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Organic Geochemistry of Palaeozoic Source Rocks of the Irish Sea, UK.

Energy and Marine Geoscience Programme

Commissioned Report CR/16/044

BRITISH GEOLOGICAL SURVEY

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Organic Geochemistry of Palaeozoic Source Rocks of the Irish Sea, UK.

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Foreword and Acknowledgements

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Malcolm Gall (OGA) is thanked for technical review of this report. Bill McLean is thanked for extraction of data from legacy reports.

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Summary

The East Irish Sea gas and oil fields (Triassic reservoir e.g. Morecambe, Lennox) are believed to be sourced from the underlying Carboniferous strata (e.g. Armstrong et al., 1997; Quirk et al. 1999 and references therein). This study undertook a systematic screening of Rock-Eval and vitrinite reflectance data extracted from released legacy well reports with the aim of providing a data based, regional overview of Carboniferous source rock intervals and their levels of maturity in the wider Irish Sea study area. The method and description of calculated parameters used are given in Vane et al. (2015). The Palaeozoic stratigraphy of the region is described in Wakefield et al. (2016b) and the regional petroleum systems analysis in Pharaoh et al. (2016).

Released geochemical data from the Palaeozoic of the Irish Sea is sparse and a variety of stratigraphical units have been sampled, mostly from units other than the likely main source rock interval (Bowland Shale Formation and equivalents). Nine wells were evaluated: 110/02b-10, 110/07-2, 110/07b-6, 110/09a-2, 111/25-1A, 113/27-1, 113/27-2 and 113/27-3. Well 110/12a-1 was not assessed due to the absence of key maturity information. In these wells, the Pennine Lower Coal Measures, Millstone Grit Group and Bowland Shale Formation are mainly gas-prone strata of poor-fair generative potential remaining and mature to the gas window at the sampled intervals in Quadrants 110 and 113 (Figure 1). Within the limited well sample set examined, high Total Organic Carbon (TOC) coal intervals have the best generative potential remaining. The Cumbrian Coastal Group, Appleby Group and Carboniferous Limestone Supergroup present in two wells in Quadrant 111 are at oil to gas window maturity levels, but have low TOC and low residual hydrocarbon generative potential.

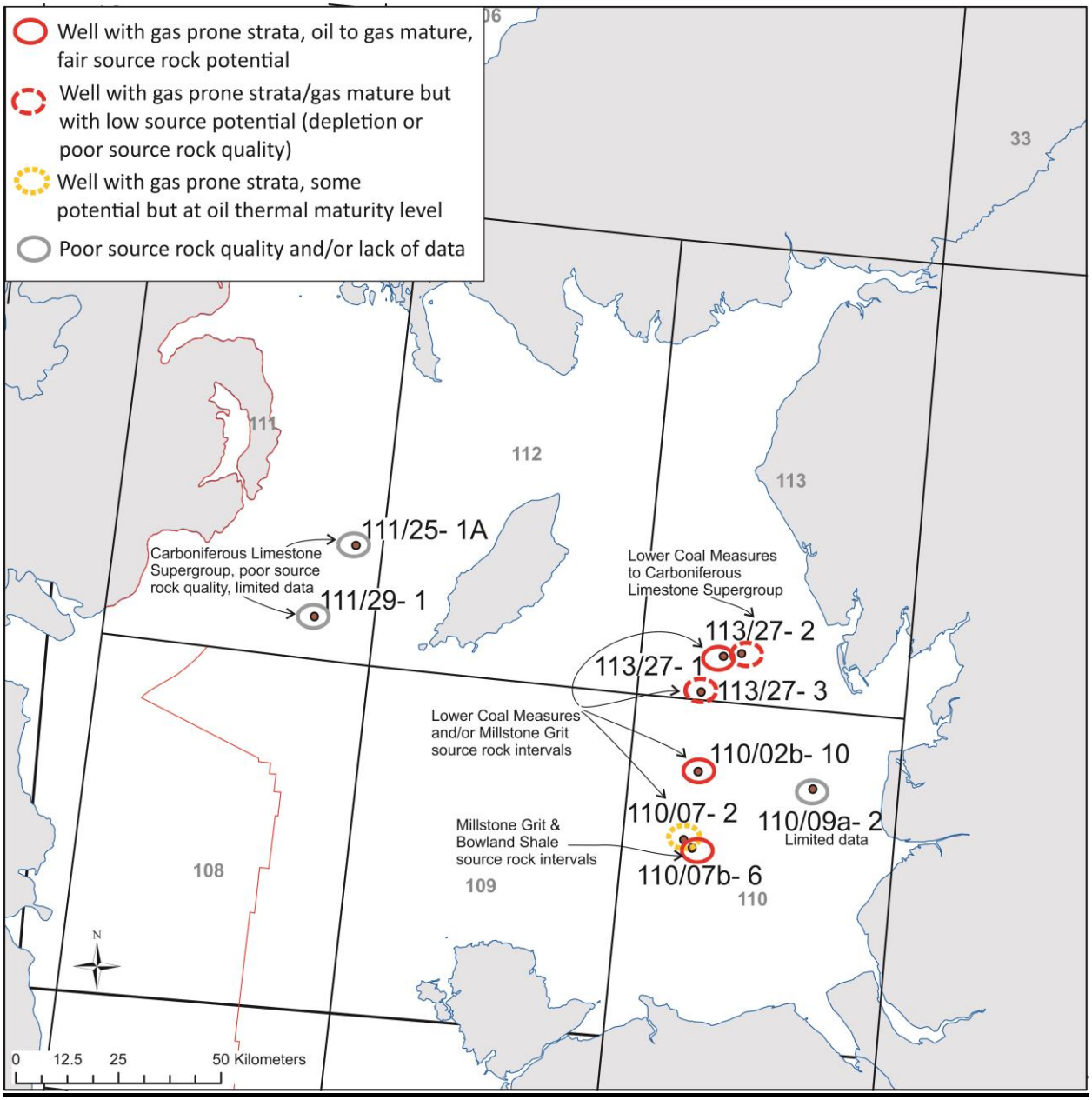


Figure 1 Summary map of well locations and geochemical results for Carboniferous source rocks in the Irish Sea study area. Note that wells penetrate different stratigraphical intervals.

1 Methodology

The method used for this systematic screening of TOC, Rock-Eval and vitrinite reflectance data extracted from released legacy reports is described in Vane et al. (2015). In the Irish Sea area, released data is sparse.

The stratigraphy is of the area is given in Wakefield et al. (2016; summary on Figure 2) and this regional source rock screening is incorporated into the basin modelling work of Gent (2016) and petroleum systems synthesis of Pharaoh et al. (2016b).

Table 1 gives an overview of the screening criteria used. The key Rock-Eval parameters are

- S1 (free hydrocarbons in mg/HC/g of rock TOC);
- S2 (generated hydrocarbons in mg/HC/g of rock TOC);
- HI (hydrogen index calculated from S2 * 100/TOC);); HI_o refers to the calculated original hydrogen index (see Vane et al., 2015)
- OI (oxygen index calculated from S3 * 100/TOC);
- TOC (Total Organic Content);
- $T_{max.}$ (Temperature of the maximum S2 peak); and
- PI (Production Index, derived from S1/S1+S2

Vitrinite reflectance (VR or R_o%) measurement of source rock thermal maturity is determined by optical microscopy. Vane et al. (2015) discuss the limitations of using a calculated VR value from the T_{max} measurement for kerogens other than Type II marine.

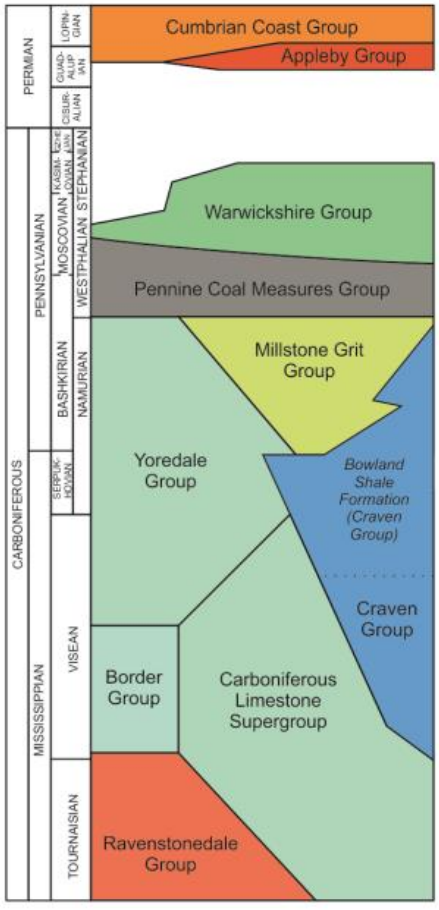


Figure 2 Summary of Carboniferous and Permian stratigraphy used in the Irish Sea area, see Wakefield et al. (2016) for further details.

Parameter	Inference & Comment
HI_o < 300 mg/g TOC	• Gas prone source rocks and will generate mainly gas*.
HI_o > 300 mg/g TOC	• Oil prone source rocks and will generate mainly oil*.
S2 < 1 mg/g and/or TOC (< 1.0 %)	• Poor or no hydrocarbon generative potential before burial, or • Good quality source interval that has been matured and generated hydrocarbons. • Where vitrinite reflectance (VR) maturity data is available VR can be used to help ascertain whether these parameter ranges were the result of hydrocarbon generation or inert maceral assemblage types.
Production Index (PI)	• An increase and stabilisation of PI values can be used as a secondary line of evidence for hydrocarbon generation. (A positive departure from a generally increasing PI value may indicate in situ generation of contamination by migrant or pollutant hydrocarbons) • High PI values (over 0.5-1) indicate generation compared to potential i.e. mature or migrated hydrocarbons.
T_{max}	• Generally reliable indicator of maturity in and around the oil window. • Should be used together with other maturity parameters in order to avoid false positives. • Requires high S2 peaks to enable reliable temperature readings on the S2 curve.
High T_{max} (>480°C) obtained with low S2	• Due to interferences from inorganic matter and technical limitations of the Rock-Eval instrument.
High T_{max} and low S2	• Can be obtained from a good source rock that has lost its potential during source rock maturation (high maturity), or from a poor source rock with high maturity. To mitigate this problem it is necessary to assess the maceral content to determine whether there are relict indications of original source richness.
S1 (free gas & oil content, some Rock Eval instruments separate gas (S0) and oil (S1)).	• poor 0-0.5 • fair 0.5-1 • good 1-2 • very good 2-4 • excellent >4
Vitrinite Reflectance (%R_o)	Criteria for thermal maturity of organic matter. • Immature = 0.2 – 0.5 • Early to mature oil = 0.5-0.7 • Mature oil = 0.7-1.0 • Late to mature oil = 1.0-1.3 • Main gas = 1.3-2.2 • Late gas = 2.2-3.0

Table 1 Summary of screening criteria used as 'rules of thumb'. Note that in detail, cut-off values will vary dependent on kerogen type (e.g. VR data - information is lacking to determine criteria for these mixed kerogen Carboniferous rocks, thus standard published values are used). *HI values below 300 can generate significant quantities of oil, see Vane et al., (2015) for discussion.

2 Wells Analysed

All depths listed are measured depths in metres and Project stratigraphic interpretations are used. Figure 2 gives a summary of the relationships between the stratigraphical intervals described.

110/02b-10 (2170.18-2540.51 m): Figures 3, 4

This well contains the Pennine Lower Coal Measures (2170.18-2353.06 m) and Millstone Grit Group (2462.78-2540.51 m). The TOC for the Pennine Lower Coal Measures ranges from 0.23 to 1.79%, with the exception of a high TOC of 72.3% from coal at 2353.06 m. The HI (32-90 mg/g) indicates gas prone source rock with some hydrocarbon potential still remaining in the coals. The measured VR for the Pennine Lower Coal Measures ranges between 0.62-1.26% R_o (with the exception of 1.80% R_o at 2304 m), the measured VR suggest that the source rocks in the Pennine Coal Measures are at oil window maturity levels (as defined in Table 1).

The Millstone Grit Group source rocks have TOC's of 1.00 to 4.32%, and HI of 32 to 150 mg/g which indicates gas prone source rocks with fair hydrocarbon generative potential remaining. The measured VR are in the range of 1.45% to 1.65% R_o with the exceptions of 2377.44 m (0.87% R_o), 2401.82 m (0.98% R_o), and 2474.98 m (0.83). The VR of mainly 1.45-1.65% R_o and T_{max} values between 471°C and 494 °C for the Millstone Grit Group indicate that the source rocks have matured to the (dry) gas window and as such are likely to have generated some hydrocarbons.

Overall, the measured VR's for this well indicate that the gas prone source rocks are at oil window maturity levels in the Pennine Lower Coal Measures, and in the gas window at greater depth in the Millstone Grit Group.

110/07-02 (1417.02-1495.96 m): Figures 5, 6

The Carboniferous stratigraphy proven in this well is the Millstone Grit Group. The source rocks have TOC's of 0.14-3.75%, and HI's of 34-91 which indicates gas prone source rocks with some hydrocarbon generative potential remaining. The measured VR's of 0.90% R_o (at 1448.10 m) and 0.90% R_o (at 1481.02 m) together with T_{max} values 440 to 444°C indicate that the source rocks are at main oil window maturity levels.

110/07b-6 (1517.90-2476.50 m): Figures 7, 8

This well contains the Millstone Grit Group (1517.90-1958.34 m) as well as Bowland Shale Formation (1984.25-2476.50 m). The Millstone Grit Group has TOC between 0.90 to 5.24%. and shale-mudstone samples have HI of 49-226 mg/g (mean 91 mg/g n=17) which indicates a gas prone source rock with fair hydrocarbon generative potential remaining. Measured VR data of 0.73-0.84% R_o and T_{max} of 433-466 °C suggests that the Millstone Grit source rocks attain early oil to main oil window maturity levels.

Bowland Shale Formation TOC values range between 0.26 and 2.96, with a high TOC (7.24%) at 2435.35 m. The HI's of 22-78 mg/g and corresponding low S2 values of <2.5 mg/g indicate gas prone source rock with poor to fair hydrocarbon generative potential remaining. Measured VR of 0.79-1.22% R_o and T_{max} of 442-488 °C suggests that the Bowland Shale Formation source rocks attained oil to early gas window maturity levels.

Overall, the source rocks in this well are at early oil to main oil window maturity levels (Millstone Grit Group) and oil to early gas window maturity levels (Bowland Shale Formation). Gent (2016) models hydrocarbon generation within this well consistent with the observed oil shows.

110/09a-2 (1436-1596): Figures 9, 10

The Pennine Lower Coal Measures are penetrated in this well, which has measured TOC and VR data available but very limited Rock-Eval data (2 data points). The very low TOC (0.11-0.85%), and HI of 11 mg/g and 6 mg/g at 1463.04 m and 1566.67 m respectively suggests that the source rocks may have generated hydrocarbon. However absence of additional S2 data and

corresponding HI from 110/9a-2 confounds any interpretation of the generative potential. The measured VR of 0.54-1.86% R_o indicates that the source rocks attained early oil window to gas window maturity levels.

111/25-1A (1404-1668 m): Figures 11, 12

This well contains the Cumbrian Coast Group (1404-1515 m), Appleby Group (1593 m), and Carboniferous Limestone Supergroup (1611-1668 m). All the formations have low TOC (0.02-0.41%), S2 values <0.2mg/g and HI's are between 33 and 175 mg/g which indicates gas prone source rocks with poor hydrocarbon generative potential. The measured VR of 0.87-0.99% R_o for the formations indicate that the source rocks are at main oil window maturity levels.

111/29-1 (1113-1450 m): Figures 13, 14

This well penetrated the Carboniferous Limestone Supergroup, with a limited dataset available. The TOC for the well is low (0.1-0.6%), and the HI of 56 mg/g at 1119 m indicates gas prone source rock. The measured VR of 0.95% R_o at 1119 m suggests a main oil window maturity level, whereas at well greater depths the VR of 1.37% at 1300 m and 1.68% R_o at 1400 m indicate gas window maturity.

113/27-1 (3063.24-3233.93 m): Figures 15, 16

This well contains Sherwood Sandstone, Cumbrian Coastal, Pennine Lower Coal Measures and Millstone Grit Groups. Measured VR data are not available, but T_{max} of 506-537 °C indicates that the source rocks are gas window mature throughout the well section. The Sherwood Sandstone has TOC <1 % and HI of only 10 to 40 mg/g and Cumbrian Coastal Group has low TOC 0.35% (n=13) and low HI of 10 to 110 mg/g (mean 50 mg/g) which confirms poor hydrocarbon generating potential.

The Pennine Lower Coal Measures (2941.32 – 3054.71 m) have low TOC (<1 %) interspersed with some high TOC (77, 60, 75 %) coal intervals at 2971.80, 3002.28 and 3032.76 m. Although S2 and corresponding HI values are not available for the coals they are likely to have some (gas) source potential. The Millstone Grit Group shows a similar pattern with coal intervals at 3063.24 m, 3093.72 m, 3124.20 m, 3154.68 m, 3185.16 m, 3215.64 m, and 3233.93 m. The TOC of the source rocks are 0.81-2.78%, with the exception of the coal intervals with TOC of 25.25-76.3%. However, corresponding HI and back-calculated S2 values are low (HI 10 to 80 mg/g; S2 0.07 to 12.88 mg/g) which suggests low generative potential remaining.

113/27-2 (1780-2532 m): Figures 17, 18

This well contains the Pennine Lower Coal Measures (1779.73-1893.42 m), Millstone Grit Group (1901.95-2367.99 m), Bowland Shale Group (2460.96-2475.59 m), and Carboniferous Limestone Super Group (2518.26-2531.97 m).

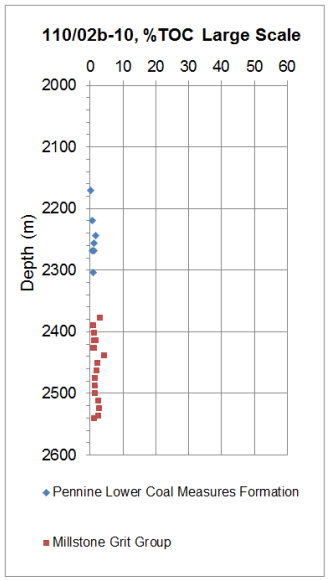
The TOC for the Pennine Lower Coal Measures ranges from 0.31 to 3.84%, with S2 of 0.04-0.38 mg/g and corresponding low HI values of 8 to 37 mg/g which suggests fair generative potential and gas prone kerogen. The measured VR of 1.00% R_o at 1843.43 m indicate that the source rocks in the Pennine Lower Coal Measures are at oil window maturity levels. The Millstone Grit Group have TOC's of 0.73-4.39%, and HI's of 7 to 79 mg/g which indicate fair to good potential and gas prone kerogen. The measured VR's of 1.04-1.31% R_o indicates that the source rocks in this formation are at main oil window to early gas window maturity levels.

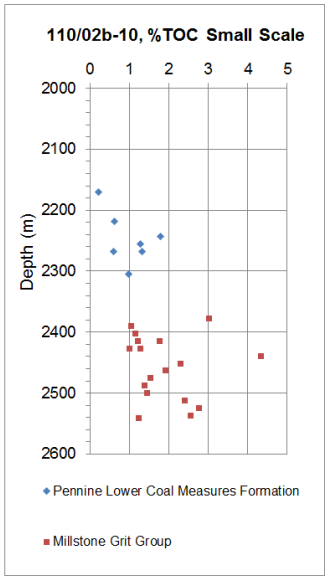
The Bowland Shale Group source rocks have TOC of 0.93 to 2.2%, and HI's of 7 to 13 mg/g, and no measured VR. The Carboniferous Limestone Supergroup samples have TOC's of 0.05 to 2.2%, and HI of 4 to 7 mg/g. The measured VR of 1.65% R_o at 2518.26 m and 2520.09 m indicate that the source rocks in this group are gas window mature. The measured VR in this well show an increase with depth and indicate oil window maturity source rocks at shallower depths and gas window maturity at the base of the well. Given the maturity levels, the poor to fair generative potential remaining (including within the Bowland Shale Formation) could result from depletion due to generation, or poor–fair original source rock quality.

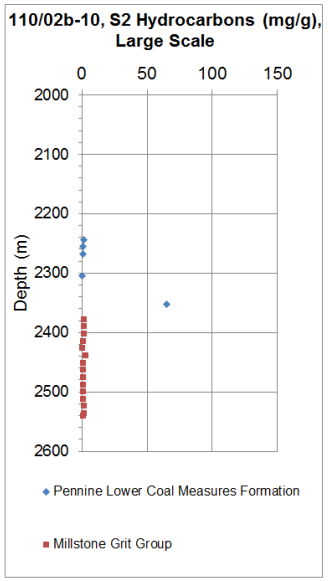
<u>113/27-3 (2896-2977 m):</u> Figures 19, 20

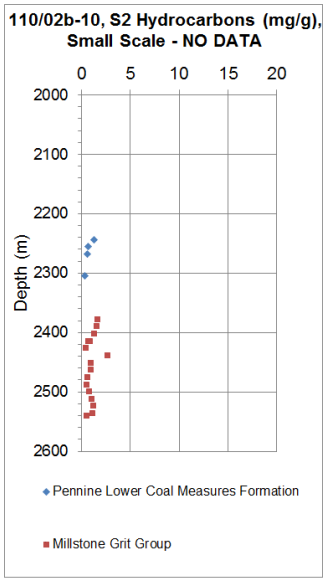
This well contains the Millstone Grit Group, the source rocks TOC's are 0.19-1.37%, and the HI's are 14-63 mg/g which suggests gas prone kerogen with limited hydrocarbon generative potential remaining. The measured VR of 1.40-1.62% R_o indicates that the Millstone Grit Group is dry gas mature.

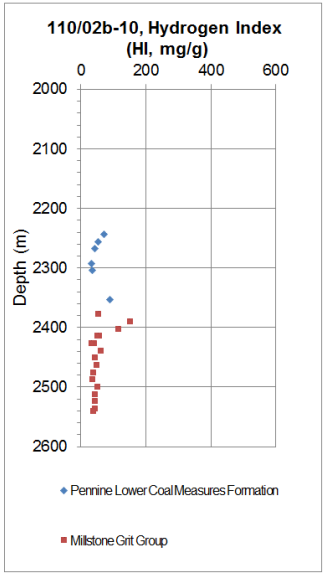
2.1 DATA PLOTS

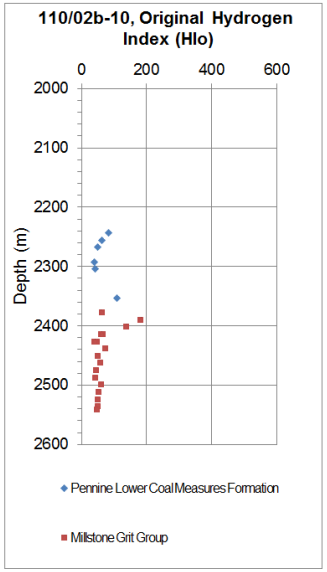


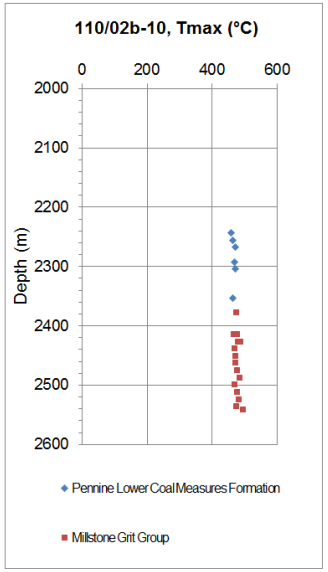


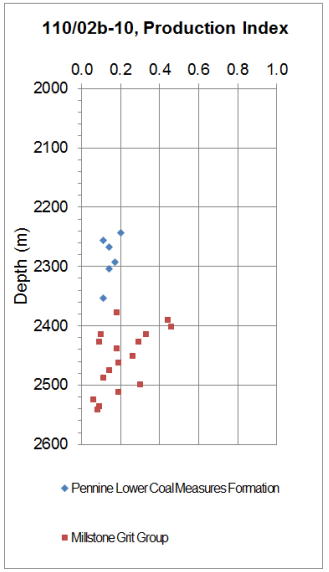












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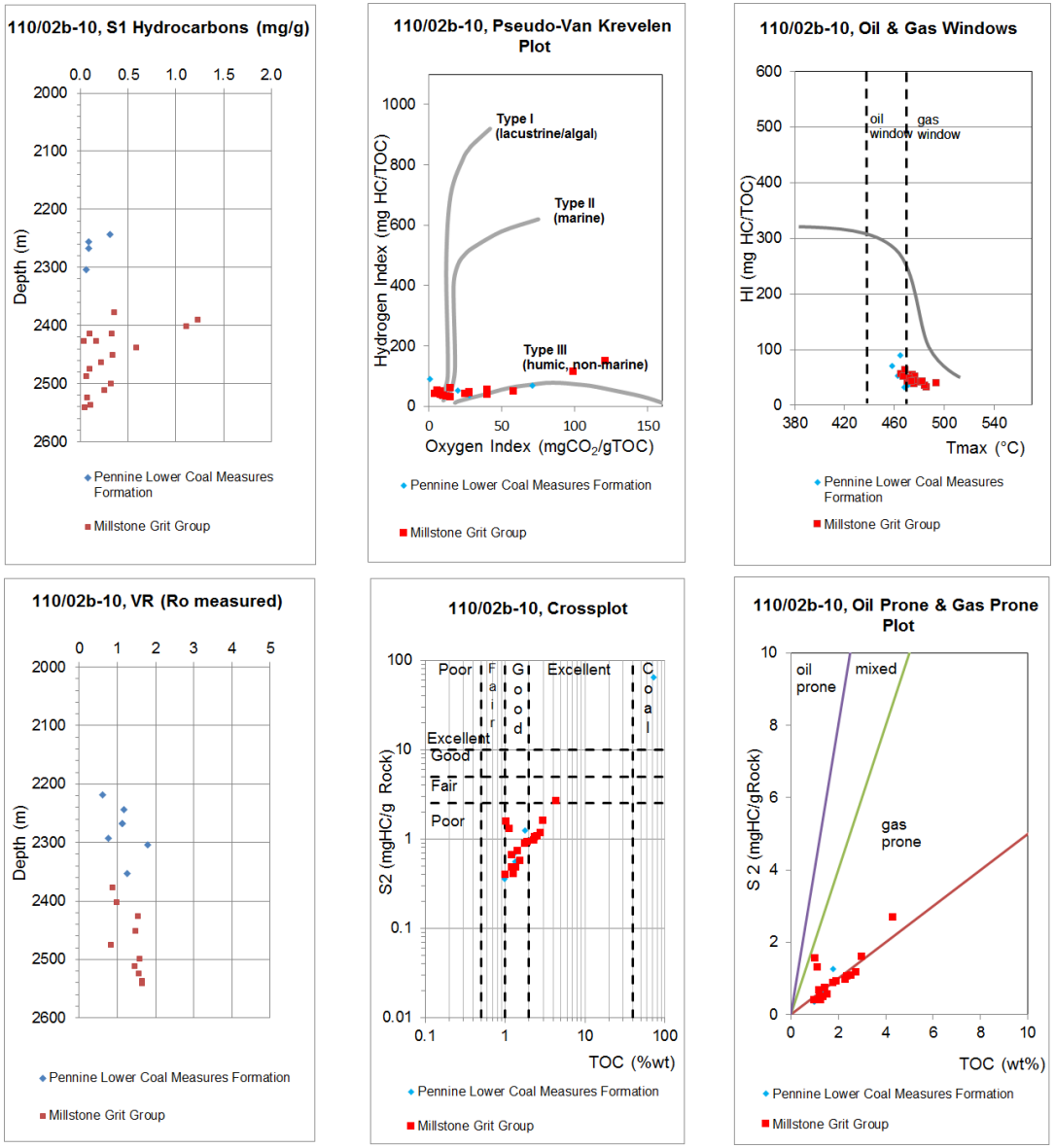

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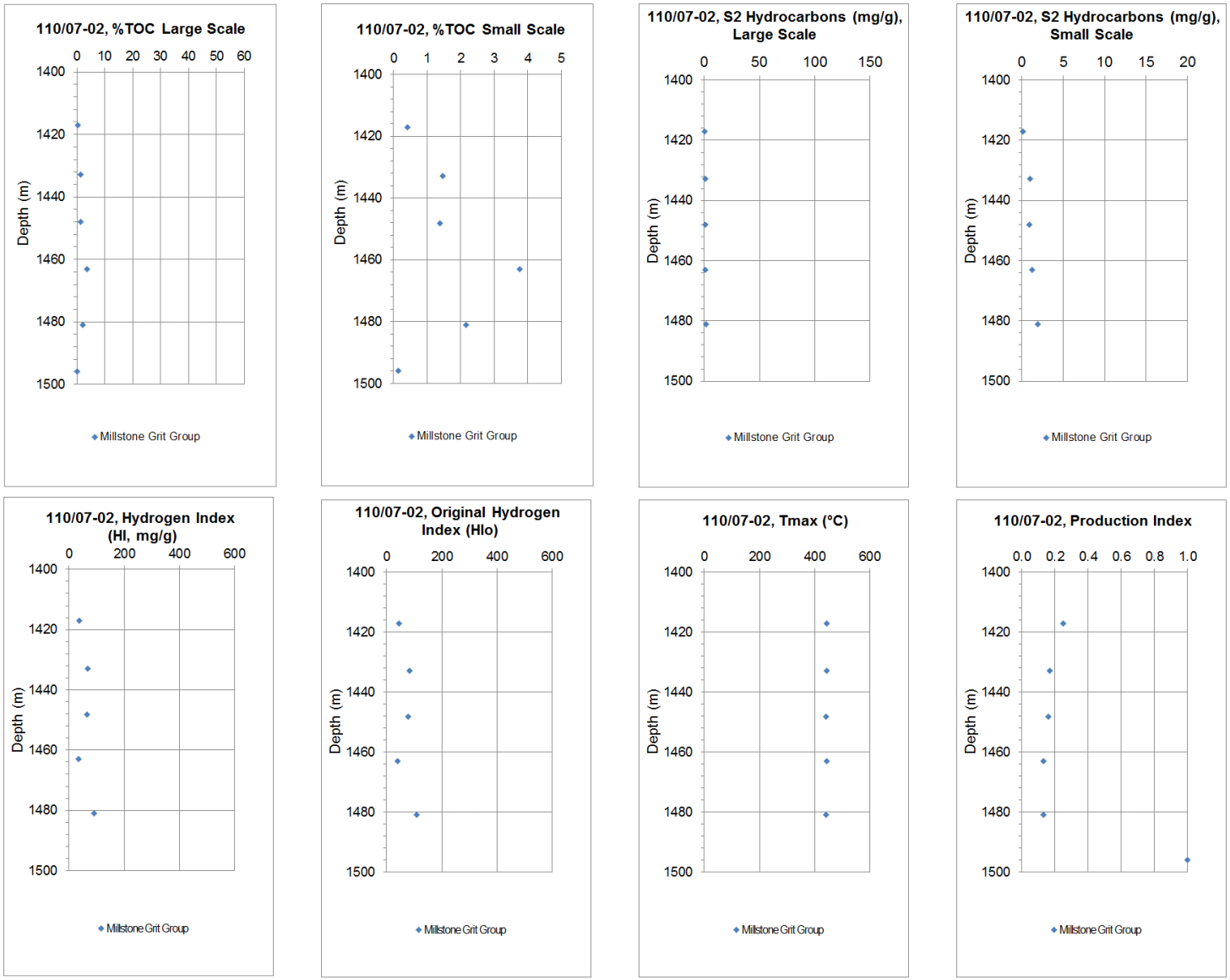

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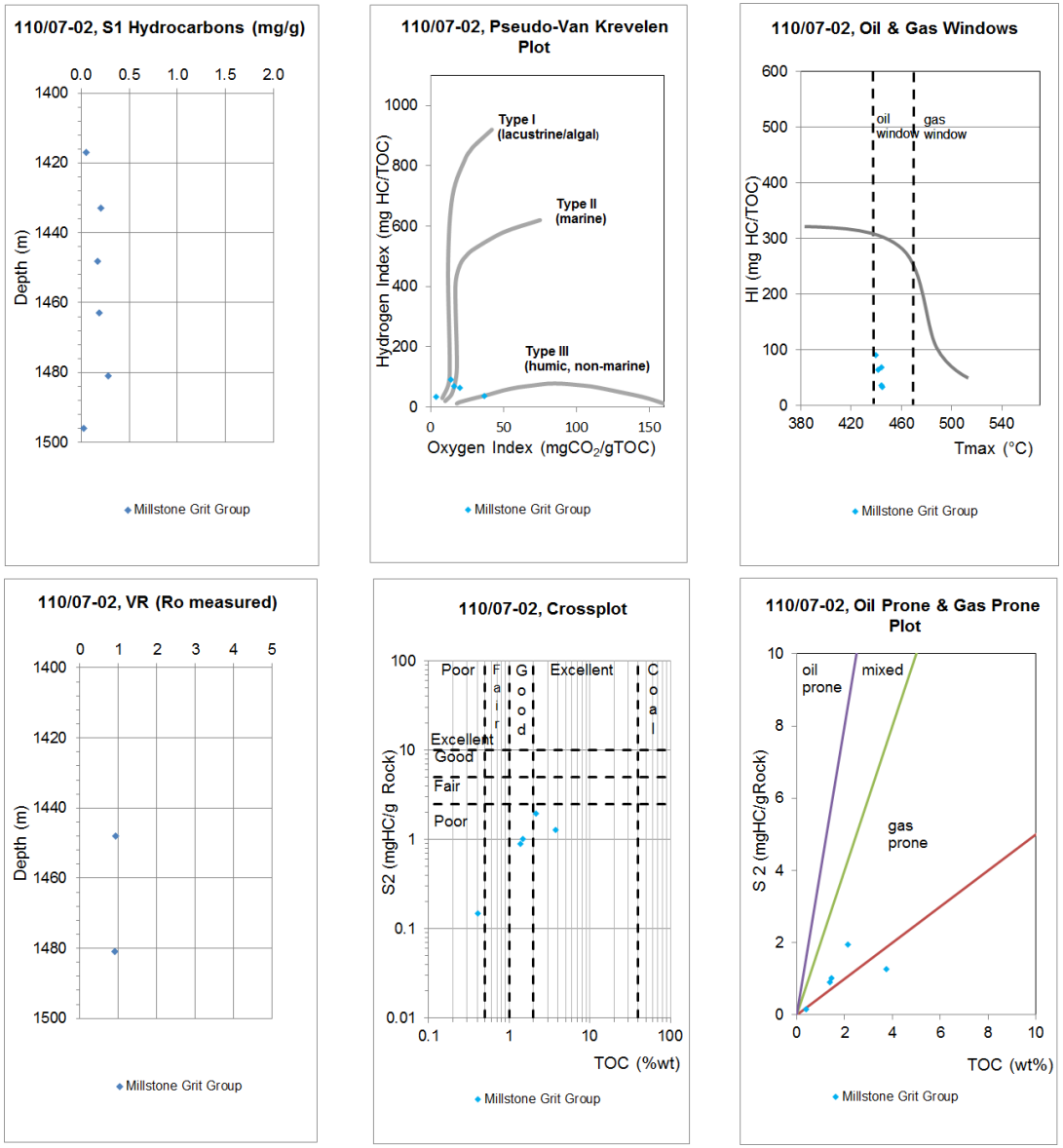

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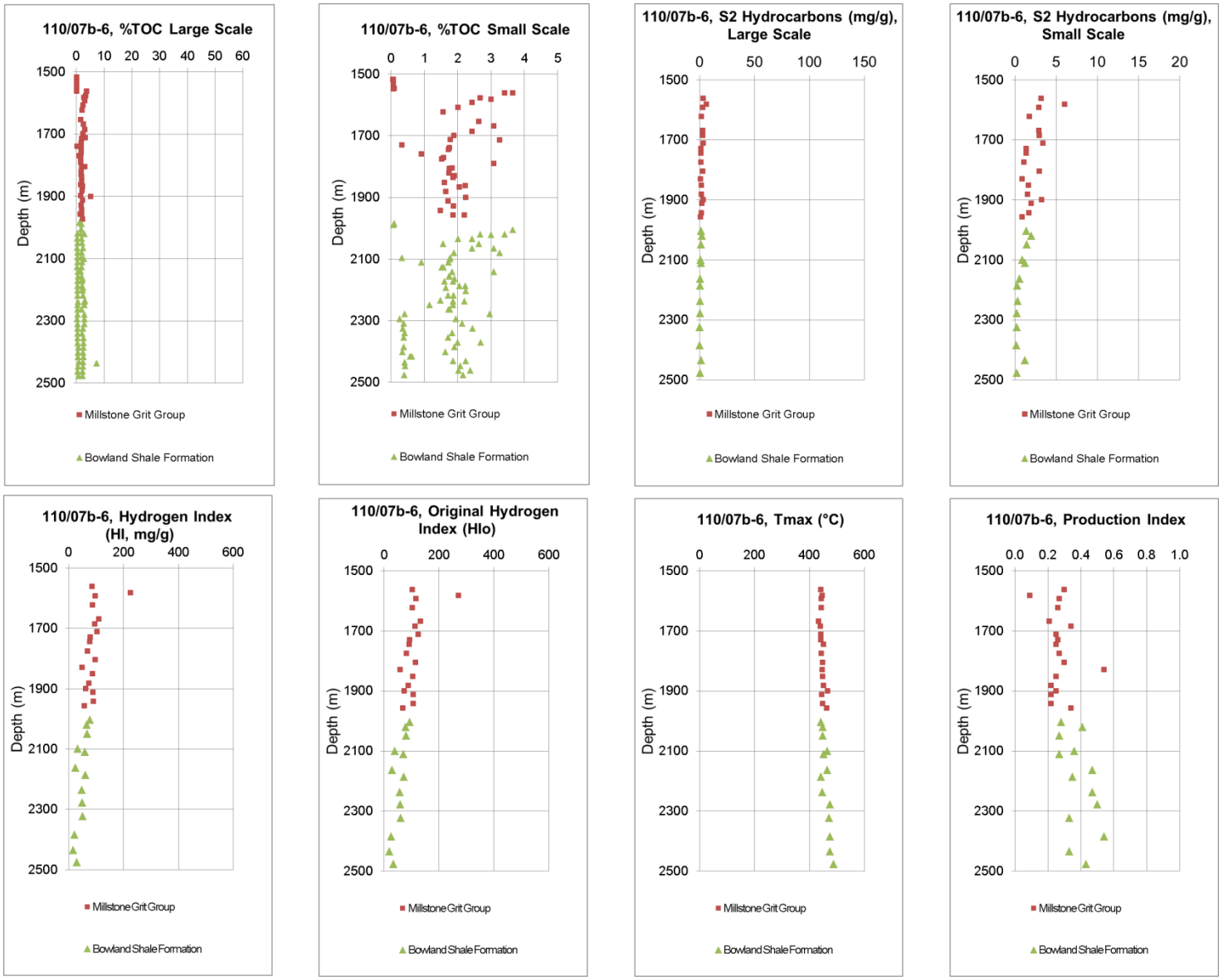

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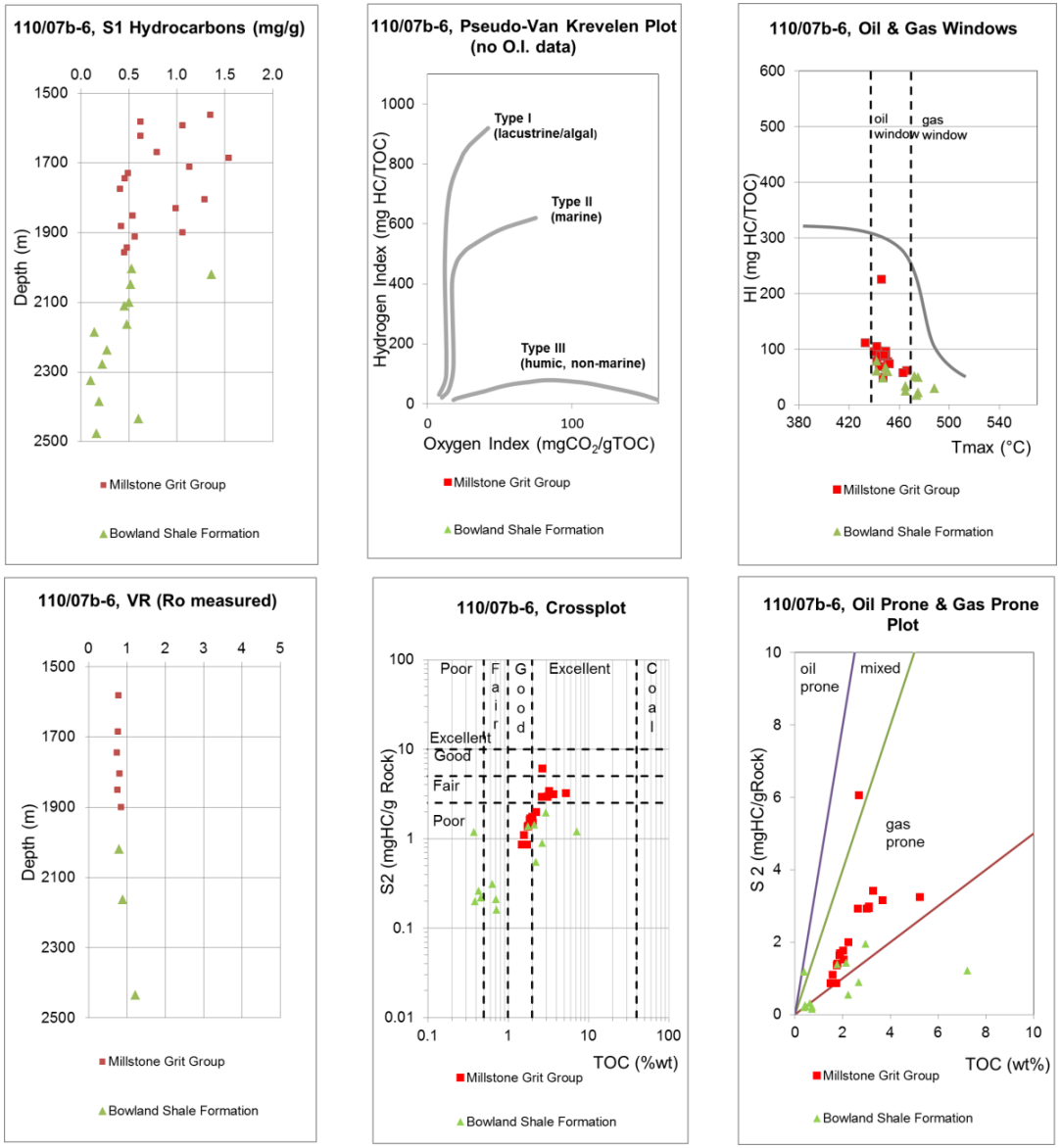

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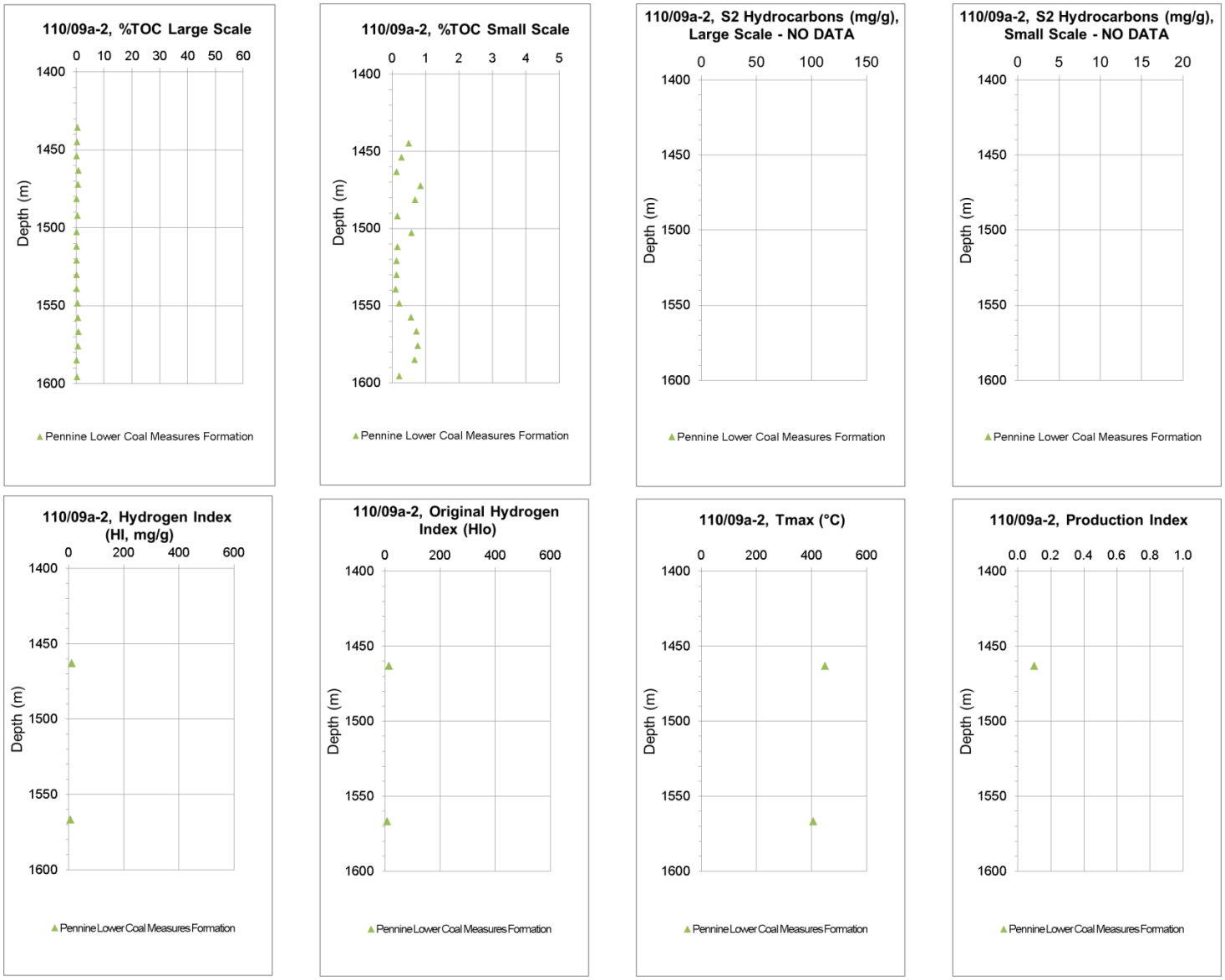

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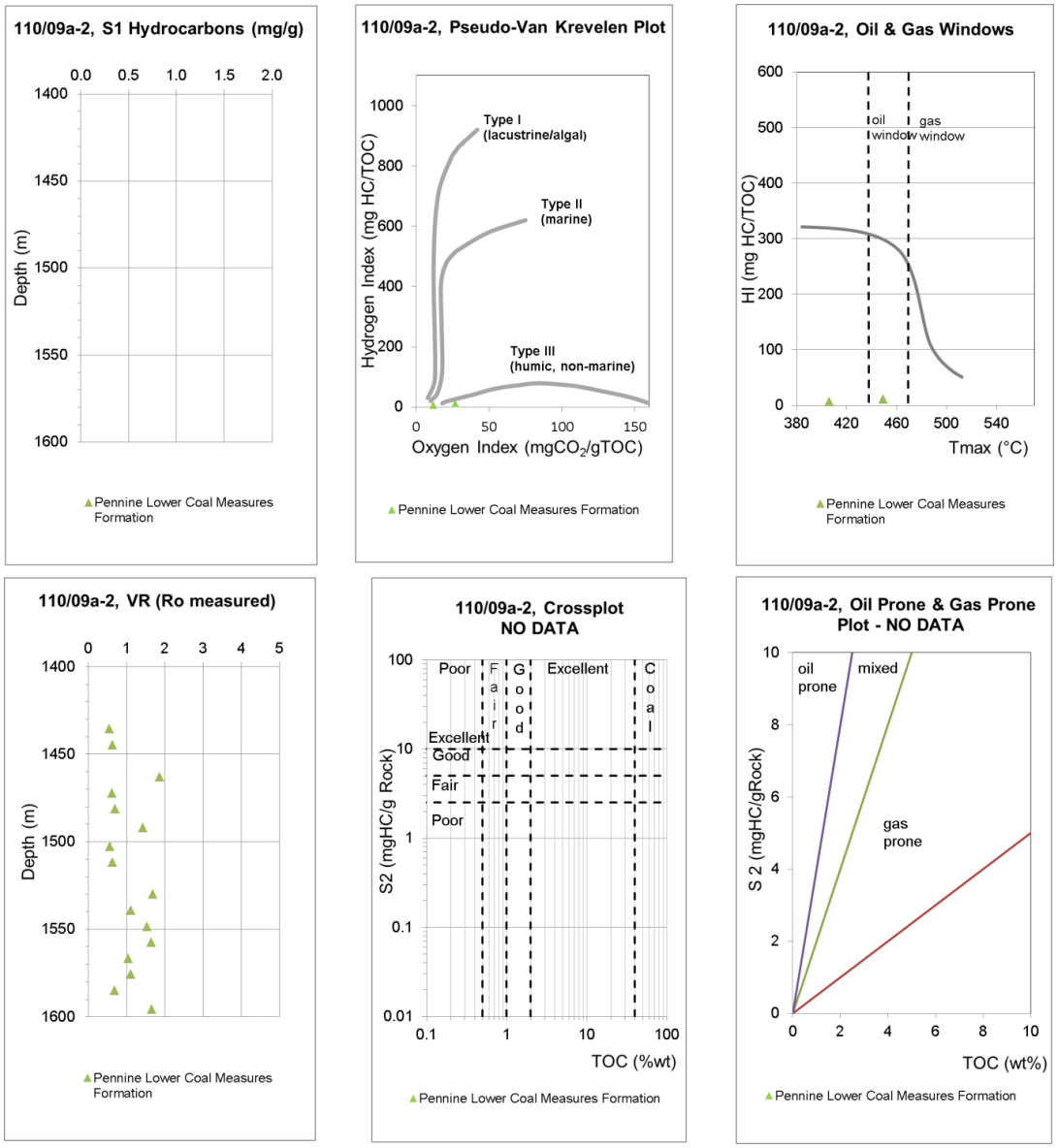

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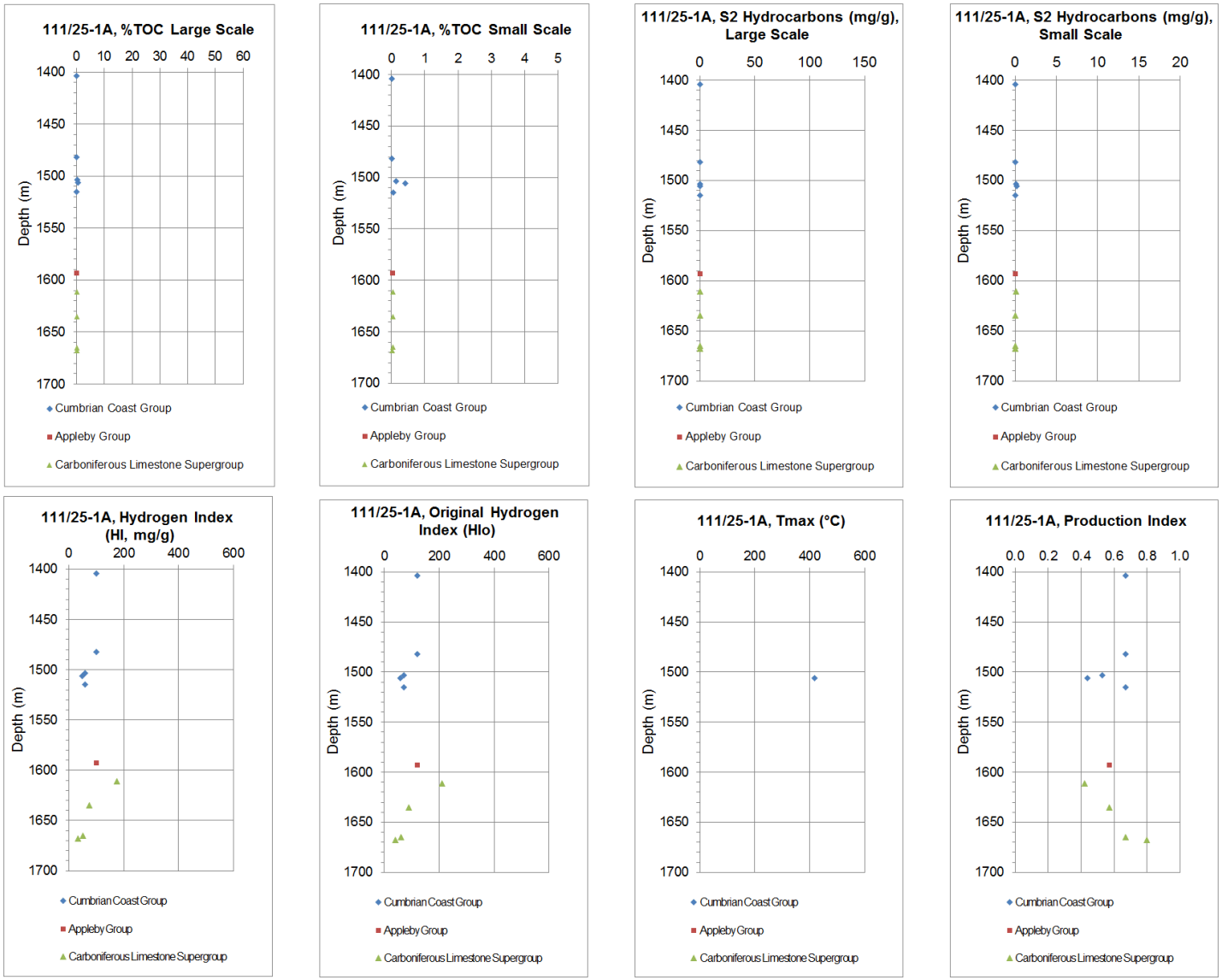
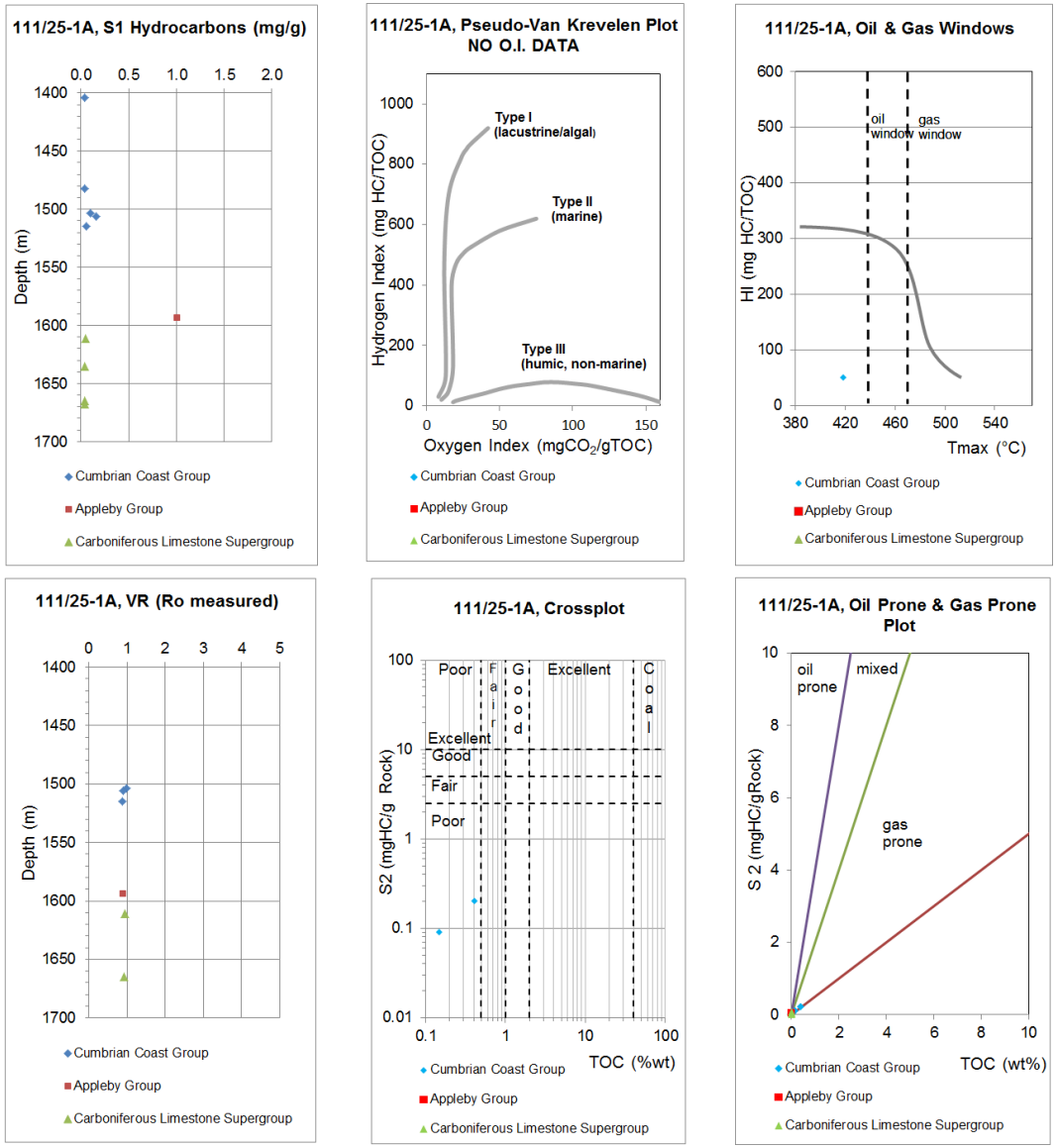


Figure 11 Well 111/25-1A (a)



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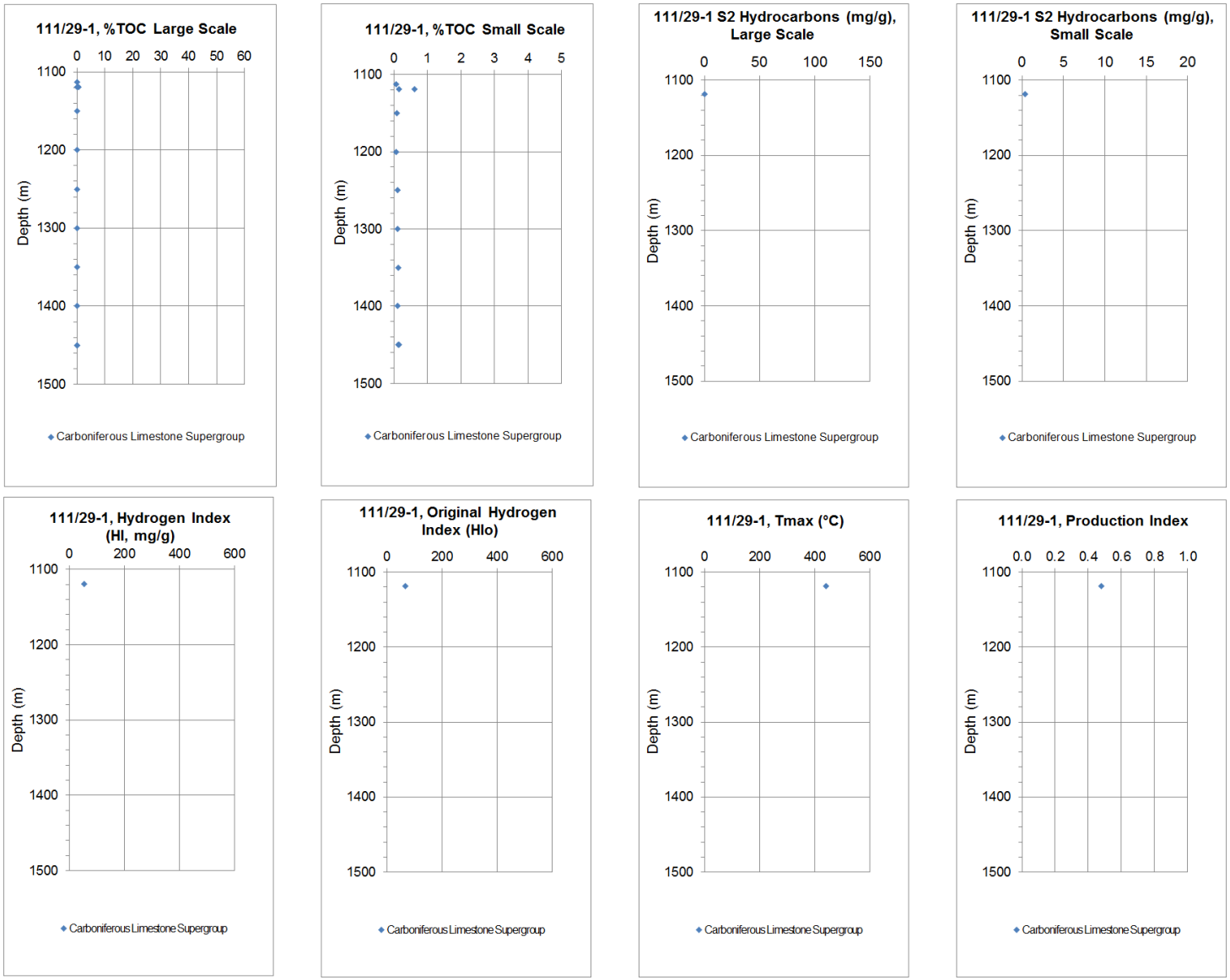

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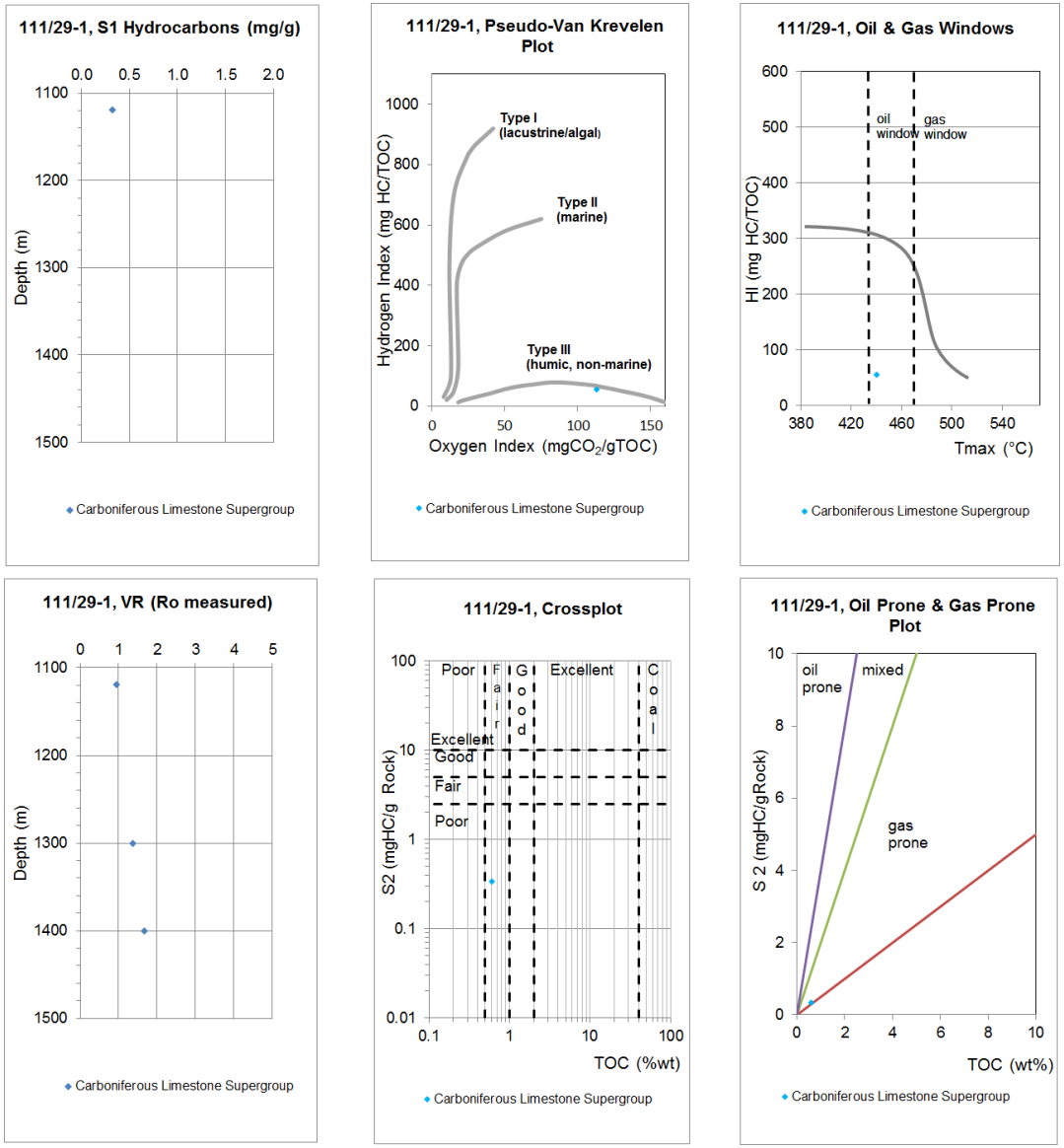

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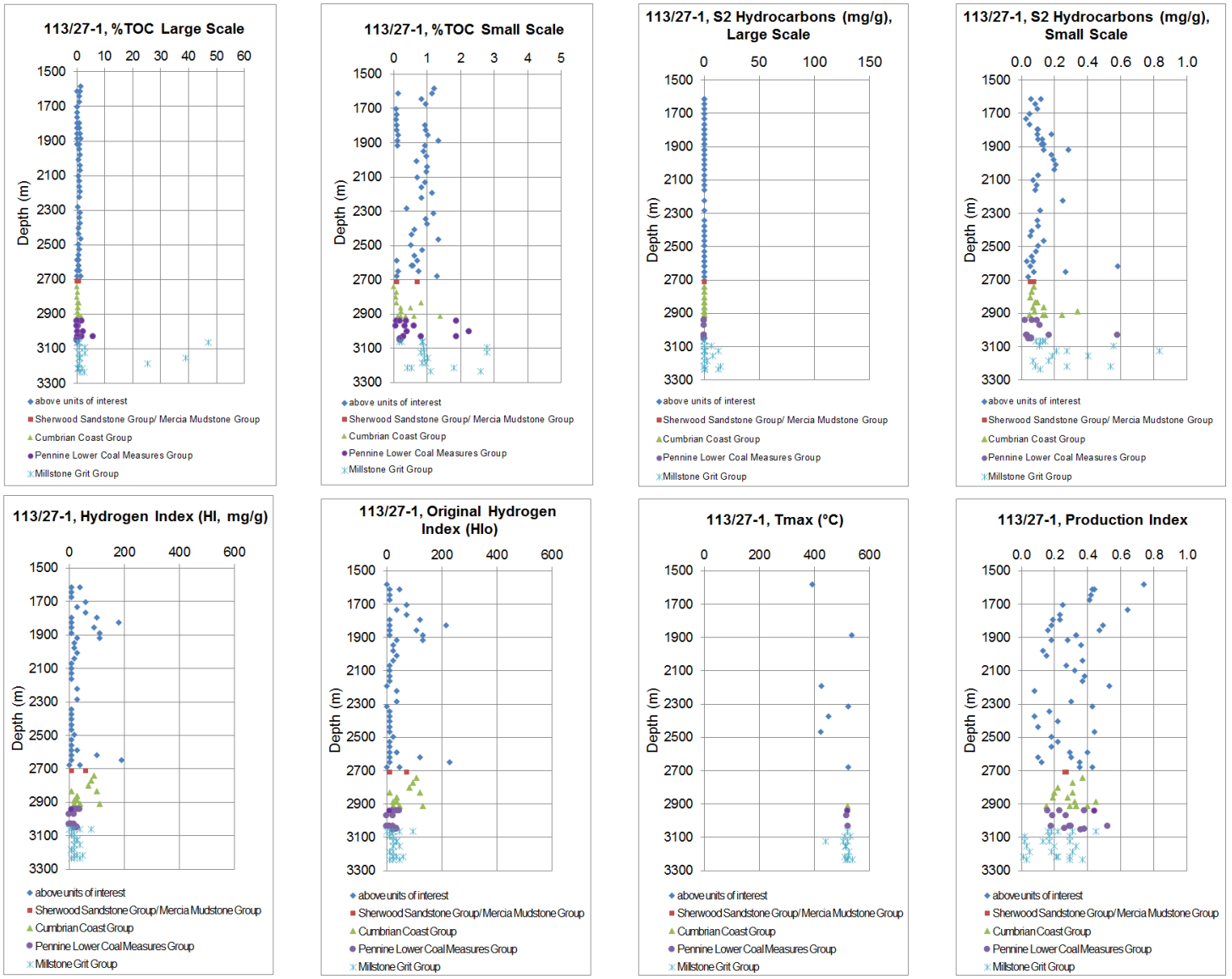

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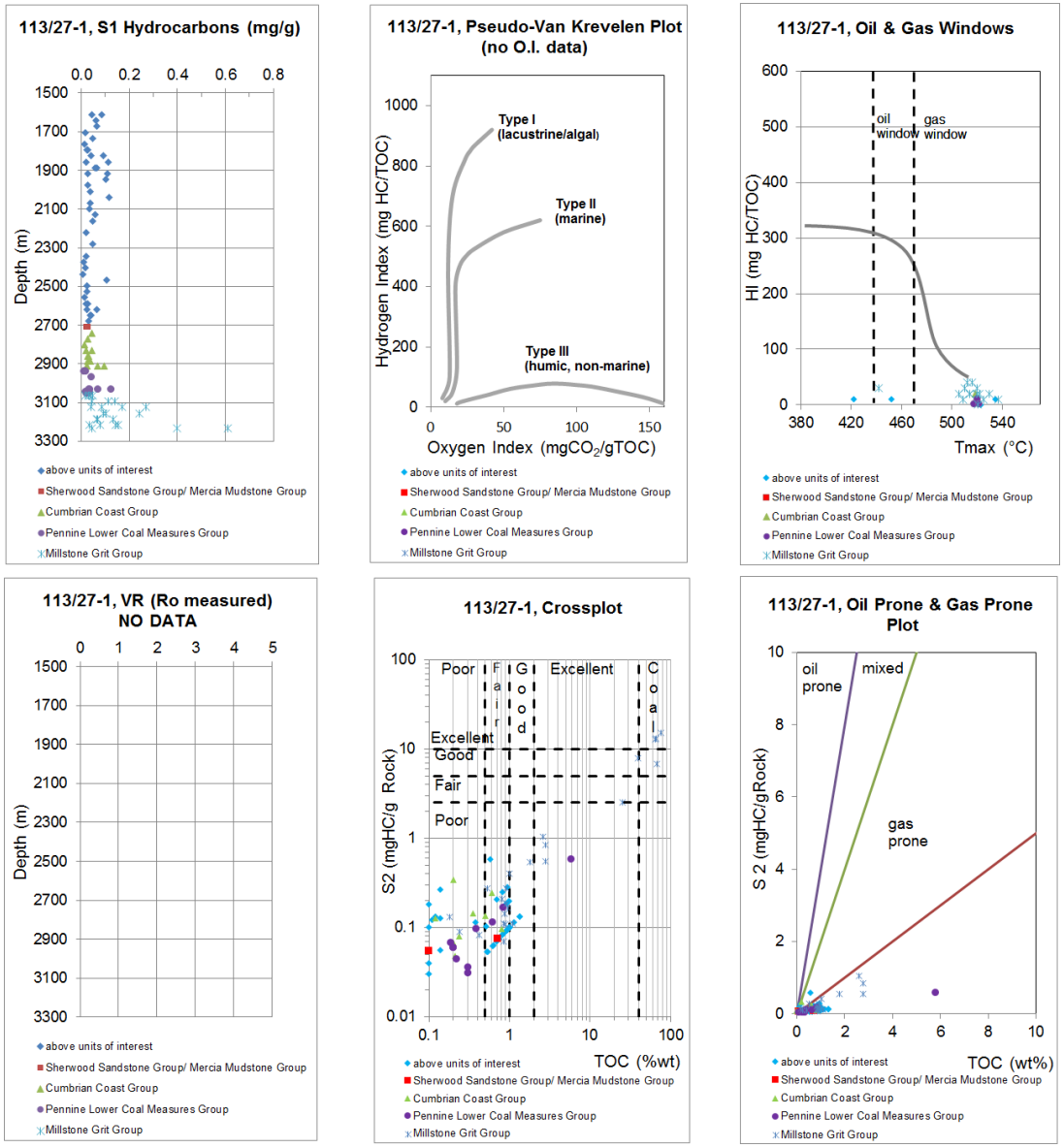

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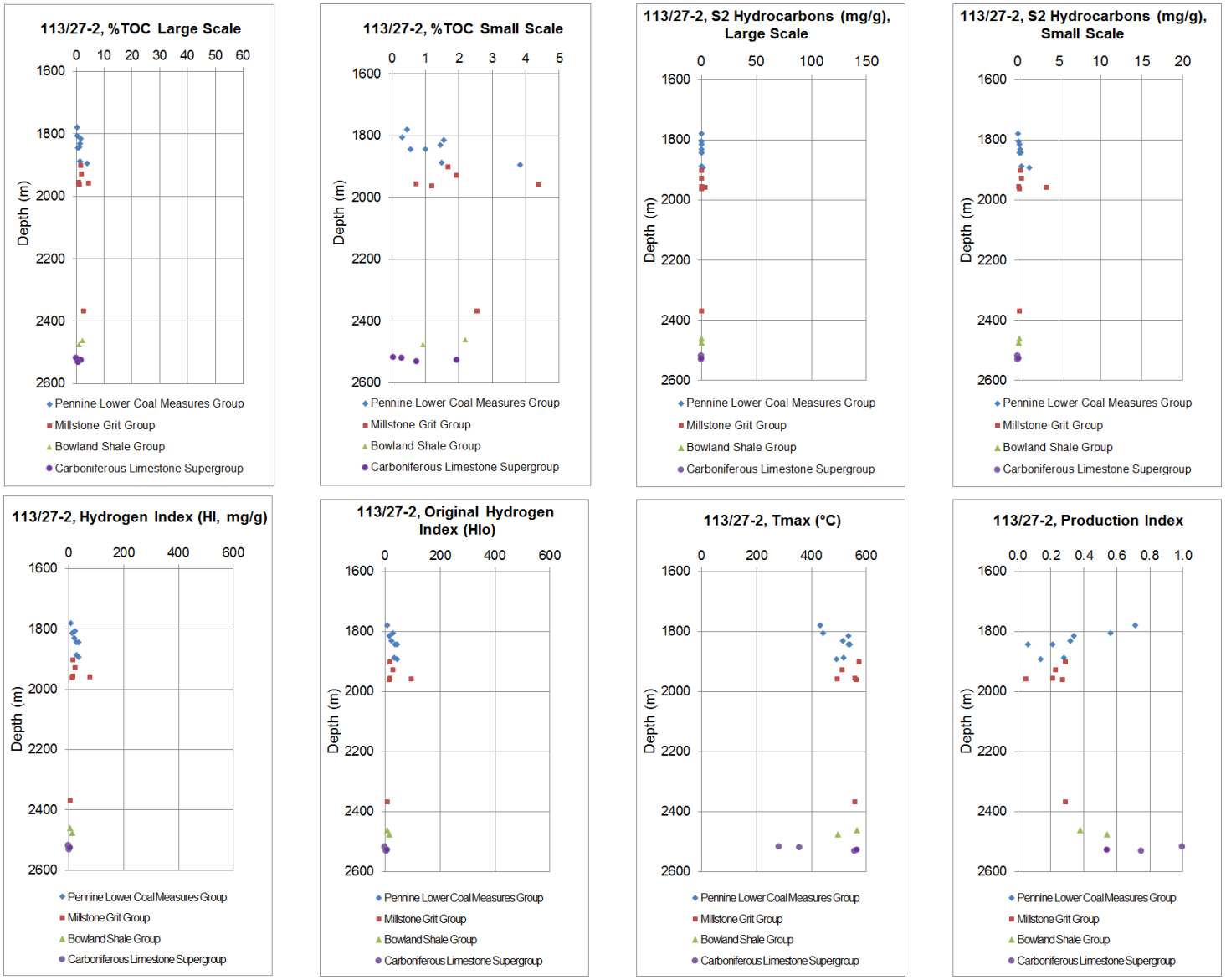

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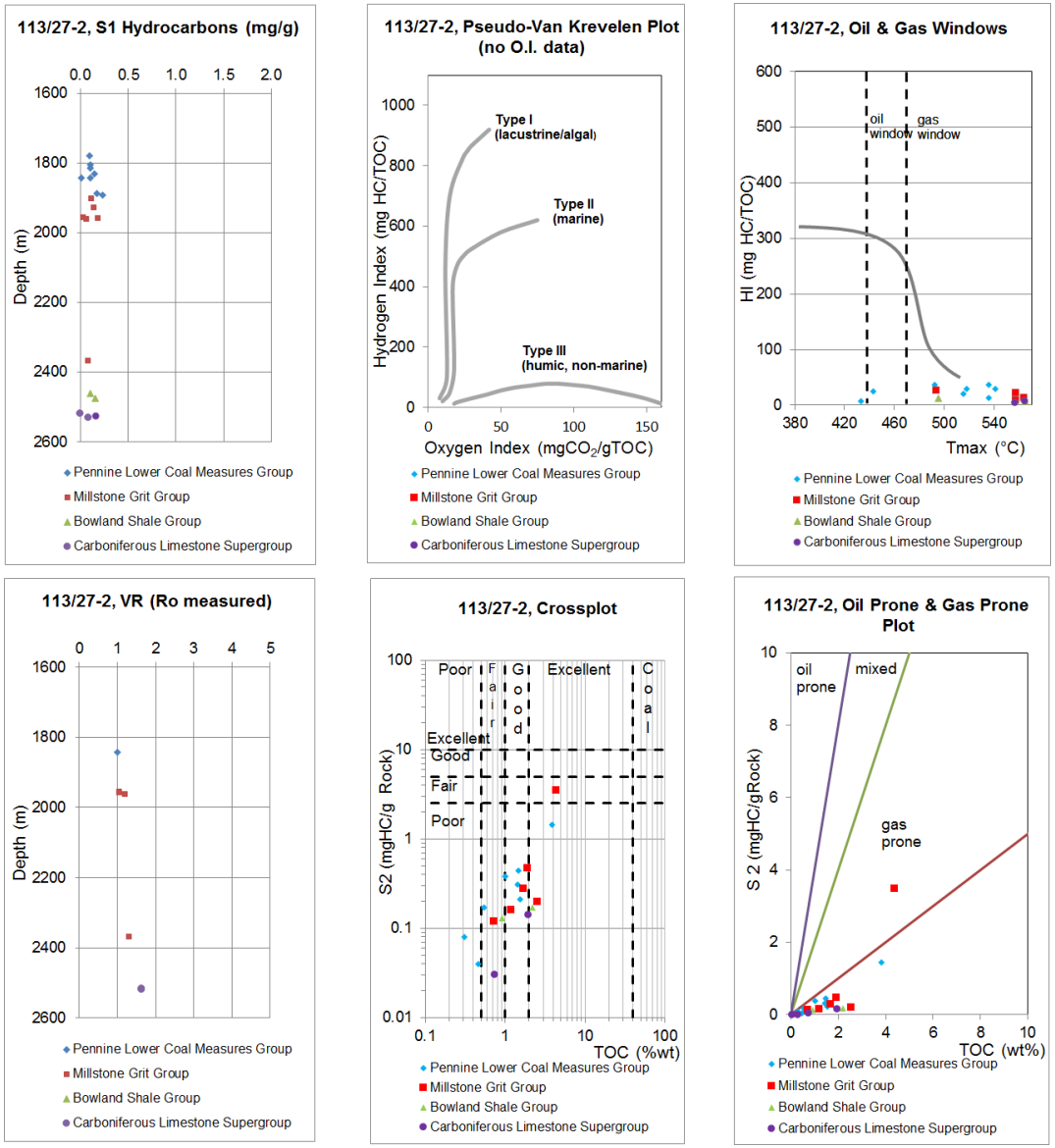

Figure 18 Well 113/27-2 (b)

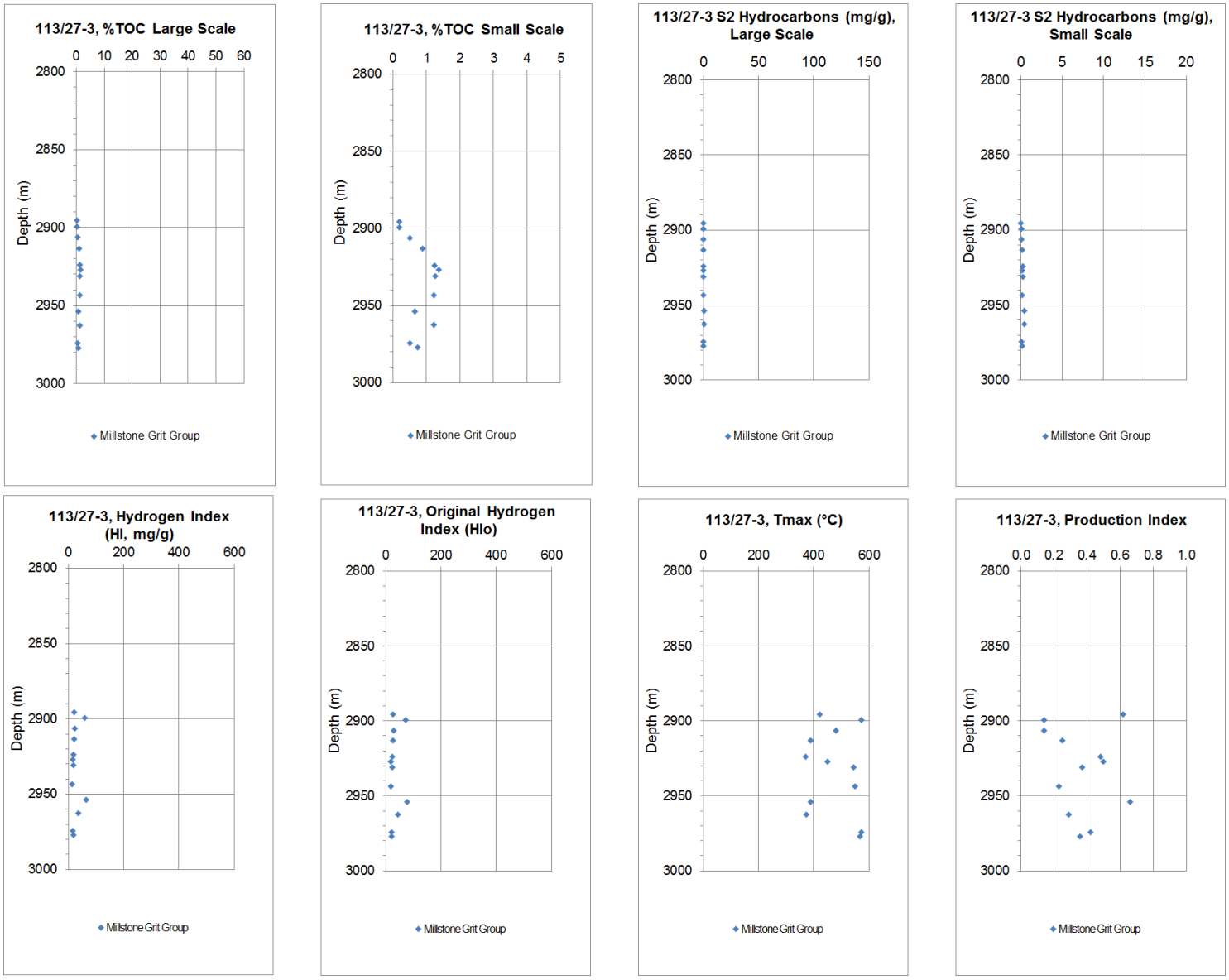

Figure 19 Well 113/27-3 (a)

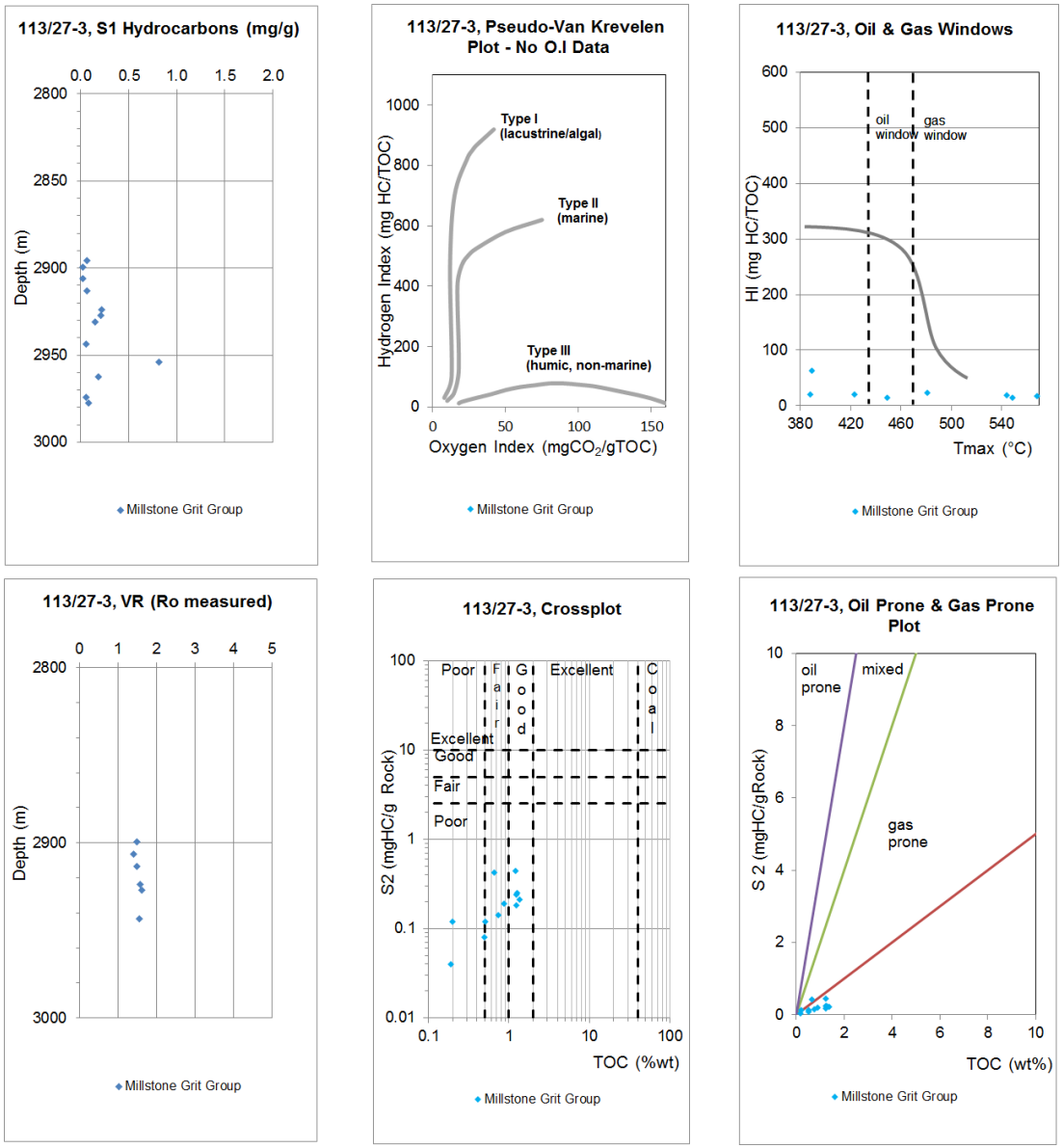

Figure 20 Well 113/27-3 (b)

3 Conclusions

The potential Carboniferous source rocks analysed in wells 110/02b-10, 110/07b-6, 110/09a-2, 111/29-1 and 113/27-2 attained oil to gas window maturity levels over the well penetration interval (Figure 1).

Potential Carboniferous source rocks in wells 111/25-1A and 110/07-2 are at oil window maturity levels. In wells 113/27-1 and 113/27-3 gas window maturity levels are attained over the Carboniferous interval.

A variety of stratigraphical units have been sampled, mostly from units other than the likely main source rock interval (Bowland Shale Formation and equivalents) which is believed to be the source rock for the East Irish Sea oil and gas fields (e.g. Armstrong et al., 1997; Quirk et al., 1999). Based on the limited dataset available, the Pennine Lower Coal Measures, Millstone Grit Group and Bowland Shale Formation are mainly gas-prone strata of poor-fair generative potential remaining and mature to the gas window in the well intervals sampled in Quadrants 110 and 113 (Figure 1). Given the maturity levels, source rock potential in these wells is likely to have been depleted by hydrocarbon generation, or the original quality of these source rocks was poor-fair. This could be further examined by detailed review of existing literature (kerogen types, biomarkers) and by new, detailed sampling and analysis.

Within the limited well sample set examined, high TOC coal intervals have the best generative potential remaining. The Cumbrian Coastal Group, Appleby Group and Carboniferous Limestone Supergroup sampled in two wells in Quadrant 111 are at oil to gas window maturity levels, but have low TOC and low residual hydrocarbon generative potential.

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