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Organic Geochemistry of Palaeozoic Source Rocks, Orcadian Study Area, North Sea, UK

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Organic Geochemistry of Palaeozoic Source Rocks, Orcadian Study Area, North Sea, UK

C.H. Vane, C. Uguna, A.W. Kim, A.A. Monaghan

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Foreword and Acknowledgements

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Contents

Foreword and Acknowledgements .... **i**

Contents .... **i**

Summary .... **iii**

1 Methodology **1**

2 Wells Analysed **3**

2.1 Data plots 6

3 Conclusions **34**

References **34**

FIGURES

Figure 1 Summary map of well locations and geochemical results for Devonian and Carboniferous strata in the Orcadian study area. The pink polygon is the Orcadian study area........ iii

Figure 2 Simplified overview of Devonian-Carboniferous stratigraphy and petroleum system elements in Quadrants 6-21 iv

Figure 3 Well 08/04-1 (a)........ 7

Figure 4 Well 08/04-1 (b)........ 8

Figure 5 Well 12/16-1 (a)........ 9

Figure 6 Well 12/16-1 (b)........ 10

Figure 7 Well 12/27-1 (a)........ 11

Figure 8 Well 12/27-1 (b)........ 12

Figure 9 Well 12/30-1 (a)........ 13

Figure 10 Well 12/30-1 (b).......... 14
Figure 11 Well 13/19-1 (a).......... 15
Figure 12 Well 13/19-1 (b).......... 16
Figure 13 Well 13/22-1 (a).......... 17
Figure 14 Well 13/22-1 (b).......... 18
Figure 15 Well 14/06-1 (a).......... 19
Figure 16 Well 14/06-1 (b).......... 20
Figure 17 Well 14/19-1 (a).......... 21
Figure 18 Figures 14/19-1 (b) 22
Figure 19 Well 14/24a-3 (a).......... 23
Figure 20 Well 14/24a-3 (b).......... 24
Figure 21 Well 14/30-1 (a) (Note there is no (b) graph as there is no data available).......... 25
Figure 22 Well 15/19-2 (a).......... 26
Figure 23 Well 15/19-2 (b).......... 27
Figure 24 Well 20/09-4A (a).......... 28
Figure 25 Well 20/09-4A (b).......... 29
Figure 26 Well 20/10a-3 (a).......... 30
Figure 27 Well 20/10a-3 (b).......... 31
Figure 28 Well 20/15-2 (a).......... 32
Figure 29 Well 20/15-2 (b).......... 33

Summary

A systematic screening of TOC, Rock-Eval and vitrinite reflectance data extracted from released legacy well reports was undertaken with the aim of providing a data based, regional overview of source rock intervals and their levels of maturity.

Released, publicly available data is sparse; much of the data for the Devonian of the Orcadian Basin is contained with confidential commercial reports (see Greenhalgh (2016) for a literature review of available information with regards to source rocks and migrated Palaeozoic oils in this area).

The regional screening approach used and technical parameters are described in Vane et al. (2015). The detailed stratigraphy is presented in Whitbread and Kearsey (2016; see Figure 2) and this regional screening is incorporated into the basin modelling work of Vincent (2016) and petroleum systems synthesis of Monaghan et al. (2016).

The fourteen wells evaluated for this report are:

8/04-1, 12/16-1, 12/27-11, 12/30-1, 13/19-1, 13/22-1, 14/06-1, 14/19-1, 14/24a-3, 14/30-1, 15/19-2, 20/09-4A, 20/10a-3 and 20/15-2 (Figure 1).

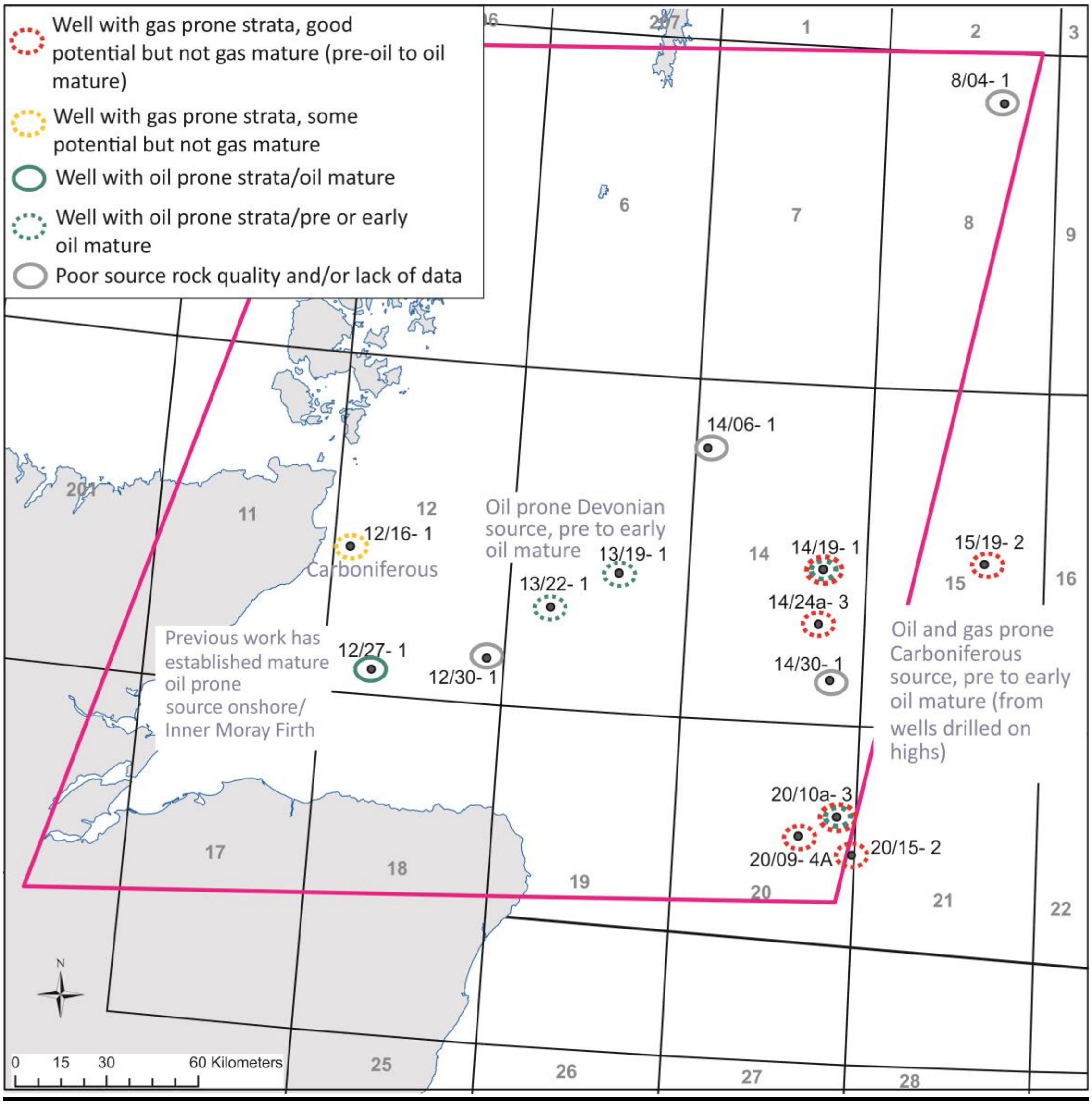

Figure 1 Summary map of well locations with geochemical data for Devonian and Carboniferous strata in the Orcadian study area. The pink polygon is the Orcadian study area.

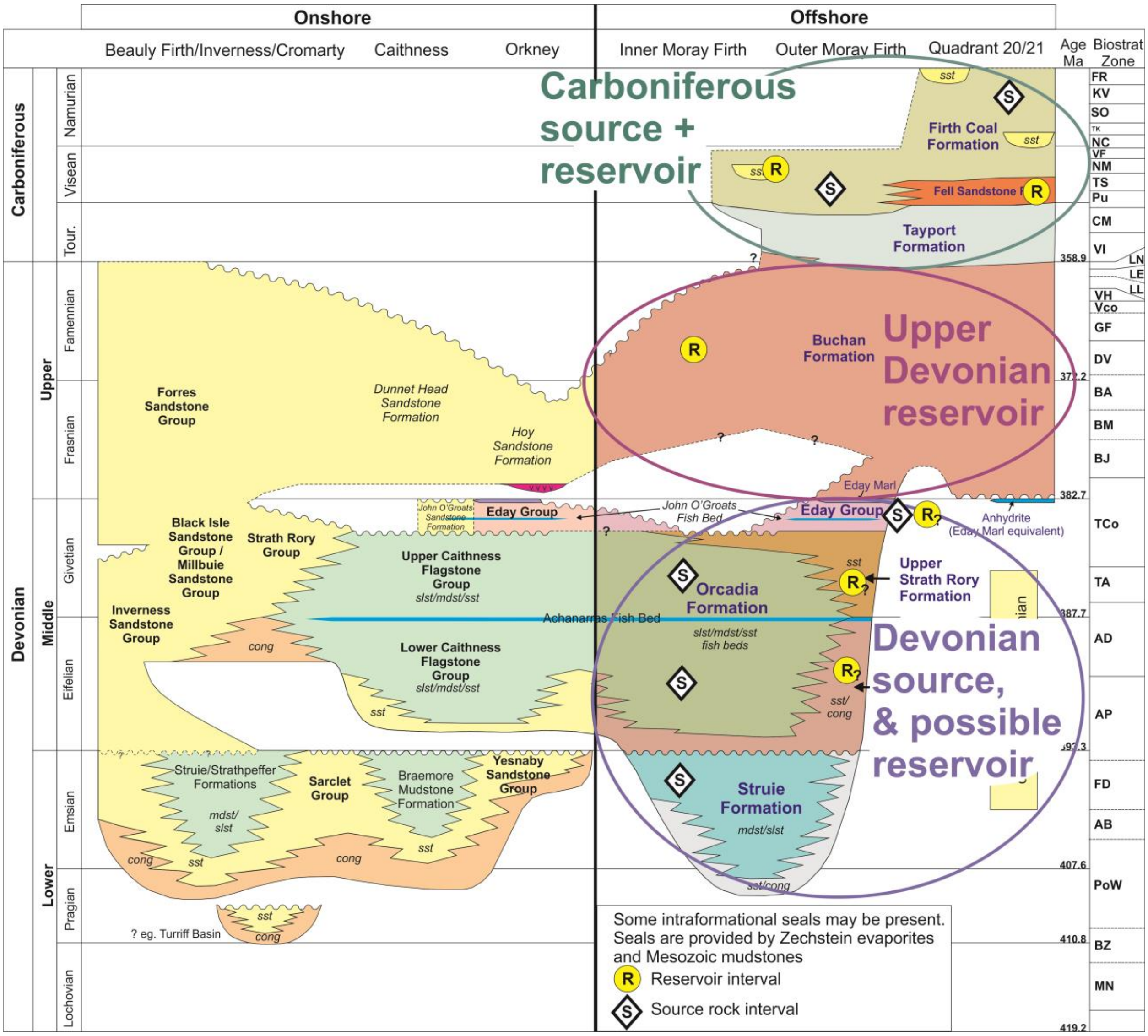

Figure 2 Simplified overview of Devonian-Carboniferous stratigraphy and petroleum system elements in Quadrants 6-21.

The Firth Coal Formation shows good gas-prone generative potential in wells in Quadrants 14, 15 and 20, though maturity levels are variably pre-oil to oil window (Figure 1). The presence of thin oil-shales/oil-prone layers in well 20/10a- 3 merits further high resolution sample analysis for certain well sections.

Limited available sample data from the Buchan Formation indicate this is a non-source rock interval (in 8/04- 1, 12/30- 1, 14/06- 1). The Devonian Struie and Orcadia formations show fair-good oil-prone generative potential in the Inner Moray Firth (12/27- 1, 13/19- 1, 13/22- 1; Figure 1). Maturity levels are variable, from pre-oil mature to gas mature.

The conclusions from this regional screening of Rock-Eval data are consistent with previous studies of the Devonian succession (see Greenhalgh, 2016 for literature review).

1 Methodology

Over 450 TOC, Rock-Eval and vitrinite reflectance data analyses from core and cuttings material of the Devonian and Carboniferous interval were compiled from released, publicly available legacy well reports and papers. A regional overview of the source rock intervals was undertaken by systematic examination of the data on a set of graphs plotted for each well, using the Project stratigraphic interpretation. Further details on the geochemical parameters and the systematic screening approach for Rock-Eval and vitrinite reflectance data is described in Vane et al. (2015).

Released data is sparse; much data for the Devonian of the Orcadian Basin is contained with confidential commercial reports (see Greenhalgh (2016) for a literature review of available information with regards to source rocks and migrated Palaeozoic oils in this area). The stratigraphy is of the area is given in Whitbread and Kearsey (2016) and this regional source rock screening is incorporated into the basin modelling work of Vincent (2016) and petroleum systems synthesis of Monaghan et al. (2016).

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 Ro%) 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.

The spore colouration index (SCI) is an estimate of source rock thermal maturity based upon microscopy. The data discussed in this report are based on a scale of 1-10 after Cooper (1990 and references therein).

The oil saturation index [(S1 x 100)/TOC] is a measure of the free oil from Rock-Eval-measured S1 in relation to TOC, that has been applied to oil shale resources (Jarvie 2012). When the oil saturation index exceeds the sorption potential of oil in kerogen, potentially producible oil is likely to be present in the pore space. Experimentation suggests that the sorption potential for oil in kerogen is approximately 100 mg oil/g kerogen, so oil saturation index values above 100 are taken to indicate the presence of potentially producible oil (Jarvie & Baker 1984, Sandvik et al. 1992, Jarvie 2012).

Parameter	Inference & Comment
HI_o of < 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 (% Ro)	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
Spore colouration Index (SCI)	Criteria for thermal maturity after Cooper (1990) • Immature 1-3.5 • Early mature oil 3.5-5.0 • Mature oil 5.0-7.0 • Main gas 7.0-9.5 • Late gas 9.5-10

Table 1 Summary of screening criteria used as 'rules of thumb'. Note that in detail, cut-off values will vary dependent on kerogen type. *HI values below 300 can generate significant quantities of oil, see Vane et al. (2015) for discussion.

2 Wells Analysed

Depths listed below are measured depths, in metres. Project stratigraphic interpretations are used.

<u>8/04-1 (1042.4-1472.2 m)</u>: Figures 3, 4

This well contains the Buchan Formation.

Rock-Eval data was not available and a single TOC value of 0.67 wt% was available at 1042 m. The thermal maturity of 8/04- 1 is poorly constrained as the well report suggests that the picked cuttings are contaminated with Palaeocene and Cretaceous cavings which explains the non-systematic changes in VR from 1042 m 0.32% Ro to 1262 m 1.33% Ro. The original analytical report judged that true thermal maturity is measured on the samples at 1344 m (1.86% Ro), to 1472 m with Ro of 1.84%, which is post mature for oil and mature for gas.

<u>12/16-1 (2385.1-3682.8 m):</u> Figures 5, 6

The well section comprises of the Firth Coal Formation, Tayport Formation and the interval tentatively assigned to the Upper Devonian interval.

The Firth Coal Formation (2400.3-2811.8 m) has low TOC values (<1.0%), with the exception of 2669.4 m and 2766.1 m with TOC's of 38.2% and 2.4% respectively. The available HI values (n=6) for the Firth Coal Formation range between 77-195 mg/g TOC, which together with the corresponding S2 values of <5 suggest poor to fair generation potential remaining. Measured VR data was not available for the Firth Coal Formation, but the T_{max} values at 2669.4 m (450 °C) and 2766.1 m (453 °C) suggest early-oil window maturity for the coal sample. This interpretation is confirmed by the spore colouration index of 4.5 (early oil window).

The Tayport Formation (2827-3116.6 m) TOC, Rock-Eval S2 and HI (n=2) all suggest poor – fair hydrocarbon generation potential remaining in the source rock. The measured VR's of 0.98% Ro at 2870.9 m and 0.97% Ro and 2979.4 m as well as the corresponding spore colouration index value of 5 indicates that the source rocks of the Tayport Formation are at oil window maturity.

No TOC or Rock-Eval data are available for the Upper Devonian (3131.8-3682.8 m); however, the measured VR of 1.21% Ro to 1.96% Ro (between 3284.2 and 3682.8 m) suggests early gas to main gas generation maturity window.

Overall, the source rock in 12/16- 1 well is not mature enough to generate either oil or gas in the Firth Coal Formation, while the Tayport and Upper Devonian source rocks are of sufficient maturity to generate oil and gas respectively, but data is lacking on source rock quality.

<u>12/27-1 (1679.4-3322.6 m)</u>: Figures 7, 8

This well contains the Upper Permian (Zechstein) (1679.4-1685.5 m) and Struie Formation (2347-3316.2 m).

The Upper Permian TOC and HI are 0.94-1.09% and 64-85 mg/g respectively, while the measured VR range from 0.44-0.73% Ro. The HI suggest the source rock has limited generation potential remaining and the measured VR indicates pre-oil to early oil window maturity.

The TOC for the Struie Formation (2347.0-3316.2 m) is between <1.0-2.39%, S2 is in the range of 1.10-7.30 mg/g, and HI varies between 110-452 mg/g. Combined, the high S2 and HI displayed by the source rock in the Struie Formation indicates that it is mainly oil prone and could generate a good amount of petroleum. The measured VR for the Struie Formation indicates early oil to oil window maturity (0.5-1.02% Ro) between 2369.8-2987.0 m, and oil to gas window maturity (0.82- 1.65% Ro) between 3027.8-3316.2 m.

The measured VR from this well suggest that between 1679.4-2987.0 m the source rock is mature enough at some intervals to generate oil. At greater depths (3027.8 and 3316.2 m), the Struie Formation has lower HI values (143 and 163 mg/g) which could be due to the source rock being depleted by oil generation (marginally seen in the PI plot), a notion partly confirmed the >1.35% Ro (gas maturity level).

<u>12/30-1 (2249.4-2694.4 m):</u> Figures 9, 10

This well contains the Zechstein and Rotliegend groups, and Buchan, Eday Marl, and Middle Eday Sandstone formations.

The TOC range from <1.0 to 1.63%, the S2 (1.45 to 1.85 mg/g) and HI (98 to 116 mg/g) of the Permian and Buchan Formation strata indicate that the rock has poor gas generative potential. Measured VR was not available; however the T_{max} of 438 to 440°C suggest early oil maturity. A single spore colouration index of 3 at 2349.2 m (Upper Permian (Zechstein) suggests pre-oil window maturity at that level.

<u>13/19-1 (1409.7-2139.4 m)</u>: Figures 11, 12

This well contains the Upper Permian (Zechstein) (1531.6-1569.7 m), Kupferschiefer (1592.6 m), Lower Permian (Rotliegend) (1600.2 m), Buchan (1630.7-1691.6 m), Eday Marl (1714.5-1752.6 m), Middle Eday sandstone (1775.5-1813.6 m), Eday Flagstone (1836.4-1938.5 m), Lower Eday sandstone (1966-1978.2 m), and Orcadia (2026.9-2139.4 m) formations.

The TOC's of this well are generally <1.0% apart from 6 depths across all the formations that have values between 1.11 to 6.09%. The S2 range is between 0.94 to 12.88 mg/g, and the HI ranges from 124 to 525 mg/g. With the exception of one high HI value in the Eday Flagstone (HI of 525 mg/g at 1900.4 m), the Orcadia Formation (HI 313 to 461 mg/g and S2 1.95 to 4,15 mg/g) is the primary source rock in well 13/19- 1 with a fair, oil prone hydrocarbon generative potential. The low T_{max} (362 to 445 °C) and measured VR (0.53% Ro at 1966 m) for the Lower Eday Sandstone Formation, as well as the spore colouration index of 3.5, confirm that the rocks in this well are of pre-oil window maturity.

<u>13/22-1 (1204-1440.2 m):</u> Figures 13, 14

This well contains the Middle Eday Sandstone (1204 m), Eday Flagstone (1234.4-1356.4 m), Lower Eday Sandstone (1386.8 m), and Orcadia (1417.3-1440.2 m) formations. Well reports note oil staining through the section. The TOC for the formations varies between 0.36 and 2.81%, and the HI ranges from 129 and 561 mg/g. The T_{max} and measured VR are 429-435 °C and 0.35-0.71% Ro respectively. The measured VR for the source rocks indicate pre-oil to early oil window maturity. However, spore coloration index values of 5.5-6.0 suggest peak oil maturity. One plausible explanation is VR suppression. Previous work has shown that this occurs in amorphous rich kerogens (Type I and II) due to the retention of volatiles that would normally be expelled, which in turn limits the aromatisation and condensation reactions that drive expected increases in VR values with increasing maturity (Carr, 2000). Marshall (1998) documents suppression of VR values in amorphous organic matter facies lacustrine rocks from 12/27- 1 and suggests it is a phenomenon prevalent in Orcadian Basin lacustrine rocks.

The Eday Flagstone, Lower Eday Sandstone, and Orcadia formations have S2 values which generally exceed 10 mg/g, this indicates good hydrocarbon generative potential. Combined with the HI values of >400 and OI of <50 suggest a Type II oil prone kerogen, however, the single outlier (HI 129 and OI 94 mg/g) also indicates a minor contribution of Type III kerogen in the Lower Eday Sandstone Formation.

One limitation of Rock-Eval is that mixing of Type I with lower amounts of Type III kerogens can yield an apparent Type II. This notion is partly confirmed by the corresponding well report which gave a kerogen composition of 20% inertinite and 80% sapropel with minor vitrinite at lower well depths.

14/06-1 (1476.6-1763.0 m): Figures 15, 16

This well contains mudstone, siltstones and limestones of the Buchan Formation, all with very low TOC (<< 1 %).

VRo and T_{max} maturity parameters were unavailable, however two spore colouration index values of 5 to 6 and 6 to 7 suggest peak oil maturity. The HI of 143-190 mg/g suggests a gas prone rock and the low S2 values <0.40 confirm poor hydrocarbon generative potential.

14/19-1 (2377.4-2871.2 m): Figures 17, 18

This very sparsely analysed well contains the Firth Coal (2377.4-2487.2 m) and Tayport (2871.2 m) formations.

The HI is between 35-98 mg/g with exception of depth 2487.2 m with HI of 497 mg/g indicating an overall gas prone source rock with an oil prone interval. Measured VR data is not available, however T_{max} (425-452 °C) indicates the source rock is pre-oil to oil window maturity.

14/24a-3 (1572.2-1663 m): Figures 19, 20

This well contains two analysed samples from the Firth Coal Formation.

The HI (294 and 274 mg/g) and S2 of 150 indicate that the source rocks have good gas generation potential. The high percentage TOC (50-55%) confirms the presence of coal. The low T_{max} (423 and 429°C) together with the low measured VR's (0.56 and 0.45% Ro) indicate that the source rock is pre-oil to early oil window maturity. A higher maturity is indicated by the spore colouration index of 5 and the thermal alteration index of 2.5, both of which suggests early-oil maturity.

14/30-1 (2734-2925 m): Figure 21

This well is comprised of strata from the Upper Permian (Zechstein) (2734-2825 m) and Firth Coal (sand-rich facies) (2845-2925 m) formations.

The TOC's are <1.0% indicative of a poor source rock interval, and no S2 or HI data are available. Measured VR data is also unavailable. However the T_{max} of 427°C, indicate that the rocks in this well did not attain oil window maturity.

15/19-2 (2258.6-2581.6 m): Figures 22, 23

This well contains the Firth Coal Formation, with numerous coals reaching up around 4m in thickness recorded on the composite log.

The HI (176-246 mg/g) indicates a gas prone source rock with hydrocarbon generation potential remaining. Measured VR was not available but the T_{max} (432-435°C) suggests that the source rocks are at the boundary between pre-oil window and early oil maturity.

<u>20/09-4A (2298.2-2941.3 m):</u> Figures 24, 25

This well contains samples from the Zechstein Group and Firth Coal Formation.

In the Firth Coal Formation, the TOC is between 5.6-39.2%. The HI of 88-215 mg/g indicates a gas prone source rock and the consistently high S2 values (11.87-47.1 mg/g) suggest good gas hydrocarbon generation potential. Measured VR was not available, but the T_{max} of 433-441 °C suggest pre-oil to early oil window maturity, as such the source rocks in this well are not mature enough to generate gas.

<u>20/10a-3 (3558.5-4003.5m)</u>: Figures 26, 27

This well penetrated the Firth Coal Formation.

The TOC varies between 1.9% and 15.0% with a mean of 5.6% over the 445 m depth interval. The HI ranges from 71 to 236 mg/g, indicating a gas prone source rock. The S2 ranges between 1.81 to 16.1 mg/g with a mean of 7.41 (n=19), suggesting good to very good gas hydrocarbon generative potential. The measured VR is between 0.57 and 0.67% Ro which indicates the well is of early oil window maturity. T_{max} values (mean 445 °C) suggest the well is more thermally mature and entering peak-oil maturity, though caution is advised in using this parameter for gas prone kerogens (see discussion in Vane et al., 2015).

Possible oil shales with oil saturation index (OSI) values of 162 at 3910.6 and 126 to 144 at 3956.3 m suggest some oil generation may be indicated.

<u>20/15-2 (3161.3-3190 m)</u>: Figures 28, 29

This well contains the Firth Coal Formation.

The TOC varies from 0.4 to 63.6 % with very high TOC at 3176.7 m (48.7%), 3183 m (40.5%), and 3183.1 m (63.6%) from coals. The HI range of 13-255 mg/g indicates gas prone source rock. Measured VR was not available, however T_{max} of 432-479 °C indicates pre-oil to oil window maturity.

2.1 DATA PLOTS

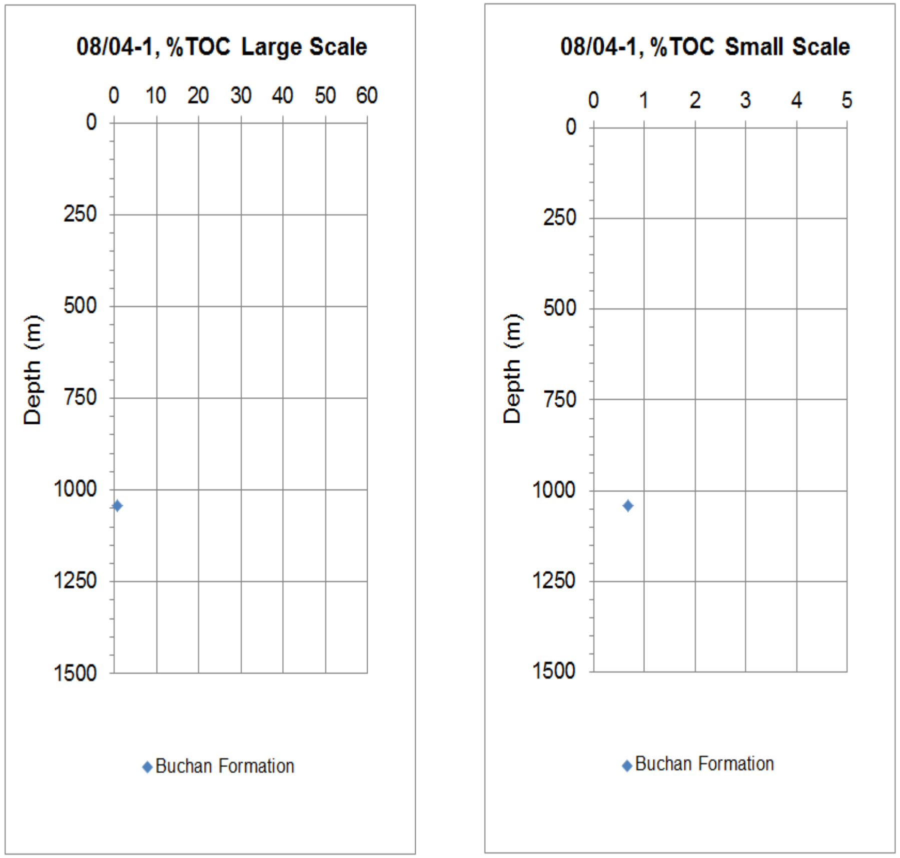

Figure 3 Well 08/04-1 (a)

(The full set of screening plots is not shown as most have no data points).

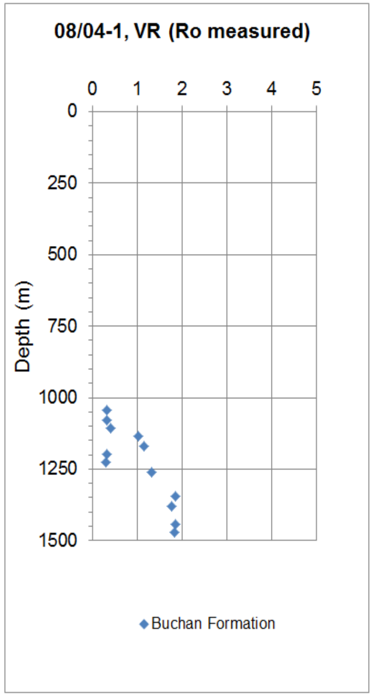

Figure 4 Well 08/04-1 (b)

(The full set of screening plots is not shown as most have no data points).

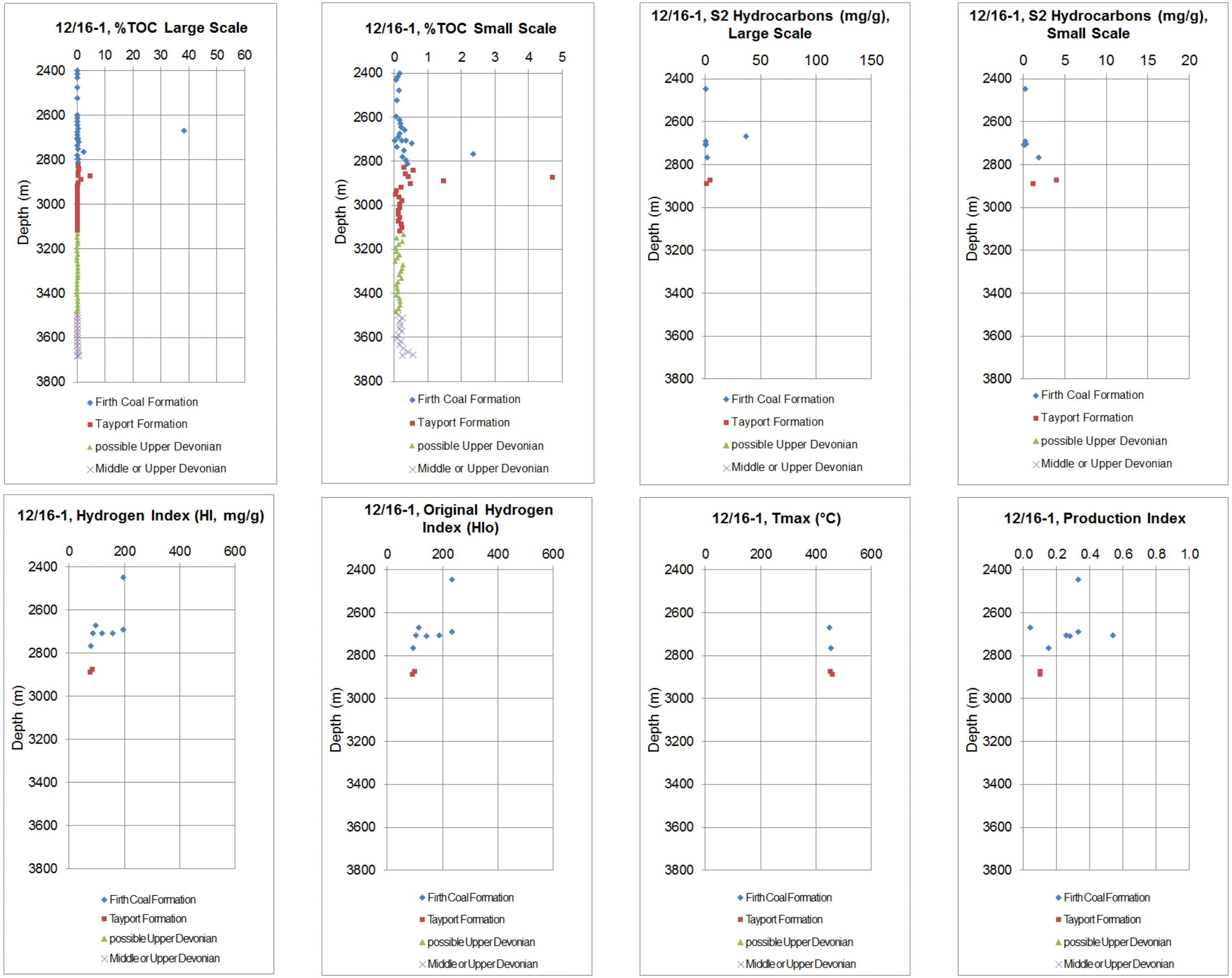

Figure 5 Well 12/16-1 (a)

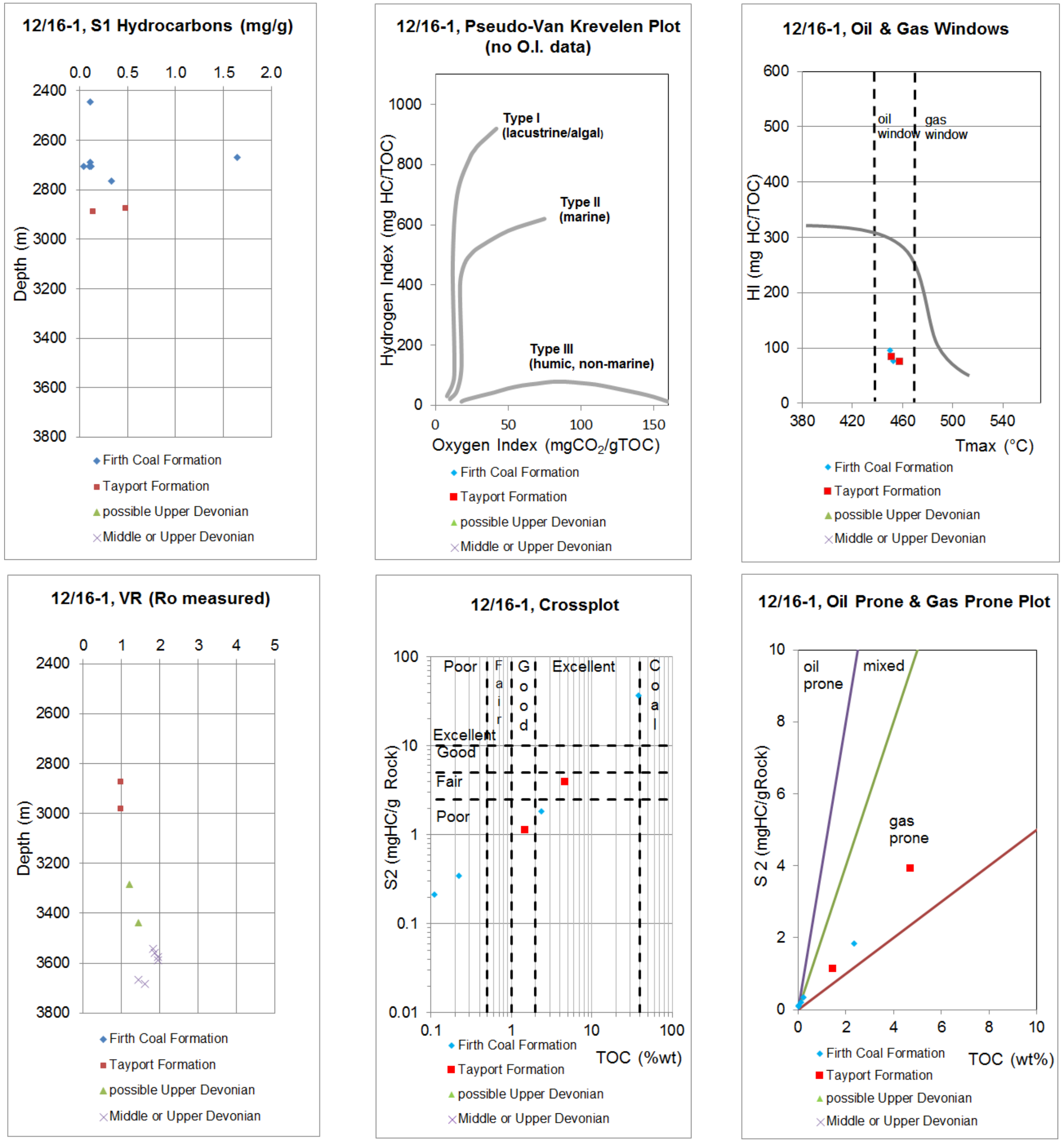

Figure 6 Well 12/16-1 (b)

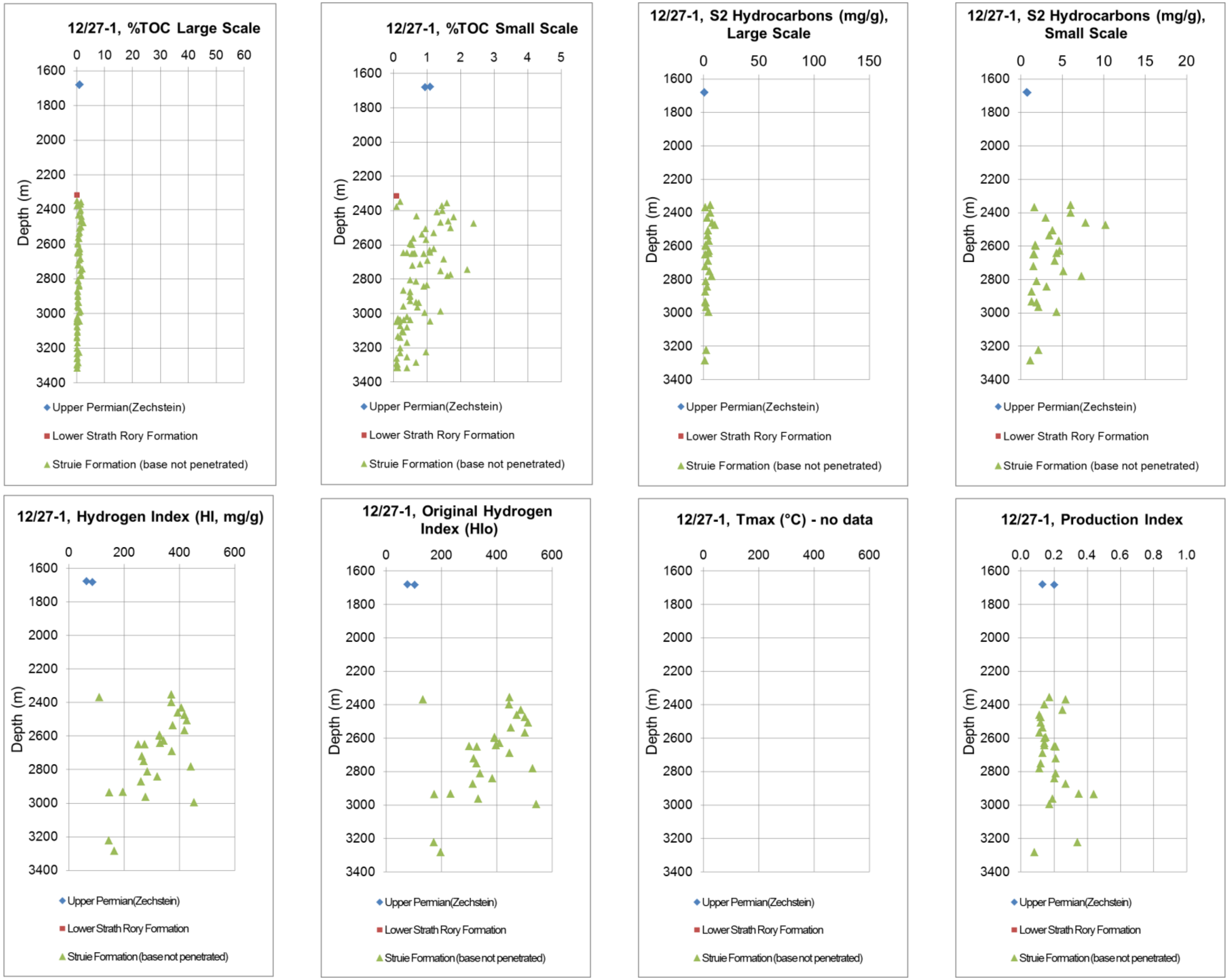

Figure 7 Well 12/27-1 (a)

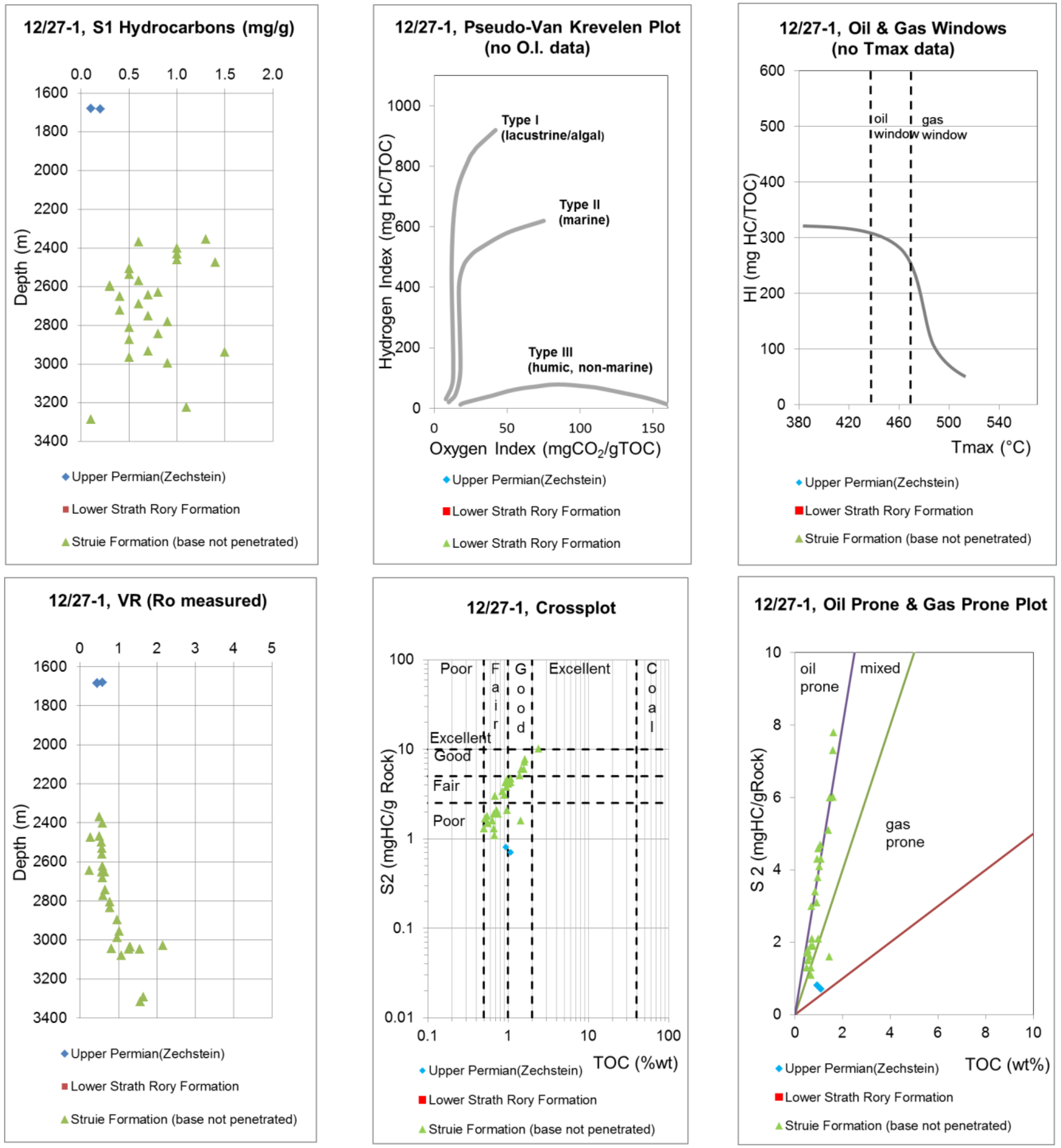

Figure 8 Well 12/27-1 (b)

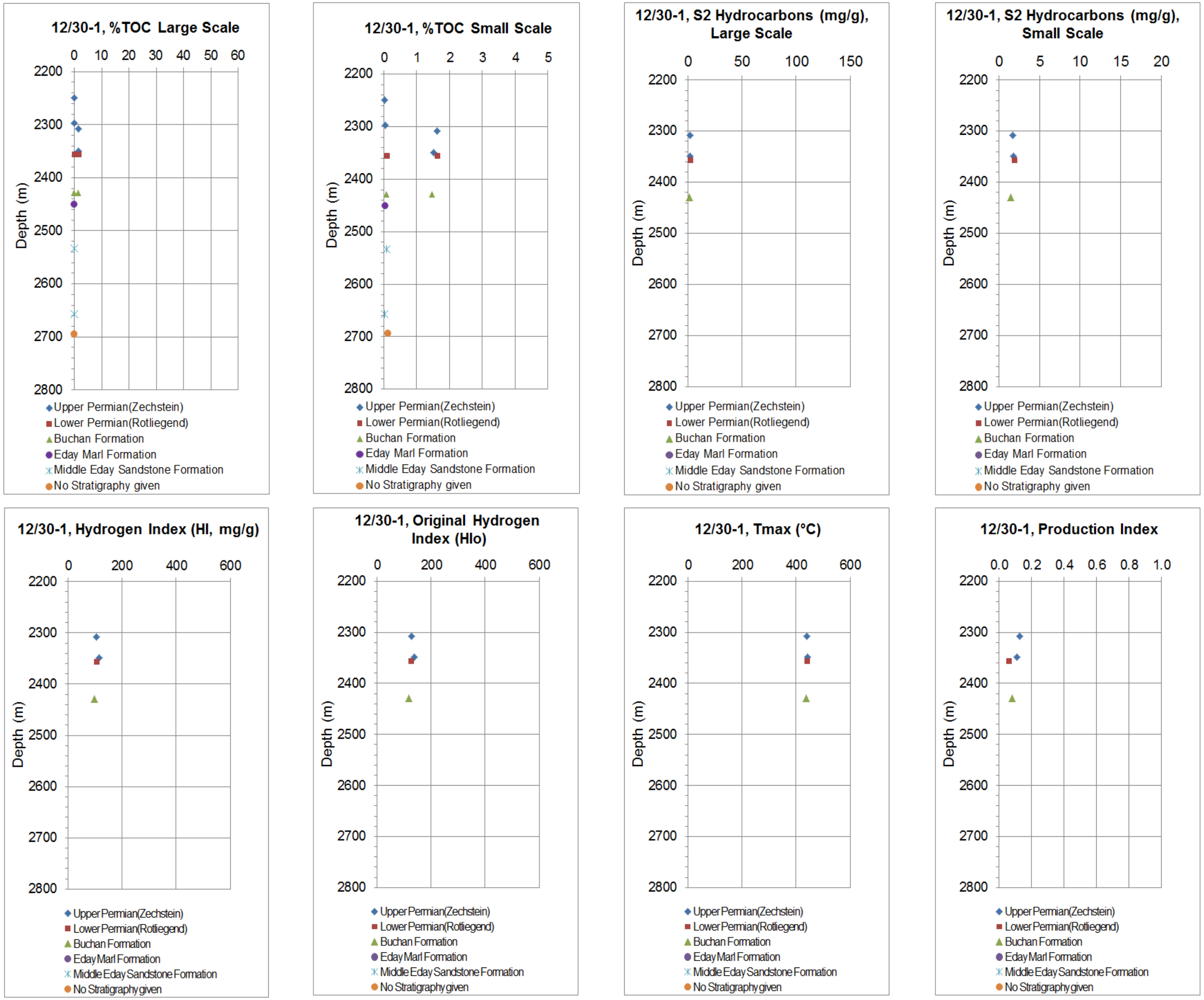

Figure 9 Well 12/30-1 (a)

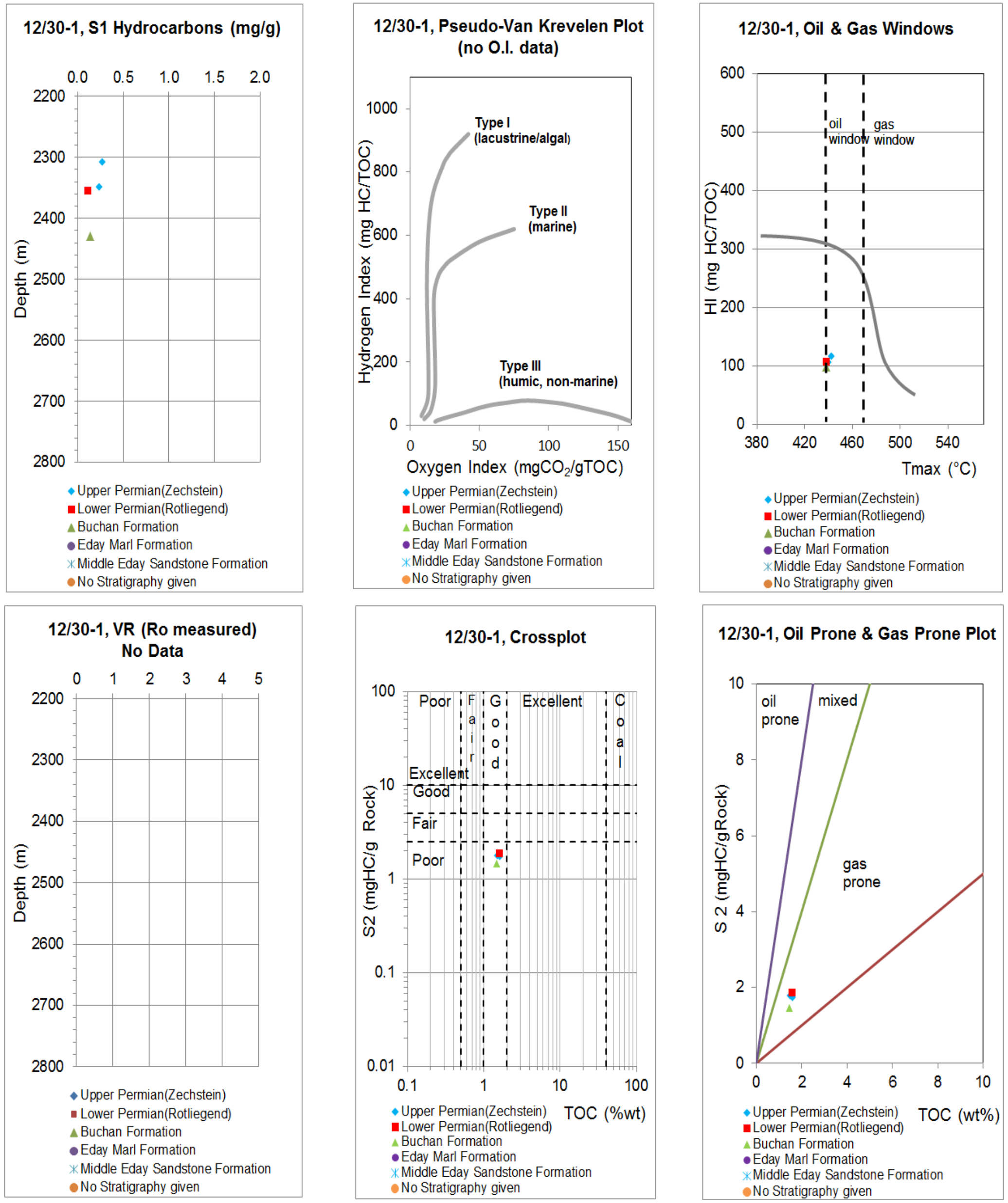

Figure 10 Well 12/30-1 (b)

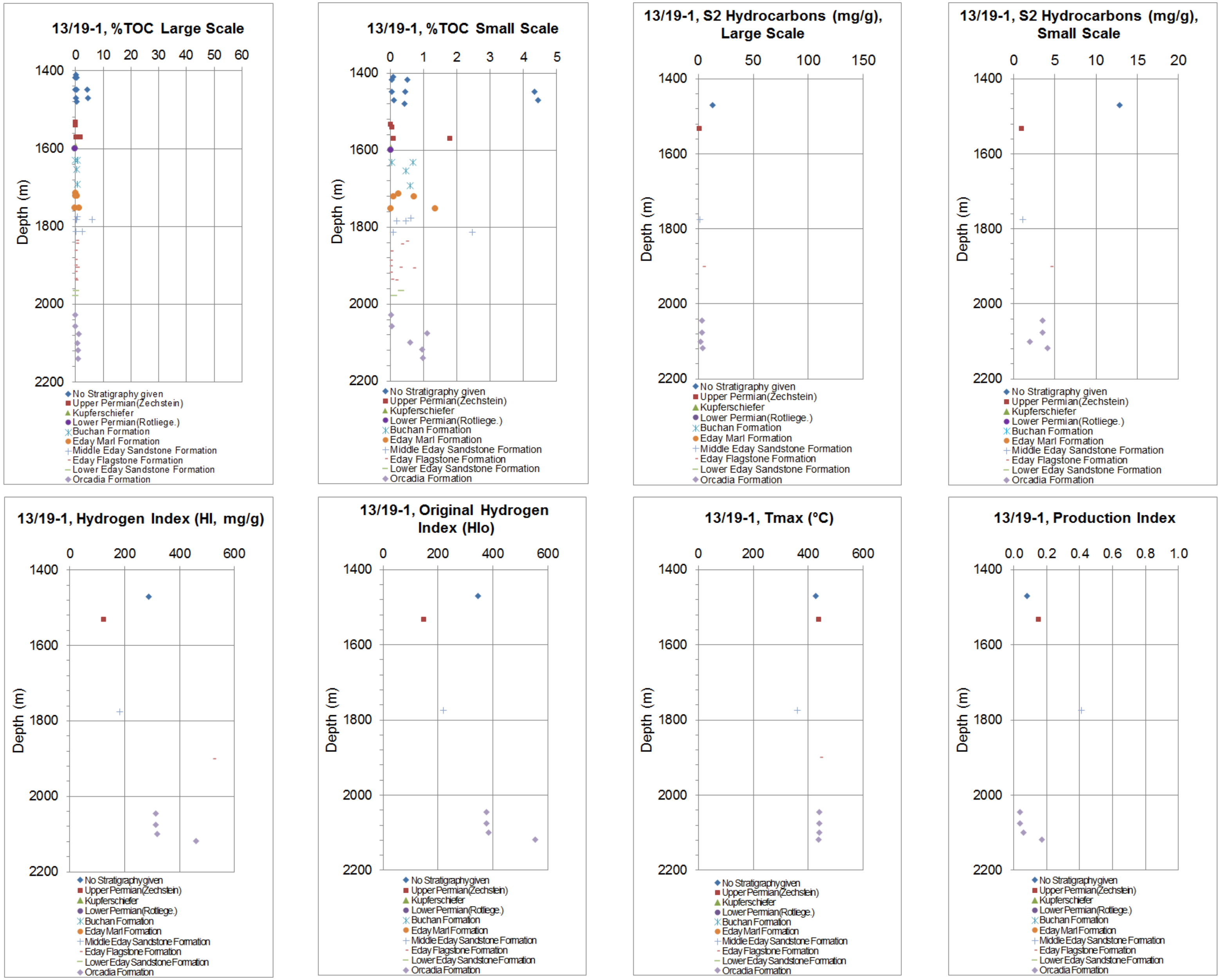

Figure 11 Well 13/19-1 (a)

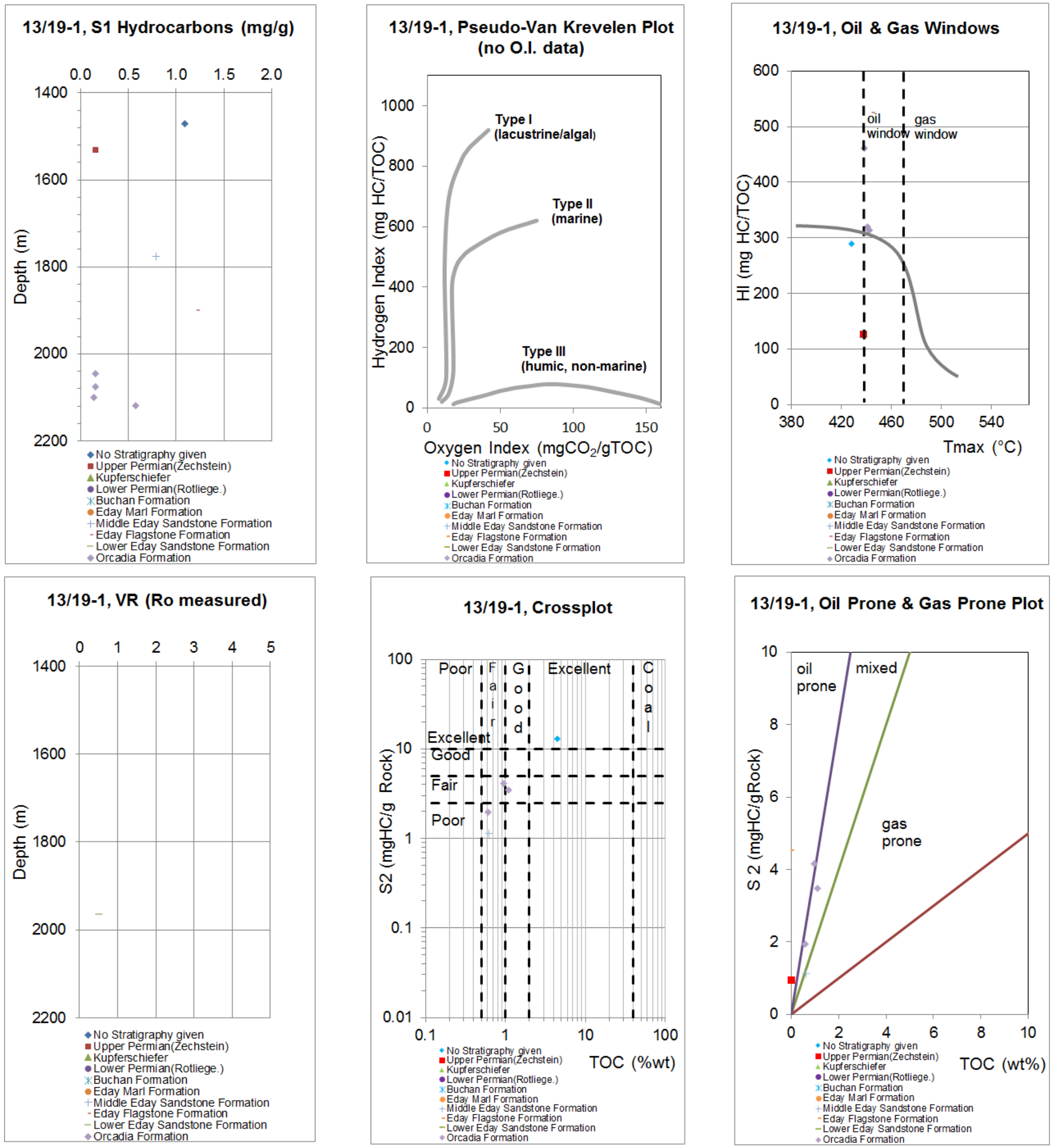

Figure 12 Well 13/19-1 (b)

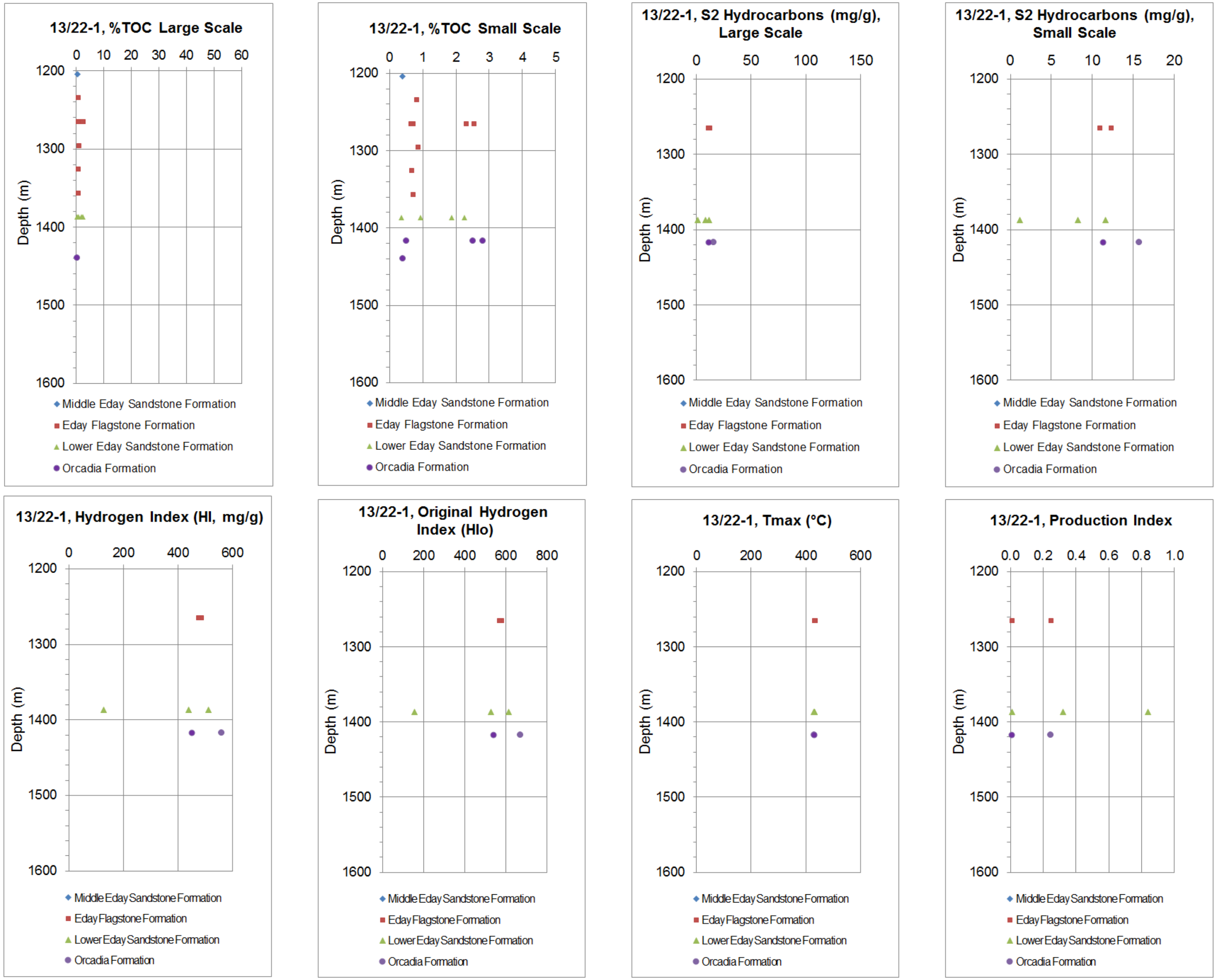

Figure 13 Well 13/22-1 (a)

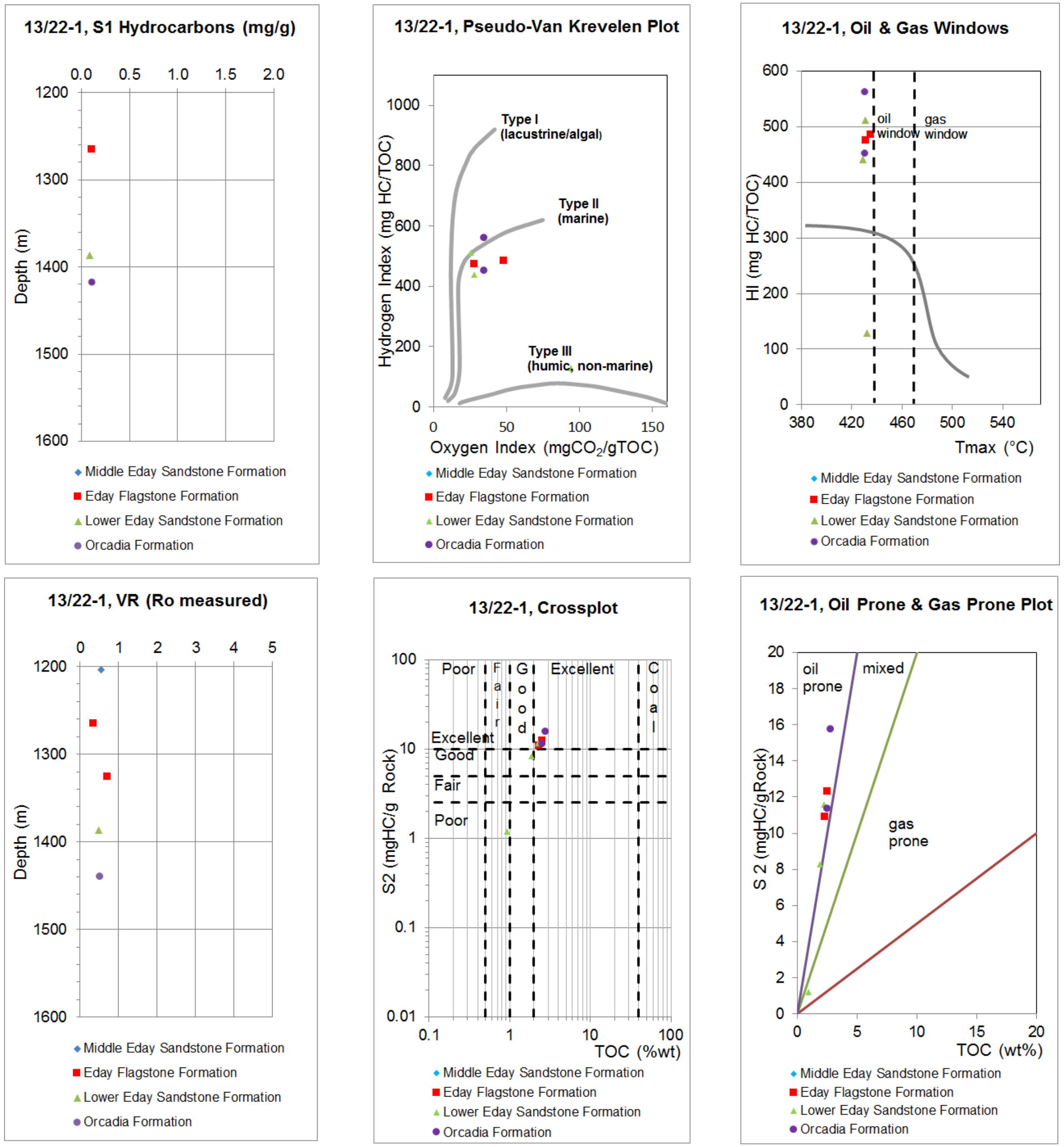

Figure 14 Well 13/22-1 (b)

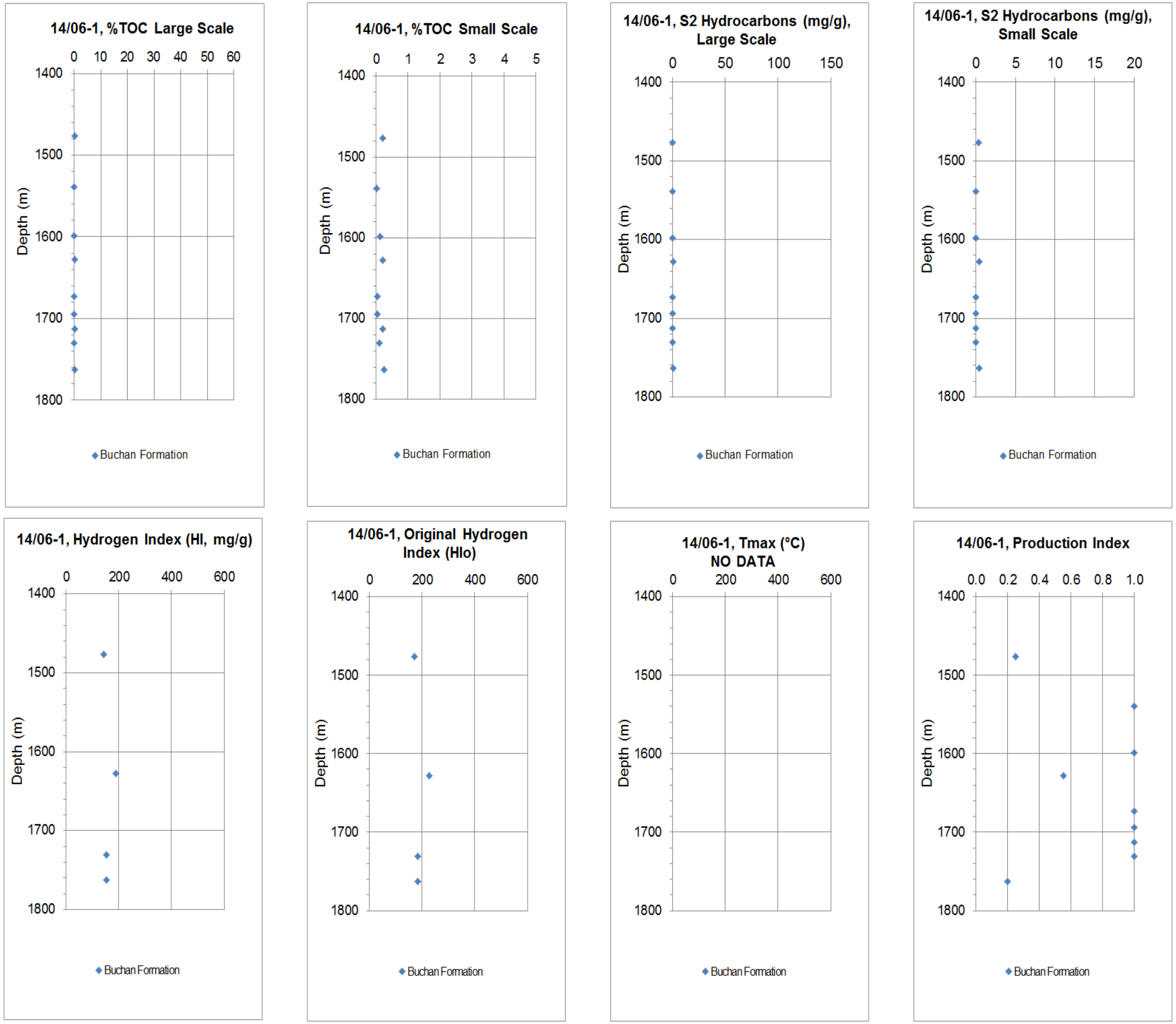

Figure 15 Well 14/06-1 (a)

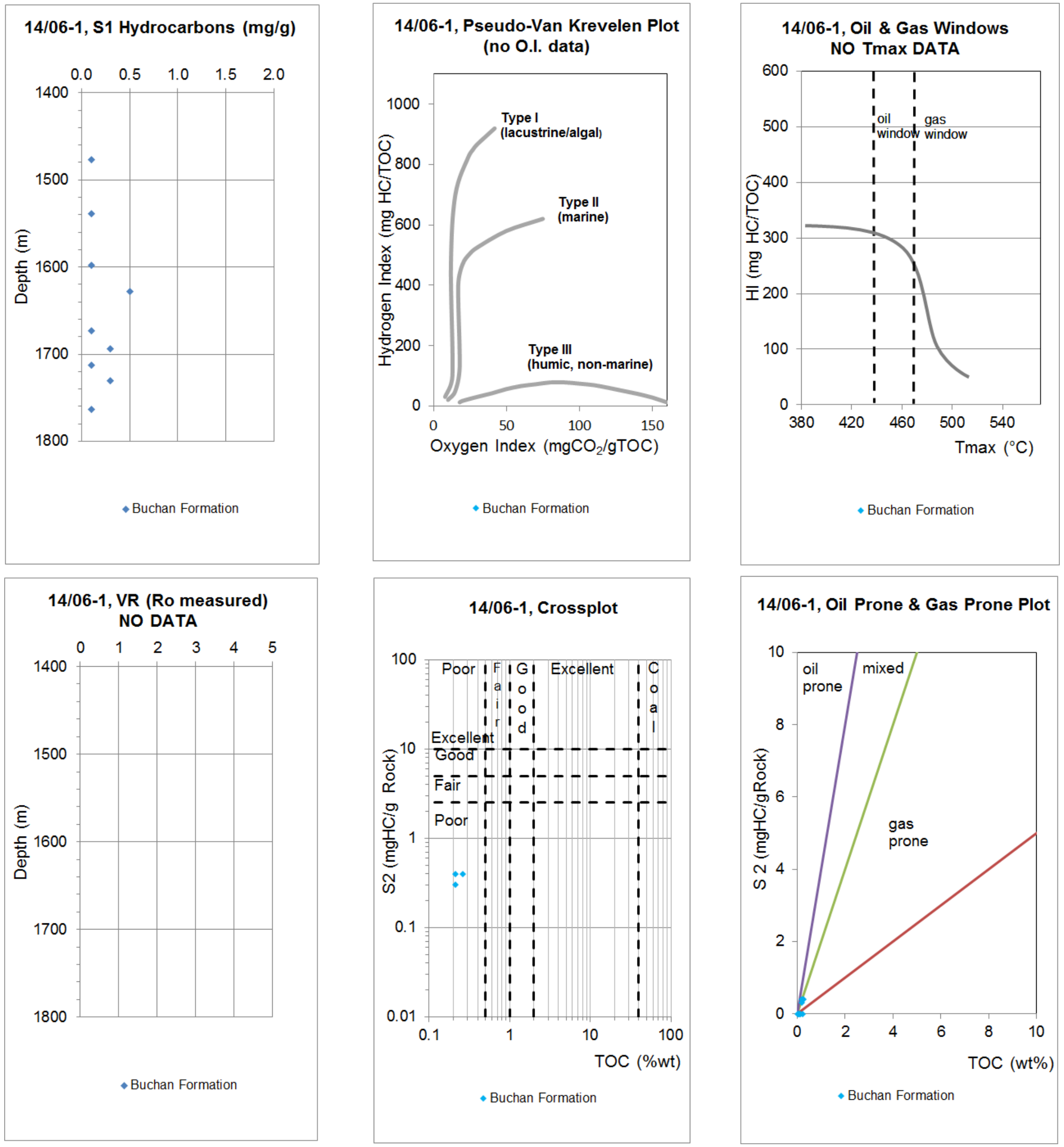

Figure 16 Well 14/06-1 (b)

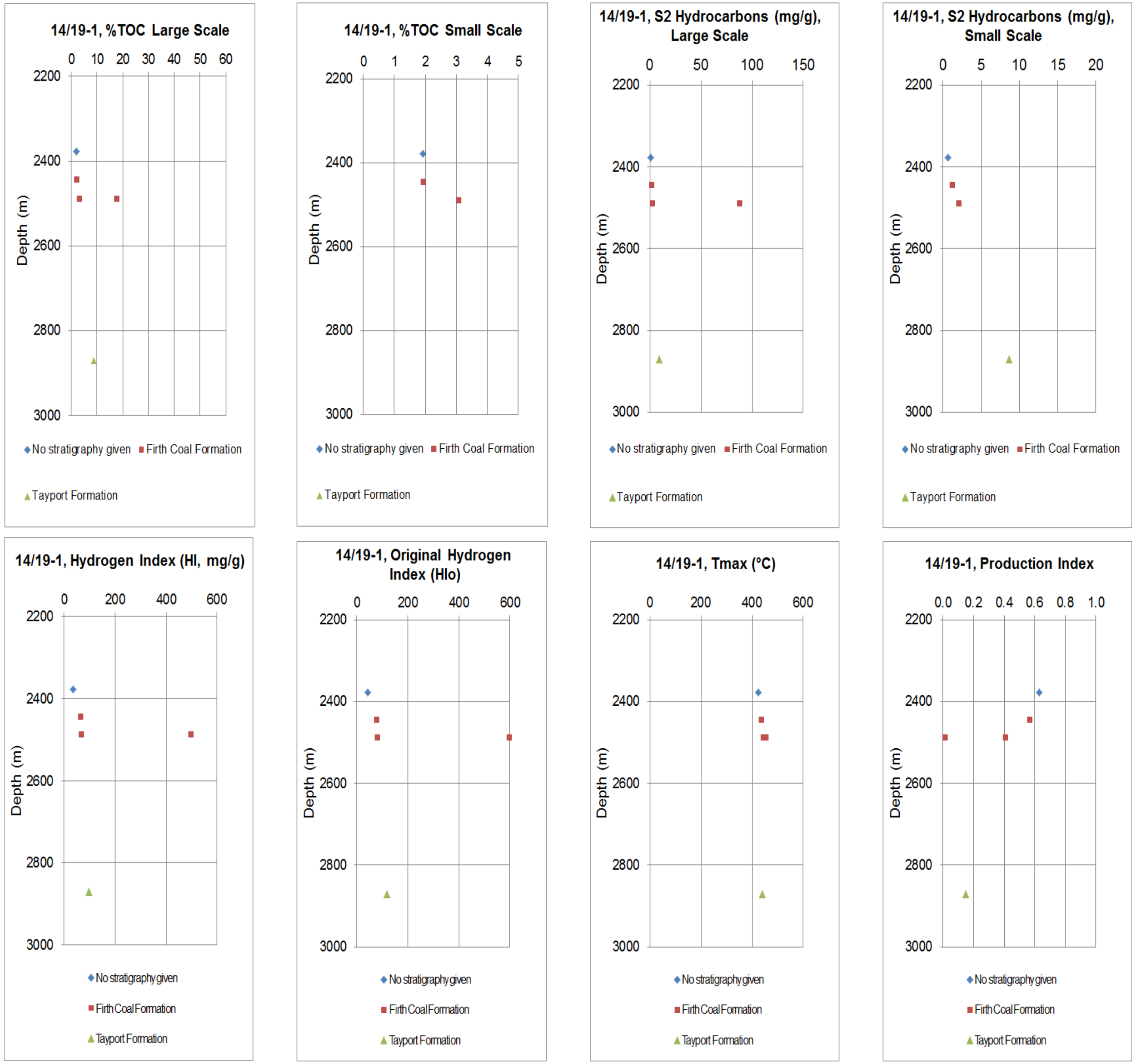

Figure 17 Well 14/19-1 (a)

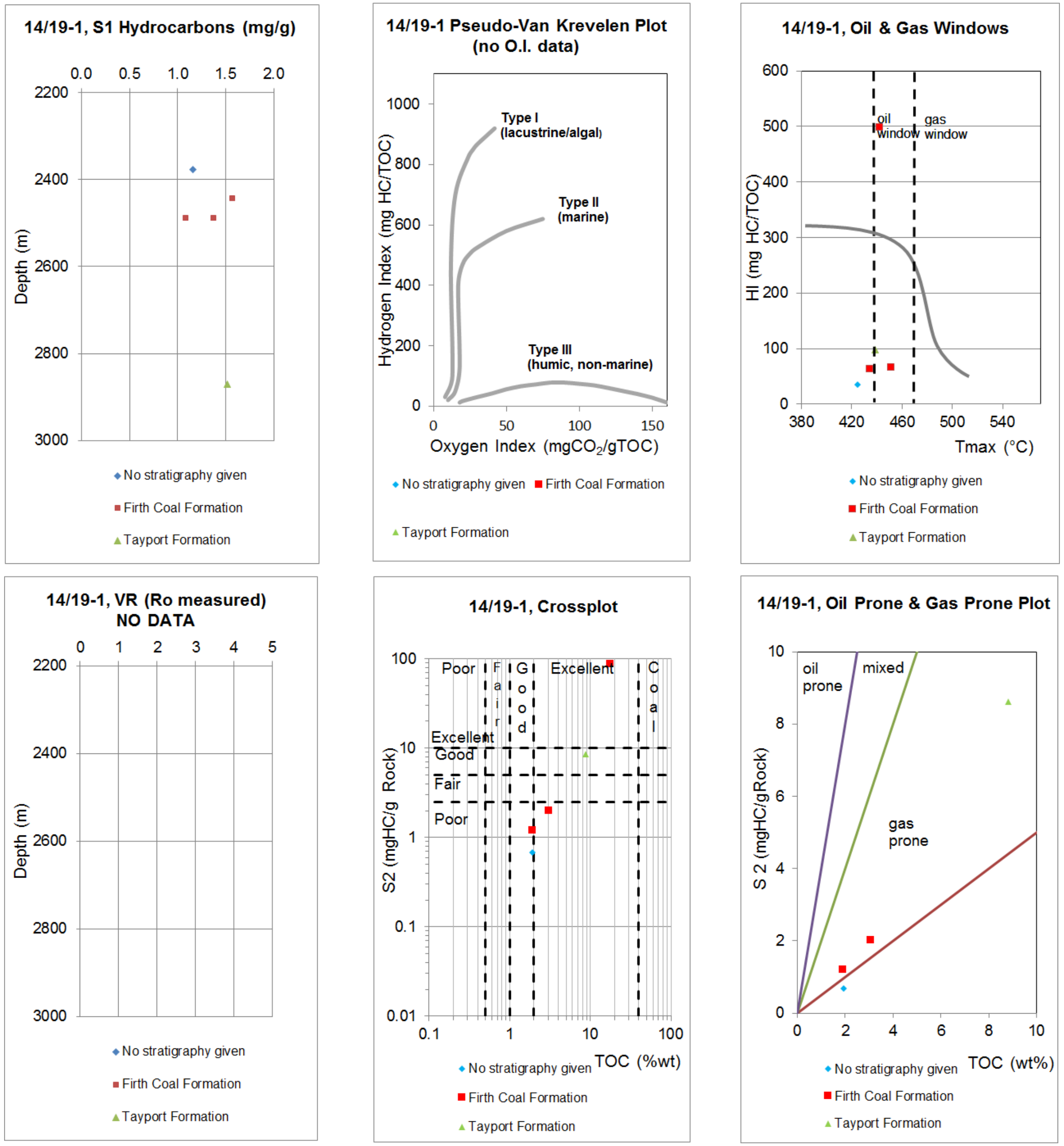

Figure 18 Figures 14/19-1 (b)

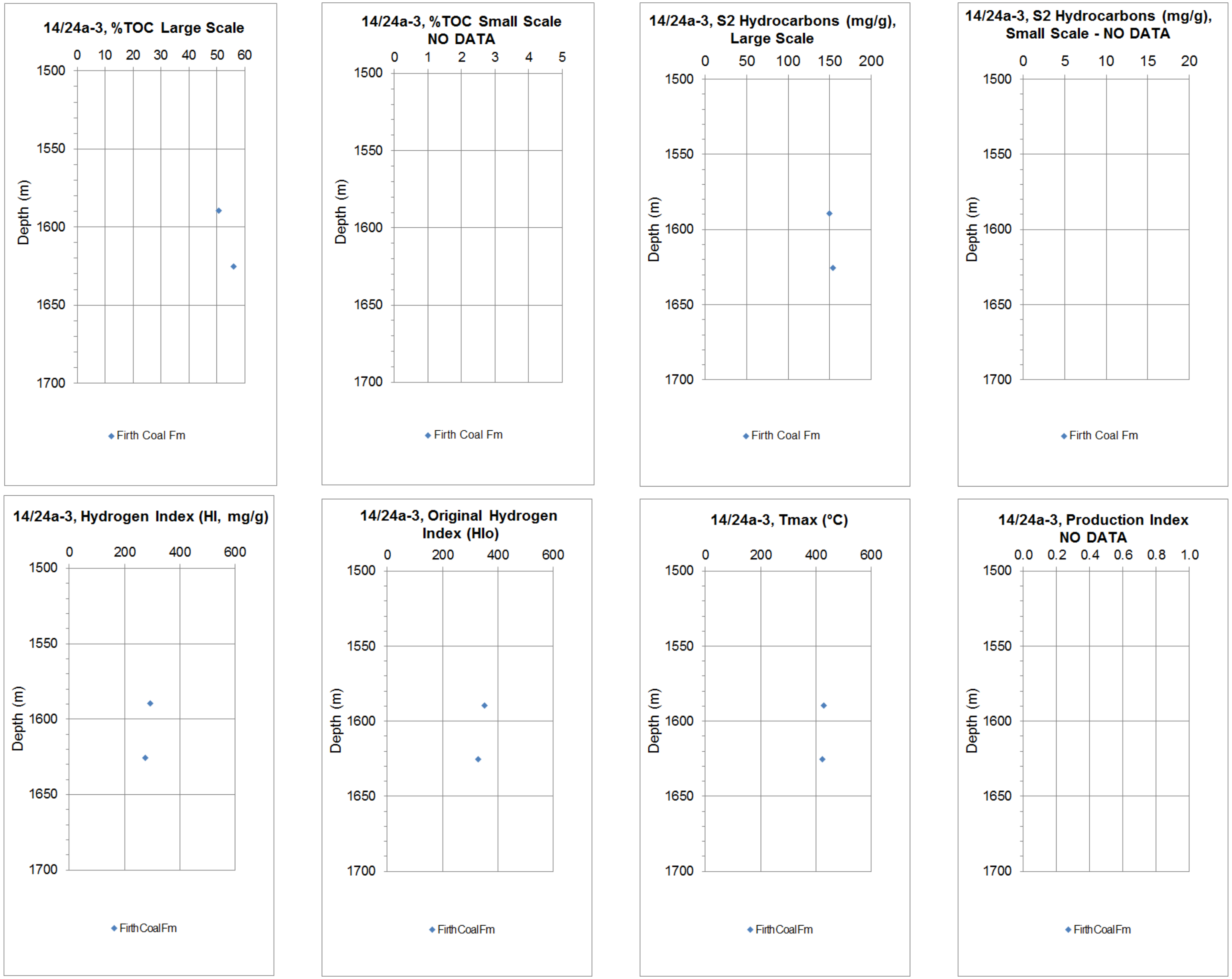

Figure 19 Well 14/24a-3 (a)

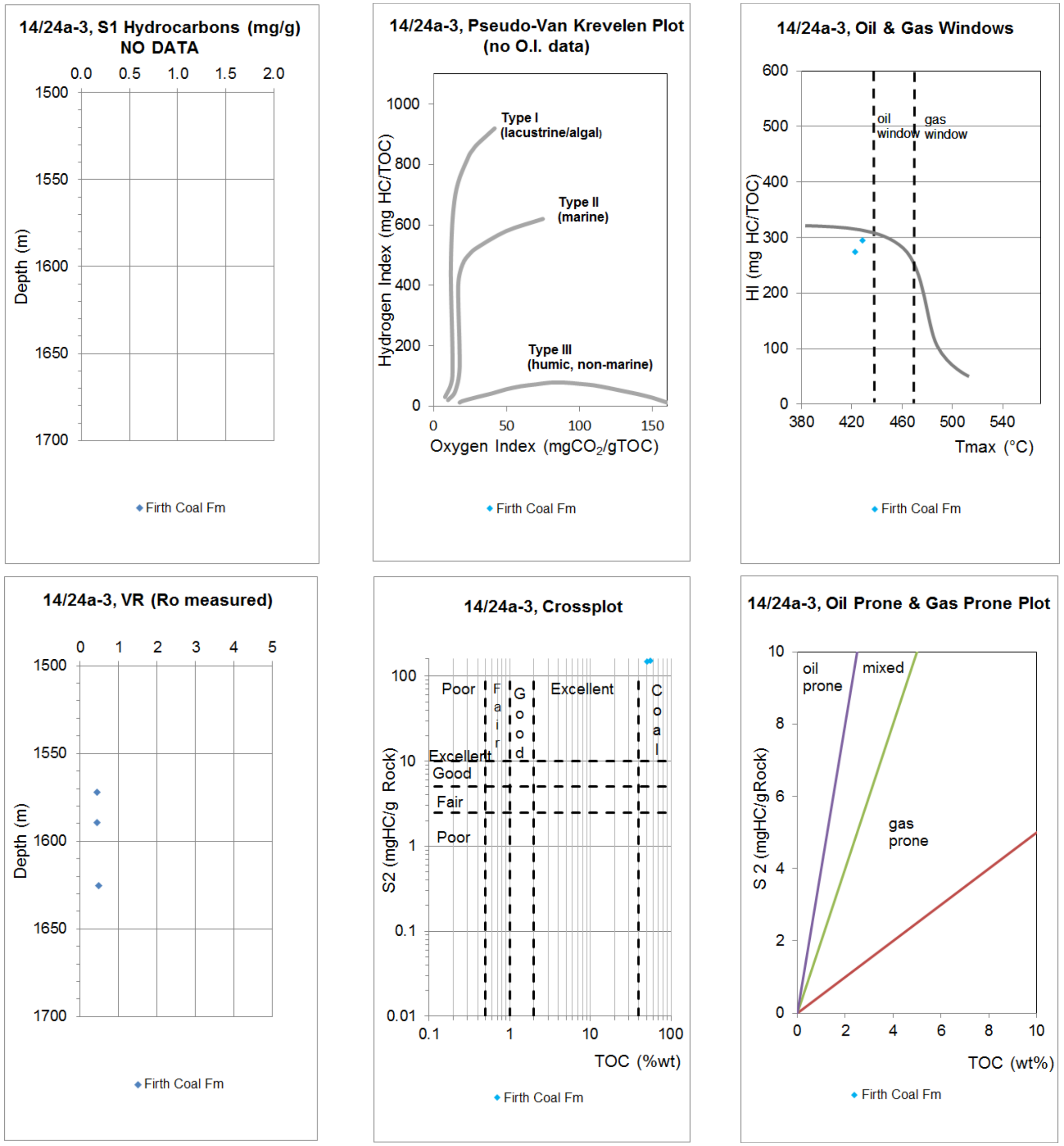

Figure 20 Well 14/24a-3 (b)

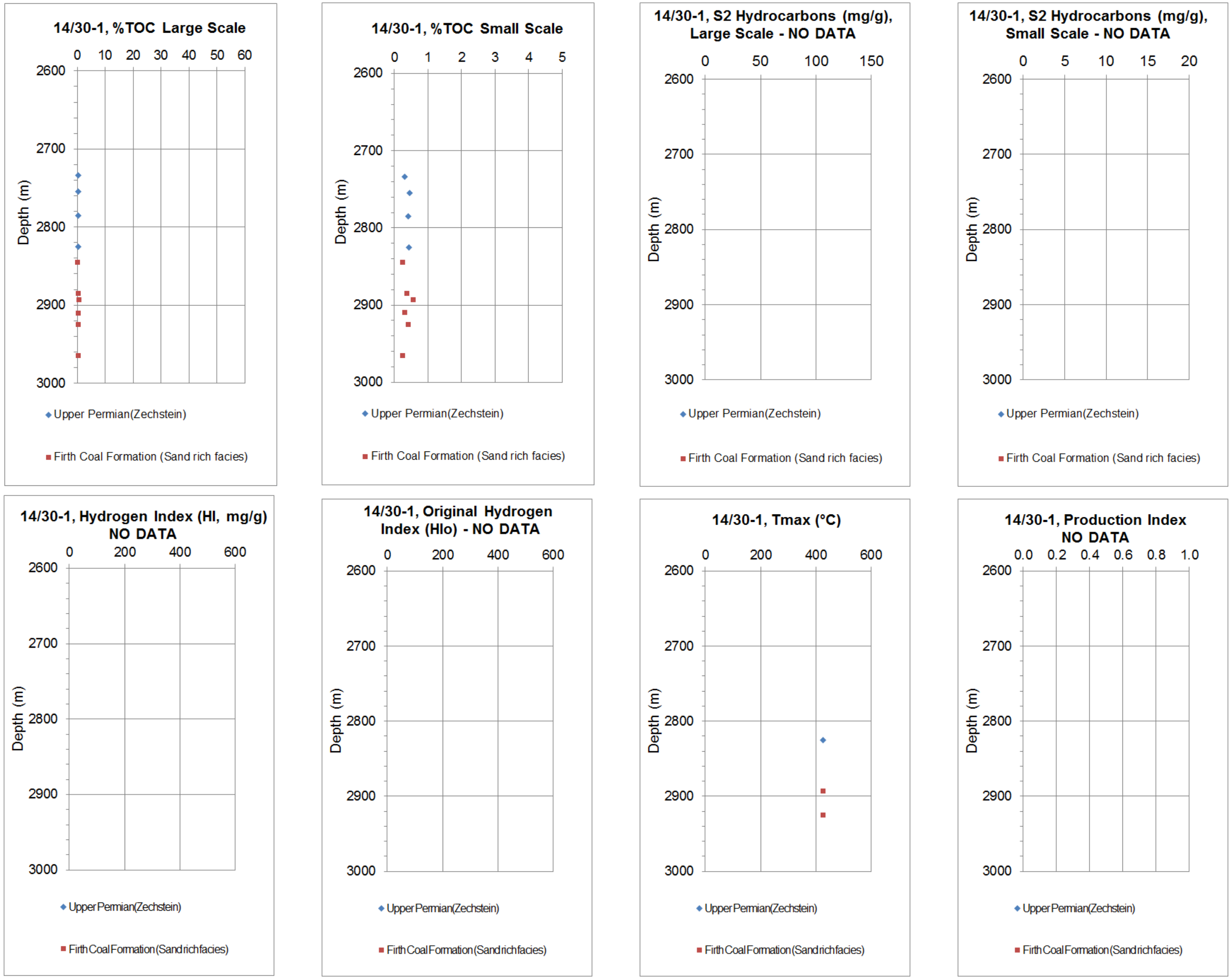

Figure 21 Well 14/30-1 (a) (Note there is no (b) graph as there is no data available).

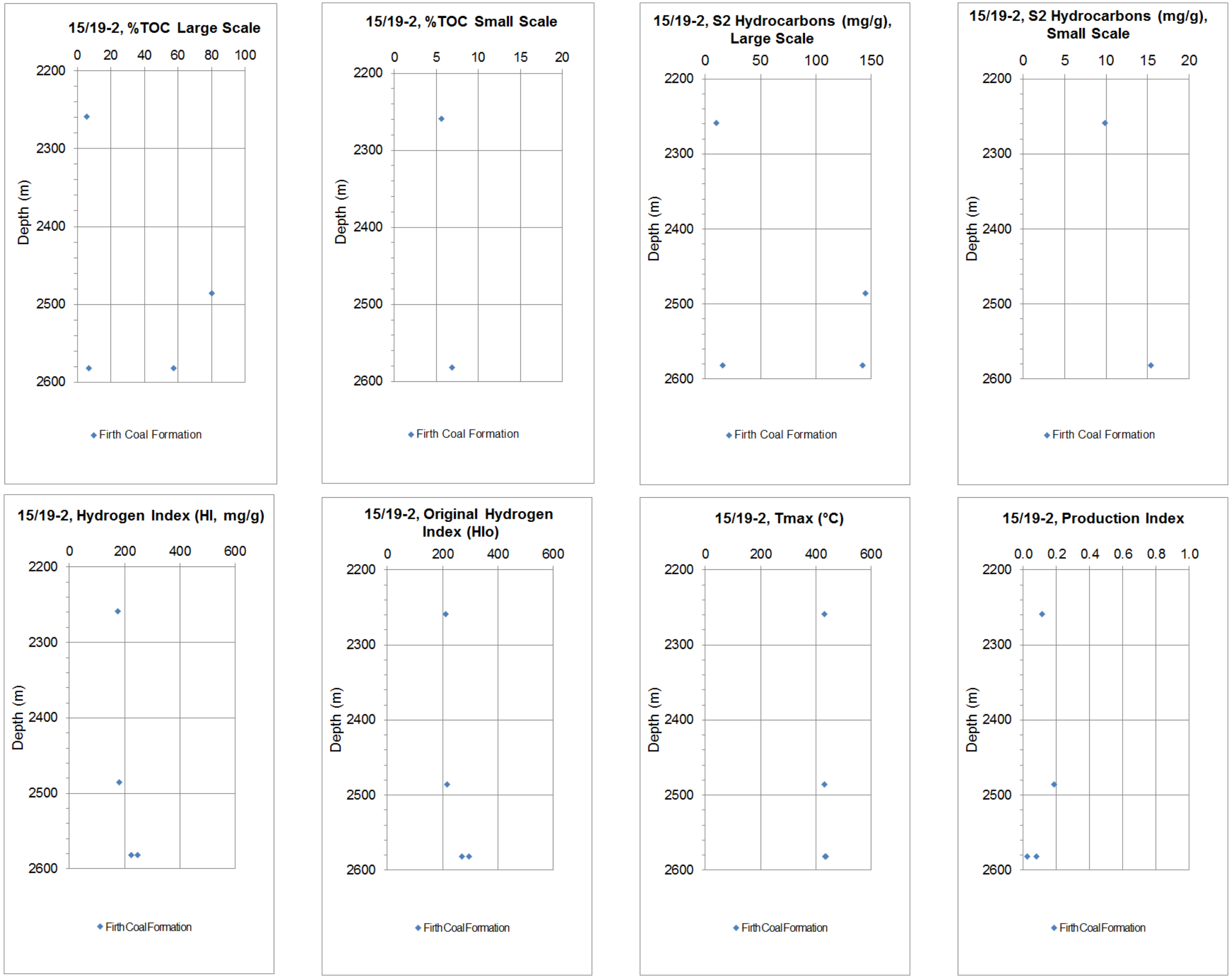

Figure 22 Well 15/19-2 (a)

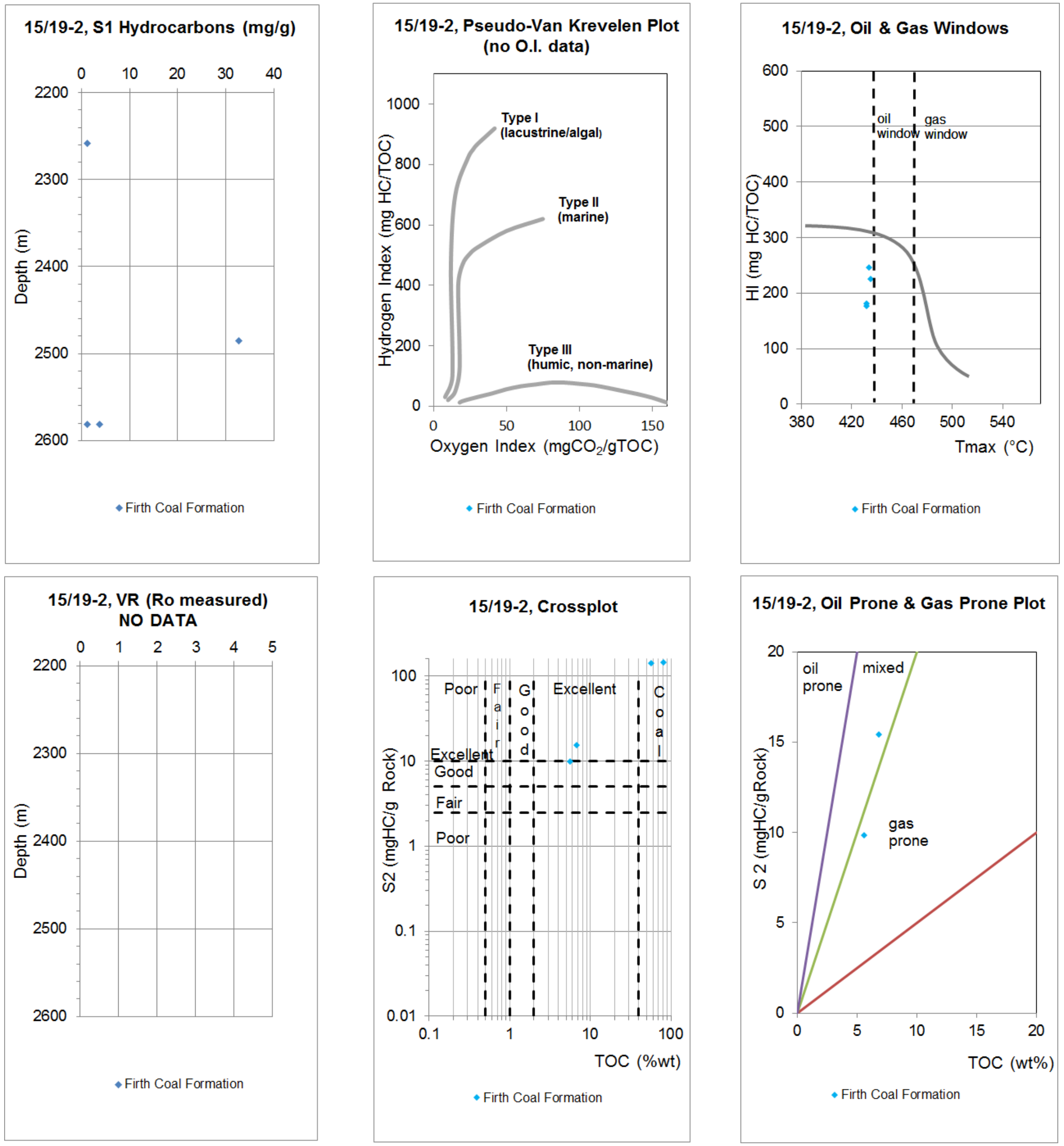

Figure 23 Well 15/19-2 (b)

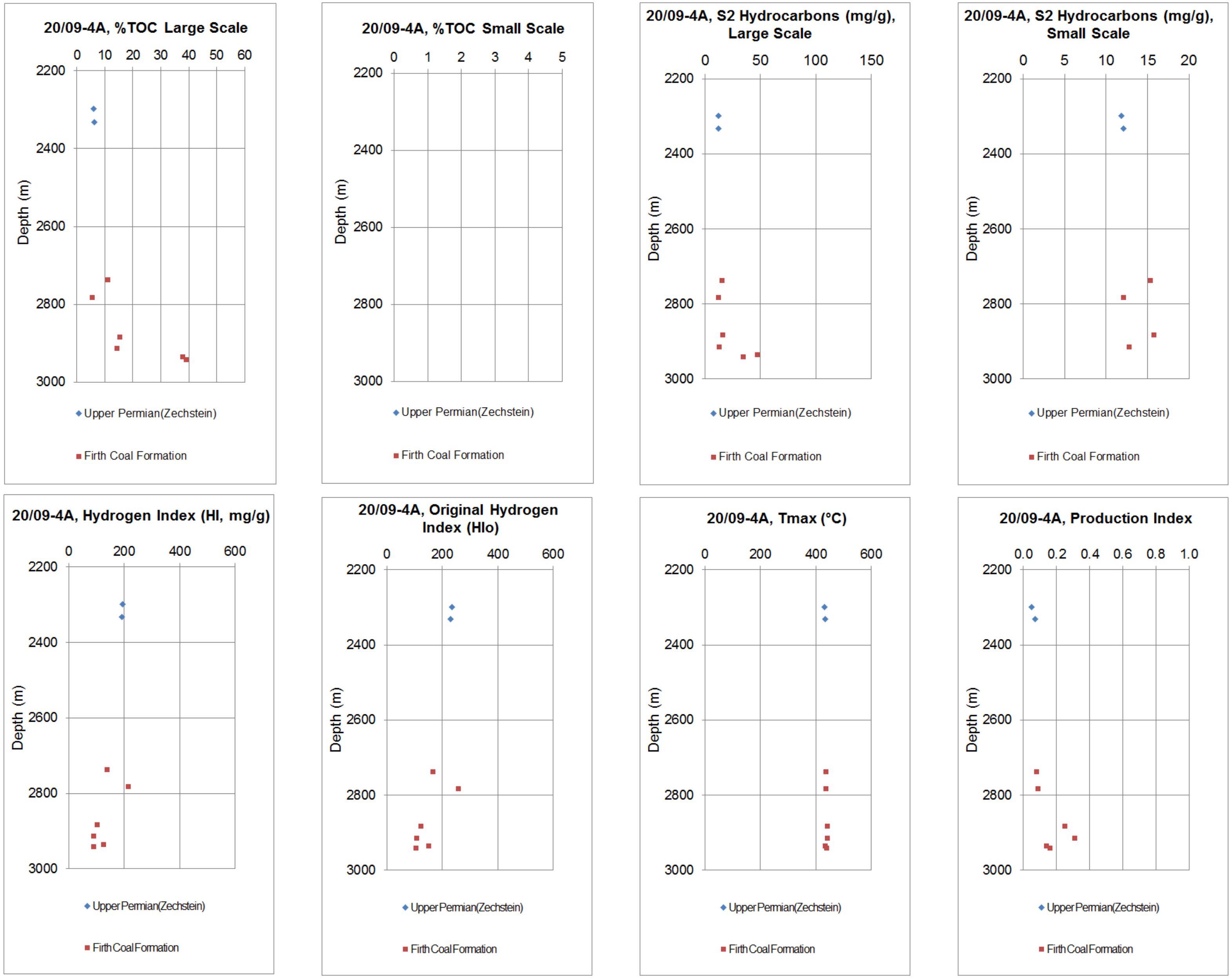

Figure 24 Well 20/09-4A (a)

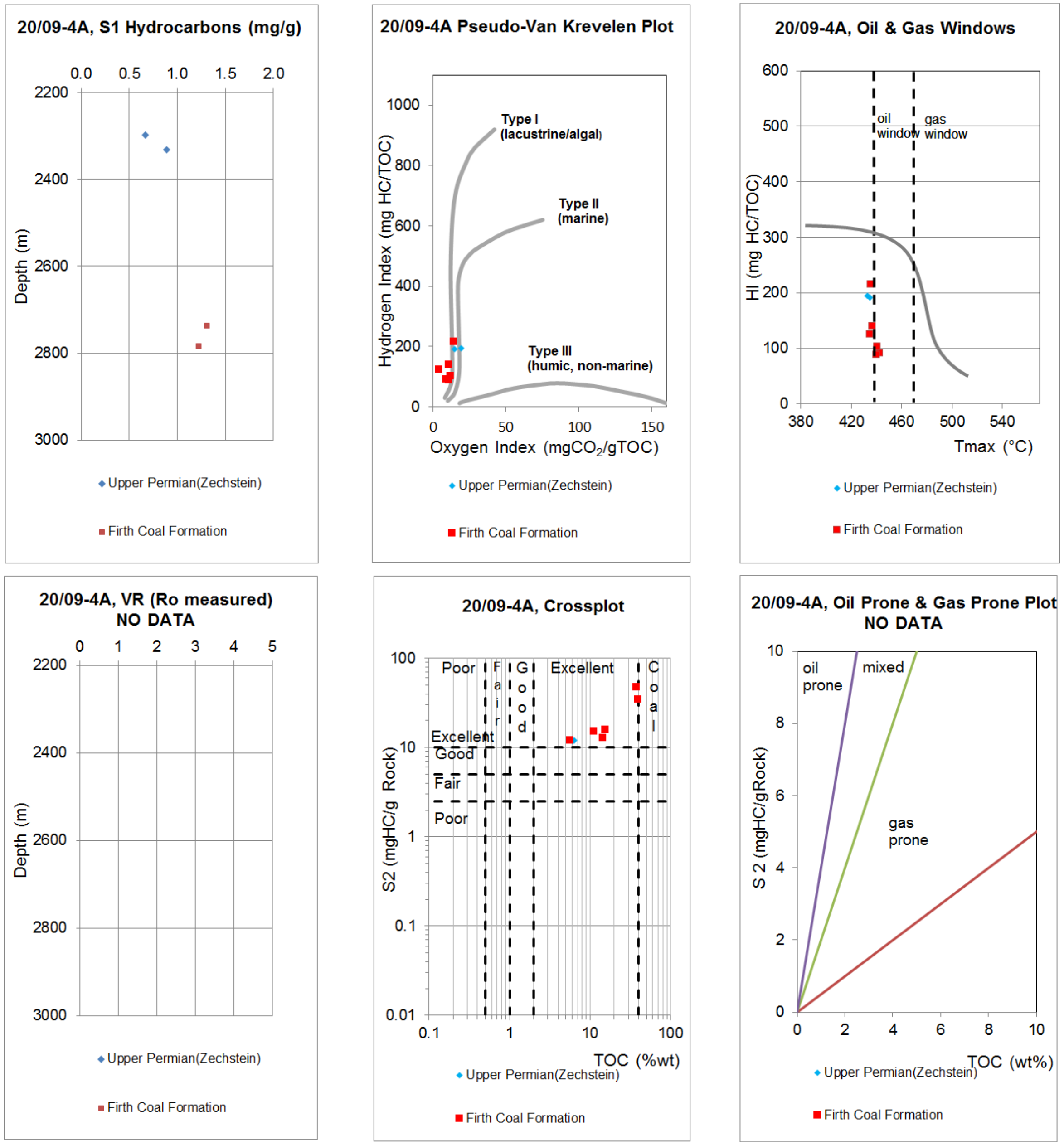

Figure 25 Well 20/09-4A (b)

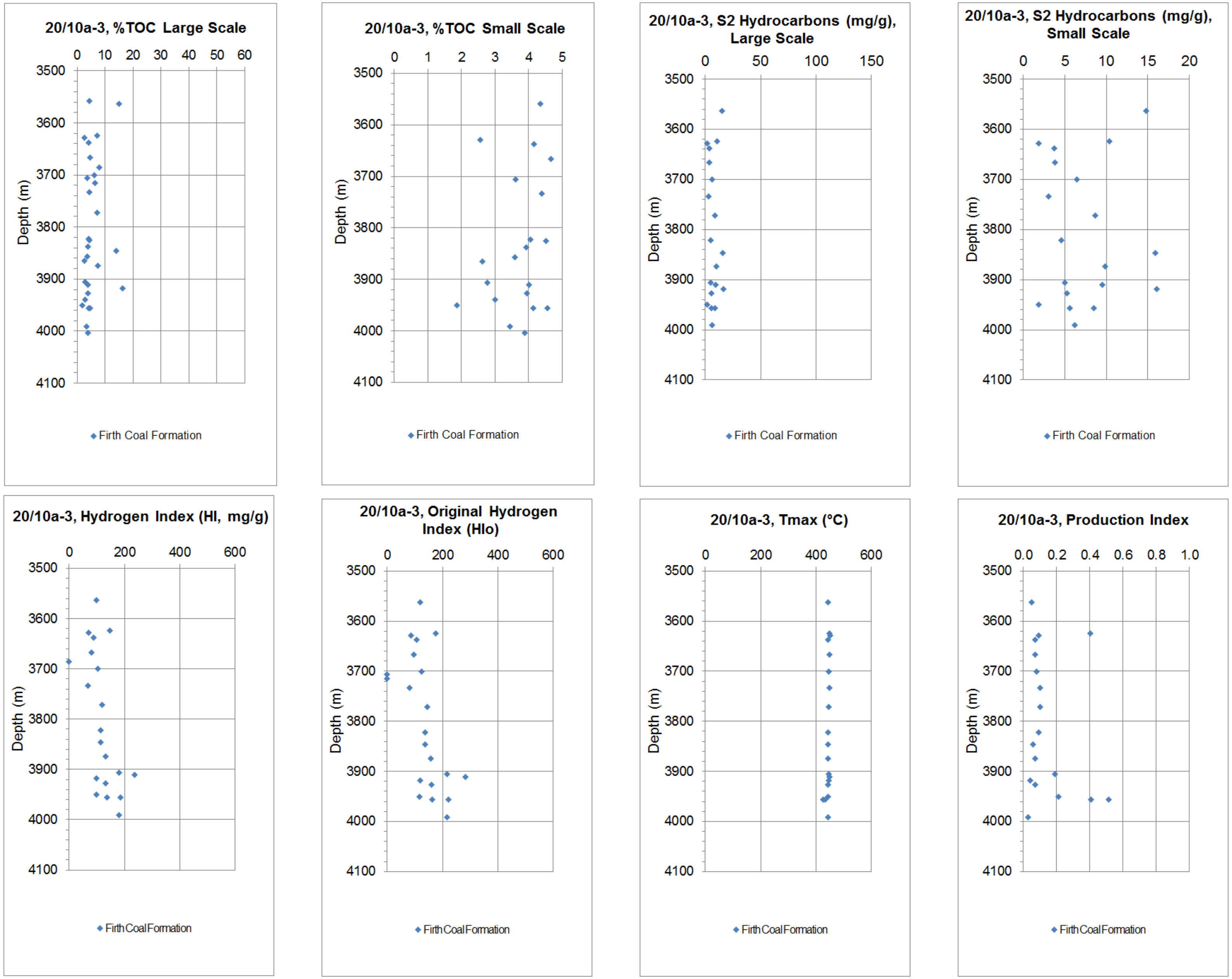

Figure 26 Well 20/10a-3 (a)

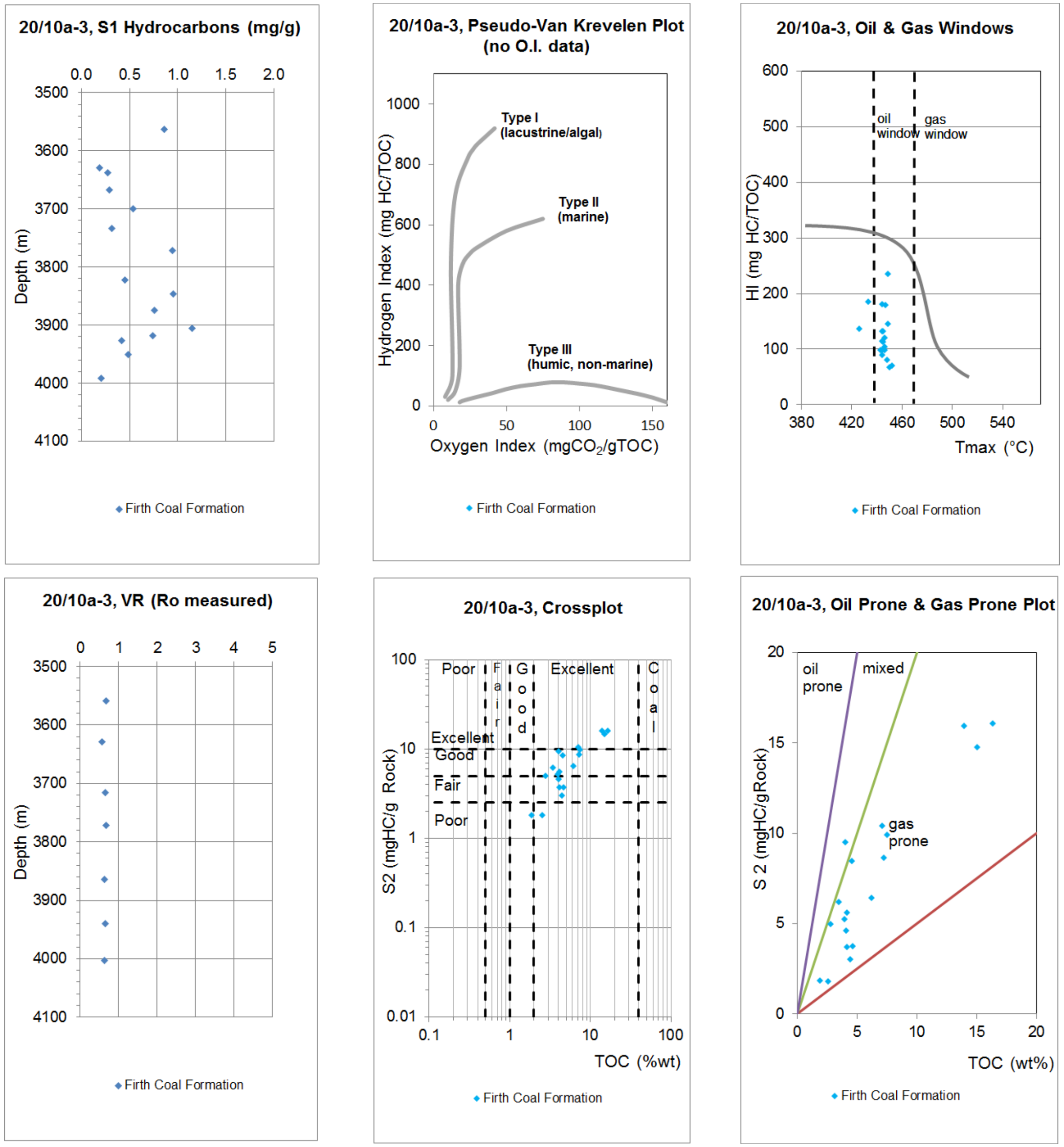

Figure 27 Well 20/10a-3 (b)

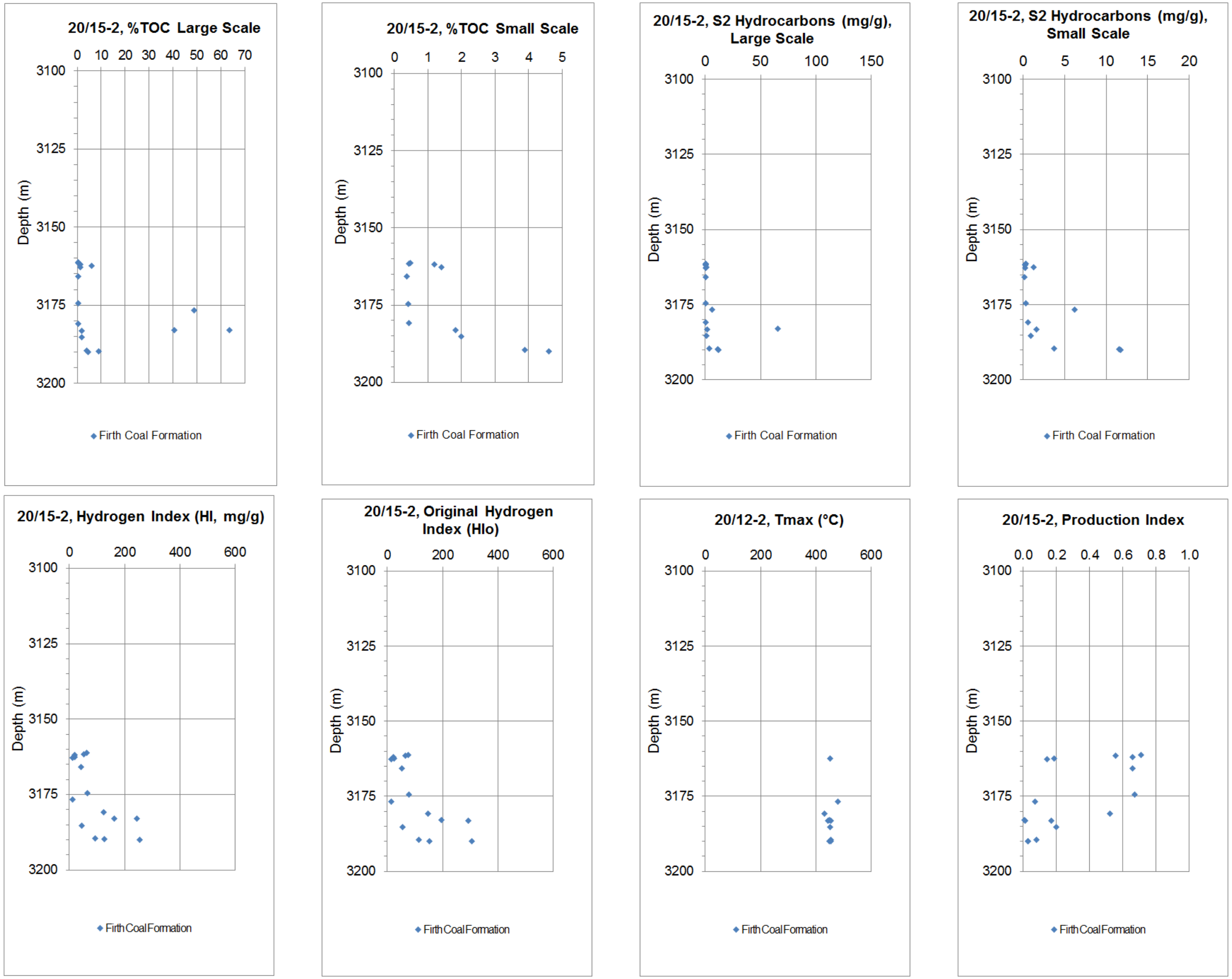

Figure 28 Well 20/15-2 (a)

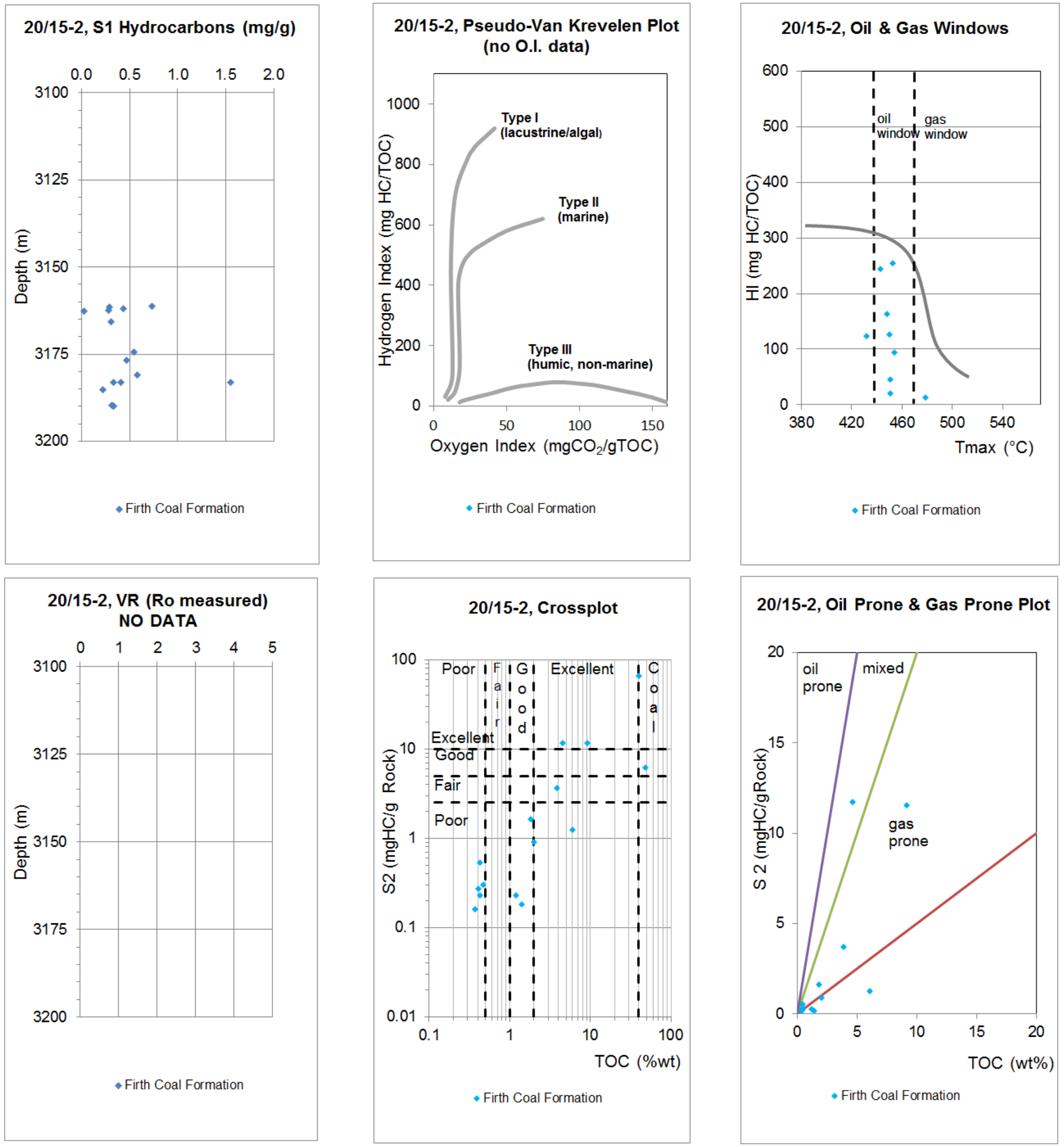

Figure 29 Well 20/15-2 (b)

3 Conclusions

The Devonian Struie and Orcadia formations show fair-good oil-prone generative potential in the Inner Moray Firth (wells 12/27- 1, 13/19- 1, 13/22- 1; Figure 1). Maturity levels are variable, from pre-oil to gas mature.

In well 12/27-1, Devonian source rocks have fair oil prone potential whilst a few sample depths have good oil generative potential. Thermal maturity increases from a VR of 0.5-1.02% Ro at 2370 to 2957 m depth (Struie Formation) and attains gas window maturity at depths over 3078m. Well 13/19- 1 contains the Orcadia Formation with fair, oil prone hydrocarbon generative potential, but pre-oil window maturity. In well 13/22- 1, Orcadia and Eday Flagstone formation source rocks are oil prone, with good residual hydrocarbon potential (HI >400, S2 >10 mg/g).

The Carboniferous Firth Coal Formation shows limited to good gas-prone generative potential in wells in Quadrants 14, 15 and 20 though maturity levels are variably pre-oil to oil window (Figure 1).

In wells 14/19- 1 and 20/09- 4A and the Firth Coal Formation source rocks are at pre-oil to early oil window maturity. The source rocks in wells 14/24a- 3 and 15/19- 2 are largely at pre-oil window maturity.

In well 20/10a- 3 the Firth Coal Formation source rock has good potential and some oil saturation index values suggest some layers have generated oil. The presence of thin oil-shales/oil-prone layers merits further analysis at higher down well resolution. Well 20/09- 4A contains a gas prone Firth Coal Formation source rock with good hydrocarbon generation potential. Well 20/15- 2 contains some gas generative potential in the Firth Coal Formation and is of variable maturity.

Situated in an outlier of Carboniferous strata, well 12/16- 1 contains gas prone source rocks with poor to fair potential and variable maturity. The Firth Coal Formation is pre-oil window. Oil window maturity is attained within the Tayport Formation and gas window maturity at depths >3116 m.

Limited samples from the Buchan Formation indicate this is a non-source rock interval (in wells 8/04- 1, 12/30- 1, 14/06- 1).

The conclusions from this regional screening of Rock-Eval data are consistent with previous studies of the Devonian succession (see Greenhalgh, 2016 for literature review) The sparse sample distribution in many of the wells with promising source rock characteristics indicate sections worthy of follow-up analytical work (e.g. in 13/22- 1, 14/19- 1).

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