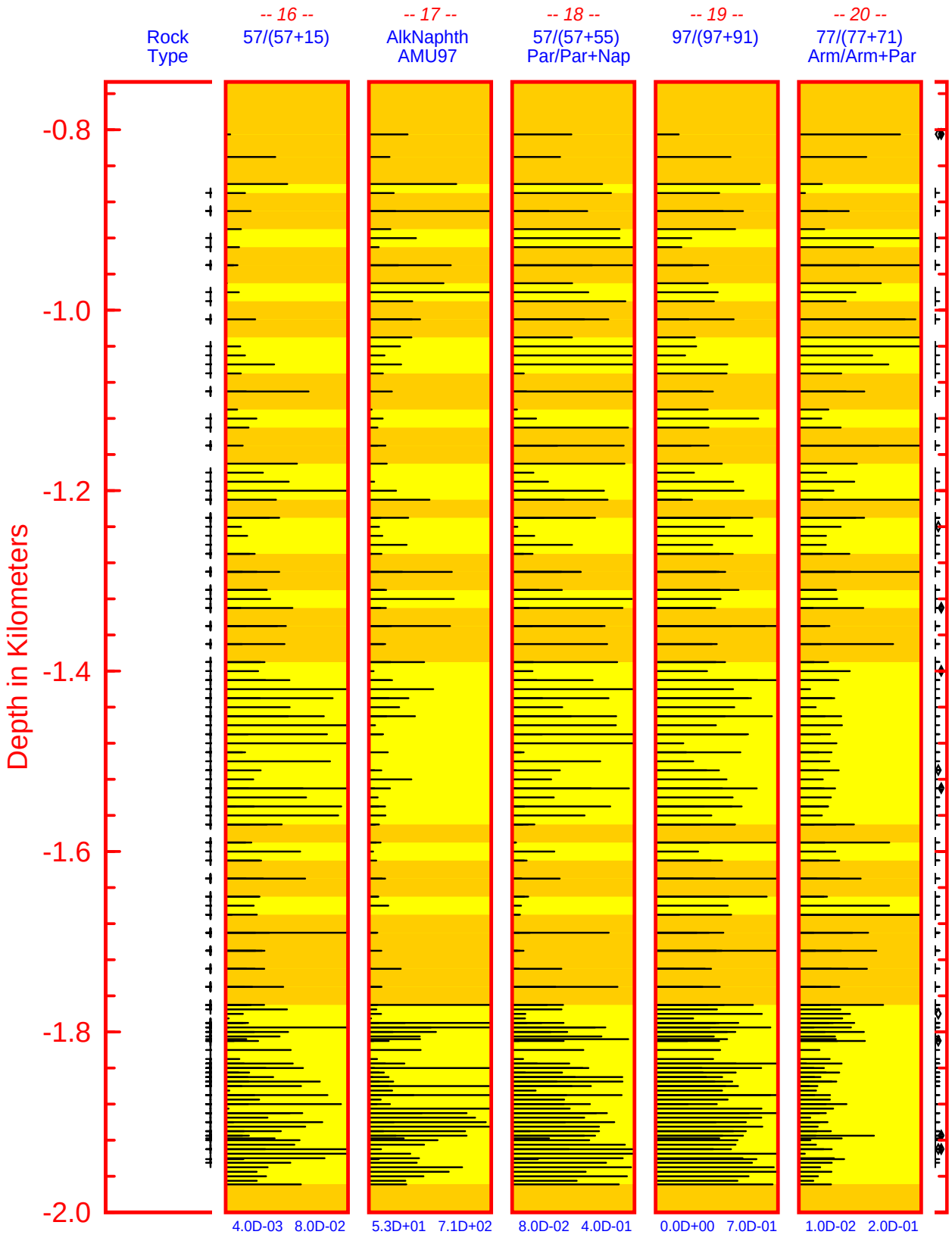


Figure 10: 90% of all FIS Data: Tracks 16 – 20 (see Sect. A.3 for explanation)

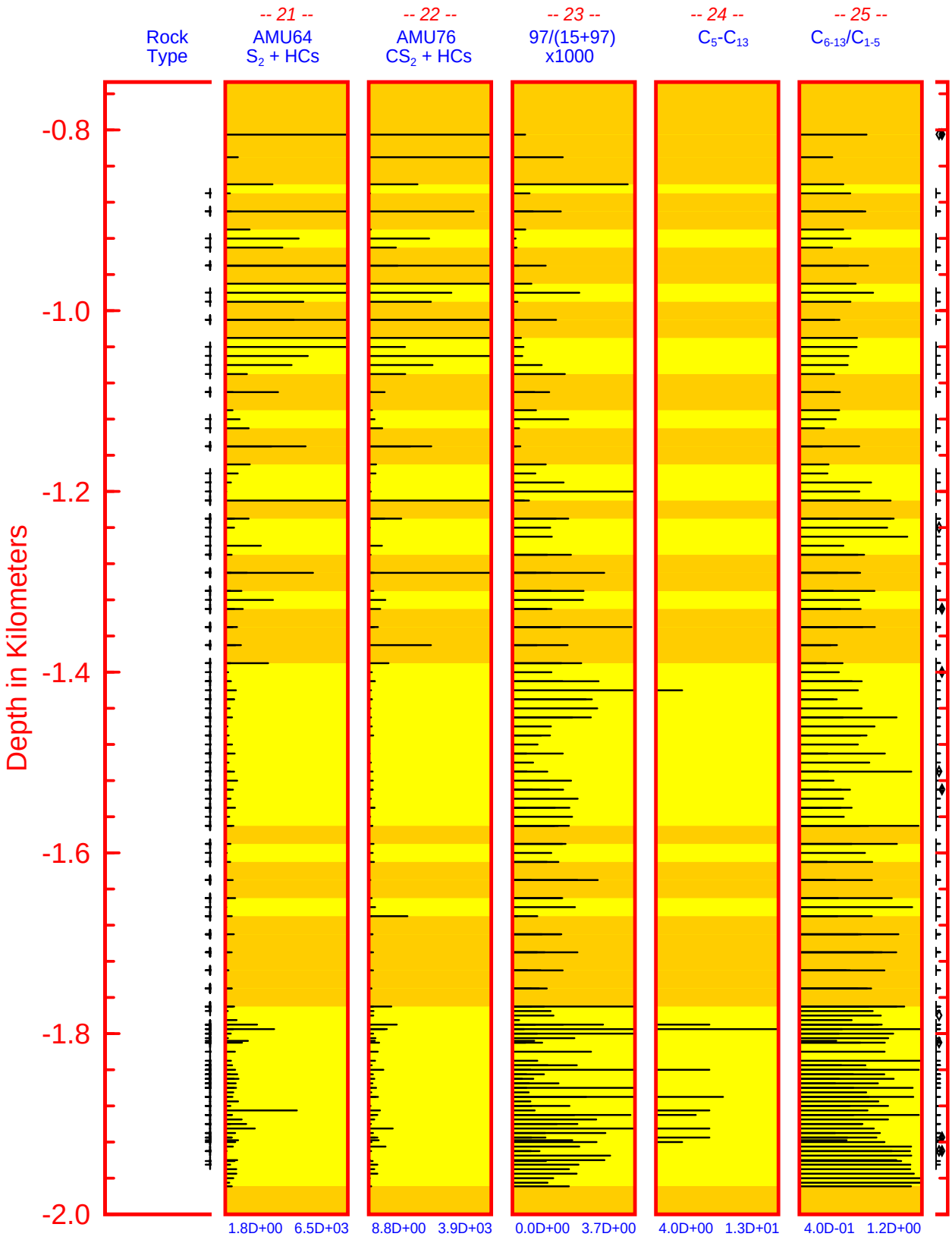


Figure 11: 90% of all FIS Data: Tracks 21 – 25 (see Sect. A.3 for explanation)

3 Photomicroscopy

Thin sections were prepared from HALLADALE 1 samples at depths warranting further examination following preliminary assessment of the *FIS* analytical results. The sections were then examined under a petrographic microscope using a variety of fluid inclusion techniques (e.g., UV-fluorescence, microthermometry, etc.) in order to verify the presence of petroleum-bearing inclusions in the rock samples and to explore textural relationships that may yield additional information on the timing of hydrocarbon migration or generation. Petrographic examination is also necessary to verify that petroleum-bearing fluid inclusions present in the samples and responsible for the observed mass spectra are not relict features (i.e., that they were not already present in the mineral grains prior to deposition). The following figures contain photomicrographs representative of samples from HALLADALE 1 at the depths indicated.

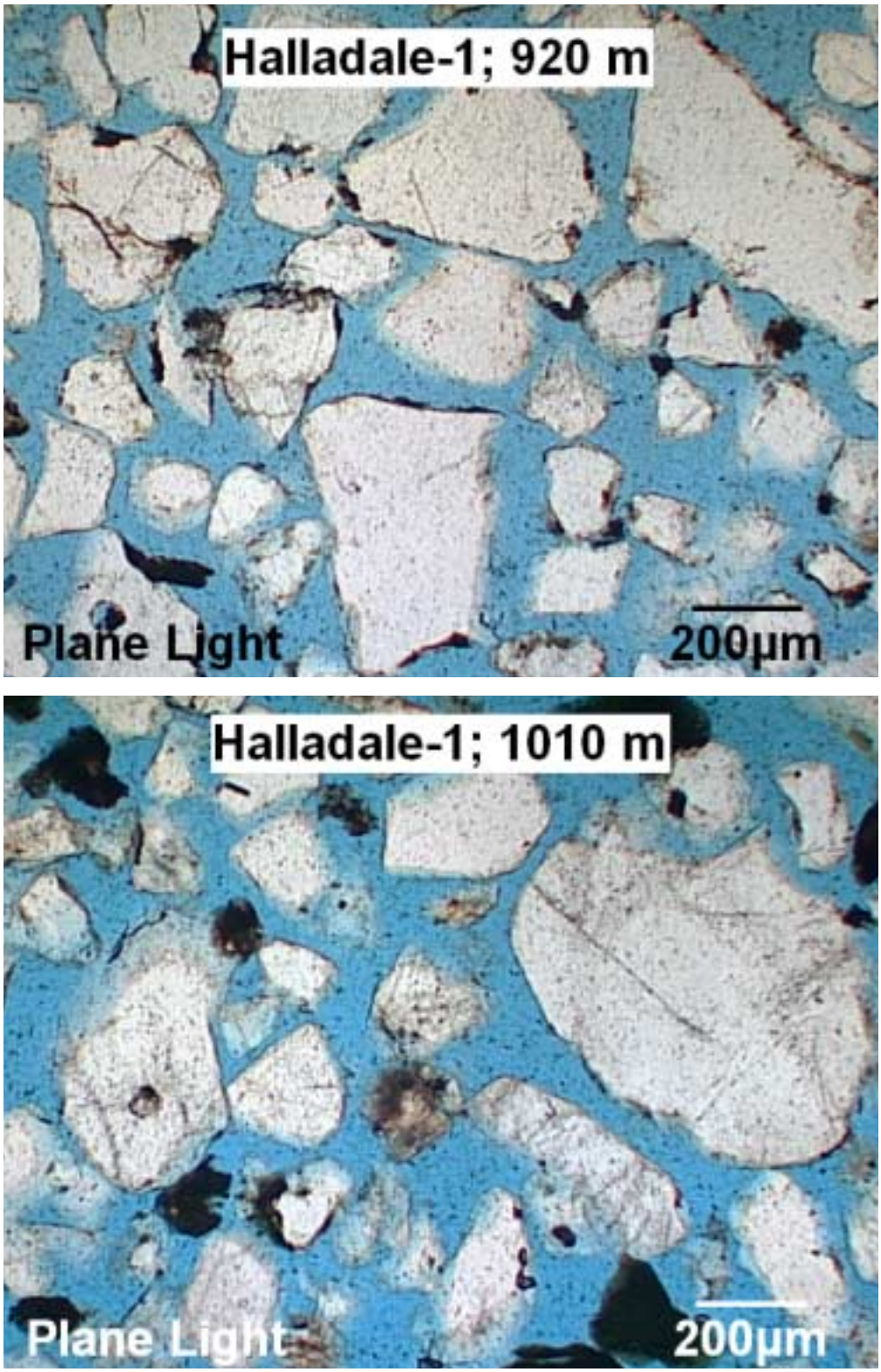


Figure 12: Photomicroscopy from HALLADALE 1

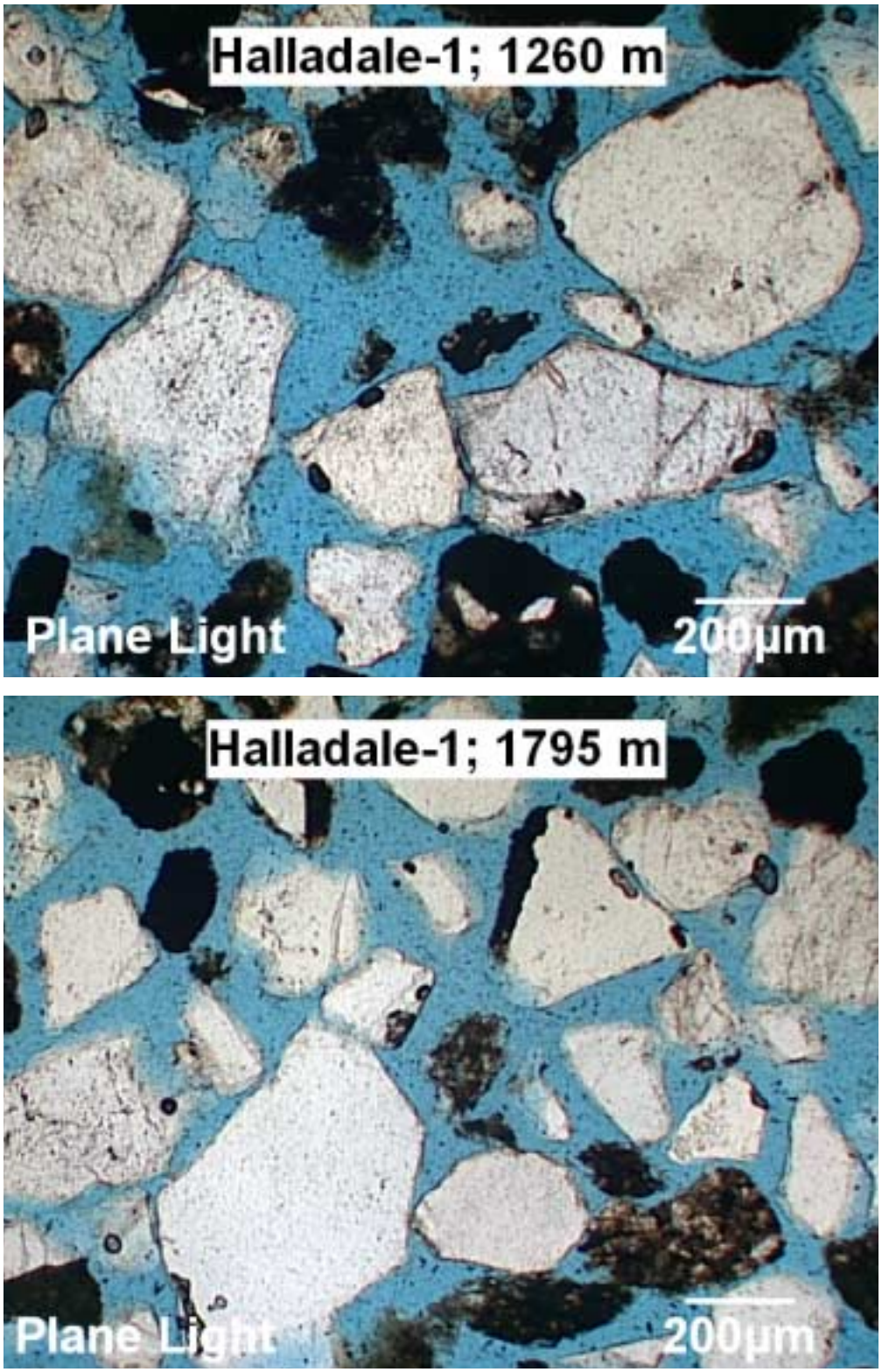


Figure 13: Photomicroscopy from HALLADALE 1

Figure 14: Photomicroscopy from HALLADALE 1

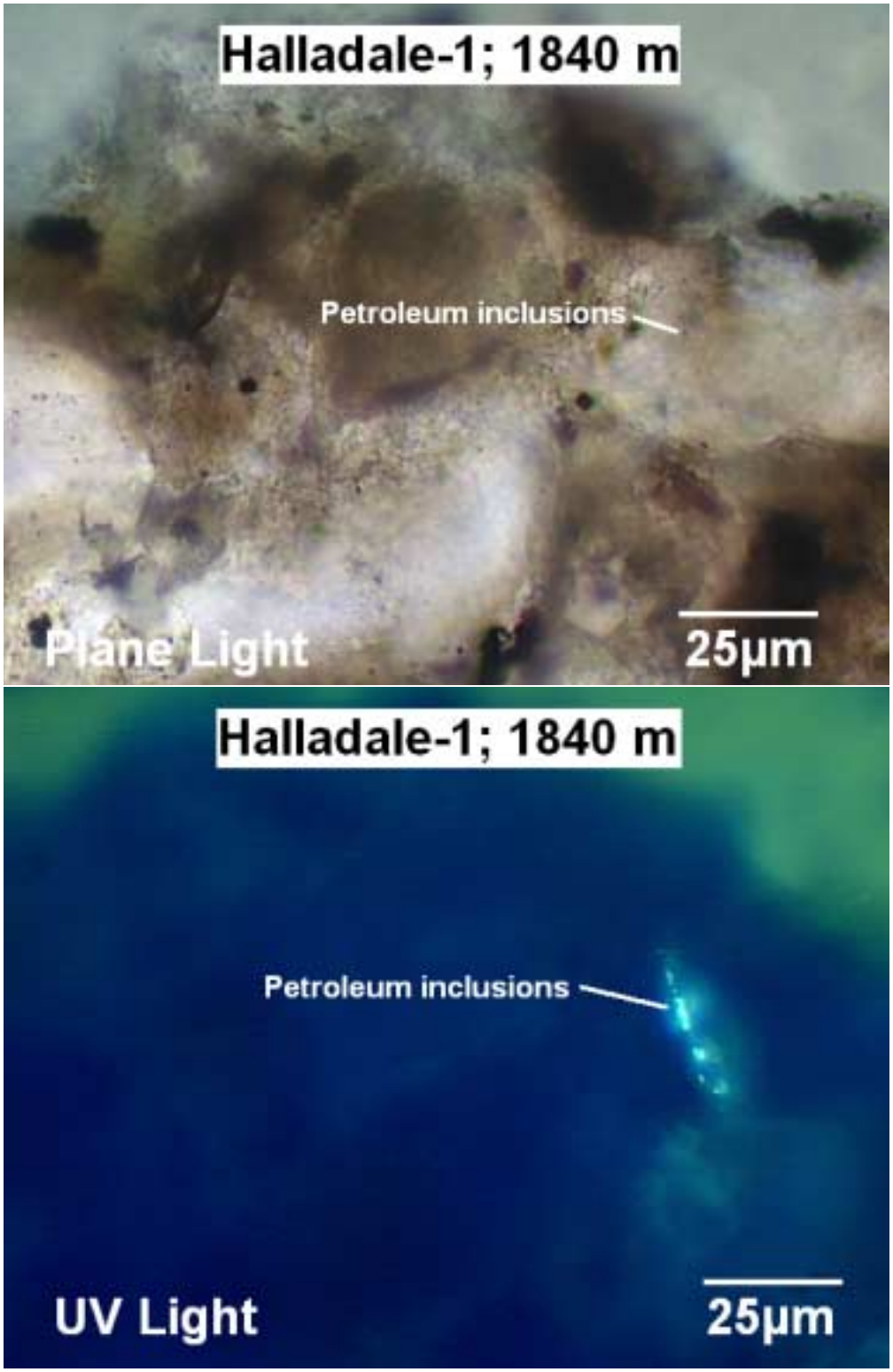


Figure 15: Photomicroscopy from HALLADALE 1

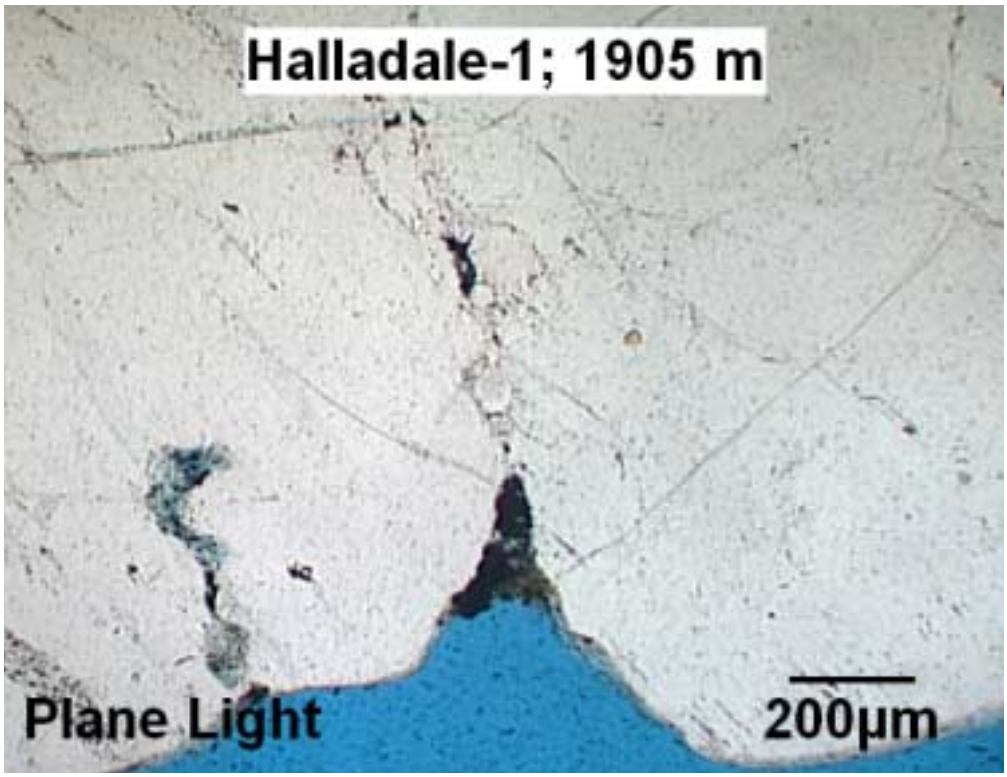


Figure 16: Photomicroscopy from HALLADALE 1

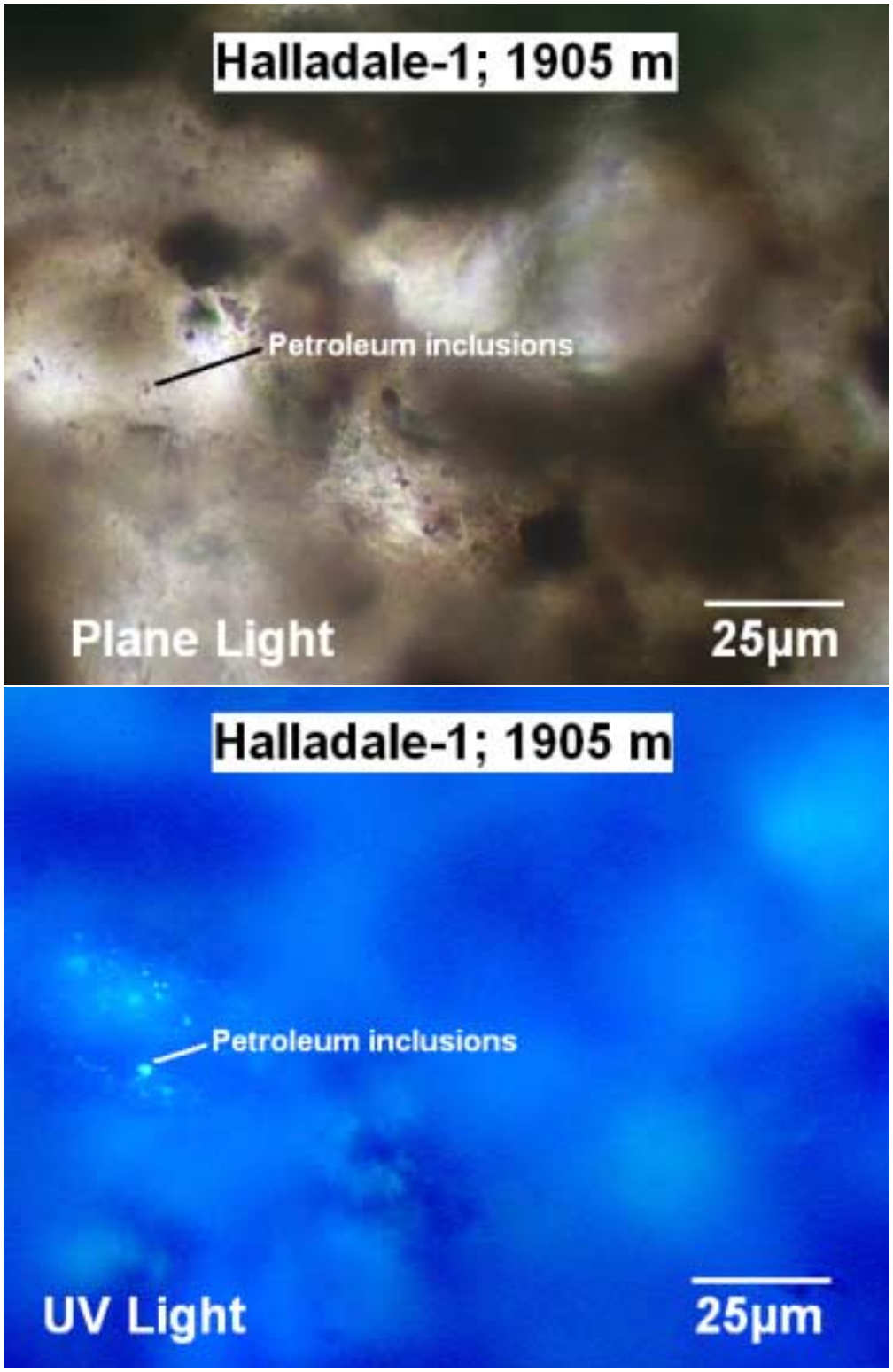


Figure 17: Photomicroscopy from HALLADALE 1

Appendices

A Interpretation of Fluid Inclusion Stratigraphy (FIS) Data

A.1 FIS Analysis

A.1.1 Introduction to FIS Analysis

Fluid Inclusion Stratigraphy involves the rapid, complete analysis of volatiles trapped as fluid inclusions in rock samples using quadrupole mass analyzers attached to an automated, high-vacuum sample introduction system. The technique documents the presence and relative bulk abundance of ionized volatile fragments with mass/charge ratio of $1 \leq m/z \leq 180$ that have been released from fluid inclusions by crushing of natural samples. This includes most geologically important inorganic species as well as organic species with less than or equal to 13 carbon atoms. The resulting analysis of the petroleum fraction is comparable to the low molecular weight fraction of a whole-oil gas chromatographic - mass spectrometric (GCMS) analysis (without devolatilization of the gas fraction); hence, the major classes of hydrocarbons (e.g., aromatics, naphthenes and paraffins) are represented. Unlike GCMS, where the quadrupole is front-ended with a GC, boiling point separation is not achieved and all species are analyzed simultaneously. Hence, significant interference can occur among species with the same mass to charge ratio. However, what FIS lacks in compound specificity, it makes up for in sensitivity and speed, allowing detection of petroleum in samples that are well beyond the reach of standard GCMS methodologies.

Prior to analysis, samples of rock material are freed of significant interfering contamination by washing, picking and magnetic separation as necessary to remove drilling fluids, lost circulation materials, other solid mud additives such as gilsonite, and metallic particles from the drillstring. Cleaned samples are loaded with appropriate standards into specially designed autosamplers and are heated in a vacuum oven for a minimum of 24 hours. This is done to remove adsorbed organic and inorganic volatile material that could interfere with the analysis. The autosampling device is placed in the vacuum system and evacuated to appropriate high vacuum. Bulk fluid inclusion volatiles are afterwards instantaneously released from each sample in a sequential manner by automated mechanical crushing. Volatile organic and inorganic species are dynamically pumped through quadrupole mass analyzers where they are ionized, separated according to their mass/charge and recorded.

Fluid Inclusion Stratigraphy is unique in several ways: 1) the methodology and theoretical framework are the result of a long-standing research and development effort, 2) the cumulative experience and database of documented case histories are the most extensive in the world and 3) the technology represents the most rapid analytical capability of its kind available. The resulting dataset can provide a nearly continuous log of present and past pore fluid chemistry through the stratigraphic section penetrated by a well, and, given adequate sample coverage, the data can be mapped in two or three dimensions.

A.1.2 Introduction to FIS Data Interpretation

The following sections provide guidelines for interpreting Fluid Inclusion Stratigraphy (FIS) data that were developed during evaluation of a large number of wells from many geologic and structural environments over the years. This methodology was followed in preparing the annotated depth plots found at the front of this report and is adequate for most circumstances. There are two levels of interpretation to be considered:

1. Interpretation of FIS data by itself (basically describing what volatiles are present and in what relative proportion).

2. Interpretation of the significance of FIS data in a geologic context to answer a specific petroleum system question.

These guidelines concentrate on addressing the first level of interpretation, both because potential geologic scenarios are too variable to be thoroughly considered here, and because the end user is in the best position to judge the ultimate significance of these data after integrating the FIS data set with other information. When interpreting FIS data, the following statements apply:

1. FIS interpretations are generally qualitative.

2. Chemical relationships displayed in FIS data are either obvious or they are unreliable as exploration tools.

3. FIS interpretations are usually simple, but may be equivocal without supporting information.

A.1.3 FIS Data Consists of Two Parts

There are two parts to a conventional FIS data set, and each must be evaluated in detail.

1. Stratigraphic profiles of critical species and species ratios with depth (Sections 2.1 & 2.2).

2. Individual mass spectra for each sample (Appendix C).

A mass spectrum is a graphical display of the log of the ion current (measured on the mass spectrometers' detectors) as a function of the mass-to-charge ratio (m/z) of the detected ions (this will become clearer after reading the sections below). The amplitude of the ion current is proportional to the quantity of each type of ion, which, in turn, is proportional to the abundance of the species in the original gas mixture. Discrete peaks occur because the charged substances have discrete masses and discrete charges (usually single and positive).

There is a tendency for end users to concentrate on interpreting the first part of the data set (depth plots) and ignore the second (individual mass spectra). However, as will be shown, evaluation of individual FIS mass spectra is as important to the overall FIS interpretation as pattern-recognition of whole-oil chromatograms is to evaluating oil families. Imagine taking a single species present in a chromatogram and plotting it as a function of depth in the reservoir without ever considering its relationship to other species that are present. Certainly useful information results, but not nearly as much as could be offered by looking at the overall species distribution in the chromatogram in addition to the absolute abundance of a species or the ratio of two species as a function of depth. Similarly, both FIS depth plots and individual mass spectra are important to the final interpretation.

A.2 FIS Mass Spectra

A.2.1 Understanding FIS Mass Spectra

FIS data are collected on quadrupole mass spectrometers. These instruments distinguish among positively charged species using an electrodynamic field produced by application of combined RF and DC voltages to two pairs of metal rods in the filter section. A species

with a specific ratio of mass to charge (m/z) will have a dynamically stable trajectory within the field formed by the voltages on the rods, while all other species are filtered out. By continuously varying the applied voltages, a range of charged substances can be sequentially stabilized and allowed to traverse the length of the filter assembly to the detector. FIS data currently provided consists of measured responses on m/z 1-180. This mass range allows detection of all volatile inorganic species as well as organic compounds with up to 13 carbon atoms (C_{13}). Detection is accomplished either with a Faraday cup, which reads ion currents directly from the filter without amplification, or by an electron multiplier, which amplifies the single charge of a given ion into a current.

In order for species to be detected they must be charged (ionized). This is accomplished by bombarding volatiles released from fluid inclusions with electrons that are thermionically emitted from a hot filament. Energy transference from electrons to neutral particles generally results in positively charged parent ions, while excess energy obtained by a molecule in the initial ionizing collision results in fragmentation of the parent molecule into several species. For a single parent molecule, the resulting mass spectrum is known as a fragmentation pattern. The distribution of ions from a given species can generally be predicted by considering all combinations of molecules and isotopic variants. The following example illustrates this concept.

Molecular carbon dioxide has a formula CO_2 and most common molecular mass of 44. In detail, the mass of a given molecule of CO_2 can be 44, 45, 46, 47, 48 or 49 because both carbon and oxygen have two significant, naturally occurring isotopes (^{12}C, ^{13}C, ^{16}O, and ^{18}O). Hence, the fragmentation pattern of CO_2 would be expected to contain the singly charged species CO_2^+, CO^+, C^+ and O^+ with all possible isotopic permutations (14 possible masses). Additionally, doubly charged species can be produced. These species, although much rarer, have m/z of exactly half of their singly charged counterparts (e.g., $^{12}C^{16}O^{16}O^{++}$ has m/z of 44/2 = 22). Some peaks associated with doubly charged ions appear midway between two integer m/z locations (e.g., $^{13}C^{16}O^{16}O^{++}$ has m/z of 45/2 = 22.5). In general, instrument parameters favor the production of singly charged species. The relative frequency at which a given species will be produced and detected reflects natural isotopic abundance, ion production statistics and instrument parameters. In the above example of CO_2, the representative fragmentation pattern shown in Table V has been reported.

Table V: Partial Fragmentation Pattern for Carbon Dioxide

Mass	Species	Abundance	Mass	Species	Abundance
6	$^{12}C^{++}$	0.0005	28	$^{12}C^{16}O^{+}$	15
8	$^{16}O^{++}$	0.00046	29	$^{13}C^{16}O^{+}$	0.15
12	$^{12}C^{+}$	6.3	30	$^{12}C^{18}O^{+}$	0.029
13	$^{13}C^{+}$	0.063	31	$^{13}C^{18}O^{+}$	0.0029
16	$^{16}O^{+}$	13	44	$^{12}C^{16}O^{16}O^{+}$	100
18	$^{18}O^{+}$	0.0088	45	$^{13}C^{16}O^{16}O^{+}$	1.2
22	$^{12}C^{16}O^{16}O^{++}$	0.52	46	$^{12}C^{18}O^{16}O^{+}$	0.38
22.5	$^{13}C^{16}O^{16}O^{++}$	0.0047	47	$^{13}C^{18}O^{16}O^{+}$	0.0034
23	$^{12}C^{18}O^{16}O^{++}$	0.0012	48	$^{12}C^{18}O^{18}O^{+}$	0.00054
			49	$^{13}C^{18}O^{18}O^{+}$	0.000043

In spite of the usage in the previous paragraph, the term "parent peak" is generally given to the most intense peak of the mass spectrum of a single compound, while the term "molecular peak" is given to the singly charged ion with the same atomic mass as that of the pure compound. In the example above, both the parent and molecular peaks of CO_2 occur at m/z = 44. It is frequently the case, however, that the most intense peak is not the molecular peak. For instance, many normal paraffins with three or more carbon atoms (n-propane and greater) have parent peaks at m/z = 43, 57 or 71.

Complex volatile mixtures have mass spectra characterized by multiple, interfering ions on a given m/z, making it difficult or impossible to find a "clean" peak indicative of a specific species. Generally, higher m/z positions display more interference, but even low m/z have these overlaps (e.g. HD^+ and $^3He^+$ both appear at m/z = 3). This brings us back to one of the original points mentioned in the Introduction: mass spectra of multicomponent gas mixtures are qualitative in the sense that the absolute abundance of most species cannot be calculated. Nevertheless, similar compounds give similar fragmentation patterns that tend to be distinct from other classes of compounds. Because of this, the major classes of organic species (paraffins, naphthenes and aromatics) can be distinguished and their relative abundance estimated. Similarly, it is useful to consider the assemblage of anomalous peaks in a given mass spectrum, as these will often indicate the presence of compounds that are concentrated by similar subsurface processes (e.g., the water-soluble species benzene, toluene and acetic acid as the primary indicators of "proximal pay"). It is these assemblages that are most useful for distinguishing among major types of FIS mass spectra, as well as inferring the presence of a specific compound even where interfering ions are possible.

A.2.2 Five Types of FIS Mass Spectra

FIS mass spectra can be classified into five end member types:

1. *Non-hydrocarbon* FIS Mass Spectra
2. *Gas-range Enriched* FIS Mass Spectra
3. *Liquid-range Enriched* FIS Mass Spectra
4. *Water-soluble Enriched* FIS Mass Spectra
5. *Sulfur-compound Enriched* FIS Mass Spectra

Mixtures and gradations among these ideal end members are common. In considering the fragmentation patterns of organic species, it is useful to keep in mind the general formulas for the three dominant hydrocarbon classes:

1. *Paraffins:* C_nH_{2n+2}
2. *Naphthenes:* C_nH_{2n}
3. *Aromatics:* C_nH_{2n-6}

Non-Hydrocarbon FIS Mass Spectra

Non-hydrocarbon spectra generally show four major clusters or "humps" centered at approximately m/z 15, 28, 42 and 55. The tallest three peaks in these spectra occur within the

first three clusters at m/z 18, 28 and 44, and are attributable largely to water and carbon dioxide (with possible contributions from nitrogen on m/z 28). Most of the other peaks in the m/z 2-46 range of non-hydrocarbon spectra can be attributed to inorganic species or very minor organic contributions. Water and carbon dioxide are the two most abundant volatile species in subsurface pore fluids, hence their predominance here. FIS analysis is a bulk extraction technique, hence, many generations of fluid inclusions are potentially analyzed simultaneously. Because hydrocarbon inclusions are always present in much lower abundance than aqueous inclusions in a given rock volume, water and CO_2 peaks will generally dominate all FIS mass spectra, even those displaying hydrocarbon enrichment.

The fourth cluster of peaks, centered on m/z 55, represents minor amounts of hydrocarbons that are present in nearly all samples, as most hydrocarbons have a significant contribution in the m/z 55-57 area. Note, however, that even the largest of these peaks is generally three orders of magnitude below the major non-hydrocarbon peaks. Also, note that m/z 55 is commonly more abundant than m/z 57. The m/z 55 peak represents a major contribution from naphthenes, while the m/z 57 peak is generally a primary paraffin peak. The relative enrichment of naphthenes over paraffins in aqueous-dominated (non-hydrocarbon) FIS spectra may reflect the relative solubility of these species in water, as the progression from least soluble to most soluble follows the general rule: paraffins<naphthenes<aromatics. It is probable that these minor species are dissolved within aqueous fluid inclusions. The solubility of even relatively insoluble C_4 paraffin in water can be several hundred parts per million, well within the detection limit of the FIS system.

Gas-Range Enriched FIS Mass Spectra

Gas-enriched spectra are characterized by strong responses on C_1-C_5 hydrocarbons with dwindling responses in the C_6-C_8 range, and essentially no response in the C_9+ range. Drier gases may exhibit responses only in the C_1-C_3 range. Naturally occurring hydrocarbon gases tend to be dominated by short-chain paraffins; hence, these are the primary peaks to look for in identifying gas FIS spectra. Predominant peaks (parent and some significant subordinates with intensity of at least 10% of the parent) for low-molecular weight normal paraffins and naphthenes (cycloparaffins) are shown in Table VI.

Table VI: Partial Fragmentation Pattern for Gas-Range Hydrocarbons

Methane	**Ethane**	**Propane**	**n-Butane**	**n-Pent**	**n-Hex**	**Cyclopent**	**Cyclohex**
16(100%)	28	29	43	43	57	42	56
15	27	28	29	42	43	70(30%)	84(75%)
14	30(25%)	27	28	41	41	41	41
13	29	44(27%)	27	27	56	55	55
	26	43	41	28	29	39	42
		39	39	29	27	27	69
		41	42	57	42	40	27
			58(9%)	72(9%)	39	29	39
					86(15%)		

Here, molecular peaks are shown with their intensities relative to the parent peak. Note that the molecular peaks for C_4-C_6 normal paraffins are not among the top five most intense peaks (a feature of fragmentation patterns that was mentioned previously). Considering the location of the above peaks, a gas-enriched mass spectrum should contain peak clusters at m/z 13-16, 26-30, 39-44 and 55-57. Note that this is precisely where the four peak clusters are located in the previously described non-hydrocarbon mass spectrum (where they were attributed largely to CO_2 and water, nitrogen and minor hydrocarbon contributions). The distinction lies in the relative proportion of these species. Gases can typically contain 90% C_1 and 95% C_1-C_3. Hence, FIS gas spectra typically have prominent C_1-C_3 clusters. The water triad at m/z 16-18, which commonly shows a pattern of monotonic increase from 16 to 18 in non-hydrocarbon spectra can become disturbed at high gas concentrations so that masses 15 and 16 become dominant, even to the point of being more intense than mass 18. Similarly, the 26, 27, 39, 41 and 43 peaks generally display significantly higher intensities than in non-hydrocarbon spectra. The ratio of mass 57 to mass 55 (C_4+ paraffins / C_4+ naphthenes) may become quite high, reflecting the paraffinic nature of many gases.

Liquid-Range Enriched FIS Mass Spectra

FIS spectra that contain significant quantities of liquid-range petroleum species display repetitive peak clusters corresponding to fragments with successive carbon numbers in the C_7-C_{13} range as shown in Table VII.

Table VII: Partial Fragmentation Pattern for Liquid-Range Hydrocarbons

Carbon #	m/z Cluster	Parent (nC)	Molecular (nC)
C7	95-101	43, 57, 41	100(14%)
C8	109-115	43, 57, 41	114(7%)
C9	123-129	43, 57, 41	128(8%)
C10	137-143	43, 57, 41	142(7%)
C11	151-157	43, 57, 41	156(4%)
C12	165-171	57, 43, 71	170(8%)
C13	179-185	43, 57, 41	184(5%)

Note, again, that molecular peaks for high-molecular weight hydrocarbon species are generally only 5-15% of the parent peak. Also note that the three most intense peaks for the C_7-C_{13} paraffins are usually the same, and represent some of the most intense peaks previously identified for the C_4-C_6 gas-range paraffins.

Only normal (straight-chain) paraffins have been considered in the above table. Typical C_6-C_{10} (gasoline) fractions contain 40% paraffins, 50% naphthenes and 10% aromatics by volume. Typical C_{11}-C_{13} (kerosene) fractions contain 30% paraffins, 50% naphthenes and 20% aromatics by volume. As the general formula for naphthenes suggests, molecular peaks are shifted downward by 2 m/z units (e.g., the C_7 naphthene molecular peak is at 98). Hence the major contribution at 43 for normal paraffins becomes 41 for naphthenes, 57 becomes 55, and so on. This is why the ratio of 57 to 55 is plotted in basic FIS data packages: to track the relative distribution of paraffinic and naphthenic compounds as well as the processes that fractionate them (e.g., dissolution in an aqueous phase; recall the solubility law for hydrocarbon species). Aromatic fragmentation patterns will be considered under the explanation of

water-soluble FIS mass spectra.

Natural liquid petroleum is a complex mixture containing hundreds of specific compounds within these classes. Thus, the qualitative nature of FIS mass spectra is reiterated. Major classes of organic compounds can be identified, distinguished and tracked semi-quantitatively, but specific compounds cannot be quantified except under special circumstances. From the foregoing discussion it becomes apparent that even though the FIS analytical procedure does not scan past the molecular peak of nC_{12}, contributions on low molecular weight species can include species well above C_{13}. The maximum carbon number contributing to the FIS mass spectrum is limited only by the volatility of the given compounds within the high vacuum system and their abundance. However, it is unlikely that $C_{20}+$ compounds contribute significantly to FIS responses, given their volumetrically low abundance and vapor pressures.

Water-Soluble Enriched FIS Mass Spectra

FIS mass spectra containing anomalous concentrations of water-soluble volatile species are perhaps the most interesting of the main spectral types. Key indicator species are acetic acid, benzene and toluene (see Table VIII). Other common compounds include methane, ethane and carbon dioxide (fragmentation patterns previously outlined).

Table VIII: Partial Fragmentation Pattern for Water-Soluble Species

Formic A.	**Acetic A.**	**Propionic A.**	**Butyric A.**	**Benzene**	**Toluene**	**Xylenes**
29	43	28	60	78(100%)	91	91
46(61%)	45	29	73	77	92(75%)	106(65%)
45	60(60%)	74(79%)	27	52	39	105
28	15	45	41	51	65	39
17	42	73	42	50	51	51
44	29	57	43	39	63	77
			88(3%)			

Aromatics tend to have strong molecular peaks, unlike many paraffinic and naphthenic compounds. The species above are easily identified in mass spectra because major peaks occur within the valleys formed between the peak clusters of predominant paraffinic and naphthenic ions. These species (particularly aromatics) are present at some level in most FIS spectra that contain liquid-range hydrocarbons, because, as outlined above, aromatic species comprise 10-30% of most oils by volume. However, typically, aromatic peaks are 0.5-1 order of magnitude less intense than the adjacent paraffin/naphthene m/z cluster. Although there are no quantitative rules, aromatics are considered anomalous when visual aromatic peak heights becomes sub-equal to, or greater than, adjacent paraffin/naphthene peak clusters. Aromatic peak heights 1-2 orders of magnitude higher than the adjacent peak clusters are not uncommon in FIS spectra that indicate strong enrichment of water-soluble species.

Organic acids represent the most common organic species reported from formation water analyses, and of these, the mono-functional acids dominate. Acetic acid and propionic acid generally have the highest reported concentrations and abundance generally decreases with increased carbon number. As can be seen from the table above, some major peaks have potential interferences with CO_2. The most promising peaks for recognition of organic acids

are m/z 60 and, perhaps, 73-74. Organic acids are considered to be present in anomalous concentration when a distinct peak occurs at m/z 60. In the absence of organic acids this location generally lies in a "peak-height valley", even on hydrocarbon-enriched FIS mass spectra. In extremely enriched samples the intensity of the 60 peak is greater than all masses in the 60-180 m/z range.

Where anomalous, the assemblage of species outlined above are present in proportions much different (and greater) than their concentrations in typical petroleum. The commonality that they hold is their relatively high solubility in water compared to paraffinic and naphthenic compounds of similar molecular weight. For instance, benzene is about 100-300 times more soluble in water than n-hexane, and about 3 times more soluble than toluene. Acetic acid is completely miscible in water. Benzene concentrations of several 10's of ppm are typical of oilfield brines, while organic acid concentrations of several thousand ppm have been recognized. Hence, these species in FIS spectra are generally interpreted to be held in solution within aqueous inclusions, rather than present within a free hydrocarbon phase. The origins of these compounds are outlined in a later section, but the most interesting from an exploration standpoint involves stripping from present-day petroleum accumulations and transport via diffusion into the surrounding water-dominated pore network. Considering relative solubility rules, one would predict that the ratio of paraffins to naphthenes (e.g., inferred by a m/z ratio such as 57/55) would be low. In fact, this is generally the case; further evidence that it is relative solubility in water that is driving the distribution of these species in water-soluble enriched FIS mass spectra.

Sulfur-Compound Enriched FIS Mass Spectra

The final type of end-member FIS mass spectrum contains anomalous concentrations of sulfur compounds. The species H_2S, COS, CS_2 and SO_2 and/or native sulfur gas are key indicators, although not all may be present in a given sample (see Table IX).

Table IX: Partial Fragmentation Pattern for Sulfur Compounds

H_2S	**COS**	**S_2(?)**	**SO_2**	**CS_2**	**S_8**
34(100%)	60(100%)	64	64(100%)	76(100%)	64
32	32	32	48	32	256(60%)
33	28		32	44	160
				78	128
					192
					258
					96
					32

As can be seen, sulfur compounds tend to have strong molecular peaks, and enrichment is indicated if some combination of the m/z peaks 34, 60, 64 and 76 display anomalous intensities. Because these m/z positions generally occur in abundance valleys, the same qualitative rules apply as for acetic acid; namely, if a discrete peak is observed at one of these primary ion locations, the species is considered anomalous. The peak intensity need not rise to the level of the adjacent paraffin peak, although in extreme cases, it may. The 60 peak has a major interference with organic acids as outlined in the previous section. Hence the presence of COS

is inferred (but not demonstrated) only in the presence of other sulfur species. The m/z 32 would appear to be a good one for indicating sulfur presence; however, this ion location suffers major potential interference from atmospheric oxygen (O_2^+).

Care must be taken when interpreting sulfur-enriched FIS spectra, because at first glance they resemble the water-soluble enriched spectra. Ideally, the distinction lies in the location of CS_2 at m/z 76 (as opposed to benzene at 78), H_2S at m/z 34 and S_2^+ and/or SO_2 at m/z 64. SO_2 presence can be verified by the presence of a paired anomaly at 64 and 48. In practice, it is sometimes difficult to distinguish between sulfur-enrichment and water-soluble species enrichment when these species are not strongly anomalous, and combinations of the two spectra occur as well.

A.2.3 Summary of the Five Spectral Types

The above is a relatively detailed account of the characteristics of the five major classes of FIS mass spectra. In the end, however, the best way to recognize and distinguish among spectral types is to compare them to the end-member examples presented herein and categorize them by eye. After examining a few examples of each, pattern recognition will become easy. Understanding the complexities outlined in the previous sections is important, but usually unnecessary for first-order interpretation of FIS mass spectra. To summarize:

Non-hydrocarbon Spectra: Characterized by four peak clusters centered on m/z 15, 28, 42 and 55; the first three being dominant. Most peaks are attributable to water and carbon dioxide.

Gas-range enriched: Characterized by strong responses on C_1-C_5 (m/z 12-72) and lesser intensities on higher molecular weight ion locations. Peak clusters may be more broad at m/z 12-30 and 37-46. Predominance of masses 15 and 16, and high 57/55 ratios is possible.

Liquid-range enriched: Characterized by the presence of C_7-C_{13}+ species as regularly-spaced peak clusters in the m/z 95-180 range, which are dominated by ions from paraffinic and naphthenic compounds. Aromatic species contribute subordinate peak clusters between the paraffin-naphthene peaks (although, typically only benzene, toluene and xylenes are resolved).

Water-soluble enriched: Characterized by methane, ethane, organic acids, benzene and toluene. Acetic Acid (m/z 60) and aromatic peak clusters (m/z 78, 91, 105) attain intensities near or greater than those of adjacent paraffin-naphthene peak clusters.

Sulfur-compound enriched: Characterized by the presence of H_2S, COS, CS_2 and SO_2 and/or native sulfur gas as indicated by anomalies on some combination of the m/z peaks 34, 48, 60, 64 and 76.

A.2.4 Combinations of Spectral Types

Combined FIS spectra are common, and appear as superimposed end member types. Although combinations of all end member spectra have been noted, the most common are gas + liquids and liquids + water-solubles. Recall that FIS is a bulk technique and samples the entire fluid history of the pore system. Hence, mixed FIS spectra might be expected if the sample has experienced temporally distinct charges of petroleum (or brine) types or contained a heterogeneous (immiscible) fluid in the pore system at some time.

A.3 Interpreting FIS Track Plots and Petrographic Data in a Geologic Context

Fluid inclusions are the only direct records of paleofluids existing in the subsurface, and as such, have the potential to record conditions accompanying geologic processes, including petroleum migration. By studying the subsurface distribution of paleofluid chemistries with FIS, one can obtain valuable and unique information on three major exploration topics:

1. Petroleum migration or paleocharge
2. Seals
3. Proximity to undrilled pay

and two major production topics:

1. Pay zone and bypassed pay delimitation
2. Reservoir compartmentalization.

The previous discussions have concentrated on identifying spectral types in FIS data. This is a necessary first interpretive step. The next task is to evaluate the significance of FIS depth trends in their own right (now knowing their spectral origins), and eventually, in light of other available information to answer specific questions, such as were enumerated above. Petrographic data from anomalous fluid inclusion zones are often critical elements of these higher order interpretations, as will be seen, which why petrographic follow-up work is conducted as a routine part of every FIS analysis (see Table of Petrographic Observations).

A.3.1 Significance of FIS petroleum indications

The most basic question that FIS can address is "Is there any evidence for present or past petroleum in this borehole?" Documentation of an FIS hydrocarbon anomaly generally provides a positive answer to this question, but could indicate other processes as well. Possible explanations for an FIS hydrocarbon anomaly are discussed in the following paragraphs.

Migration without trapping

A migration pathway may be indicated when FIS responses are low or moderate, when contamination and recycled inclusions can be discounted, when quoted visual petroleum inclusion abundances are "rare" or "several" (see Table of Petrographic Observations), and when no other petrographic or log evidence of current petroleum charge is identified in the zone. There are a number of factors that influence inclusion abundance and, consequently, raw FIS response strength, including geologic setting, extent of diagenesis, rock type and permeability. However, it has been demonstrated that both visual petroleum inclusion abundance and FIS strength within many porous reservoir rocks is proportional to hydrocarbon saturation or paleosaturation in a relative sense. Because migration occurs at average bulk-volume petroleum saturations below those encountered in charged reservoirs, FIS signal strength and visual inclusion abundance are generally lower along migration pathways than in charged reservoirs from the same area.

Current Charge

A zone that displays strong FIS hydrocarbon indications and high visual petroleum inclusion abundance (i.e., common, abundant or extremely abundant) may reflect penetrated pay, but could also indicate paleo-charge or, in some cases, a migration pathway (e.g., where inclusion abundance is enhanced by extensive microfracturing). A provisional interpretation of current charge is strengthened if residual petroleum (especially live oil stain) is identified in thin section, and particularly if water-soluble petroleum species (so-called "proximal pay indicators"; see below) are recorded in FIS data (e.g., in the seal overlying the anomaly, in the water leg underlying the anomaly, or in low permeability zones within the reservoir section itself). Any independent indications (e.g., from electric logs or mudlog gas shows) provide further encouragement.

Paleo-charge

Intervals of strong FIS response, high visual inclusion abundance (i.e., common, abundant or extremely abundant) and significant bitumen (e.g., dead oil stain or asphaltic residue) without accompanying water-soluble anomalies or independent evidence of current charge, may represent a paleo-column, but could also represent current charge or in rare cases a migration pathway. The interpretation of paleo-charge is favored if a valid DST has shown the interval to be currently wet.

Recycled inclusions

Very rarely, detritus that is generated from previous sedimentary rock may contain inherited petroleum inclusions. These inclusions must be recognized, as they clearly do not provide any useful information about the current petroleum system(s). Petrographic or microthermometric criteria can often be used to argue the origin of these inclusions, for instance, the presence of petroleum inclusions along recycled quartz overgrowths, or measured homogenization temperatures that are too high to have been produced during the current burial history. Associated FIS depth trends are usually erratic and poorly compartmentalized, and inclusion abundance is typically low. Inherited inclusions may be restricted to specific geologic units that derived detritus from a particular provenance, and are not found in intercalated chemical precipitates (e.g. bedded carbonates or diagenetic cements).

Heavy bitumen stain

In some instances, pore-occluding bitumen may contribute to FIS signals. Here, solid petroleum behaves as any other cement, and is capable of trapping residual hydrocarbons as bitumen-hosted fluid inclusions. These may be invisible due to the opacity of the solid petroleum host. Petroleum species may also desorb from pore-occluding bitumen during crushing, much as they do from mature kerogen (see below). Bitumen-sourced FIS responses may be inferred when strongly anomalous zones contain low visible petroleum inclusion abundance but have significant amounts of bitumen (e.g., common, abundant or extremely abundant). Abundant pore-filling bitumen in porous rock implies significant petroleum saturation at some time, so low visual petroleum inclusion abundance is unexpected (and not commonly encountered). In such cases it is possible either that the size of the inclusions are below the resolution of the light microscope (< 1 micron), that grain surface conditions (e.g., wettability) did not favor trapping of inclusions, or that the section was diagenetically quiescent during and after charging (i.e., little or no cementation or microfracturing).

Mature Source Rock

Mature source rock can contribute to FIS responses. Here, the signal is the combined effect of species desorbed from freshly crushed kerogen surfaces and conventional fluid inclusions that represent trapped in-situ generated petroleum. The chemistry and strength of FIS responses in source rocks tend to reflect kerogen type and maturity, at least in a general sense. Hence, mature gas-prone kerogen with limited liquids potential typically gives dry gas responses, while mature source rocks with liquid-prone or mixed kerogen types (including some coals) tend to have significant responses on both gas and liquid-range petroleum species. Furthermore, as maturation proceeds, FIS hydrocarbon responses progress from low (immature) to high (mature) to low again or dry gas (overmature). These trends are very qualitative, and FIS response in source intervals should not be used as a substitute for classical source rock analysis techniques. An in situ origin (local generation) is suggested for FIS responses if petrographic data from the anomalous zone reveals low permeability rock containing significant quantities of mature kerogen (common, abundant or extremely abundant). Liquid-prone kerogen is likely to be mature if it exhibits moderate to strong orange fluorescence. Coal-related FIS responses are often quite waxy, may be enriched in aromatics, and typically have large relative contributions from higher molecular weight species (i.e., flat spectral profiles).

Contamination

Except in rare cases, contamination is not a significant issue in FIS data. Pre-analytical washing and vacuum heating procedures are sufficient to remove most surface-adsorbed organic compounds that are volatile under FIS analytical conditions, including natural fluids such as residual oils, as well as elements of the mud system, including oil based mud. Insoluble organic additives (particularly natural materials like gilsonite) pose a greater threat, as they may not be removed by standard treatment, and can give responses similar to indigenous kerogen or bitumen. Infrequently, an organic-based mud system will contribute to FIS response, and in rare instances may be dominant. This tends to occur in recently drilled, unconsolidated mud-rich sections, which are difficult to wash without complete loss of sample. Contamination has also been suspected in some diapiric or bedded salt sections, where drilling encapsulation of these species is facilitated by the easily dissolved and precipitated halite. Processed contaminants often have a distinctive (and unnatural looking) chemistry, which might include extreme light end depletion, very low aromatics (particularly benzene, which may be removed for environmental reasons) or extremely high toluene (possibly residue from soxhlet extraction). Petrographic criteria can generally be used to assess the likelihood of contamination in a given anomalous FIS zone.

A.3.2 Petroleum Type and Quality

Interpreted petroleum type and quality is based predominantly on the characteristics of individual mass spectra from each depth as already discussed (sample spectra are located in Appendix C). Three factors are considered: the maximum carbon number detected, the qualitative abundance of low molecular weight alkanes relative to high molecular weight alkanes (including the general slope of the imaginary line connecting the C_1-C_{13} alkanes), and the presence or absence of species or ratios indicative of bacterial or thermal alteration (including souring processes). It is important to note that the interpreted petroleum type assumes a single, uniform petroleum inclusion population. The actual migration or charging history, on the other hand, may have involved multiple pulses with different composition (e.g., oil and

gas) and the relative abundance of these inclusions will influence the bulk spectra. Additionally, total inclusion abundance will affect the spectra insofar as higher molecular weight species represent a smaller volumetric proportion of petroleum and are also less volatile, hence decrease below instrumentation detection limits before low molecular weight species. Consequently, some samples with low oil inclusion abundance generate wet gas mass spectra, for instance. Optical inclusion abundance and characteristics should be consulted, where provided, to verify the interpreted petroleum type (see Table of Petrographic Observations). With the above limitations in mind, the following petroleum types are identified on the basis of spectral characteristics:

Dry gas: mostly C_1 with lesser C_2-C_3 and no higher hydrocarbons.

Wet gas: C_1-C_9 may be present, but C_6+ species are in minimal abundance. The alkane slope is extreme.

Gas-condensate: C_1-C_{11} may be present. The alkane slope is quite steep, reflecting a very gas-enriched phase.

Volatile oil: C_1-C_{13} present. Slight gas-range enrichment is observed and the alkane slope is moderate to steep.

Oil: C_1-C_{13} is present. The alkane slope may be flat to moderate.

Biodegradation is suggested if sulfur compounds such as H_2S, COS, CS_2, S_2 (+/- SO_2) and/or thiols are present in addition to petroleum species. Ratios of paraffins to naphthenes may be low as well, as bacteria typically prefer to metabolize alkanes compared to other classes of petroleum compounds. Petrographic data may provide further evidence for biodegradation in the form of low-gravity petroleum inclusions. Bacterial activity is generally restricted to maximum burial temperatures below 65-70°C; hence FIS evidence of biodegradation is most commonly observed in rocks that are currently below this temperature.

Thermal alteration of liquid petroleum species can produce spectra very similar to those generated from biodegraded hydrocarbons, because the products of two common processes, bacterial sulfate reduction (BSR) and thermochemical sulfate reduction (TSR), are essentially identical. The best distinction is made from current bottom-hole temperature data, which, if above 140°C or so may be indicative of TSR, and if below 70°C or so is more consistent with BSR. Potential interpretive problems arise in the intervening temperature range, when deeply buried sediments are unroofed or when petroleum altered at shallow depths becomes buried to greater depth. Petrographic data may help, as pyrobitumen frequently accompanies TSR, while low-gravity liquid petroleum inclusions often occur in association with bacterially altered oils. Additional temperature or thermal maturity data (including fluid inclusion homogenization temperatures) may also be useful.

The presence of significant amounts of sulfur species can indicate a sour petroleum phase, where the souring process may in some cases be a reflection of the source rock, but could also reflect BSR or TSR. A study of TSR sour gas pools in Canada suggests that evaluating the relative proportion of products and reactants can provide a measure of sour gas potential. As TSR progresses, long-chain alkanes decrease while low molecular weight petroleum species increase along with CO_2, aromatics organic acids and the various sulfur compounds enumerated above. Ironically, H_2S alone may not be as accurate an indicator of H_2S content, as it is scavenged naturally (e.g., to form pyrite in iron-rich rocks) and by the metallic internal surfaces of the analytical system.

A.3.3 Water-soluble Anomalies and Proximal Pay Indications

Water-soluble species, particularly benzene and toluene, have been used for decades to search for geochemical halos surrounding petroleum accumulations. The limitation of conventional techniques is that fluid samples are rarely intentionally collected from wet reservoirs. However, similar water-soluble species anomalies have been found in FIS data. Compounds generally include some subset of the following: methane, ethane, CO_2, acetic acid, benzene, toluene and xylenes, as well as low paraffin-to-naphthene and high aromatic-to-paraffin ratios. There are three dominant sources of this FIS volatile suite: maturation of kerogen-rich rock, thermal alteration of liquid petroleum, and diffusive stripping from a present-day charged petroleum reservoir proximal to the borehole. The latter of these three possibilities is the most important from an exploration standpoint, and is the FIS analog of the classic technique of analyzing formation fluids for benzene.

Criteria to distinguish among the three potential sources of water-soluble anomalies are often found during petrographic examination. A kerogen source may be inferred if the interval contains a substantial amount of mature kerogen, and where FIS responses include appreciable contributions from other hydrocarbon species (e.g., where water-soluble species are superimposed on an otherwise normal hydrocarbon response). Thermal alteration may be expected if pyrobitumen is present, and, particularly, if sulfur compounds are also detected in FIS data (see discussion above). These species may have resulted from thermochemical sulfate reduction at temperatures above 140°C. Extreme examples of this process are found in deep Devonian sour gas pools of the Western Canada Sedimentary Basin.

True "proximity to pay" (a.k.a., PTP) anomalies tend to occur in cuttings from shale rich lithologies, that are geometrically connected to penetrated or lateral pay. Examples include top or lateral lithologic or structural seals to a charged reservoir, and transition zones or water legs underlying petroleum. The signal is always a present-day feature and is thought to result from drilling encapsulation of penetrated pore fluids within easily sheared or thermally reconstituted lithologies. A significant amount of unpublished analytical data as well as a large body of empirical observation support this interpretation, although details of the process are still debated. Petrographic criteria are generally sufficient to interpret PTP signals, and these include absence of evidence for the other two possible origins, as well as presence of distinctively sheared, shale-rich cuttings.

PTP signals can be found along with direct FIS hydrocarbon indications in flushed reservoirs. Here, the water-soluble anomalies may be sourced from irreducible petroleum saturation with the paleo-reservoir, or may indicate an updip charge (possibly the leaked or structurally disturbed petroleum column that once resided at the well location).

PTP anomalies can be classified into two chemical subtypes: acetic acid + benzene dominant, and benzene dominant. Acetic acid is though to be sourced from high molecular weight compounds within the petroleum phase; hence, its presence suggests the nearby accumulation is oil or gas-condensate. Benzene without accompanying acetic acid suggests a drier petroleum phase, most likely wet gas. Dry gas generally does not give a PTP response because the key indicator species are not present in the petroleum phase, hence cannot be fractionated into nearby aqueous fluid.

When PTP anomalies are identified, a possible link to a nearby reservoir should be investigated. Many scenarios are possible, including an overlying penetrated charge, lateral production in a shallower section that is not under closure at the well location, or charge in remaining updip closure in a reservoir that tested wet at the well location.

A.3.4 Seals

FIS seals are inferred at boundaries marking abrupt changes in FIS species strength or chemistry. The underlying assumption is that detected fluids are more or less synchronous on either side of the boundary and that some process has prevented free mixing of species across this barrier. In detail the boundary may represent a change in lithology, poroperm or a structural element. In the case of in-situ generated petroleum the boundary might represent a transition from poor to better source rock, or immature to mature source intervals. In the case of migrated petroleum the boundary might represent the extent of petroleum migration through porous rock, or the top seal to a present or past petroleum column. Basal compartment limits may represent seals or, in some cases, fluid contacts or paleocontacts (see below). In general, only the tops of FIS compartments are identified on interpreted FIS depth plots. If fluids were not synchronous on either side of the compartment boundary (e.g. a post-migration unconformity) then the seal interpretation would be in error. Seals may be selective or chromatographic, in which case low molecular weight species may migrate across the boundary, while higher molecular weight species do not.

A.3.5 Microseepage

FIS microseeps are analogous to gas chimneys seen in seismic data, and surface manifestations of deeper charge identified in surface geochemical surveys. They are interpreted to result from near-vertical migration of light hydrocarbons followed by bacterial alteration in the shallow subsurface at temperature-depth conditions permissible for bacterial activity. Most bacteria are restricted to temperatures below 65-70°C; hence, anomalies may be observed in the upper 1-3 km of rock column, depending on the prevailing geothermal gradient. Key indictor species include light hydrocarbons, CO_2, possibly organic acids and aromatic compounds, and sulfurous volatiles, including H_2S, COS, CS_2, S_2 (+/- SO_2) and in some cases thiols. H_2S is often sequestered within pyrite in iron-rich siliciclastics, hence is less common in shale-bearing lithologies. Inclusion formation in such low temperature environments may be aided by precipitation of bacterial carbonate. FIS microseeps are geometrically distinct, often beginning at the surface and abruptly disappearing at the appropriate temperature-controlled depth.

The presence of an FIS microseep appears to be a good indicator of deeper charge in the immediate vicinity, although weak seeps may represent regional signals within shallow aquifers. Data suggest that these anomalies overlie 75-80% of productive reservoirs, while only 10% of non-productive areas display similar signals. Hence, the presence of a strong seep within a dry hole might indicate deeper or nearby lateral charge in the area.

A.3.6 Fluid Contacts

The basal boundary (abrupt or transitional) of any strong FIS compartment is a candidate for a present or past fluid contact, although the interpretation is often equivocal. The most compelling evidence for a present day contact occurs where hydrocarbon-dominant FIS signals (the petroleum leg) give way to water-soluble dominant signals (PTP in the water leg) and where visual petroleum inclusion abundance displays a parallel decrease. When inclusion abundance is high in the petroleum zone but PTP signals are not present in the water leg, it is possible that a paleo-charge is recorded. If the base of the anomaly corresponds to the base of the reservoir, or an abrupt decrease in reservoir quality, then the actual fluid contact (or

paleo-contact) may reside further downdip.

A.4 Individual Track Plots

A.4.1 Explanation and Significance of Individual Track Plots

The following is a synopsis of the significance of the different patterns of mass abundances and abundance ratios shown in Tracks 1-25. Note that not all species are quantified using their parent or molecular peaks (e.g., methane at $m/z = 15$) in order to minimize interfering contributions from other species.

A.4.2 Ratios vs. Absolute Abundance

Both ratios of key ionized compounds as well as absolute abundances of key compounds (relative to a natural oil inclusion standard) are used in interpretation. Absolute abundances of species can be influenced by the efficiency of inclusion formation, the size distribution of the inclusions, the saturation and residence time of the fluid within the pore system and the relative proportion of fluid of a given composition that moved through that stratigraphic compartment. Chemical ratios, on the other hand, are not as susceptible to lithologic/diagenetic controls on inclusion formation/distribution, hence, may be better suited for displaying chemical compartments in some cases. They are also useful for enhancing some of the subtle trends within the data, and for characterizing chemical variability among petroleum inclusion compartments, which could be related to source, timing, or migration process. Ratio plots are not completely independent of inclusion abundance, as the intensity of mass spectrometer responses is somewhat non-linear with respect to ion concentration. Both types of plots should be considered during interpretation.

Track 1: Total Response - This represents the sum of the positive responses on all measured masses from $1 \leq m/z \leq 180$. These data are potentially useful for some data normalization schemes, or for estimating the relative percentage of a given compound in the analyzed sample. Note that responses are generally dominated by water and carbon dioxide, and that absolute quantification is not possible because water cannot be quantitatively analyzed with this system. The polar nature of water causes it to adhere to metallic surfaces inside the instrument resulting in false readings by the detector. However, two characteristics of the total response are noteworthy. First, total responses are often orders of magnitude greater for samples yielding proximity spectra than for other samples originating outside the hydrocarbon zone, even though the lithologies are usually clay rich, hence low in natural inclusion abundance. This is one line of evidence that leads us to hypothesize that proximity samples are dominated by drilling induced inclusions which trap some of the present day formation fluid. Secondly, inferred petroleum migration compartments are often characterized by high total responses. This suggests that both organic and inorganic inclusions are anomalously represented within these compartments. The significance of this correlation is not fully understood, but may document a fracture forming process occurring during focused movement of basinal fluids, including petroleum. If so, it may eventually provide additional information about the nature and mechanisms of secondary petroleum migration.

Track 2: $m/z = 44$ Dominant peak for carbon dioxide (CO_2^+), with possible minor contribution from C_3^+ hydrocarbon fragments and acetic acid. Anomalous values have been noted associated with pan-evaporative dolomitization of limestones in China and Oman. CO_2 response is often

high in proximity samples which show elevated levels of acetic acid. CO_2 is generally present in anomalous concentrations in FIS microseeps, where it is a product of bacterial alteration of seeping light hydrocarbons.

Track 3: $m/z = 34$ - Dominant peak for hydrogen sulfide (H_2S^+). Anomalous values associated with petroleum may indicate sour oil or gas. H_2S is also noted at times in association with shallow dry gas of probable biogenic origin (including FIS microseeps) and with some proximity zones. H_2S is probably not quantitatively analyzed due to rapid scavenging by metallic surfaces of the analytical system.

Track 4: 34/(34+15) - H_2S/(H_2S+methane). Not frequently used, but ratio tends to be elevated in sour gas zones.

Track 5: 4/(4+2) - Helium fraction $^4He^+/(^4He^+ + H_2^+)$; ratioed to mass $m/z = 2$ to indicate the presence of anomalous He. Helium anomalies have been found in association with unconformities, thrust faults which sole in crystalline rocks, arkosic detritus sourced from such crystalline rocks (e.g., granite wash), gas sourced from old, radioactive shales and mafic hypabyssal volcanic rocks. An abrupt change in helium abundance has been documented within Precambrian rocks worldwide. It is possible that this reflects a fundamental evolutionary step in the Precambrian atmosphere.

Track 6: Air Confidence - This represents the results of an algorithm which performs five tests for the presence of the air components nitrogen, oxygen, and argon. The plot is scaled in integer values from zero to five, corresponding to zero to five positive tests. Values in the 4-5 range indicate a high confidence for air. Some anomalies may represent small leaks in the vacuum system. Natural air inclusions have been recognized in vadose cements below paleoexposure surfaces, as well as in some aeolian sands and evaporites.

Track 7: 30/(30+15) - ethane/(ethane+methane). Except for very dry gas, petroleum migration zones generally show elevated ratios of ethane to methane, provided that the petroleum is transported as a separate phase. Petroleum transported as a dissolved solute species in aqueous solution (e.g., in the case of proximity) may have low ratios of ethane to methane, due to the relatively higher solubility of methane in solution.

Track 8: $m/z = 15$ - CH_3^+; mostly derived from methane, with minor contributions from all other paraffins and NH_2^+, if present. Used as a relatively clean peak for methane; response is nearly as great as for the methane molecular peak. Anomalies are associated with oil and gas migration as well as water zones carrying significant dissolved gas. Distinction between dry gas and oil is accomplished by comparing responses on higher molecular weight fragments (e.g., $m/z = 97$). Transport in aqueous solution is suggested by co-occurrence of other water-soluble hydrocarbons as well as high ratios of water soluble to water insoluble species (e.g., 60/57, 55/57, 77/71). Methane dominated dry gas of possible biogenic origin is often documented in offshore wells at depths above 1200 m. These zones also often indicate anomalous sulfur species, which might document the activity of sulfate-reducing bacteria. In rapidly buried, relatively young sections, (e.g., offshore Trinidad and Gulf Coast) biogenic gas inclusions may be detected to much greater depths. These are FIS microseeps and are thought to sourced from leakage of light petroleum from depth.

Track 9: $m/z = 30$ - Ethane molecular peak ($C_2H_6^+$). Use similar to that of methane ($m/z = 15$).

Track 10: $m/z = 60$ - Acetic aid (CH_3COOH), with possible contribution from COS in some environments. Acetic acid anomalies may be sourced from source rock maturation, thermal alteration of liquid petroleum or diffusive stripping from oil or gas-condensate accumulations (the latter are known as proximity-to-pay indications or PTP). It is thought that PTP represent samples of present day formation fluids, which are entrapped during drilling, probably through thermal and mechanical processes acting on clay-bearing lithologies in the neighborhood of the drill bit. Our understanding of the sources and sinks of organic acids and water-soluble aromatics, particularly benzene, suggest that the signal must be actively fed; hence, it is unlikely that we would see these signals preserved for geologic time in paleo-reservoirs, or along migration paths, although this has not been fully demonstrated. The strength of the signal is dependent on so many variables, including drilling conditions, lithology, formation fluid and oil chemistry, temperature, hydrodynamics, etc., that it is doubtful that quantitative assessment of distance from accumulation is possible. As with most FIS interpretations, documenting proximity is deemed significant, while its absence is not necessarily so, unless a particular area is well calibrated. Thermal processes within the reservoir in which liquid-range petroleum is broken down to lower molecular weight petroleum with one byproduct being organic acid probably source acetic acid, in the context described above. As such, the presence of organic acid anomalies with benzene and or toluene anomalies suggests that the accumulation has some liquid-range component, although a few barrels of condensate per MMCF of gas appears to be enough to provide a signal, at least in relatively low salinity formation fluids which are very close to pay zones. As mentioned above, other sources of organic acids are possible, including maturation of source rocks (particularly coals), severe thermal degradation of oil (particularly during thermochemical sulfate reduction) and stripping from residual oil in high Sw zones or recently flushed reservoirs; hence, the nearby reservoired hydrocarbons may very well be subeconomic. COS and acetic acid can be expected in some of the same environments, so the distinction between the two is not always possible. However, COS tends to be less water soluble, and has a higher affinity for the petroleum phase than acetic acid.

Track 11: $m/z = 78$ - Benzene ($C_6H_6^+$). High values are associated with samples containing inclusions with liquid-range petroleum, as well as samples displaying "proximity" signals. A distinction can be made between these two by looking at individual spectra, or by comparing the response on the relatively insoluble paraffins (e.g., $m/z = 57$ or 71). Note however, that some samples may indicate both oil inclusions and proximity to pay; and it is here that individual mass spectra must be studied. Such mixed spectra are indicative of some pay zones (particularly those with significant Sw, as well as zones through which petroleum has migrated, and are now water wet, but are presently in communication with the previously migrated petroleum. Benzene rich proximity signals without associated acetic acid may indicate a nearby wet gas accumulation.

Track 12: $m/z = 91$ - Toluene ($C_7H_7^+$). This ion is interpreted in much the same way as benzene ($m/z = 78$). However, toluene has lower water solubility, so tends to be less anomalous or even absent from some proximity zones.

Track 13: 60/(60+57) - Acetic acid/(acetic acid + paraffins). This ratio tends to deflect to higher values in water bearing zones and shallow microseeps and to lower values in petroleum inclusion zones. Very high values are associated with proximity zones. Acetic acid has tremendous water solubility, while paraffins are relatively insoluble in water.

Track 14: 78/(78+91) - benzene/(benzene+toluene). This ratio is of limited utility in many cases, as these species are often not abundant enough to provide a coherent depth plot. In some cases, oil inclusion zones tend to deflect toward lower values, while proximity zones tend to deflect toward higher values. This is because oils typically have benzene to toluene ratios of about 0.5, while benzene has about 3 times higher solubility than toluene in water. Water washed oils will have lower ratios as will oils that have lost lighter ends through a semi-permeable seal.

Track 15: $m/z = 57$ - Paraffin fragment ($C_4H_9^+$). Anomalous values are associated with zones of oil and wet gas inclusions. Paraffins have lower solubility than other hydrocarbon classes, hence ratioing to these can define migration and reservoir processes (see next entries).

Track 16: 57/(57+15) - Paraffins/(paraffins+methane). This ratio plot displays the proportion of C_4 and greater paraffins relative to methane. The ratio will generally deflect to higher values in oil inclusion zones and toward lower values in dry gas zones. The ratio will also generally decrease within proximity zones due to the high solubility of methane relative to C_4^+ paraffins in aqueous solution.

Track 17: $m/z = 97$ - Alkylated naphthenes fragment ($C_7H_{13}^+$); basically naphthenes with methyl chains. This species tends to be anomalously high in petroleum inclusion zones which contain an appreciable liquid component (e.g., oils and condensates).

Track 18: 57/(57+55) - Paraffins/(paraffins+naphthenes). This ratio can be used for several purposes. Very low values are indicative of biodegraded oil, because bacteria prefer the paraffinic fraction. Low values are also documented in some proximity zones, due to the limited solubility of paraffins relative to naphthenes in aqueous solutions. Very high values are typical of dry gas zones as gases tend to be enriched in paraffins, although this trend must be used with caution. It is better to observe the relative change in this ratio with depth: If it decreases from baseline through a petroleum inclusion zone, liquid petroleum is more likely; if it increases, a lighter fraction might be expected. Again, these are generalizations which must be used cautiously. It is always best to follow up FIS work with thin section petrography to further investigate the characteristics of the entrapped petroleum phase. This ratio may also be used to identify transition zones from low to high Sw, and low-contrast pay zones. In general, we find that residual oil within water-rich zones under pay intervals tends to have higher ratios, probably due to the washing of more soluble naphthenes from the petroleum prior to entrapment. However, the water leg itself may have low ratios due to preferential concentration of naphthenes in the water phase.

Track 19: 97/(97+91) - Alkylated naphthenes/(alkylated naphthenes + toluene). This ratio tends to deflect toward higher values in zones containing liquid petroleum inclusions and toward lower values in proximity zones. Alkylated naphthenes are relatively water insoluble as compared to toluene.

Track 20: 77/(77+71) - C_6^+ aromatics/(C_5^+ paraffins+C_6^+ aromatics). This ratio tends to deflect toward higher values in zones of proximity and toward lower values in zones containing liquid petroleum inclusions. Both trends reflect the relative solubility of aromatics (high) and paraffins (low).

Track 21: $m/z = 64$ - C_5^+, S_2 and SO_2. Volatilized native sulfur has been noted in conjunction with sour gas pools in Canada, and, along with other chemical indicators may indicate sour gas risk. In some cases, mass 64 appears to be concentrated in water legs to these pools, or

wet reservoir sections that are plumbed to a deeper source of these species. It has also been found in conjunction with FIS microseeps.

Track 22: $m/z = 76$ - CS_2 and C_6^+ hydrocarbons. CS_2 has been found in conjunction with biodegraded hydrocarbons, in association with FIS microseeps and as a byproduct of thermochemical sulfate reduction.

Track 23: 97/(15+97)*1000 - Alkylated naphthene/(alkylated naphthene + methane) - This track can be used to illustrate the relative proportions of low and high molecular weight species. The track deflects to higher values in oily or light end depleted zones and to lower values in gassy zones.

Track 24: $C_5 - C_{13}$ Presence - This algorithm records the highest molecular weight range hydrocarbon group present in each individual spectra, and provides a quick visual record of zones containing the corresponding petroleum compounds. For example, if the C_5 group is the highest molecular weight range hydrocarbon group present in a given sample, a ranking of 5 is assigned; if C_6 is the highest carbon number represented, then a ranking of 6 is assigned, and so on until a ranking of 13 is assigned if the presence of species in the C_{13} range is detected. Mathematically, the algorithm tests for the presence of a group (i.e., carbon number) by scanning the spectra for a coherent signal comprised of at least two out of three of the major peaks associated with the particular molecular weight range.

Track 25: C_{6-13}/C_{1-5} - A semi-quantitative parameter relating the abundance of liquid-range hydrocarbons to gas-range hydrocarbons. The ratio can be used in a qualitative sense to construct "psuedo GOR's".

A.4.3 Mass Assignments

In addition to the Tracks 1-25 described above, mass spectra over the range $1 \leq m/z \leq 180$ are presented for each individual sample in Appendix C. The following descriptions contain additional information about species assignments for individual masses:

- $m/z = 2$ - Hydrogen (H_2^+); largely from H_2O, which makes up most of the evolved fluid in almost all samples.
- $m/z = 3$ - Deuterated hydrogen and helium-3 (HD and $^3He^+$).
- $m/z = 12$ - Carbon (C^+).
- $m/z = 14$ - Nitrogen (N^+) and CH_2^+; Nitrogen in conjunction with argon and oxygen anomalies suggests air. If not an analytical artifact (episodic burps of atmosphere leak into the analytical chamber), the presence of air may indicate a vadose zone below a subaerial exposure, or the presence of aeolean sand. If response on mass $m/z = 14$ exceeds that on masses $m/z = 13$ and $m/z = 15$ then nitrogen is likely present. CH_2^+ will generally be accompanied by relatively larger responses on $m/z = 15$ (CH_3^+), and $m/z = 16$ (CH_4^+) (due to it's fragmentation origin from CH_4, for instance). The most convincing distinction between analytical artifact and paleo-air occurs when several closely spaced samples have air anomalies, or when several replicate analyses of the same sample give the same result.
- $m/z = 16$ - Molecular peak for methane (CH_4^+), but major interference by O^+ fragment of water.

- $m/z = 17$ - Dominated by OH^+ fragment from water
- $m/z = 18$ - Dominated by water parent peak (H_2O^+)
- $m/z = 22$ - Doubly charged carbon dioxide ($CO2^{2+}$); minor contribution from neon ($^{22}Ne^+$)
- $m/z = 28$ - Dominated by diatomic nitrogen (N_2^+) and CO^+ fragment from carbon dioxide. Minor C_2^+ hydrocarbon contribution
- $m/z = 32$ - Oxygen (O^+) and sulfur (S^+). If $m/z = 32$ is larger than $m/z = 31$ and $m/z = 33$, oxygen is likely. If sulfur is present other likely peaks, such as $m/z = 34$ (H_2S), $m/z = 48$ (SO^+) and $m/z = 64$ (S_2^+, SO_2^+) should be checked. Oxygen can be a possible paleoexposure indicator when used in conjunction with other peaks (see discussion on Air Confidence, and Nitrogen).
- $m/z = 40$ - Argon (Ar^+) with possible significant interference by C_3^+ hydrocarbon fragments. High value of $m/z = 40$ relative to adjacent $m/z = 39$ and $m/z = 41$ peaks suggests argon.
- $m/z = 48$ - Sulfate fragment (SO^+); also, C_4^+
- $m/z = 55$ - Naphthene fragment ($C_4H_7^+$). High values are found in petroleum inclusion bearing intervals. Naphthenes have intermediate solubility between aromatics and paraffins. This m/z is usually ratioed to $m/z = 57$ (see below).
- $m/z = 71$ - Paraffin fragment ($C_5H_{11}^+$). Same use as $m/z = 57$.
- $m/z = 77$ - Aromatic fragment ($C_6H_5^+$). Same general use as for benzene and toluene.
- $m/z = 85$ - Paraffin fragment ($C_6H_{13}^+$). Same use as $m/z = 57$.
- $95 \leq m/z \leq 103$ - peaks centered within this range are mostly $C_7 - C_8$ fragments
- $110 \leq m/z \leq 115$ - peaks centered within this range are mostly $C_8 - C_9$ fragments
- $122 \leq m/z \leq 126$ - peaks centered within this range are mostly $C_9 - C_{10}$ fragments
- $134 \leq m/z \leq 138$ - peaks centered within this range are mostly $C_{10} - C_{11}$ fragments
- $148 \leq m/z \leq 152$ - peaks centered within this range are mostly $C_{11} - C_{12}$ fragments
- $160 \leq m/z \leq 164$ - peaks centered within this range are mostly $C_{12} - C_{13}$ fragments
- $175 \leq m/z \leq 180$ - peaks centered within this range are mostly $C_{13} - C_{14}$ fragments

B Reference Spectra

In order to insure consistent and high-quality results during routine Fluid Inclusion Stratigraphic Analysis and the intercomparability of wells analyzed weeks, months or even years apart, a number of machine-dependent parameters are monitored on a daily basis through the analysis of internal analytical standards. Information recorded during these analyses are used to evaluate the performance of individual components of the stratigraphic analyzers. Additionally, this information permits characterization of any systematic fluxuations that may have affected species sensitivity during the course of an FIS Analysis and are, in fact, used quantify these effects during post-analytical data reduction. The natural materials used as internal standards are described briefly below.

B.1 Oil Inclusion Reference Standards

Oil inclusion reference materials (petroleum inclusion-bearing siliceous carbonate rock fragments from the Kindblade Fm., Lawton, Oklahoma), are analyzed 11 times during each analytical run. The results are given in Figure 18. Ideally, spectra should show a whole-oil like signature with good representation of ionized fragments out to at least $m/z \approx 150$. Daily variation occurs due to inhomogenieties in inclusion abundance and distribution within individual samples of this natural rock, as well as from minor instrumental fluctuations.

B.2 Frac Sand Hydrocarbon Background Standards

Clean quartz sand, devoid of hydrocarbons, is analyzed 22 times during each analytical run. The results are given in Figures 19 and 20. Ideally, spectra should show no structured responses on $m/z > 60$.

B.3 Cooked Frac Sand Hydrocarbon Background Standards

Clean quartz sand which has been heated to 1000°C to remove a large percentage of the fluid inclusion population is analyzed 11 times during each analytical run. The results are given in Figure 21. Ideally, these spectra should show approximately an order of magnitude less total response than those from the preceeding "Frac Sand Standard", as well as an increase in air components (e.g., nitrogen at $m/z = 28$; oxygen at $m/z = 32$; argon at $m/z = 40$) resulting from entrapment of air into evacuated cavities during the heating treatment. These spectra should also show little to no structured response for $m/z > 60$.

B.4 Kindblade Trackplots

Selected peaks from oil inclusion inclusion reference standards used to monitor internal standardization and normalization procedures.

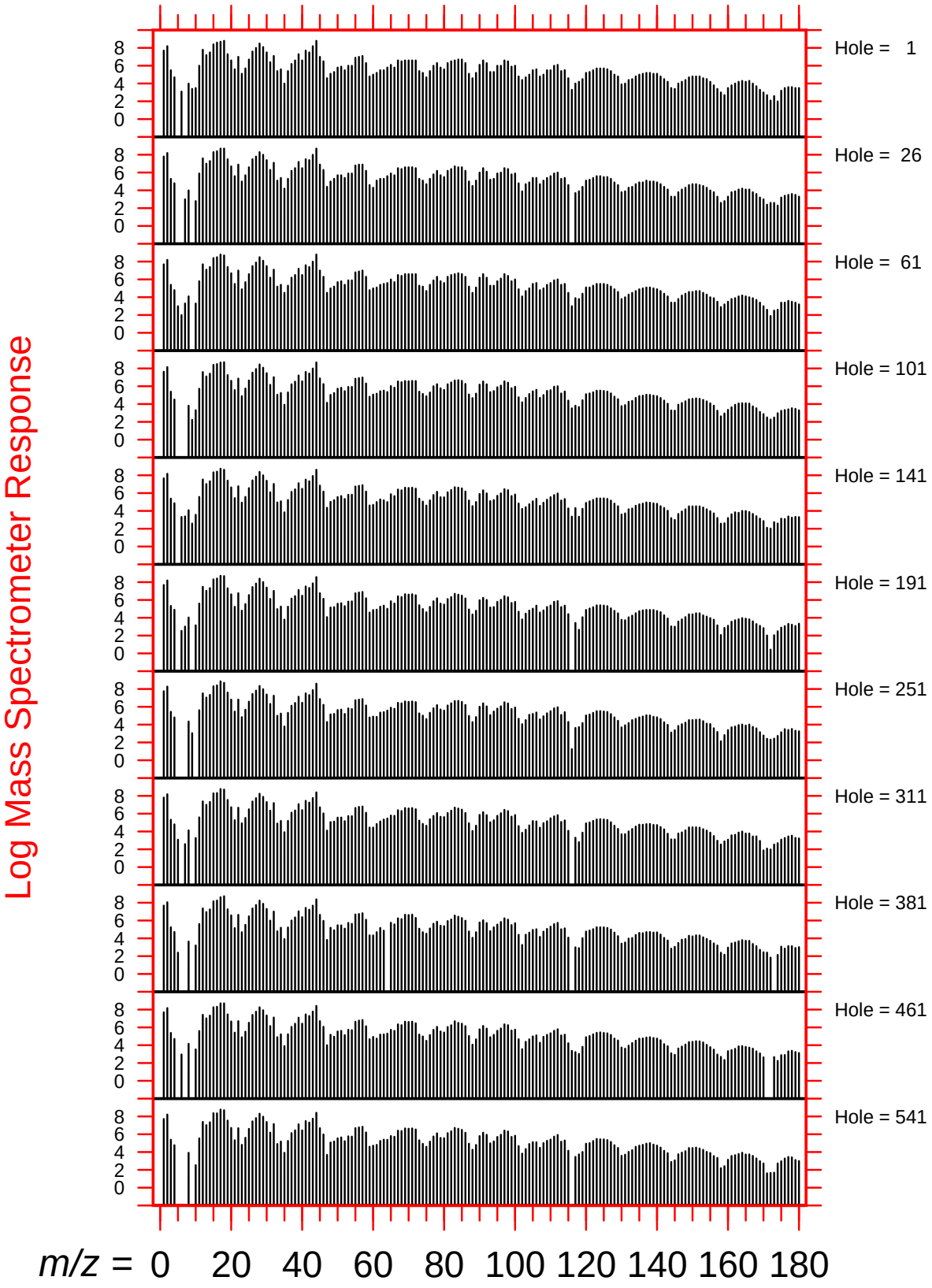


Figure 18: Oil Spectra

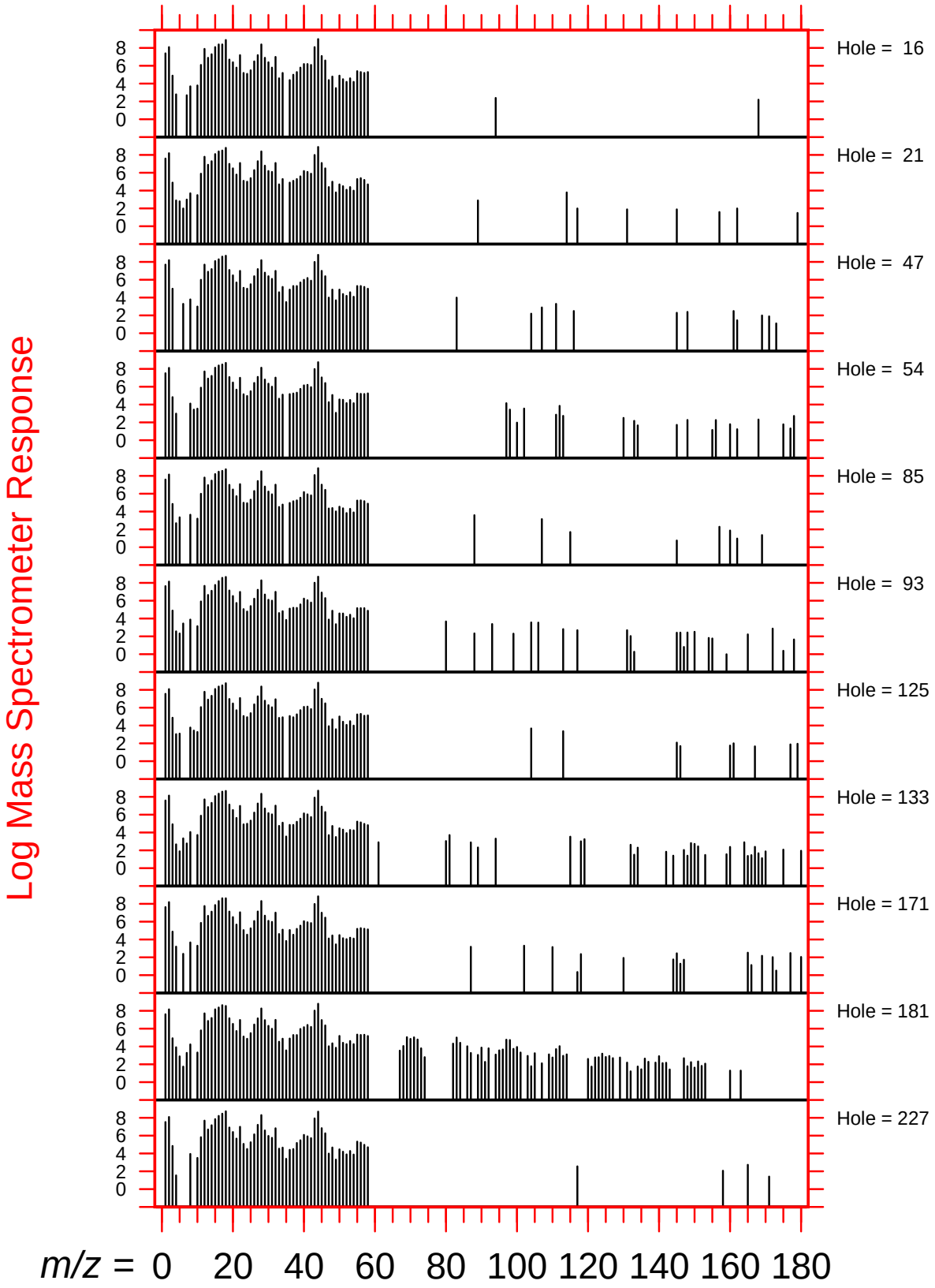


Figure 19: Frac Sand Spectra

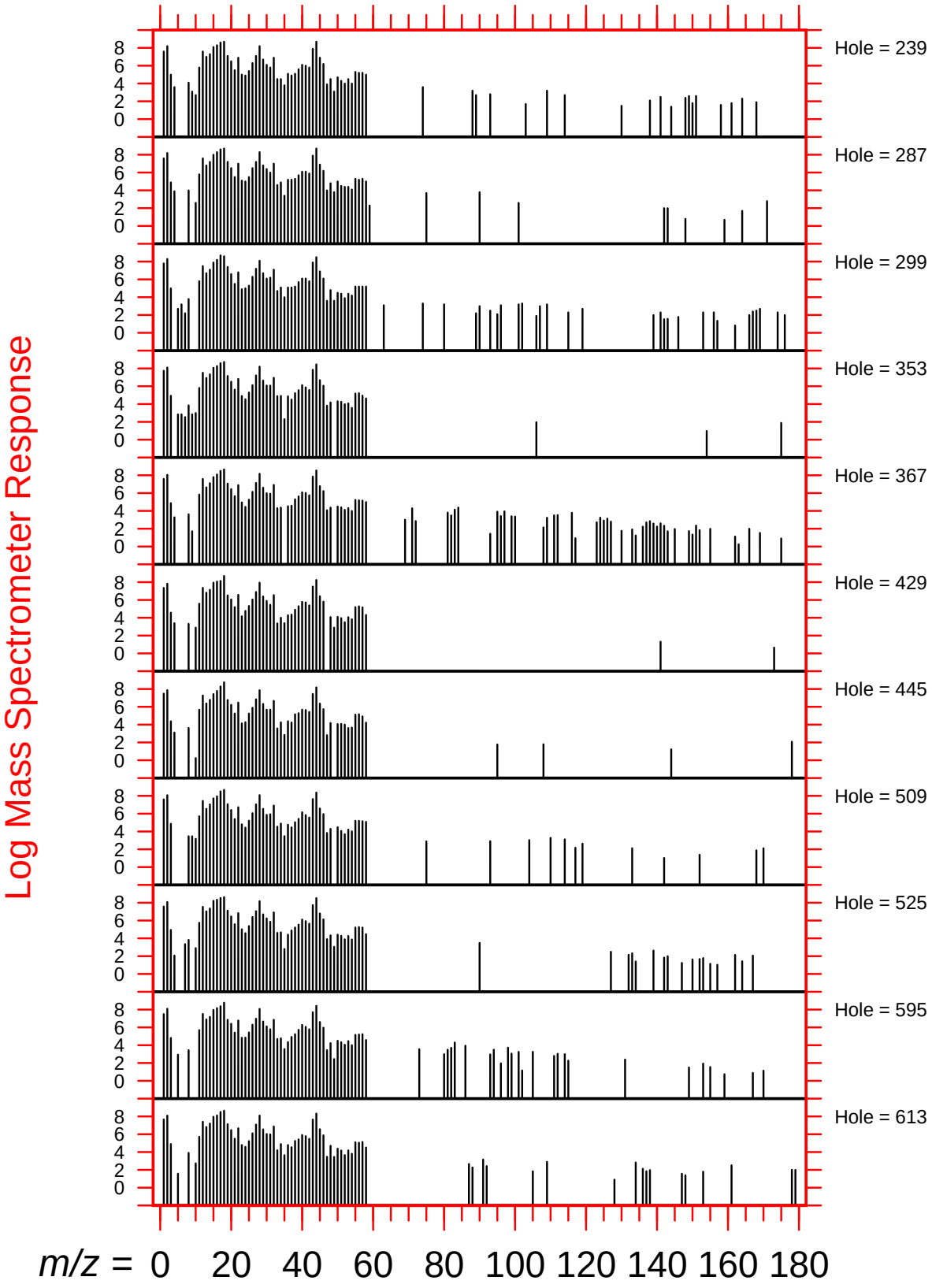


Figure 20: Frac Sand Spectra

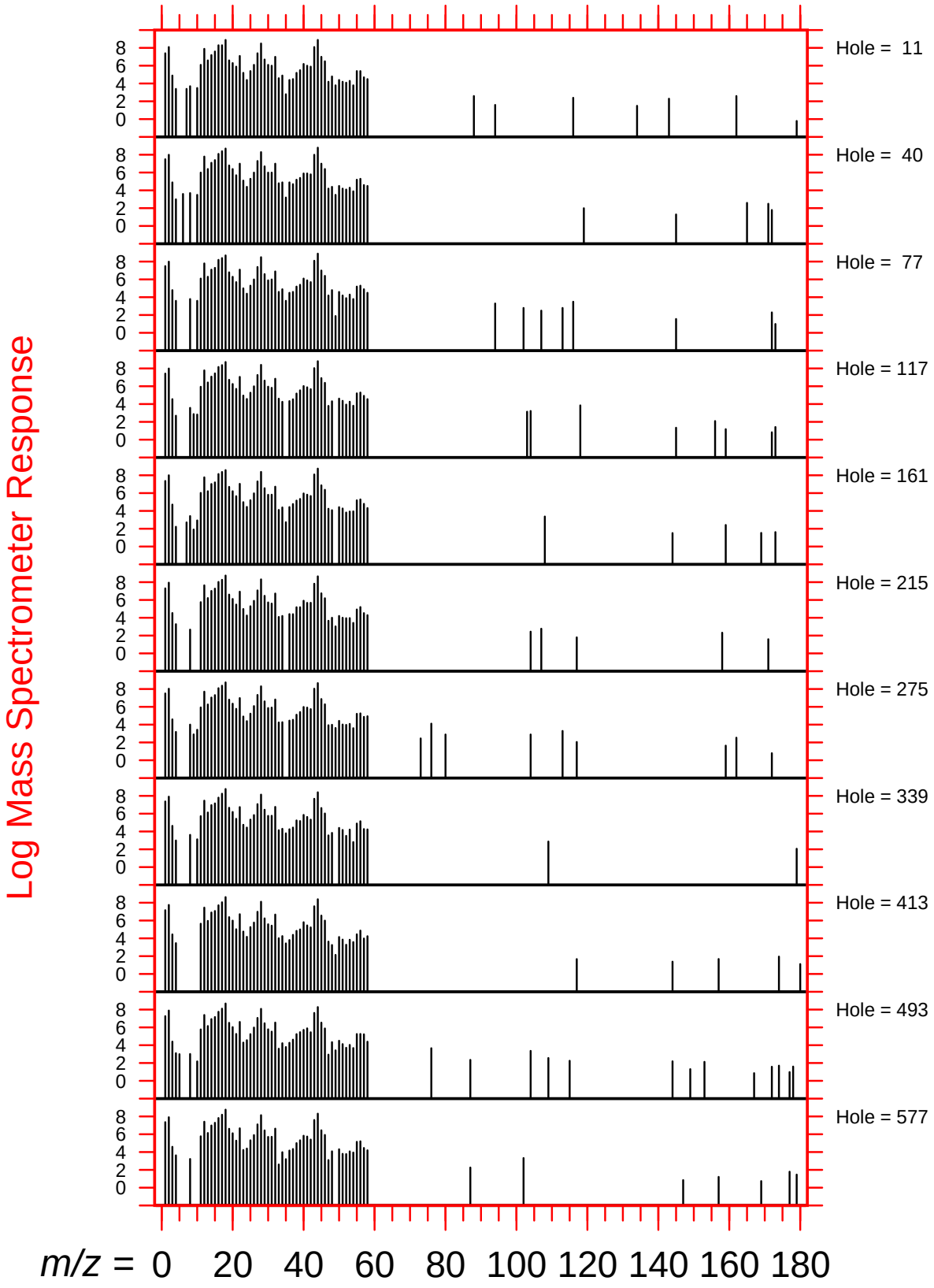


Figure 21: Cooked Frac Sand Spectra

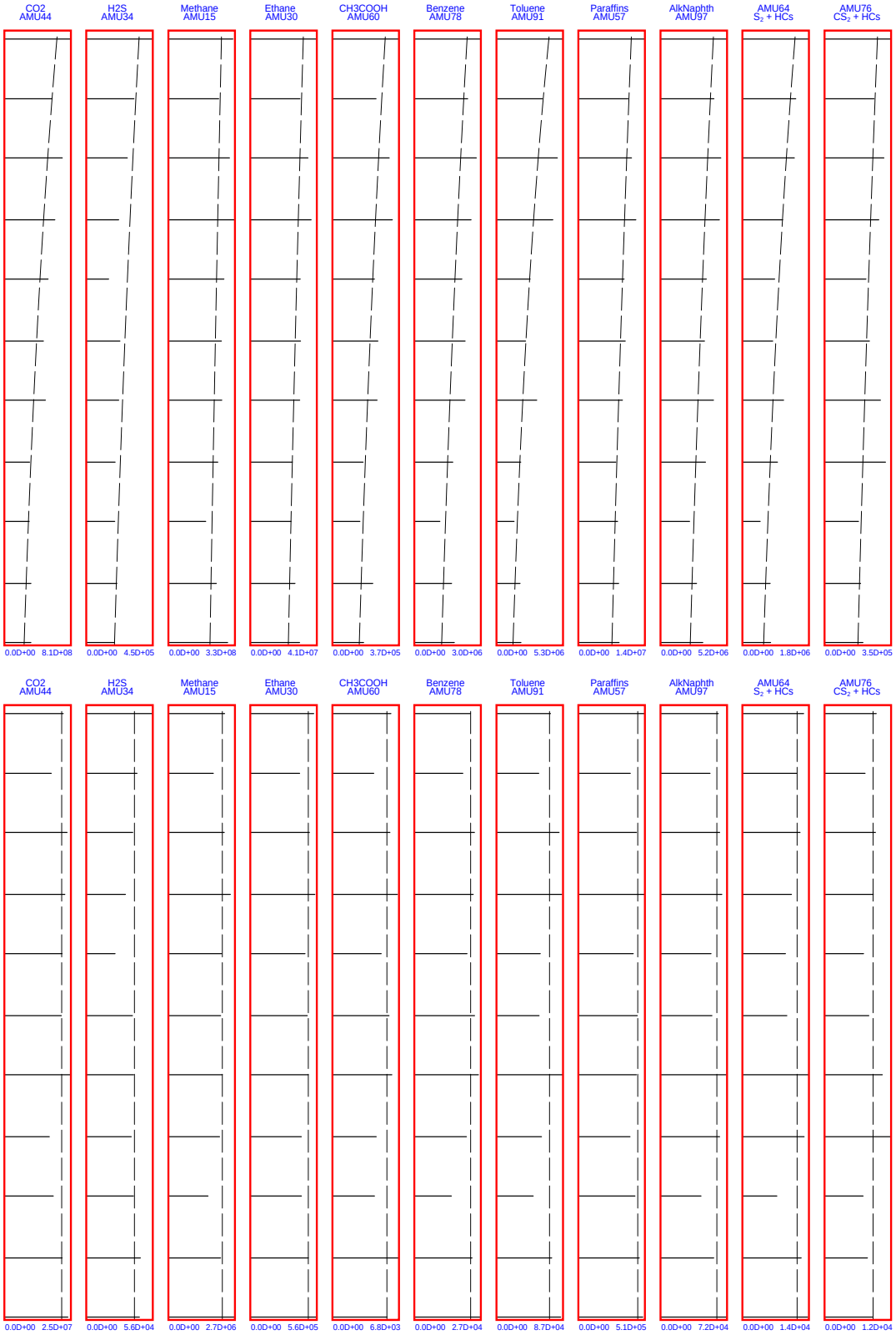
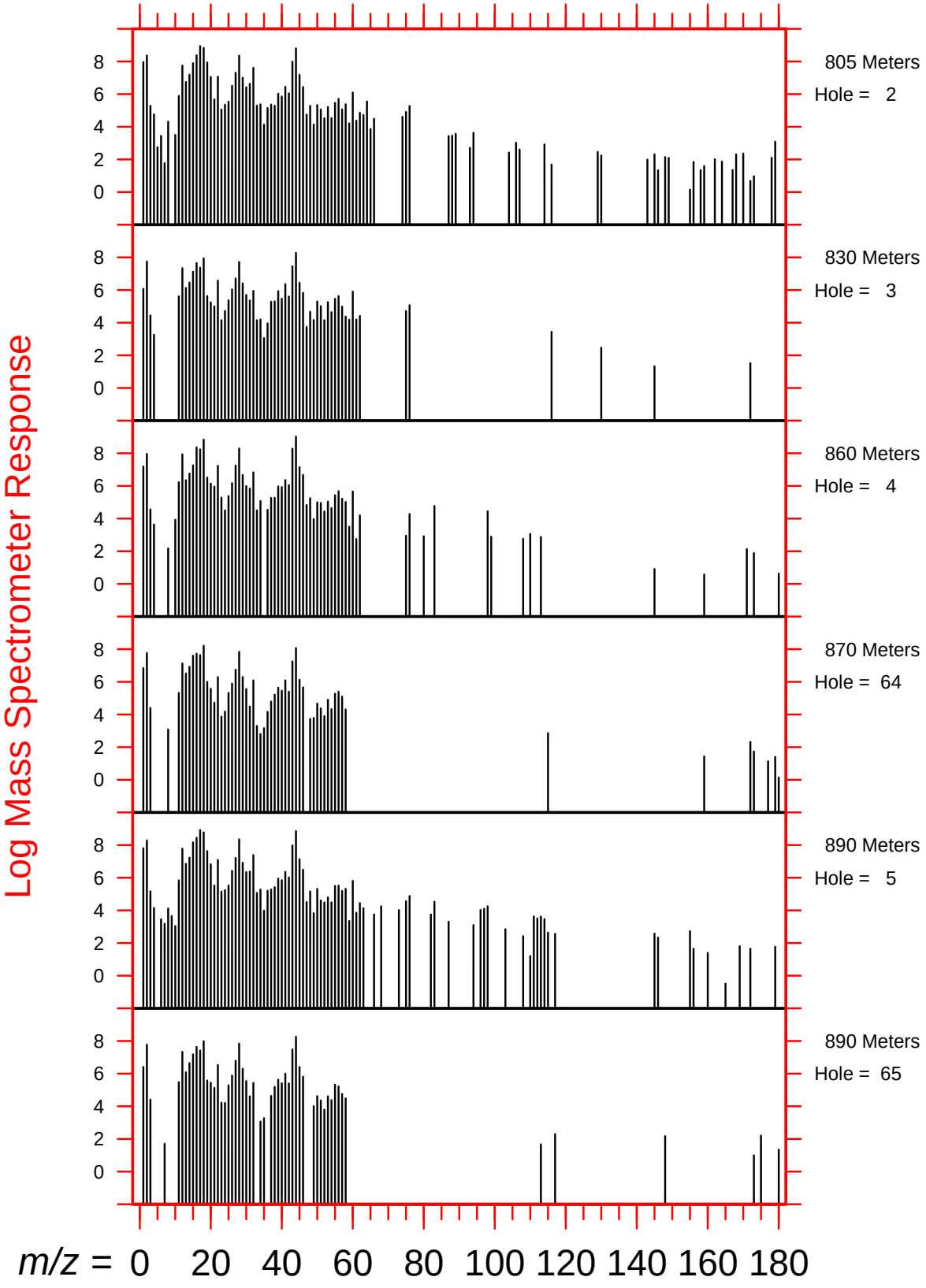
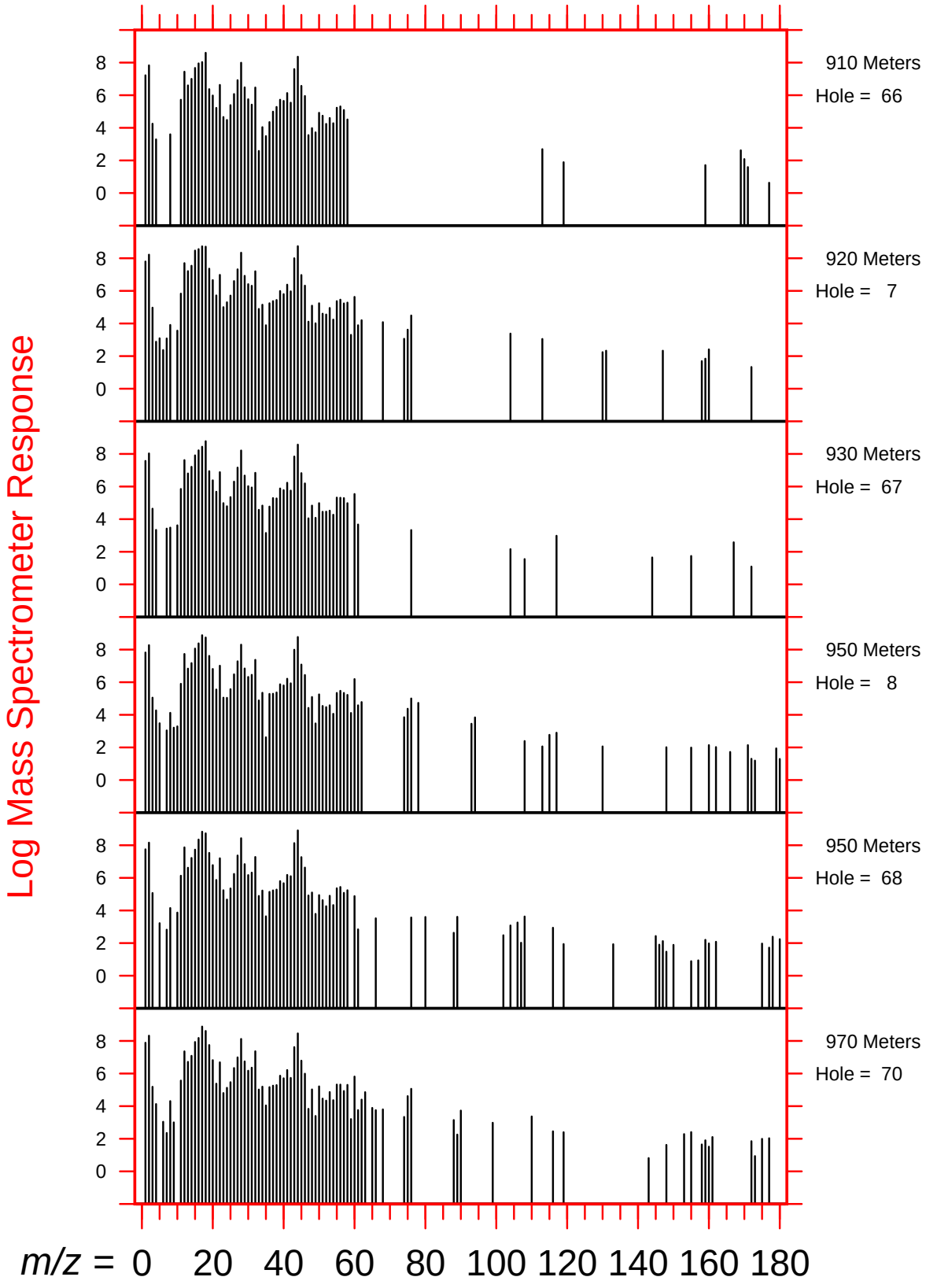


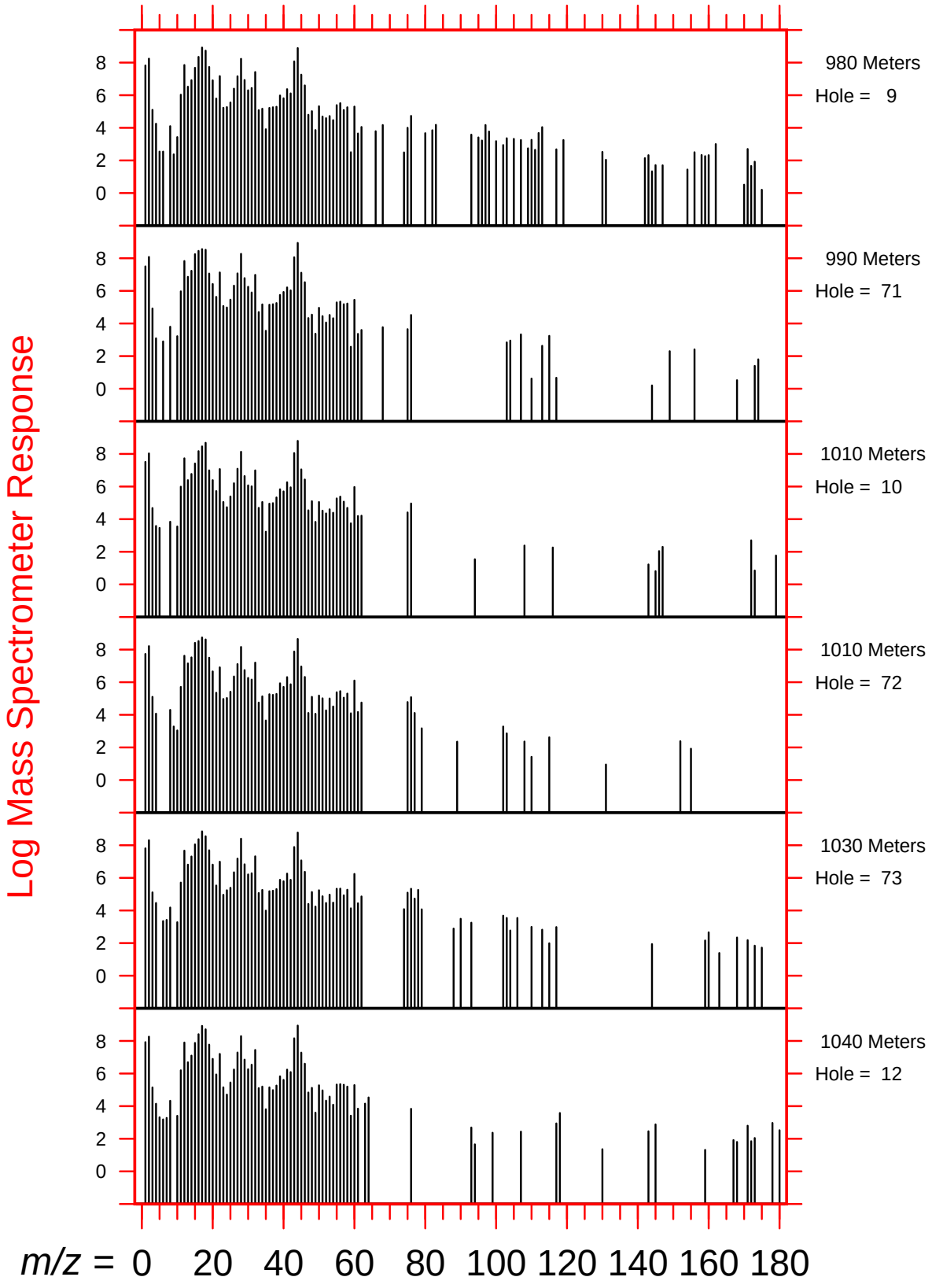
Figure 22: Kindblade Oil Standards Before (top) and After (bottom) Correction

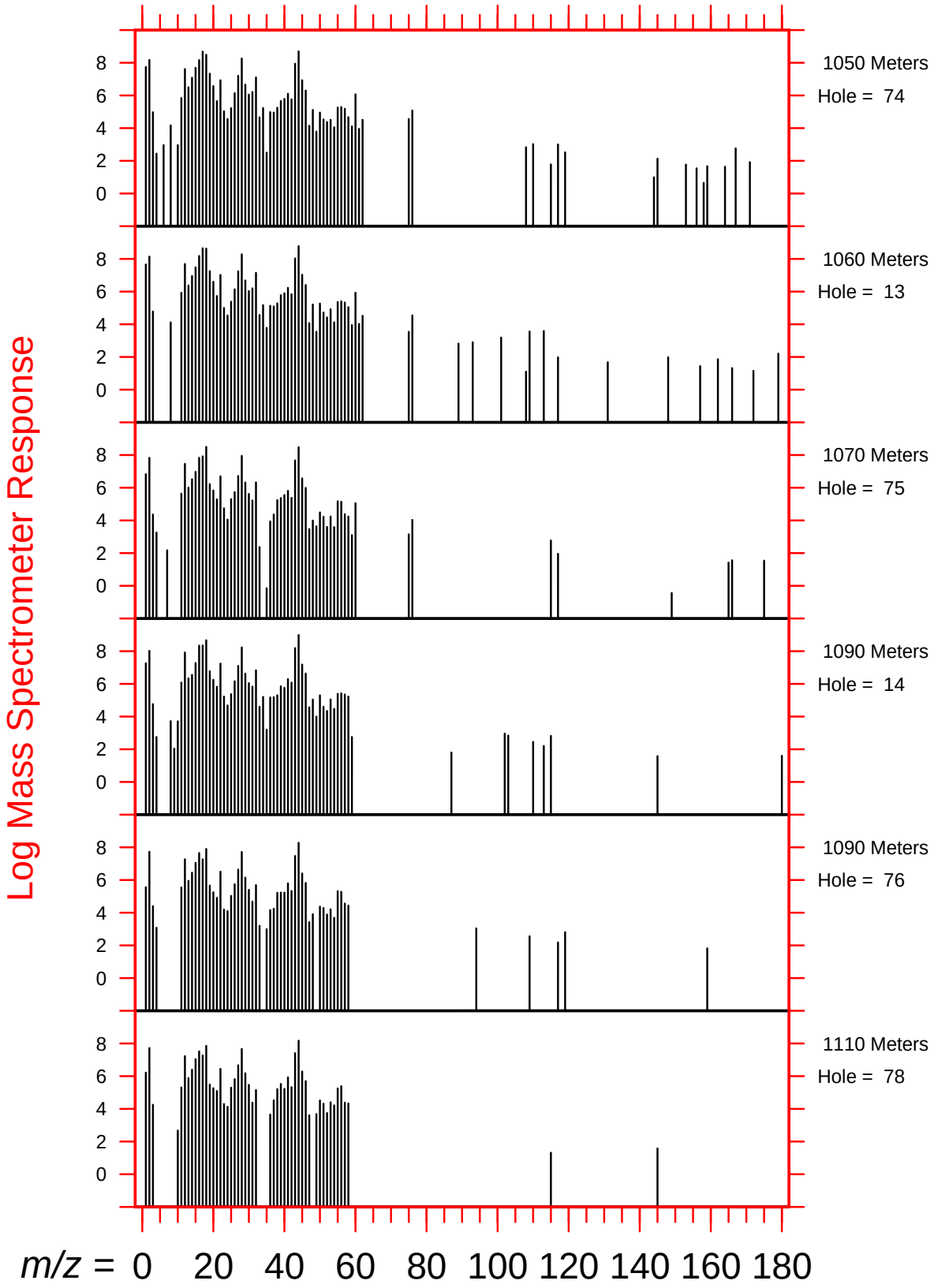
C Individual Spectra

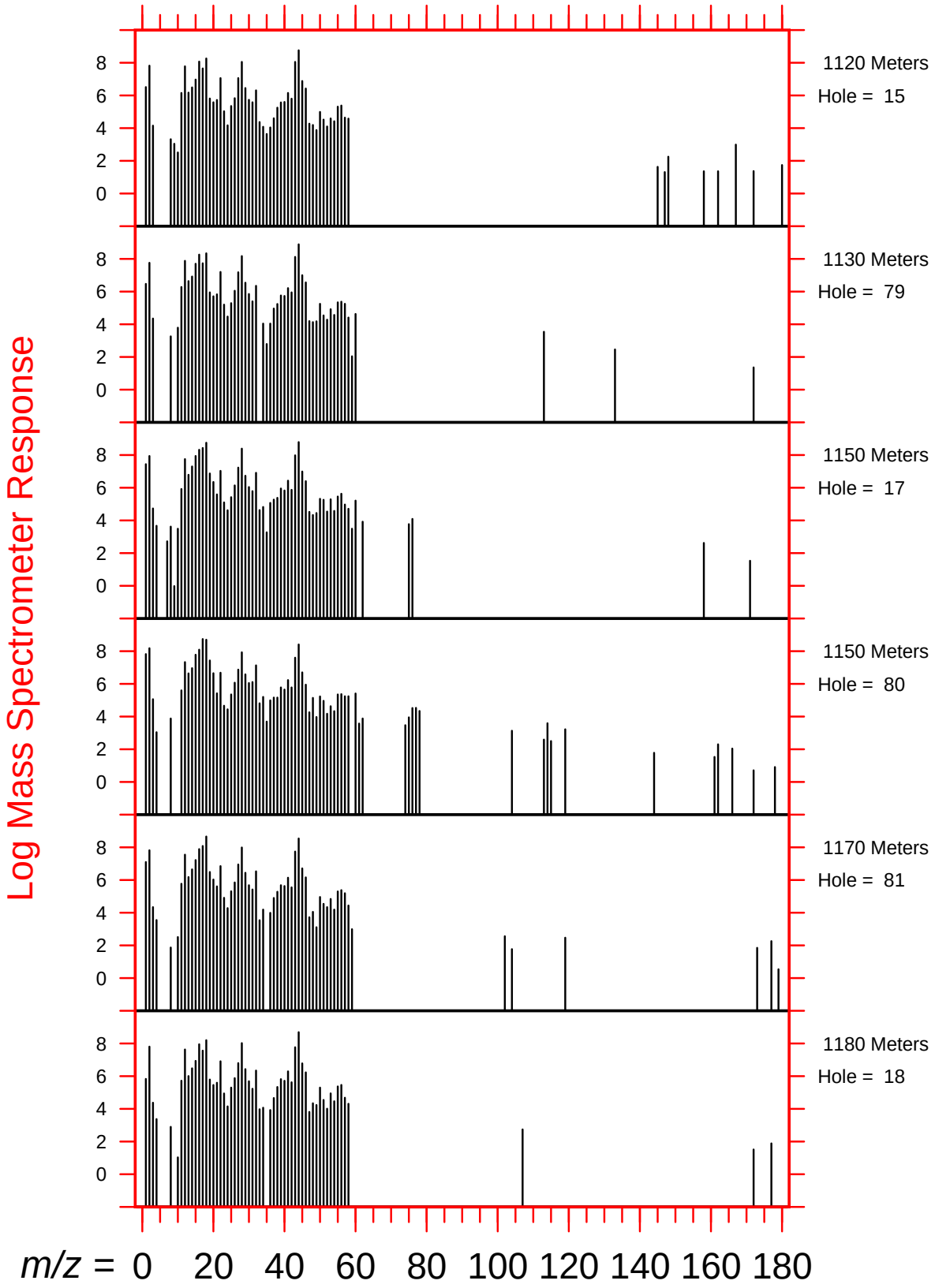
Individual spectra for each sample from HALLADALE 1 are shown on the following pages. Each spectrum is indexed according to depth and indicates the log of the millivolt response for atomic mass units (AMU, m/z) from $2 \leq m/z \leq 180$.

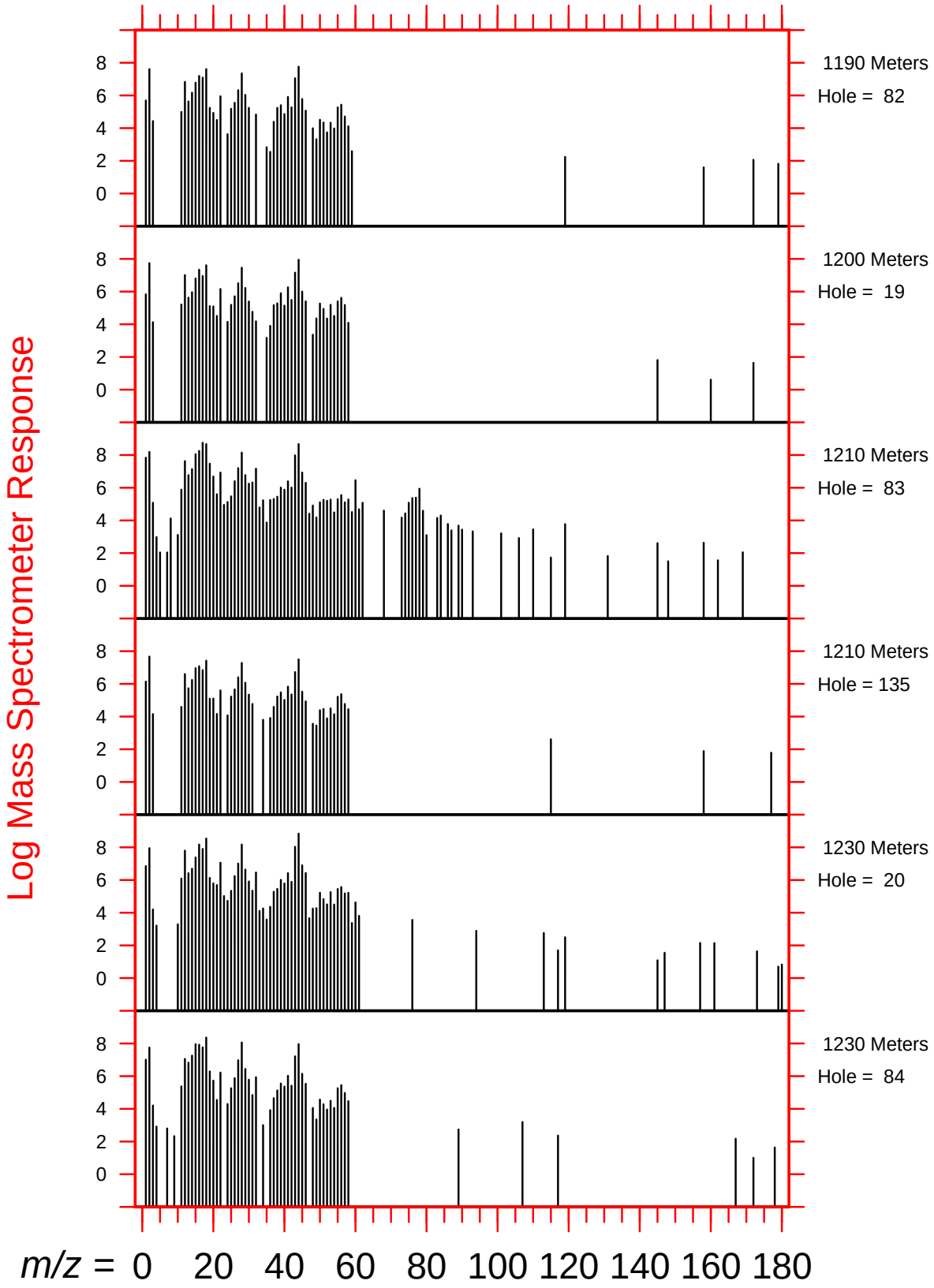

Log Mass Spectrometer Response
805 Meters
Hole = 2
830 Meters
Hole = 3
860 Meters
Hole = 4
870 Meters
Hole = 64
890 Meters
Hole = 5
890 Meters
Hole = 65
m/z = 0 20 40 60 80 100 120 140 160 180

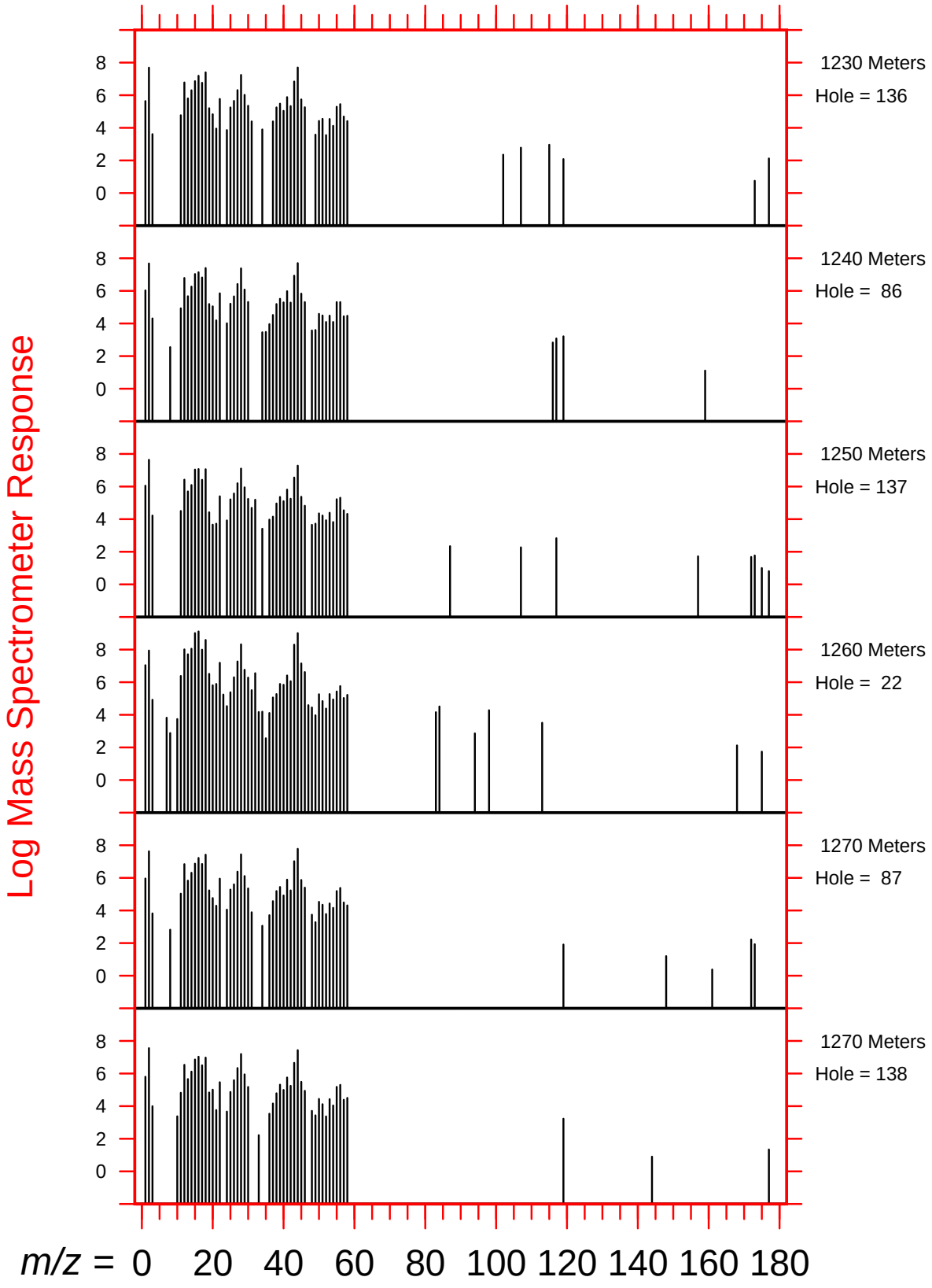

Log Mass Spectrometer Response
910 Meters
Hole = 66
920 Meters
Hole = 7
930 Meters
Hole = 67
950 Meters
Hole = 8
950 Meters
Hole = 68
970 Meters
Hole = 70
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

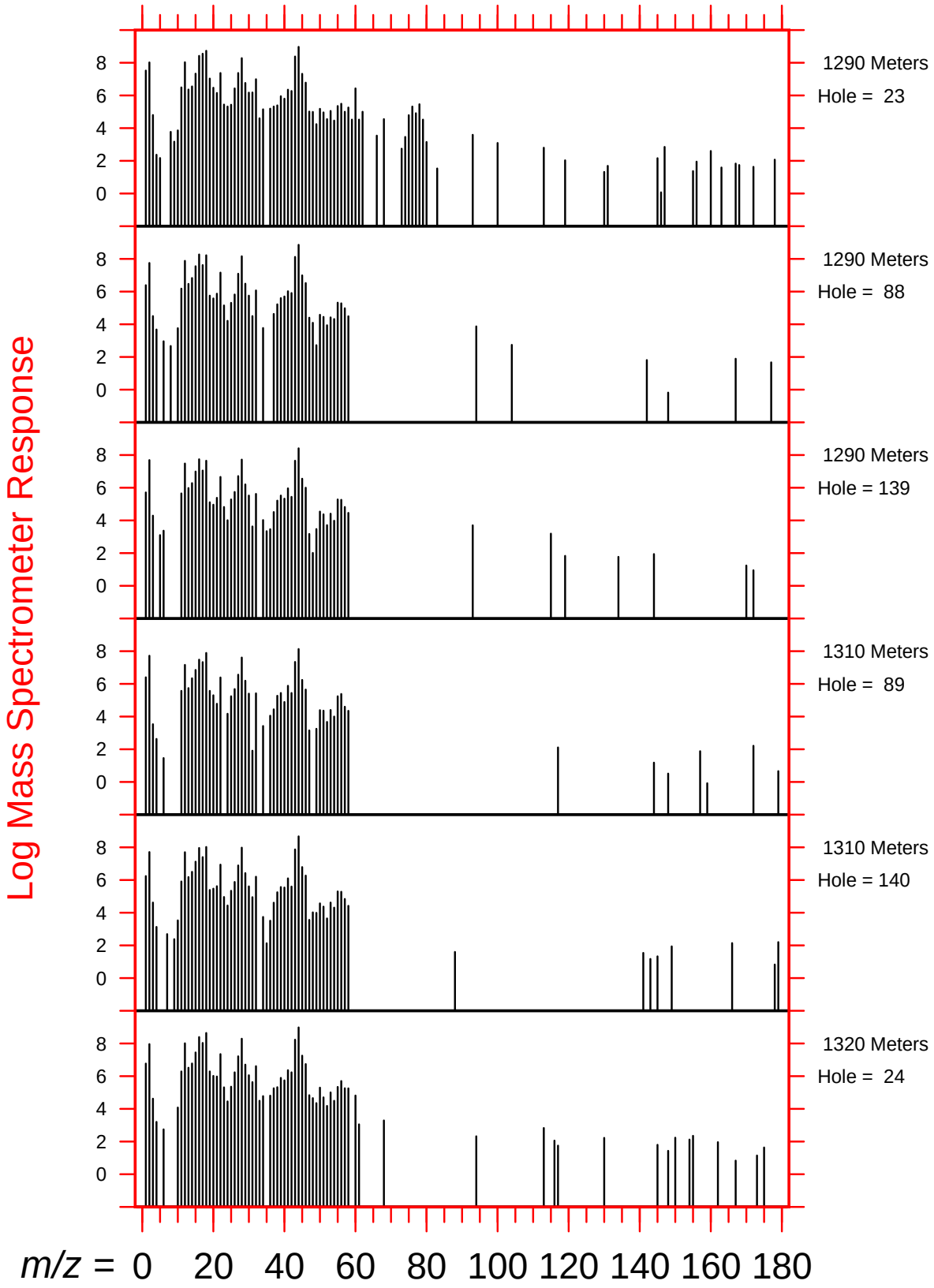

Log Mass Spectrometer Response
980 Meters
Hole = 9
990 Meters
Hole = 71
1010 Meters
Hole = 10
1010 Meters
Hole = 72
1030 Meters
Hole = 73
1040 Meters
Hole = 12
m/z = 0 20 40 60 80 100 120 140 160 180

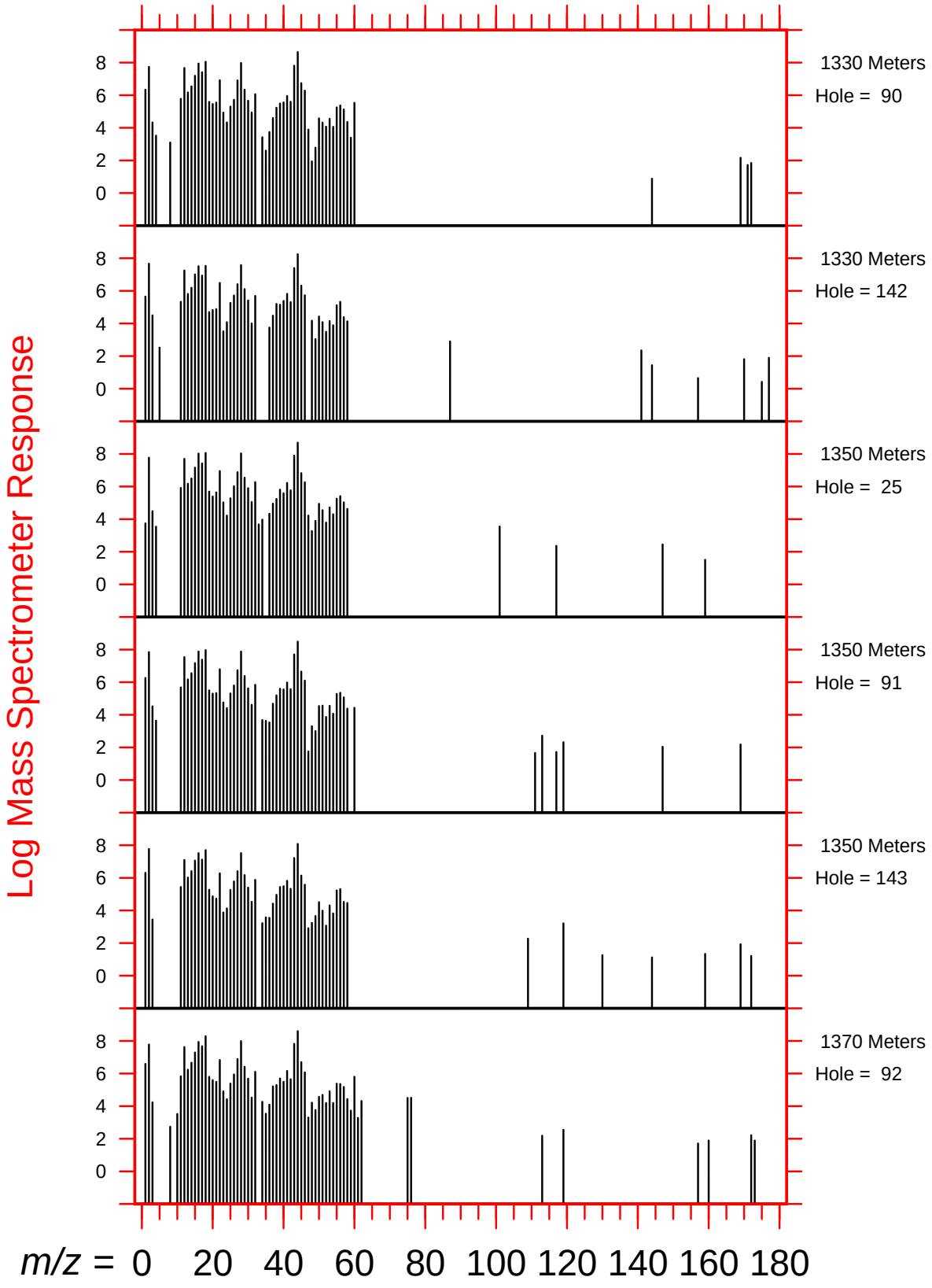

Log Mass Spectrometer Response
1050 Meters
Hole = 74
1060 Meters
Hole = 13
1070 Meters
Hole = 75
1090 Meters
Hole = 14
1090 Meters
Hole = 76
1110 Meters
Hole = 78
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

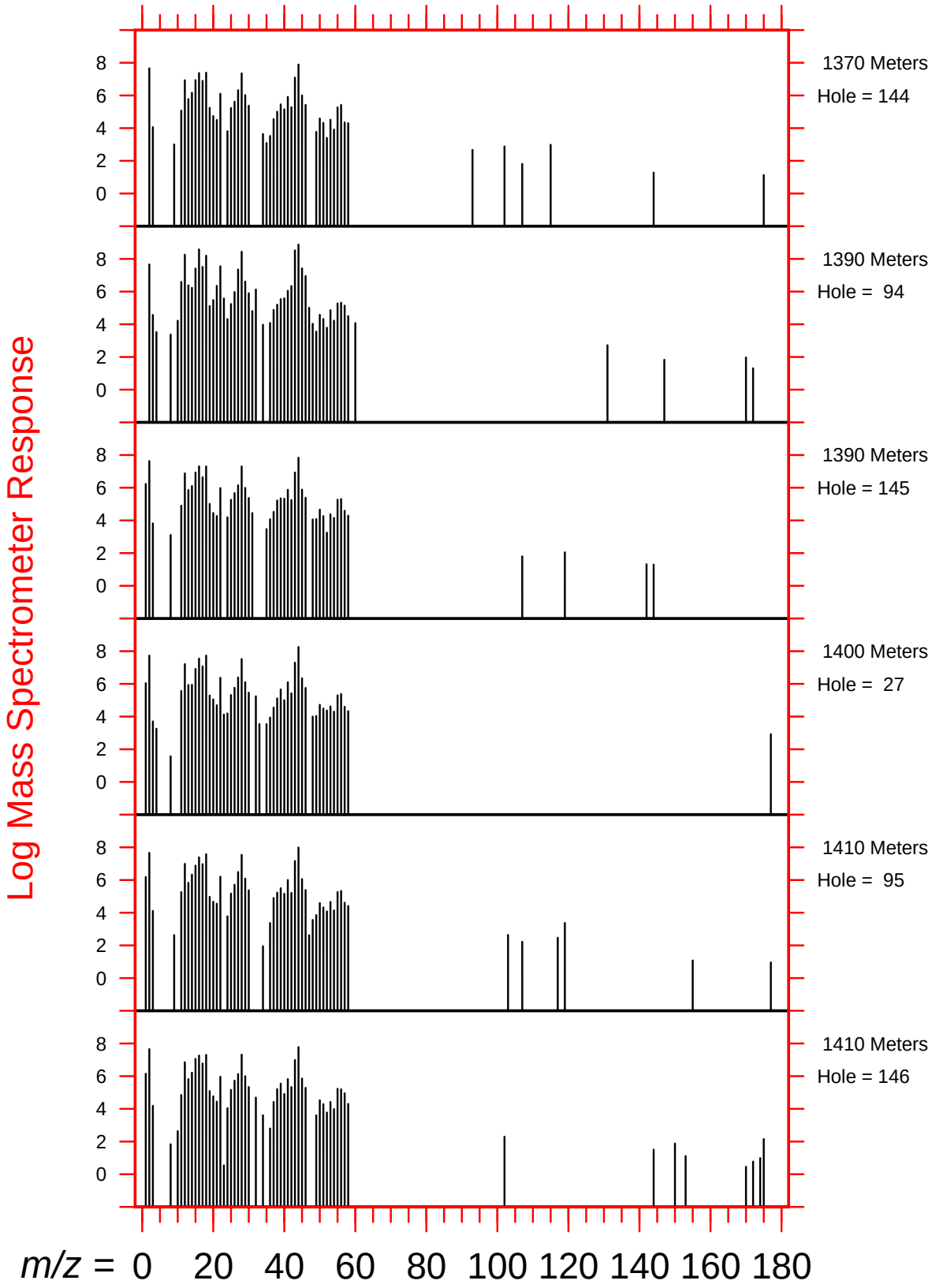

Log Mass Spectrometer Response
1120 Meters
Hole = 15
1130 Meters
Hole = 79
1150 Meters
Hole = 17
1150 Meters
Hole = 80
1170 Meters
Hole = 81
1180 Meters
Hole = 18
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

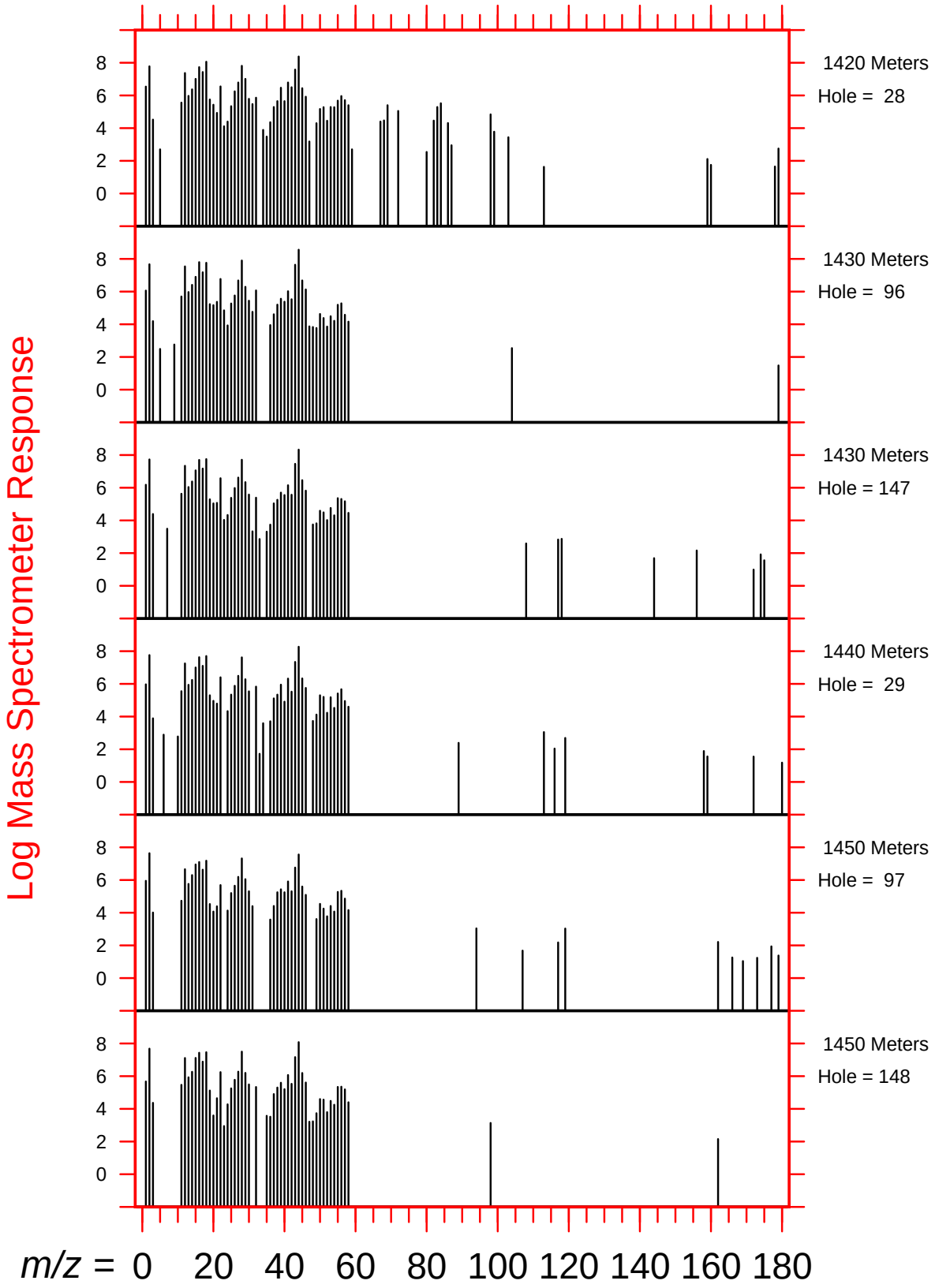

Log Mass Spectrometer Response
1190 Meters
Hole = 82
1200 Meters
Hole = 19
1210 Meters
Hole = 83
1210 Meters
Hole = 135
1230 Meters
Hole = 20
1230 Meters
Hole = 84
m/z = 0 20 40 60 80 100 120 140 160 180

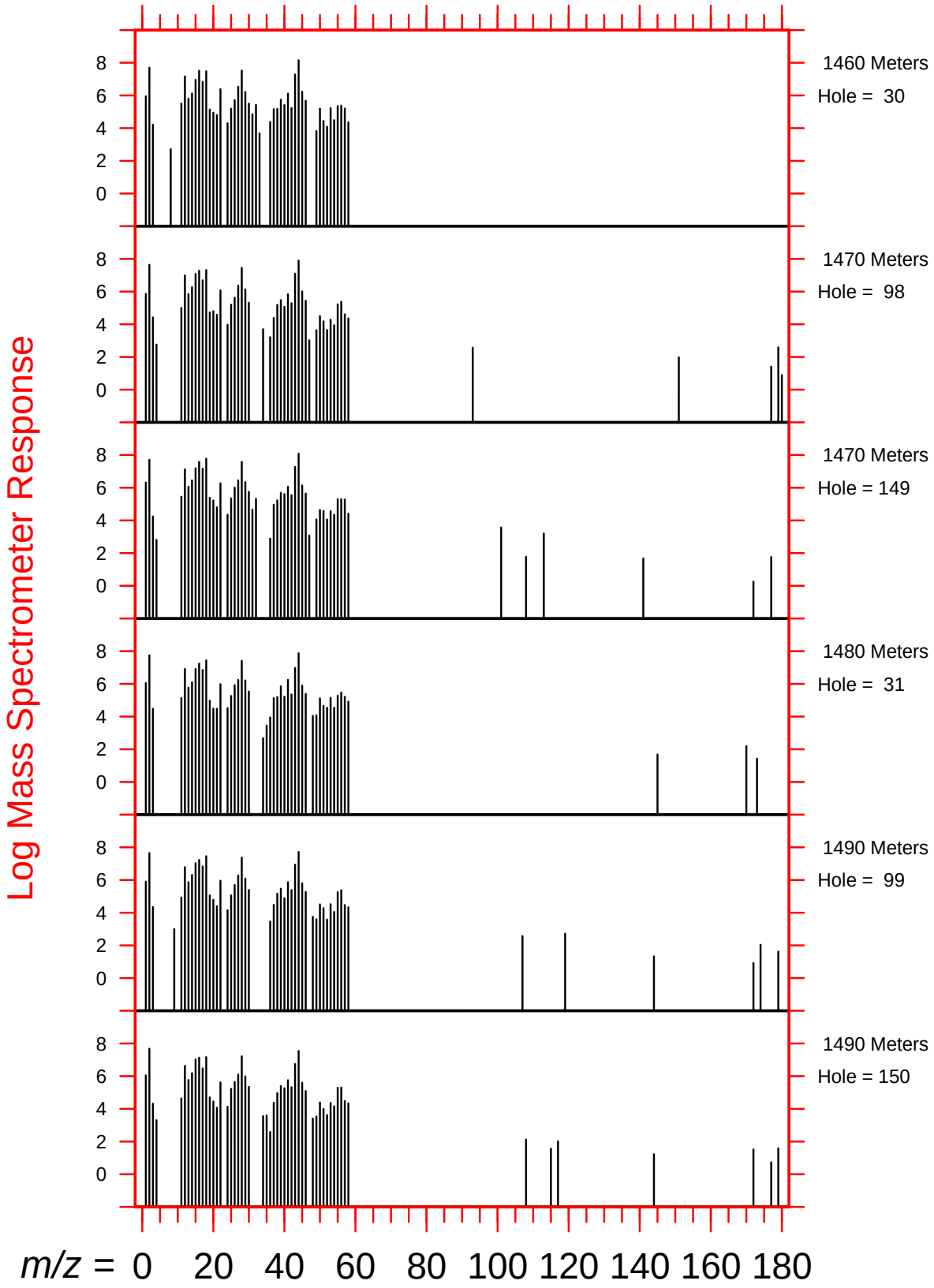

Log Mass Spectrometer Response
1230 Meters
Hole = 136
1240 Meters
Hole = 86
1250 Meters
Hole = 137
1260 Meters
Hole = 22
1270 Meters
Hole = 87
1270 Meters
Hole = 138
m/z = 0 20 40 60 80 100 120 140 160 180

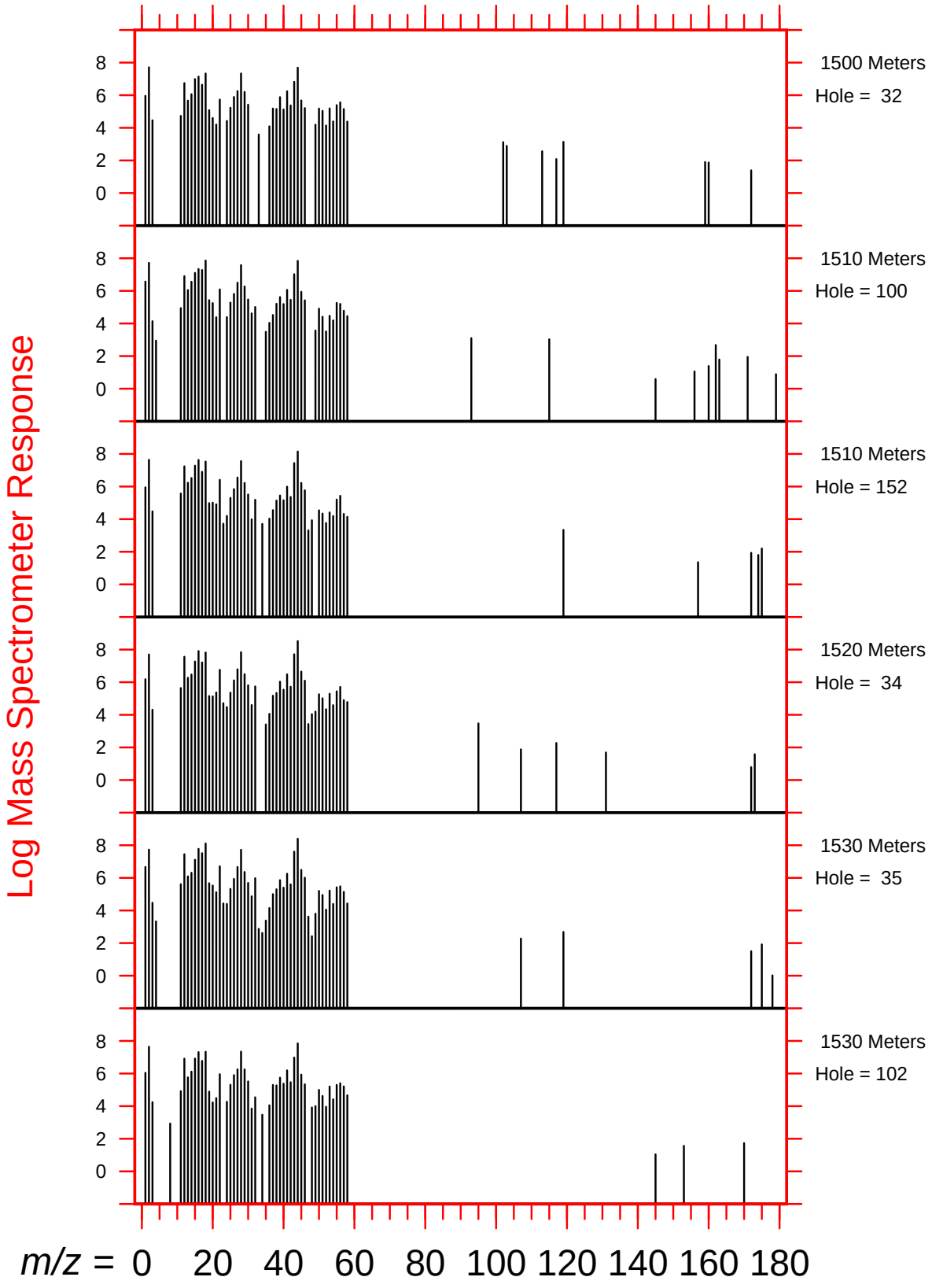

Log Mass Spectrometer Response
1290 Meters
Hole = 23
1290 Meters
Hole = 88
1290 Meters
Hole = 139
1310 Meters
Hole = 89
1310 Meters
Hole = 140
1320 Meters
Hole = 24
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

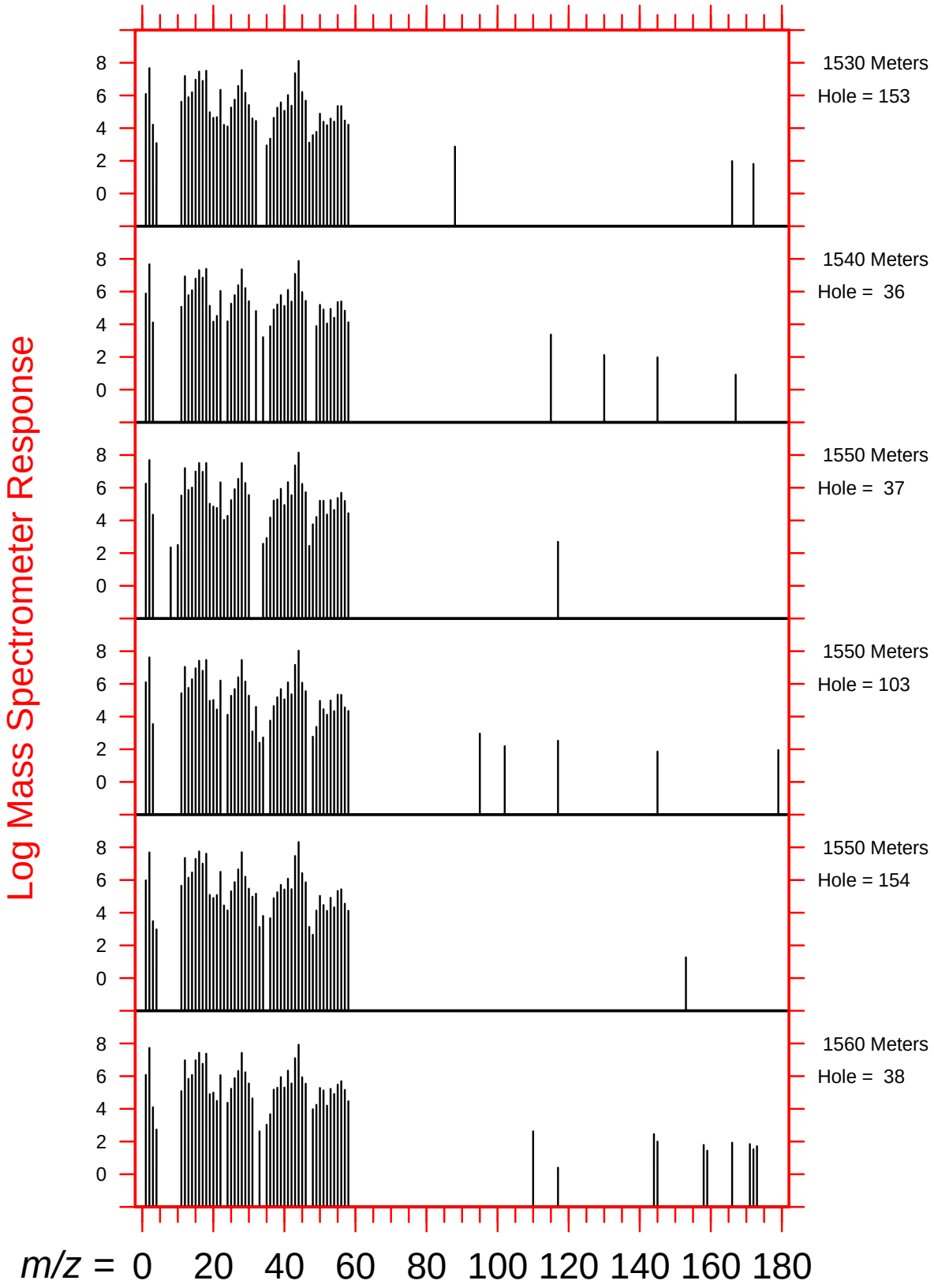

Log Mass Spectrometer Response
1330 Meters
Hole = 90
1330 Meters
Hole = 142
1350 Meters
Hole = 25
1350 Meters
Hole = 91
1350 Meters
Hole = 143
1370 Meters
Hole = 92
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

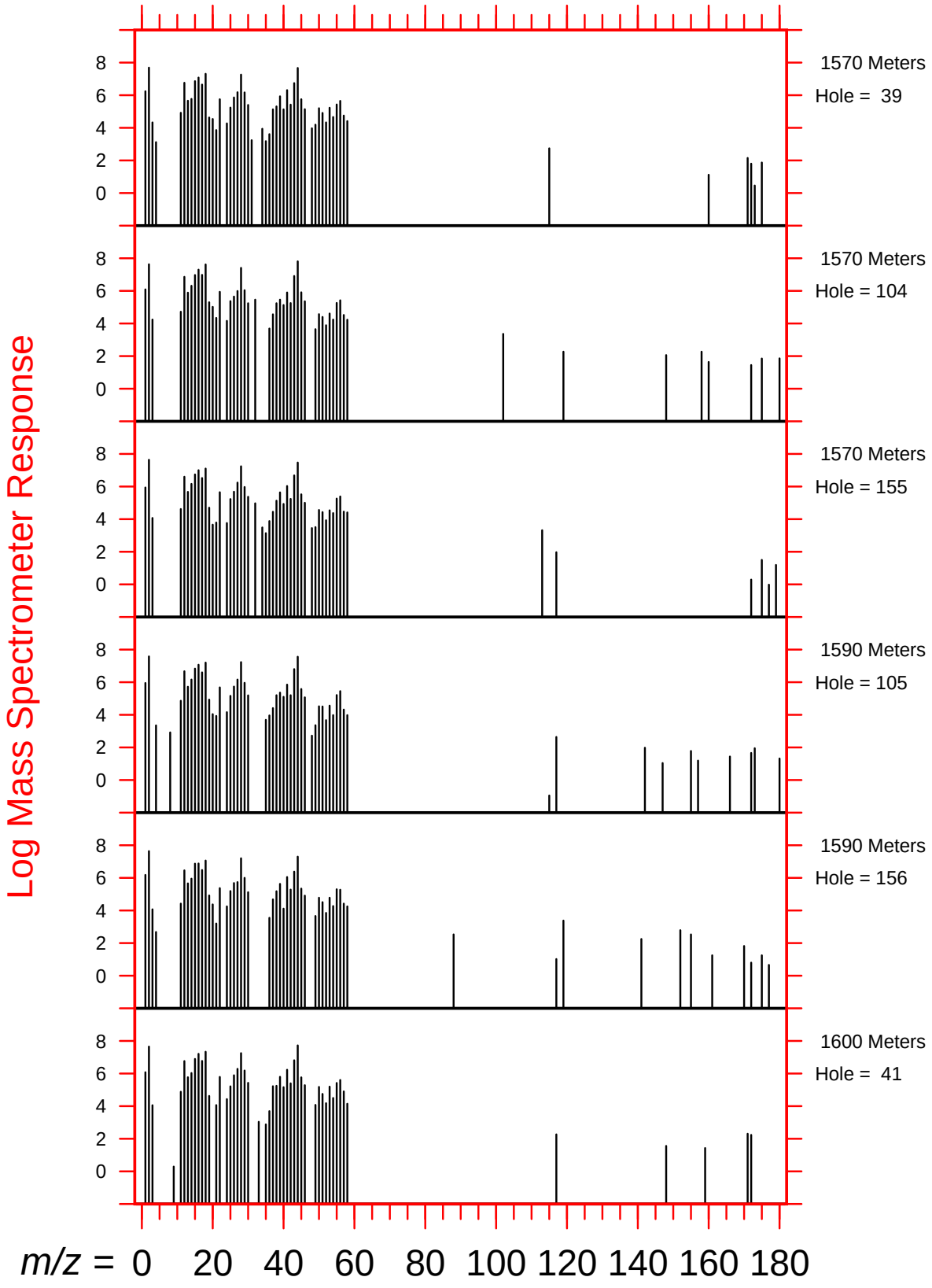

Log Mass Spectrometer Response
1370 Meters
Hole = 144
1390 Meters
Hole = 94
1390 Meters
Hole = 145
1400 Meters
Hole = 27
1410 Meters
Hole = 95
1410 Meters
Hole = 146
m/z = 0 20 40 60 80 100 120 140 160 180

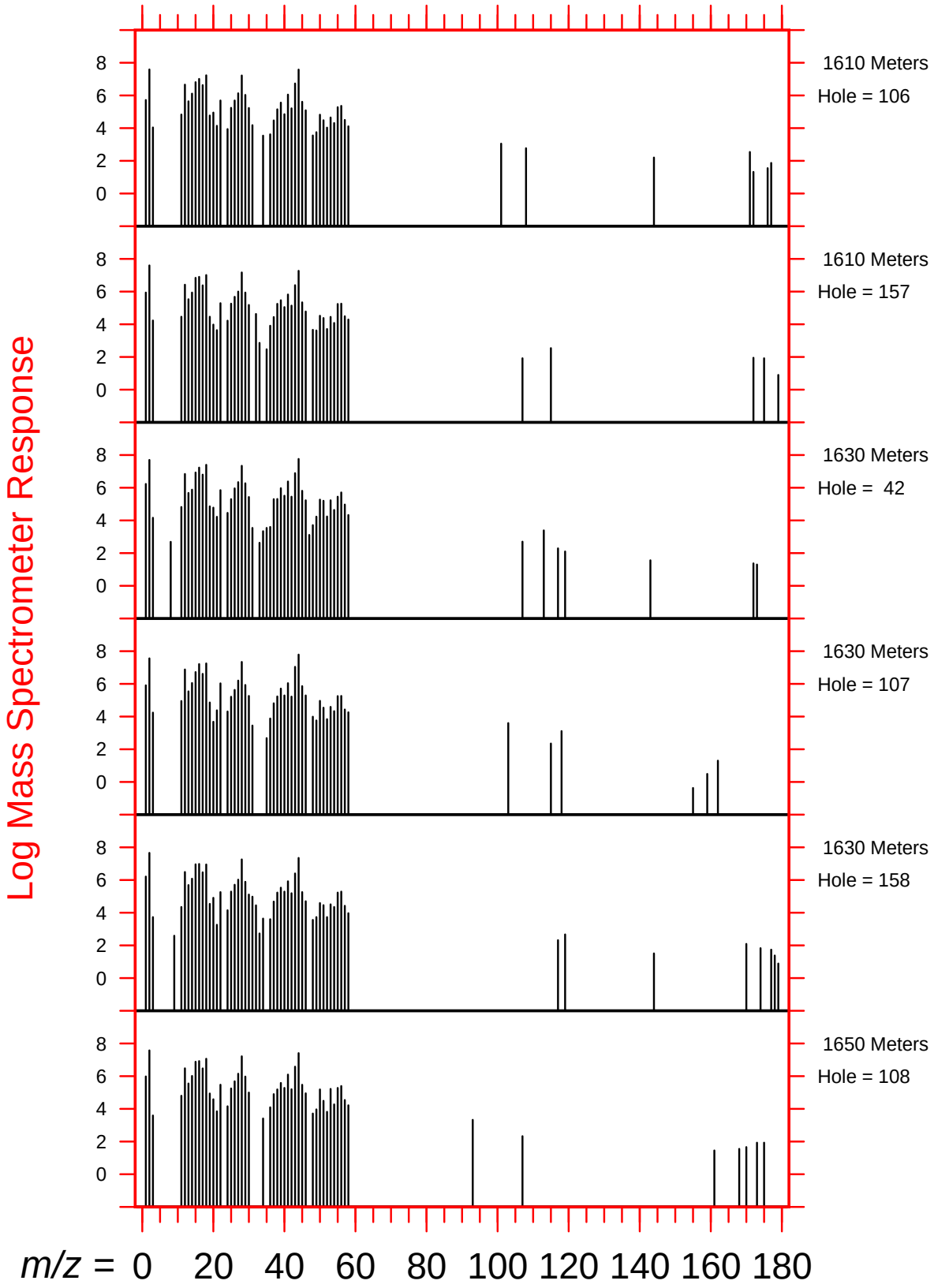

Log Mass Spectrometer Response
1420 Meters
Hole = 28
1430 Meters
Hole = 96
1430 Meters
Hole = 147
1440 Meters
Hole = 29
1450 Meters
Hole = 97
1450 Meters
Hole = 148
m/z = 0 20 40 60 80 100 120 140 160 180

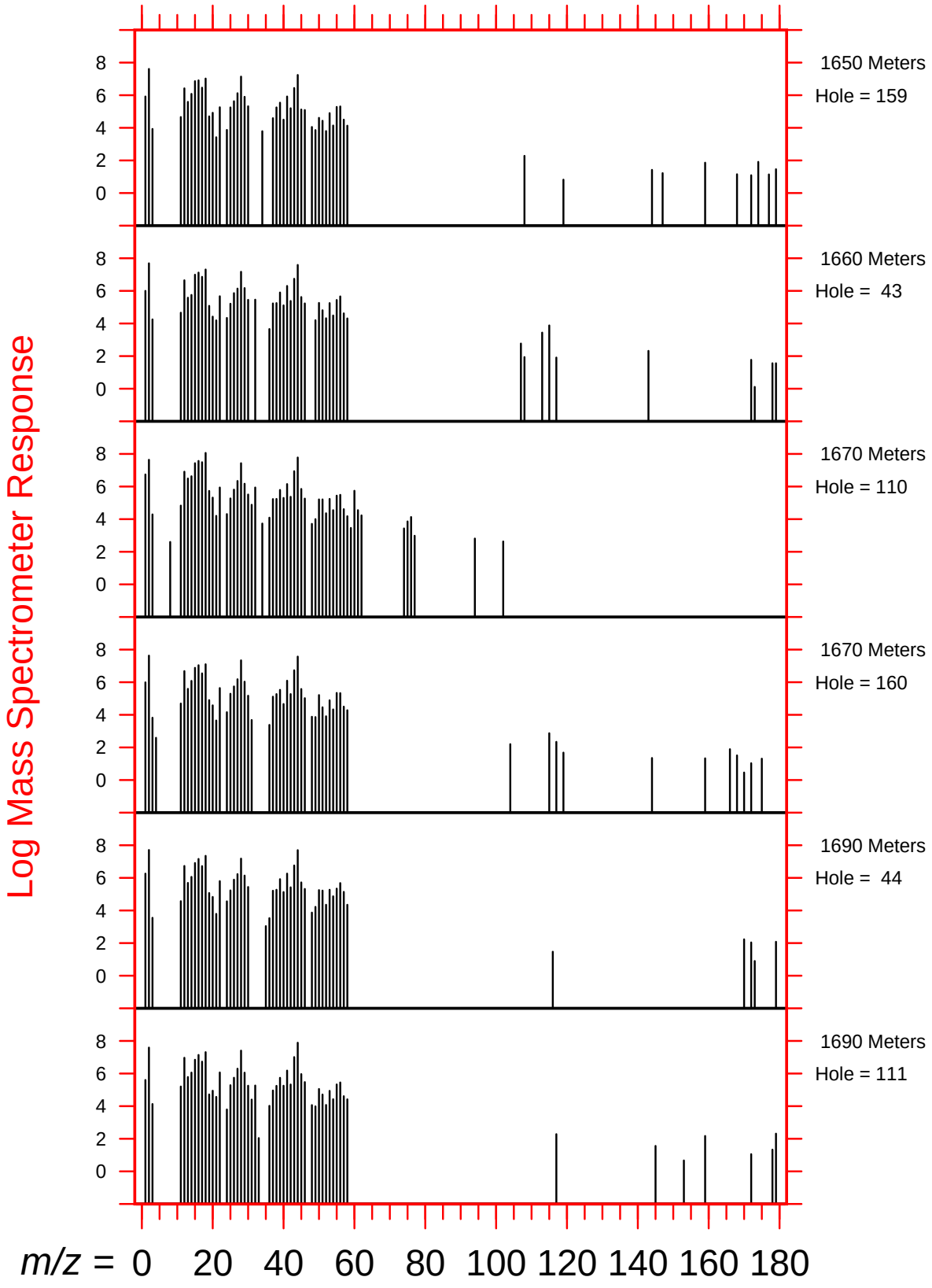

Log Mass Spectrometer Response
1460 Meters
Hole = 30
1470 Meters
Hole = 98
1470 Meters
Hole = 149
1480 Meters
Hole = 31
1490 Meters
Hole = 99
1490 Meters
Hole = 150
m/z = 0 20 40 60 80 100 120 140 160 180

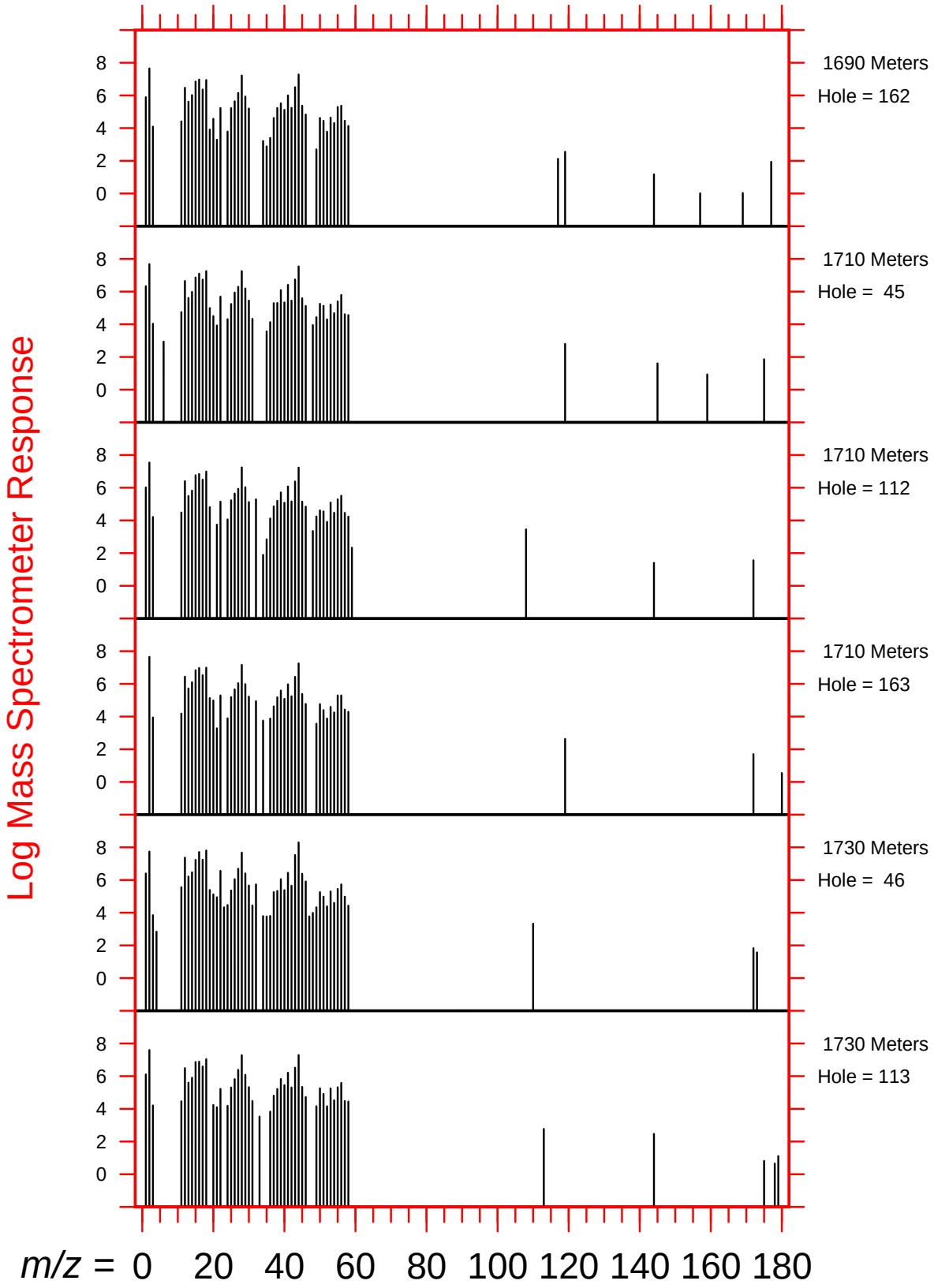

Log Mass Spectrometer Response
1500 Meters
Hole = 32
1510 Meters
Hole = 100
1510 Meters
Hole = 152
1520 Meters
Hole = 34
1530 Meters
Hole = 35
1530 Meters
Hole = 102
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

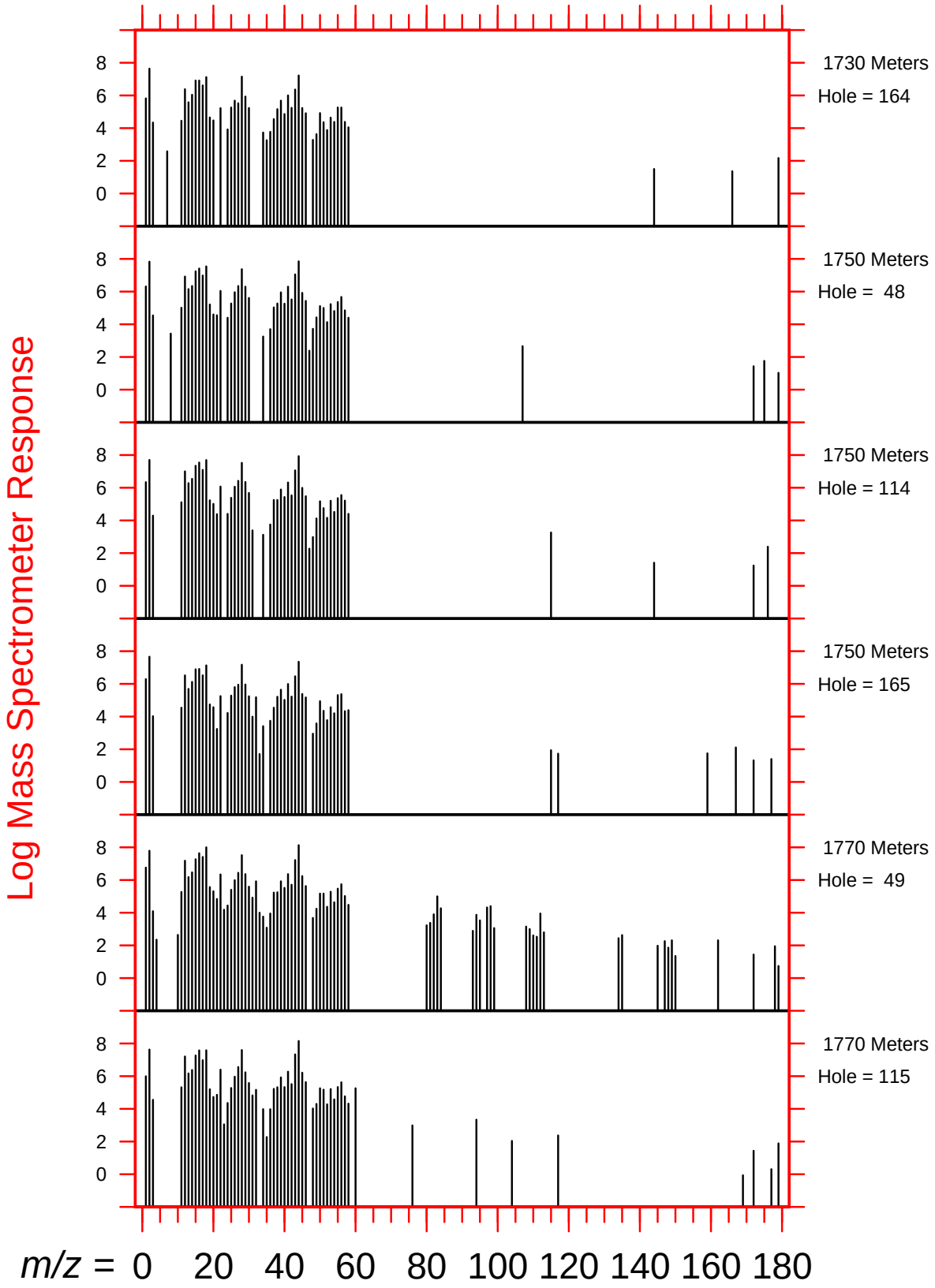

Log Mass Spectrometer Response
1530 Meters
Hole = 153
1540 Meters
Hole = 36
1550 Meters
Hole = 37
1550 Meters
Hole = 103
1550 Meters
Hole = 154
1560 Meters
Hole = 38
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

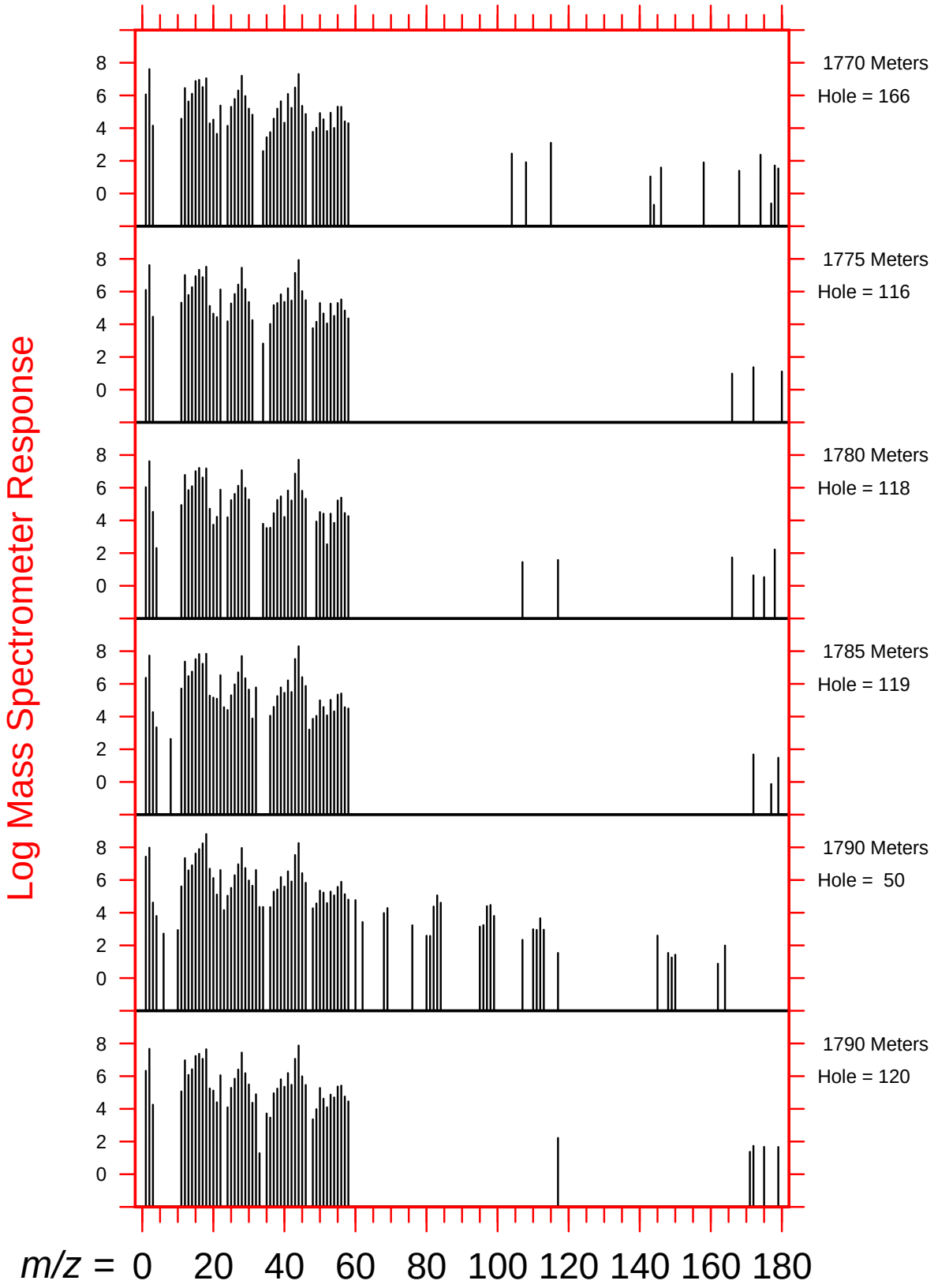

Log Mass Spectrometer Response
1570 Meters
Hole = 39
1570 Meters
Hole = 104
1570 Meters
Hole = 155
1590 Meters
Hole = 105
1590 Meters
Hole = 156
1600 Meters
Hole = 41
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

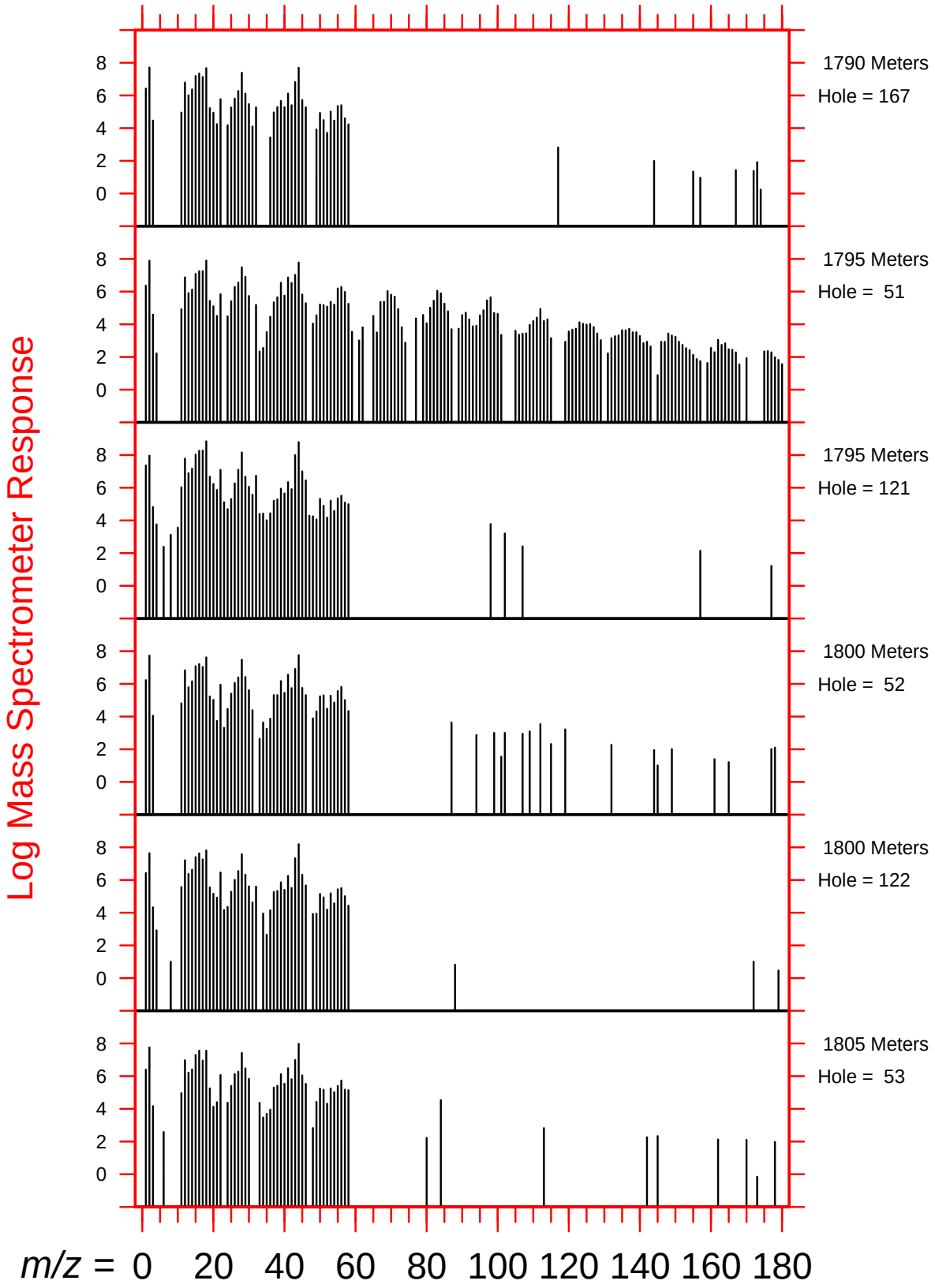

Log Mass Spectrometer Response
1610 Meters
Hole = 106
1610 Meters
Hole = 157
1630 Meters
Hole = 42
1630 Meters
Hole = 107
1630 Meters
Hole = 158
1650 Meters
Hole = 108
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

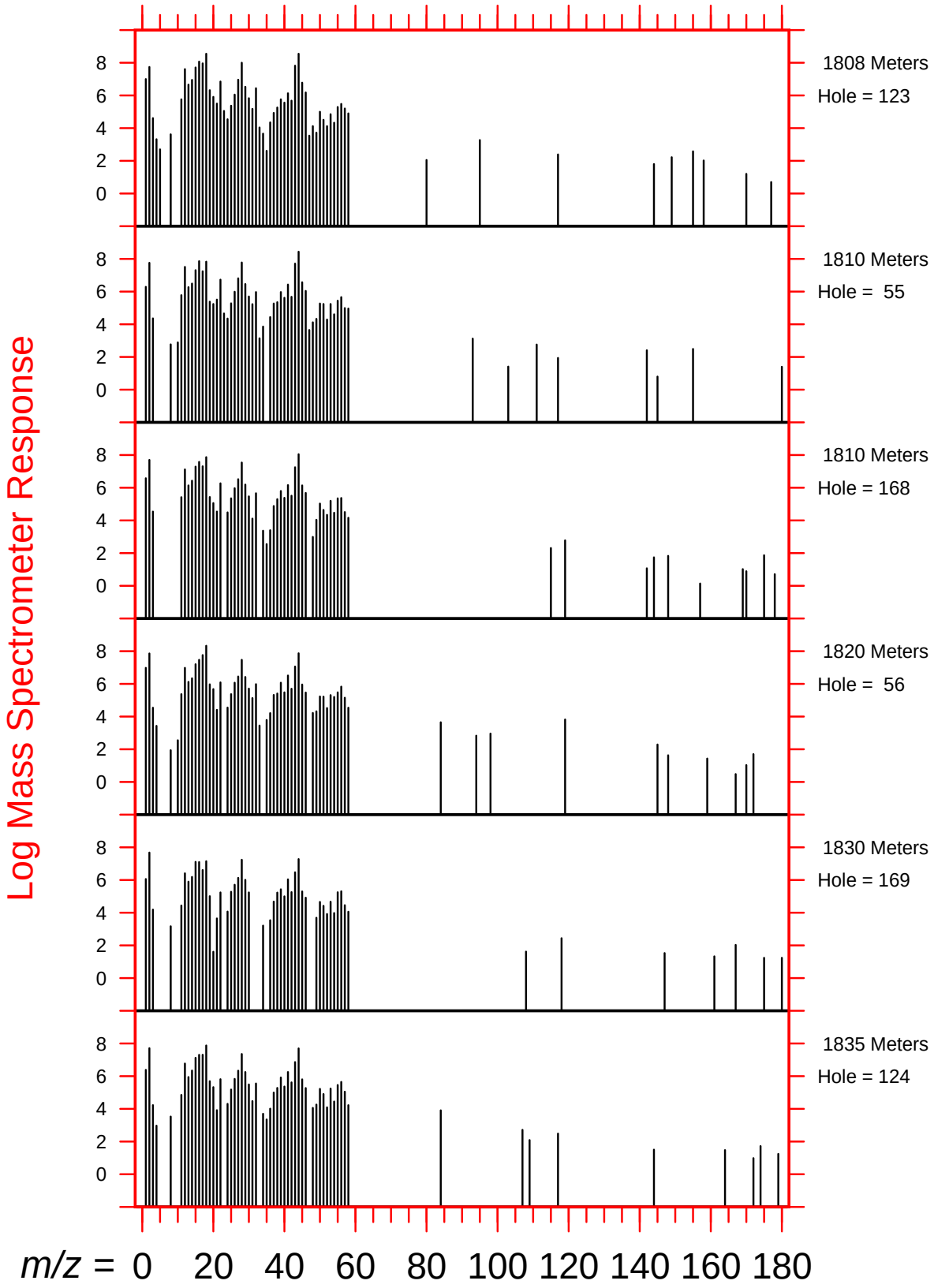

Log Mass Spectrometer Response
1650 Meters
Hole = 159
1660 Meters
Hole = 43
1670 Meters
Hole = 110
1670 Meters
Hole = 160
1690 Meters
Hole = 44
1690 Meters
Hole = 111
m/z = 0 20 40 60 80 100 120 140 160 180

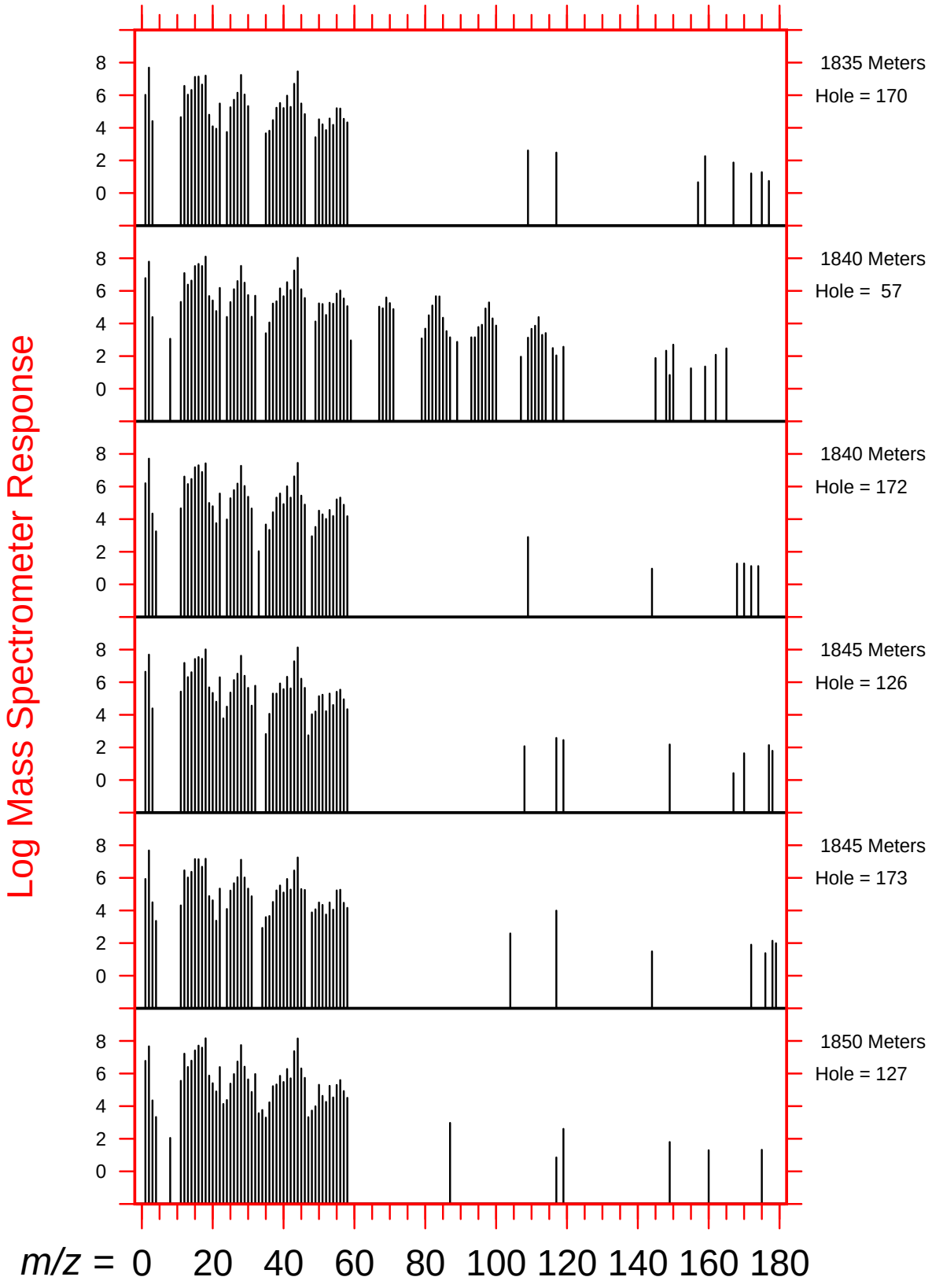

Log Mass Spectrometer Response
1690 Meters
Hole = 162
1710 Meters
Hole = 45
1710 Meters
Hole = 112
1710 Meters
Hole = 163
1730 Meters
Hole = 46
1730 Meters
Hole = 113
m/z = 0 20 40 60 80 100 120 140 160 180

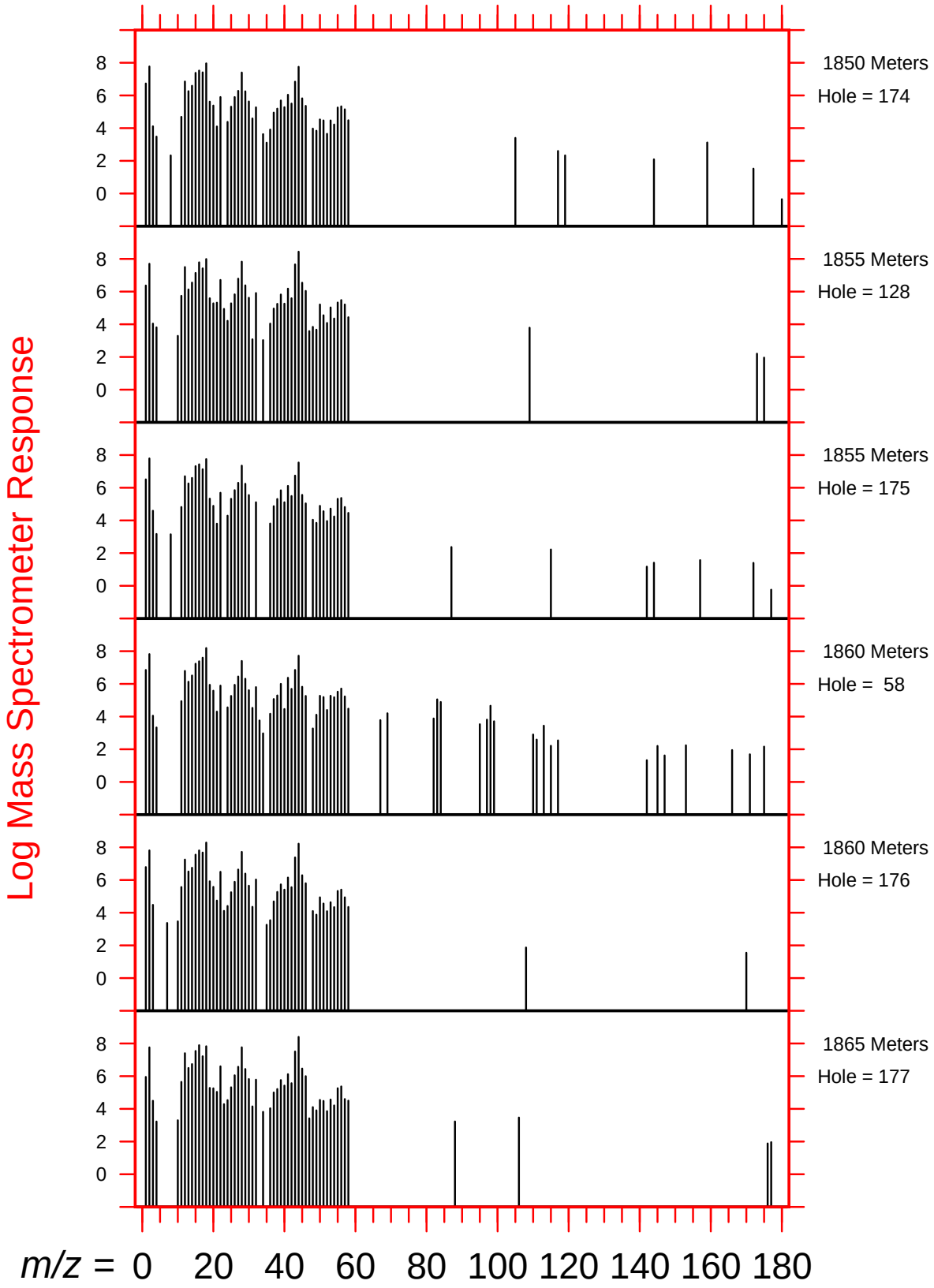

Log Mass Spectrometer Response
1730 Meters
Hole = 164
1750 Meters
Hole = 48
1750 Meters
Hole = 114
1750 Meters
Hole = 165
1770 Meters
Hole = 49
1770 Meters
Hole = 115
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

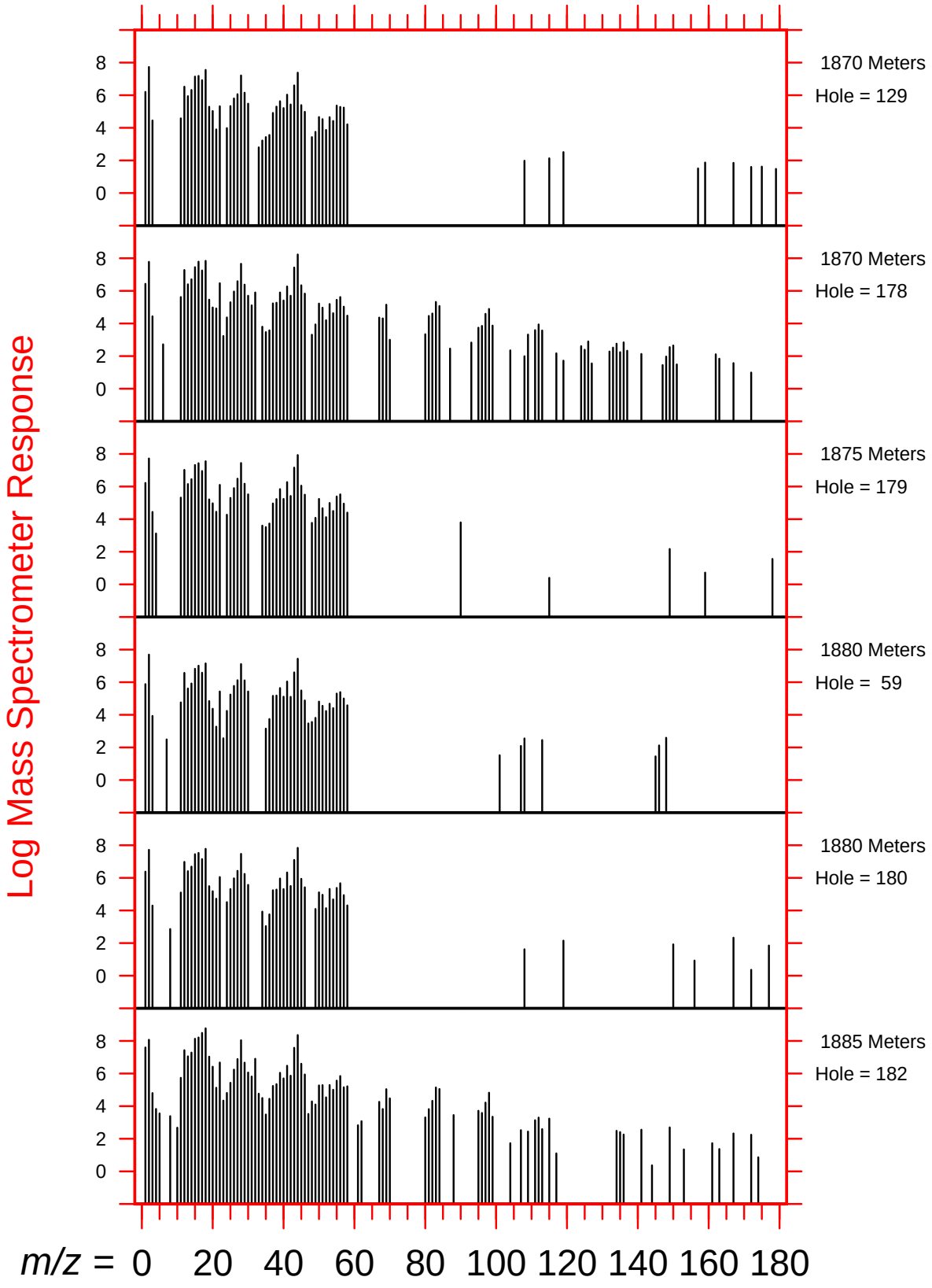

Log Mass Spectrometer Response
1770 Meters
Hole = 166
1775 Meters
Hole = 116
1780 Meters
Hole = 118
1785 Meters
Hole = 119
1790 Meters
Hole = 50
1790 Meters
Hole = 120
m/z = 0 20 40 60 80 100 120 140 160 180

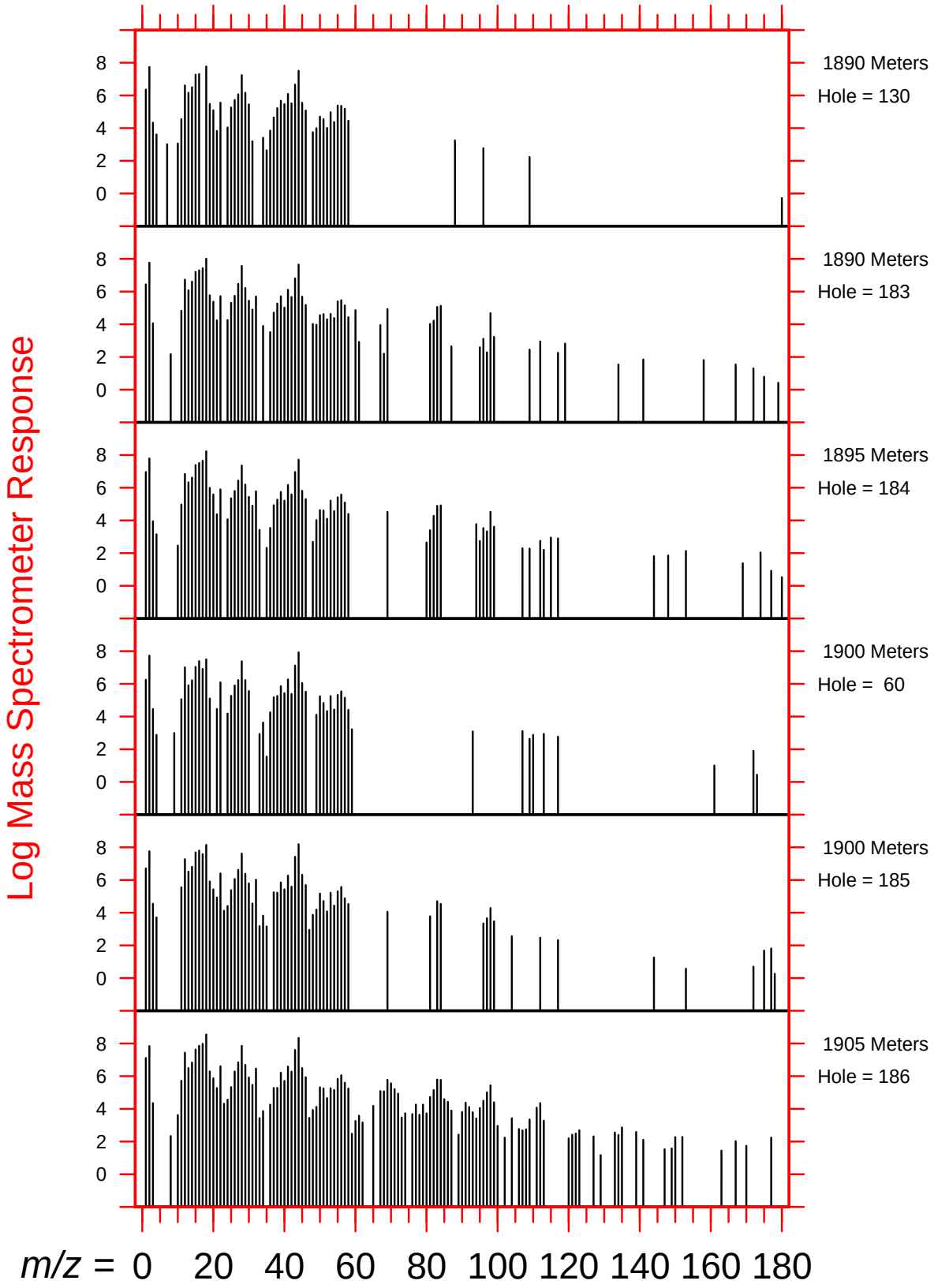

Log Mass Spectrometer Response
1790 Meters
Hole = 167
1795 Meters
Hole = 51
1795 Meters
Hole = 121
1800 Meters
Hole = 52
1800 Meters
Hole = 122
1805 Meters
Hole = 53
m/z = 0 20 40 60 80 100 120 140 160 180

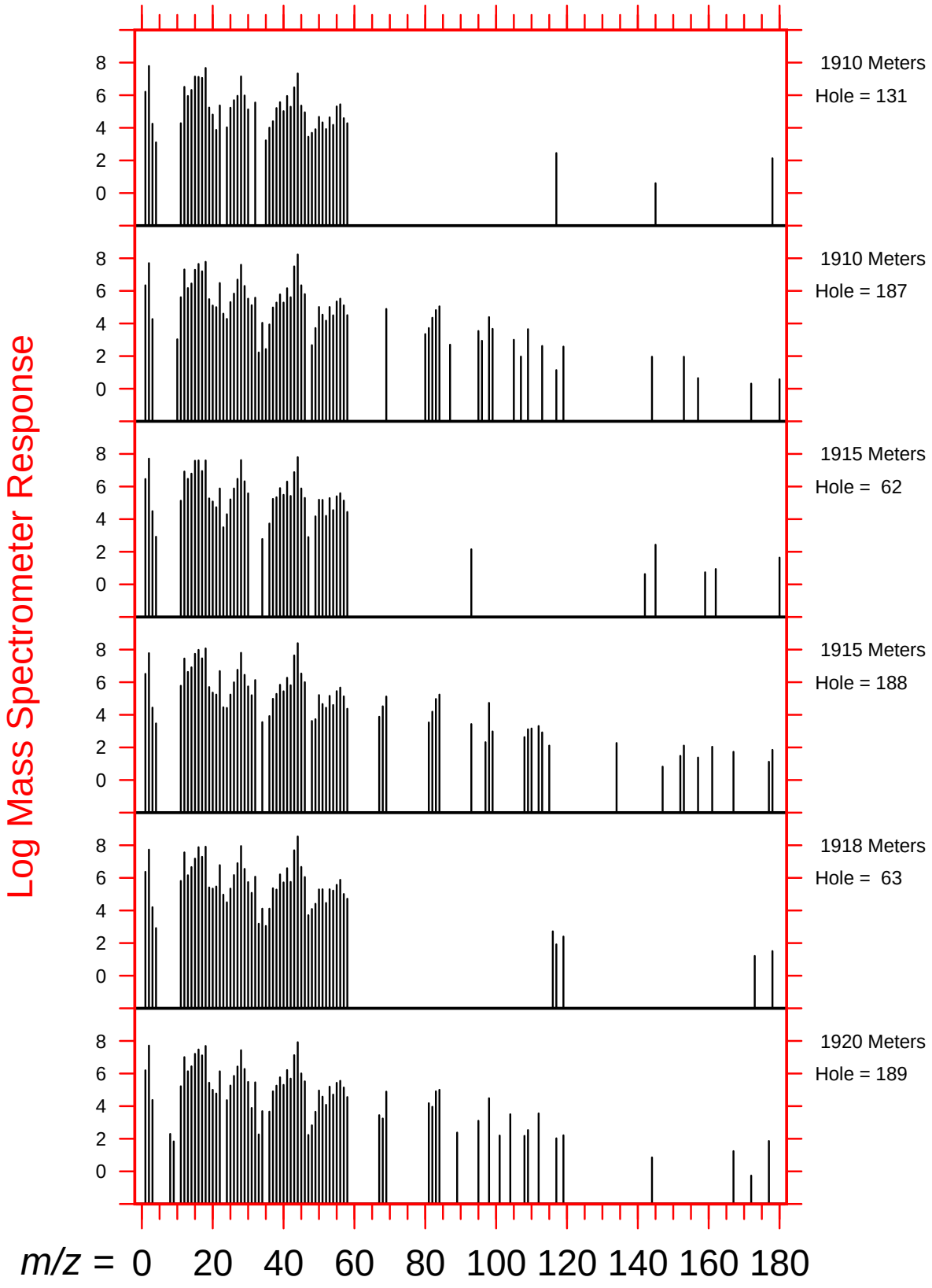

Log Mass Spectrometer Response
1808 Meters
Hole = 123
1810 Meters
Hole = 55
1810 Meters
Hole = 168
1820 Meters
Hole = 56
1830 Meters
Hole = 169
1835 Meters
Hole = 124
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

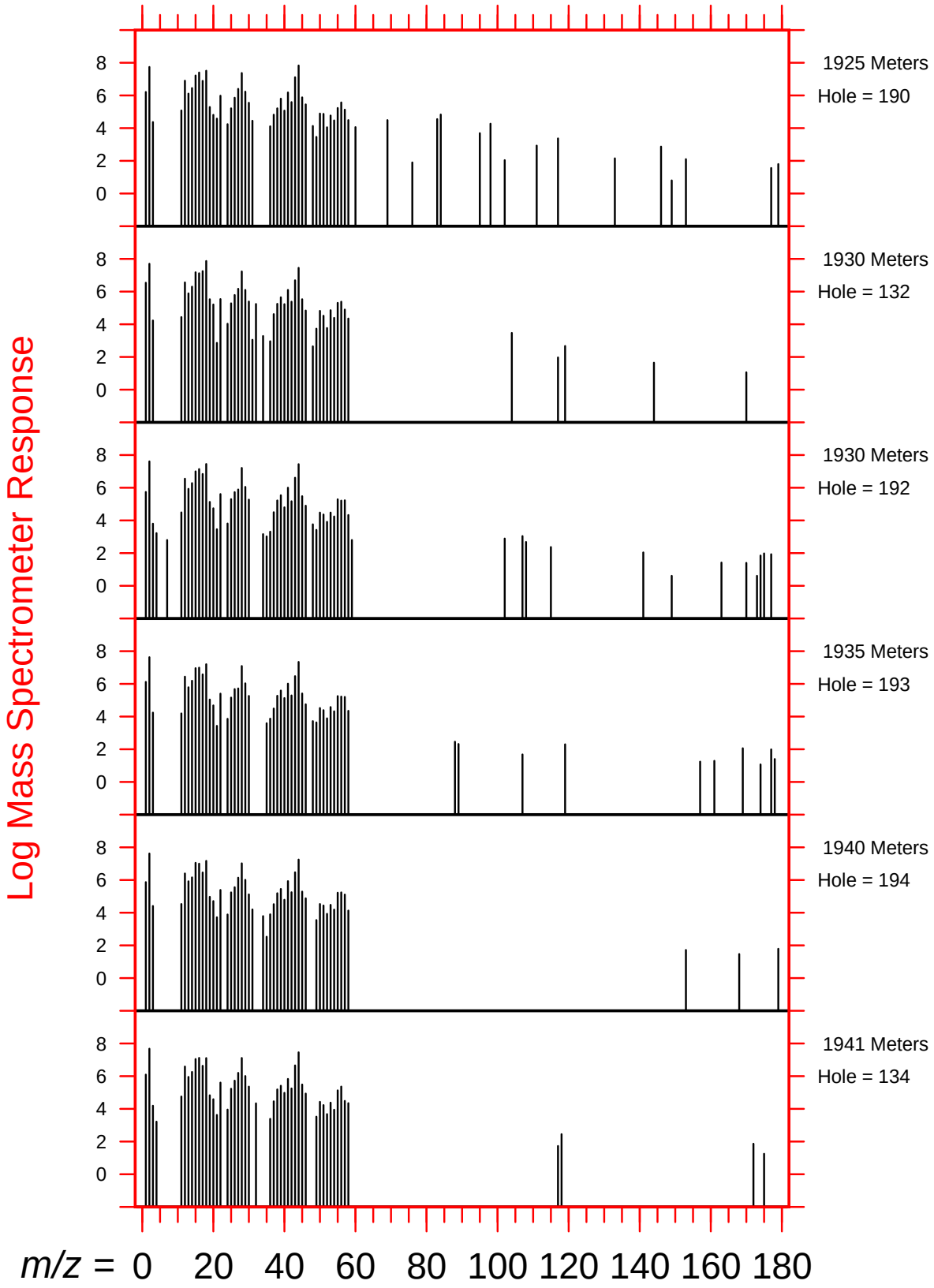

Log Mass Spectrometer Response
1835 Meters
Hole = 170
1840 Meters
Hole = 57
1840 Meters
Hole = 172
1845 Meters
Hole = 126
1845 Meters
Hole = 173
1850 Meters
Hole = 127
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

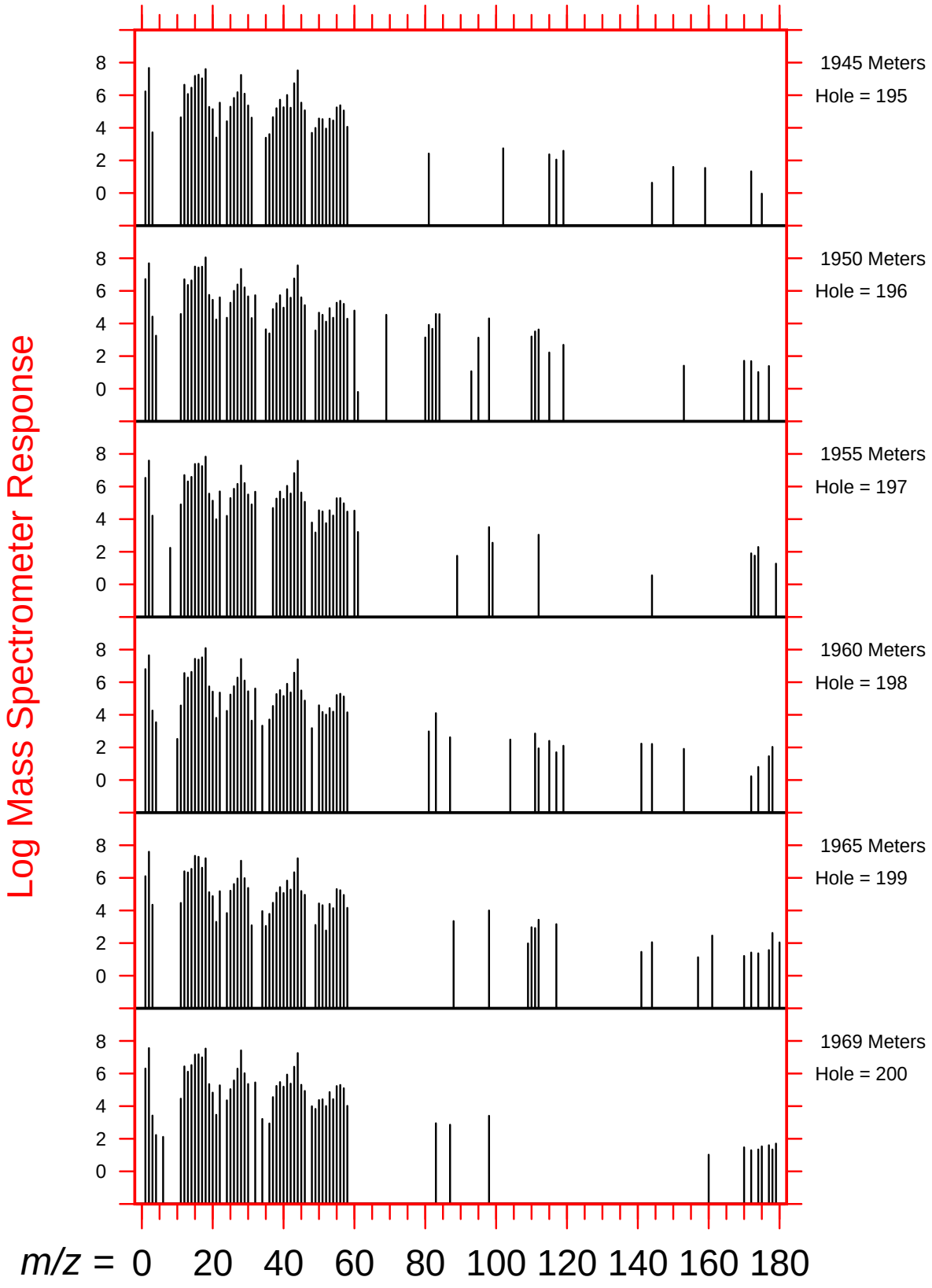

Log Mass Spectrometer Response
1850 Meters
Hole = 174
1855 Meters
Hole = 128
1855 Meters
Hole = 175
1860 Meters
Hole = 58
1860 Meters
Hole = 176
1865 Meters
Hole = 177
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180


Log Mass Spectrometer Response
1870 Meters
Hole = 129
1870 Meters
Hole = 178
1875 Meters
Hole = 179
1880 Meters
Hole = 59
1880 Meters
Hole = 180
1885 Meters
Hole = 182
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180


Log Mass Spectrometer Response
1890 Meters
Hole = 130
1890 Meters
Hole = 183
1895 Meters
Hole = 184
1900 Meters
Hole = 60
1900 Meters
Hole = 185
1905 Meters
Hole = 186
m/z = 0 20 40 60 80 100 120 140 160 180


Log Mass Spectrometer Response
1910 Meters
Hole = 131
1910 Meters
Hole = 187
1915 Meters
Hole = 62
1915 Meters
Hole = 188
1918 Meters
Hole = 63
1920 Meters
Hole = 189
m/z = 0 20 40 60 80 100 120 140 160 180


Log Mass Spectrometer Response
1925 Meters
Hole = 190
1930 Meters
Hole = 132
1930 Meters
Hole = 192
1935 Meters
Hole = 193
1940 Meters
Hole = 194
1941 Meters
Hole = 134
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180


Log Mass Spectrometer Response
1945 Meters
Hole = 195
1950 Meters
Hole = 196
1955 Meters
Hole = 197
1960 Meters
Hole = 198
1965 Meters
Hole = 199
1969 Meters
Hole = 200
0
2
4
6
8
m/z = 0 20 40 60 80 100 120 140 160 180

Halladale-1 Fluid Inclusion Stratigraphy (FIS)

Halladale-1 DW3

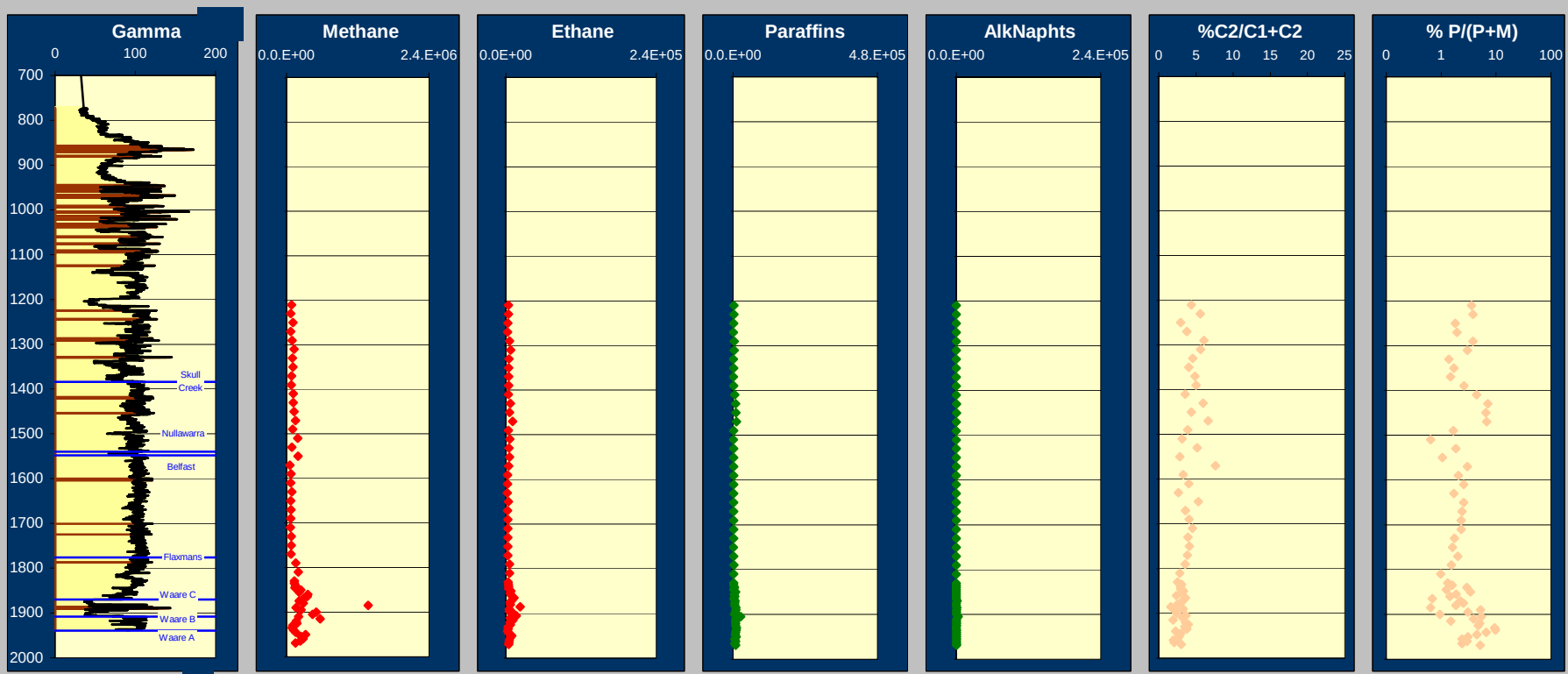
Fluid Inclusion Stratigraphy

Hydrocarbon Indicators

Lab: FIT

Depth Unit: metres

C1Threshold	C1 Threshold
2.00E+06	2.00E+06



Comments:

No significant anomalies are present with the exception of a strong dry gas signal at 1885m (Waare C)

	Min	Max	Depth Grid
Depth Range Analysed	1210	1969	
Depth Range to View	700	2000	100
Over-ride defaults	700	2000	100

Halladale-1 DW3

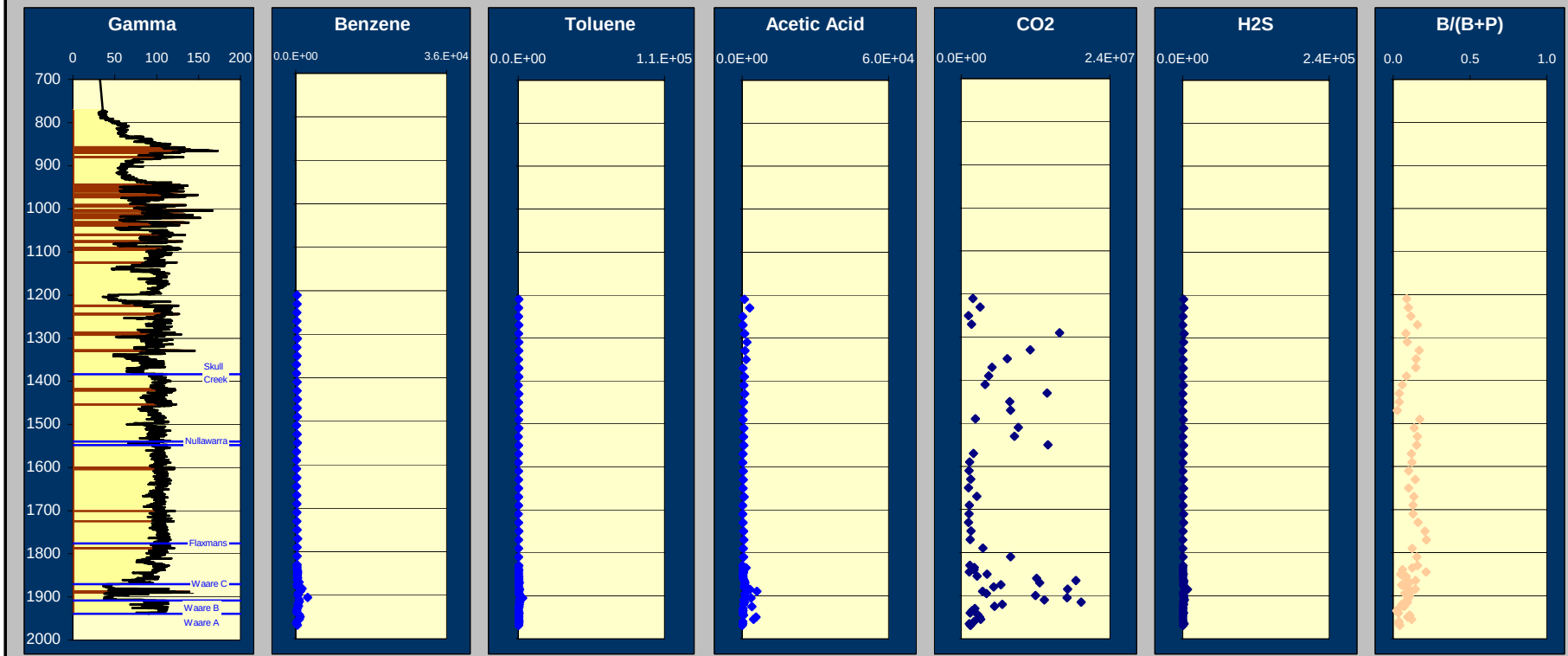
Fluid Inclusion Stratigraphy

Proximity-to-Pay Indicators

Lab: FIT

Depth Unit: metres

B Threshold 1.00E+04



Comments:

No significant and consistent PTP anomalies present.

Large CO2 anomalies persist throughout the section, consistent with Type III o.m. especially within Waare Fm.

(Adjust Depth Range on the Hydrocarbon Sheet)

Halladale 1 DW3

Composite Well Log

Scale 1:500

Origin

Well Location