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Central North Sea HPHT Pressure Cell Study

Methodology Report

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Introduction to the project

HPHT (high pressure, high temperature[1]) fields in the Central North Sea (CNS) account for a significant portion of UK total production. Expediting the successful exploitation of new HPHT structures in the UKCS can play a major role in maximising economic recovery and extending the asset life of existing infrastructure. While HPHT conditions are recorded in a number of UKCS basins, by far the largest resource attributable to HPHT producing fields, discoveries, and mature prospects lies within the Central Graben of the CNS.

This pressure cell study focusses on the Jurassic and Triassic stratigraphic intervals in the CNS. These pre-Cretaceous intervals are sealed by mudstones of the Kimmeridge Clay Formation or the Cromer Knoll Group (Gaarenstroom et al., 1999; Swarbrick et al., 2005). The objectives of this study are to provide a regional understanding of overpressure distributions or pressure cells in the Central North Sea together with a supporting QC'd well pressure database. This will:

i. support improved mapping of overpressure distributions for prospective plays,

ii. develop an understanding of the subsurface pressure regimes onto which the HPHT portfolio of leads and prospects can be mapped and distinguished from the NPNT (normal pressures and temperatures) portfolio,

iii. provide a publicly released dataset on which further research and analysis can be based, through universities, industry collaboration, etc. without the barrier of high data costs and complex data licensing arrangements,

iv. help identify gaps in the data that is currently available.

v. stimulate exploration activity around key producing infrastructure in a timely manner

vi. support more accurate models for top seal integrity[2] and column heights modelling, therefore reducing volumetric uncertainty,

vii. provide a dataset that can be used to help polarise the potential for carbon capture and storage (CCS) in Triassic-Jurassic reservoirs.

This study combines well pressure data with historic and published structural interpretations to generate a pressure cell map for the pre-Cretaceous strata of the UK CNS. A pressure dataset comprising 194 wells was generated from released well data on the National Data Repository (NDR) by Ikon Science Limited (Ikon Science). Pressure cells were interpreted from the well data, based on aquifer overpressure interpretations. Pressure cell boundaries were derived from structural interpretations in the published literature (Eratt et al., 1999; Keller et al., 2005; Archer et al., 2010; Hollywood and Olson, 2010; Charles and Ryzhikov, 2015) and industry reports (relinquishment reports listed under references and other unpublished industry reports). This report is intended to be a summary of some of the key publicly available and published data, it should act as guide rather than replace detailed analysis of overpressure distribution and its controlling factors.

Methodology

Dataset

A well pressure dataset was generated by Ikon Science and includes analysis on fluid type, fluid gradient, and overpressure, where possible, from 194 wells (see Appendix 1 Figure 1). The wells selected for the study provide a good geographical coverage of the area of interest and were selected for their sampling of the Triassic and Jurassic intervals, for calibration of key fields and to constrain pressure variations across the main structural elements of the basin.

[1] HPHT conditions are in this study defined as pressures >10,000 psi initial aquifer pressure and > 300°F (~150°C) in temperature sensu Winefield et al., 2005.

[2] In the UK Central North Sea and Moray Firth ca. 38% of dry holes are associated with seal failure (Mathieu, 2015). Rudolph and Goulding (2017) show that seal failure is increasingly common in the most mature basins.

All pressure data, either reservoir pressure data or Leak-Off Tests (LOTs) and Formation Integrity Tests (FITs), were assessed for magnitude and quality subject to what informationis available from the NDR. A standardised criterion for assessing reservoir pressure data was used to assign a quality flag to all data to produce a unified pressure database. The pressure data was assigned a quality flag based on analysis of pressure build-up plots available on the NDR (note that for c.50% of wells there was no build-up plots available in published well reports and therefore the quality is flagged as 'unknown').

A regionally consistent approach was taken to calculate overpressures relative to a consistent hydrostatic gradient of 0.445 psi/ft in all wells. More detail on the methodology Ikon Science followed to create the pressure dataset can be found in the report supplied by Ikon Science (Appendix 1). It is of note that this pressure study did not include history matching of the data to account for data from wells that were drilled after depletion of a connected reservoir. There will therefore be some inherent variation in the pressure data within a given cell where pressure depletion has taken place. The data have however been selected to minimise this issue where possible.

All stratigraphic data referenced in the pressure database have been taken from the OGA Collated Well Tops database[3]. Where the OGA database did not have reported tops, Ikon Science used the stratigraphy in the end of well report but applied the equivalent nomenclature from the OGA Collated Well Tops database (Appendix 1).

To map pressure cells, aquifer overpressure is required. In most cases the amount of aquifer overpressure was derived from wells with direct measurements in the water leg. However, in 19 of the selected wells, the amount of aquifer overpressure was derived indirectly by projecting gradients through the hydrocarbon leg to a known (mapped or petrophysically defined) hydrocarbon/water contact and then estimating the range of aquifer overpressure. The specific methodology for each of the 19 wells is provided in this report.

Additional pressure data added by the OGA

In a few instances, the available data in the Ikon Science pressure database was not adequate to constrain an interpretation of a pressure cell. Additional raw pressure data was added to the dataset by the OGA from files within the NDR. These data had not previously been contained in the Ikon Science dataset but were deemed to add value to the pressure evaluation carried out in this study. These data are therefore not covered in Appendix 1 and have not undergone Ikon Science's quality assessment. The additional data is summarised in table 1.

Well	Data type	NDR File ID
21/20b- 4Z	RFT (Jurassic)	96680308
21/25- 2	RFT (Jurassic)	1905512
21/20b- 4Z	RFT (Jurassic)	96680308
22/11b- 13	MDT (Jurassic)	2000989
22/02- 3	RFT (Triassic)	233270598
22/16- 6	DST (Jurassic)	257265624
22/16- 6Z	XPT (Jurassic)	244964758
22/22a- 7	MDT (Jurassic)	235853309

Table 1 Data for 8 wells added by the OGA to the Ikon Science pressure database. This additional data was taken from reports held within the NDR.

[3] OGA Collated Well Tops are available via the Open Data Site (direct link: OGA Collated Well Tops)

Pressure cell mapping

Within a connected system or pressure cell, aquifer overpressures will be consistent. To interpret pressure cell regimes, pressures should therefore be compared as aquifer overpressure. (Winefield et al. 2005). The pressure cell map presented here (Figure 1) is based on aquifer overpressures within the Triassic and Jurassic succession of the Central North Sea. Where the measured pore pressure exceeds the hydrostatic pressure, the excess pressure is called “overpressure”. A pressure cell describes an area of similar overpressure with a change in overpressure magnitude occurring at the boundary to a neighbouring pressure cell (Gaarenstroom et al., 1999, Winefield, 2005).

Determining aquifer pressures from hydrocarbon pressure points

Absolute pressures measured in the hydrocarbon leg cannot be used directly to compare aquifer overpressure due to different fluid densities. Based on the hydrocarbon fluid type and column thickness, they measure higher apparent overpressure compared to the aquifer. However, a large proportion of wells in the database have pressure measurements taken only within a hydrocarbon column. Spatially, this resulted in some areas not having adequate data to resolve the pressure cell distribution in detail and so further analysis was undertaken to derive an aquifer pressure in some wells.

Where pressure measurements were taken in a hydrocarbon bearing interval, the aquifer overpressure can be calculated if a hydrocarbon-water-contact (HWC) is known from direct observations, formation evaluation or petrophysical analysis of well data within a hydrocarbon accumulation. In these examples, the aquifer pressure was calculated by taking the pressure at the intersect between the hydrocarbon gradient and water gradient (0.445 psi/ft) at the HWC depth (see Figure 2). An observed contact between hydrocarbon and water (GWC = gas-water-contact; OWC = oil-water-contact) is the preferable contact type to be used for analysis.

Where pressure measurements were taken in a hydrocarbon bearing interval and no HWC was observed, or the well did not drill below the hydrocarbon leg, the HWC was estimated from either (in order of increasing uncertainty):

a) a known field HWC;

b) a range of possible contacts between a water up to (WUT) and hydrocarbon down to (HDT); or

c) mapped structural spill or leak points for the drilled structure (e.g. from publications or field development plans).

Using oil-down-to (ODT) and gas-down-to (GDT) may lead to an overestimation of aquifer overpressures whereas WUT and spill point may lead to an underestimation of aquifer overpressures (Figure 2).

Where multiple pressure measurements were available from a hydrocarbon leg, and displayed a clear gradient, this hydrocarbon gradient was used. Where only sparse data points were available, a standard hydrocarbon gradient was applied to the pressure points based on the reported fluid type (standard gradients used: oil = 0.3 psi/ft; condensate = 0.2 psi/ft; gas = 0.1 psi/ft, Figure 2). This may introduce a minor error where fluids vary from these assumptions, but in the absence of accurate fluid data and without conducting further detailed analysis, this approach was considered adequate at a regional scale.

In the more uncertain scenarios, the aquifer pressures were estimated by taking the pressure at the intersect between the hydrocarbon gradient and water gradient (0.445 psi/ft) at either HDT and WUT depths, or possible spill/leak point depths, to provide a range of possible pressures for each well (Figure 2). This approach introduces uncertainty ranges typically in the 10’s of psi overpressure, but in some isolated cases the uncertainty can be much higher.

As mentioned above, this study did not include production history matching of the pressure data. There will therefore be some inherent variation in the pressure data within a given cell where a well is drilled after depletion of a connected reservoir.

In total, additional analysis to derive aquifer pressures were carried out for 31 wells, where aquifer pressures were not supplied in the Ikon Science database. 19 of these wells only had data recorded in the hydrocarbon column. For 12 of the 31 wells, based on additional well information, the fluid type was either reclassified as water or a combination of water and hydrocarbon leg data was available to calculate aquifer pressure. Further detail on the additional analysis carried out for these wells is given below.

Aquifer overpressure was calculated for each well as the difference between normal hydrostatic pressure, based on a gradient of 0.445 psi/ft, and the calculated/estimated aquifer pressure described above. The minimum and maximum overpressure value assigned to a pressure cell was rounded to the nearest ten psi.

Pressure cell boundaries

Boundaries between pressure cells are commonly either faults, halokinetic structures or stratigraphic boundaries. In this study most of the large-scale changes in pressure regime are associated with the main rift faults that have been identified from seismic interpretation.

Halokinetic (pod/interpod and diapiric) structures are not directly incorporated in this regional pressure cell study and would require detailed mapping of the Zechstein salt and Mesozoic pod/interpod permeability architecture, which was beyond the scope of this work.

Most pressure cell boundaries in this report are digitised faults from published literature (Erratt et al., 1999; Keller et al., 2005; Archer et al., 2010; Hollywood and Olson, 2010; Charles and Ryzhikov, 2015) or relinquishment reports provided by licence operators, published through the OGA's Open Data Portal[4]. Some pressure cell boundaries are interpreted from other data sources provided to the OGA. These include historic field development plans, company presentations, and licence round application material. Faults from these sources are summarised and placed as pressure cell boundaries where a marked change in overpressure magnitude exists.

Pressure cell interpretation

A pressure cell map was generated by plotting the distribution of aquifer overpressures for the Jurassic and Triassic. Wells with similar ranges in aquifer overpressure were interpreted to be within individual pressure cells (Figure 1). A pressure cell boundary was drawn between wells of differing aquifer overpressure using regional faults as a guide to its position. In some places a pressure cell boundary is clearly required, but very little faulting is mapped. Here it is assumed the pressure cell is bounded by a halokinetic structure and/or unmapped faults. The main output of this study is a combined pressure cell map in which both Jurassic and Triassic aquifer overpressures are summarised. This approach resulted in full coverage of the CNS HPHT core area.

A general relationship between overpressure and depth is observable in these data, confirming trends identified in published literature (Gaarenstroom et al., 1993; Winefield et al., 2005, Figure 3). Highest overpressures are generally encountered in the deeper graben areas, specifically in the West and East Central Graben and in the Fisher Bank Basin (Figure 1, Figure 3). Here the aquifer overpressure commonly lies in a range of 7000 to 9000 psi. On the highs, such as the Forties-Montrose High and the Josephine High, aquifer overpressure is between 1000 and 4500 psi. Towards the basin margins the pressure approaches hydrostatic. Overpressures decline in a stepwise fashion across fault terraces from the graben onto the Forties-Montrose High.

Due the combined Jurassic/Triassic pressure cell interpretation the difference between Jurassic and Triassic overpressure distribution is not resolved in the combined pressure cell map. This leads to overpressure ranges within a given pressure cell of 250 psi to 1000 psi (Figure 1). To supplement the combined pressure cell map, two additional maps using only Jurassic (Figure 4) and only Triassic (Figure 5) data have been produced. Good aquifer data coverage in the Jurassic (103 wells with aquifer data) allows for a pressure cell map with only a few gaps whereas Triassic aquifer overpressure data was only available for 44 wells yielding a sparsely populated pressure cell map. Comparisons between the two are therefore only indicative and would best be underpinned by further analysis and additional data. In the graben settings (West and East Central Graben, Fisher Bank Basin) the Triassic generally has higher overpressures than the overlying Jurassic succession. In contrast, on the Forties-Montrose High and the Josephine High the Triassic shows lower overpressures compared to the Jurassic (overpressure difference between 50 psi and 1000 psi).

Overpressure differences can also be found within a single formation. An example for this is the Jurassic Fulmar Formation in the West Forties Basin which is discussed in more detail in the respective section of this report (West Forties Basin). Here the Jurassic Fulmar Formation is developed in two sand intervals with separate aquifer gradients. An overpressure range of more than 500 psi is encountered in these two sand intervals (wells 21/20a- 1 and 22/16a- 2) which illustrates that summarising overpressure on the stratigraphic period level does not resolve all stratigraphic overpressure complexities.

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[4] Relinquishment reports can be accessed here: https://data-ogauthority.opendata.arcgis.com/pages/relinquishments

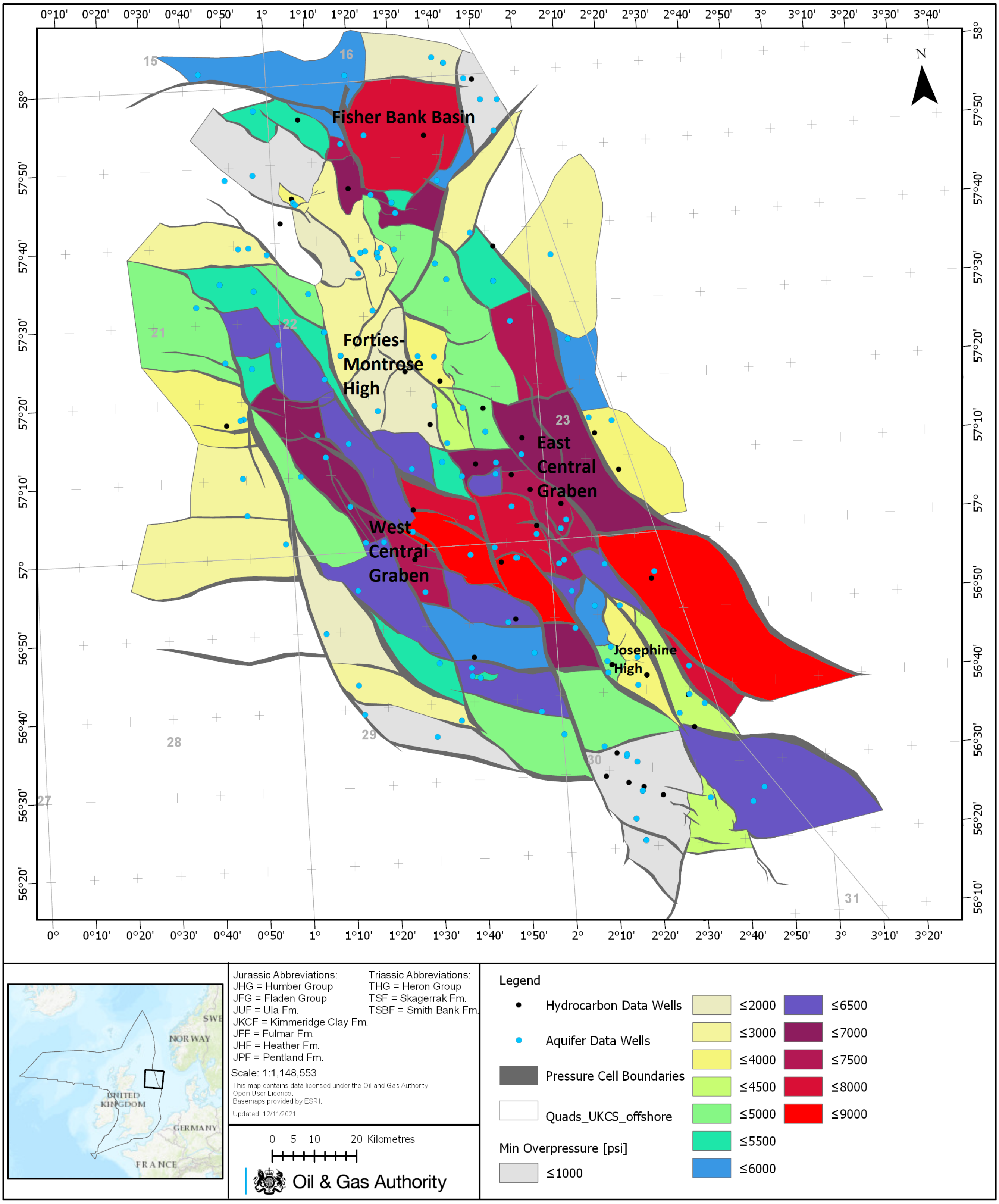

Figure 1: The combined Jurassic and Triassic pressure cell map shows the general trend of high overpressures in grabens and low overpressures on highs. All 194 wells contained in the pressure dataset are marked on the map.

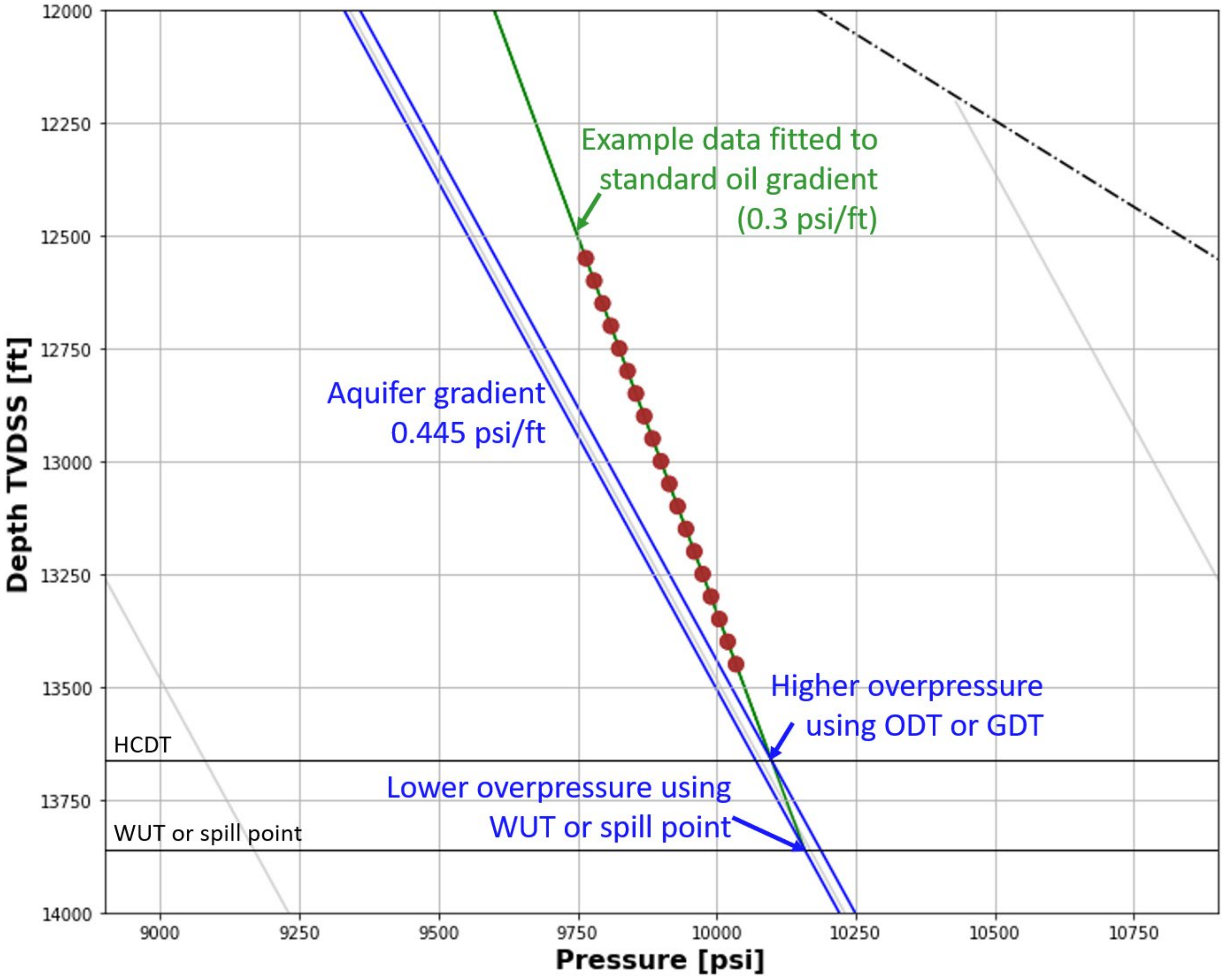

Figure 2: Illustration of fitting a hydrocarbon pressure gradient to pressure data and extrapolating from the data points to different kinds of contacts. The determined aquifer overpressure is the difference between the expected hydrostatic pressure and the measured pressure at the contact depth. Overpressure may be overestimated using an hydrocarbon down to (HCDT) and may be underestimated using a WUT or spill point.

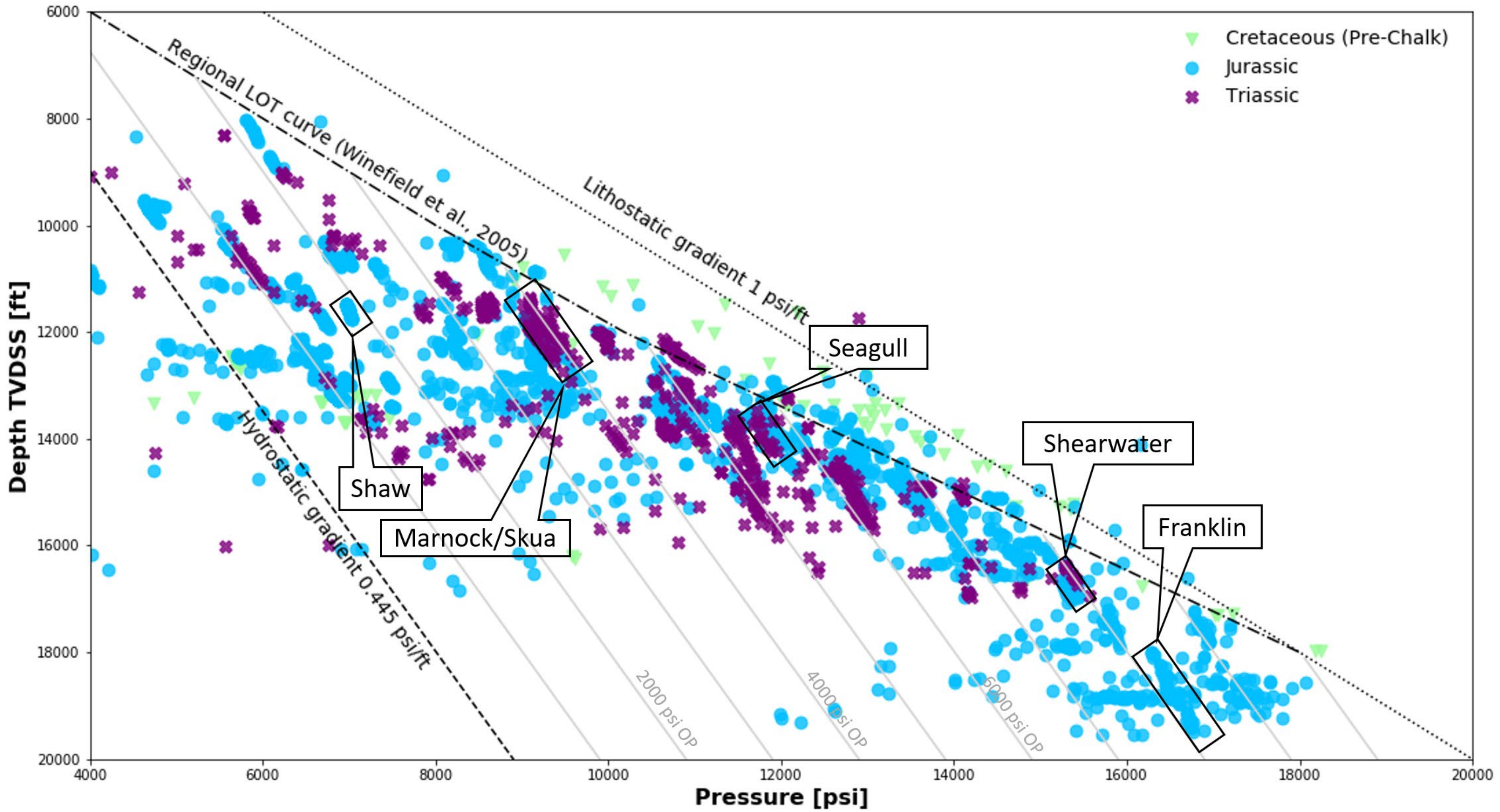

Figure 3: Pressure vs depth plot showing all data points available to this study. Highlighted are data from some fields illustrating the presence of high overpressures in the Central Graben (Shearwater, Franklin, >8000 psi overpressure) and lower overpressures on the Forties-Montrose High (Shaw, <2000 psi overpressure). Seagull and Marnock/Skua are situated in the East Forties Basin, the former closer to the Central Graben HPHT core area, the latter closer to the Forties-Montrose High.

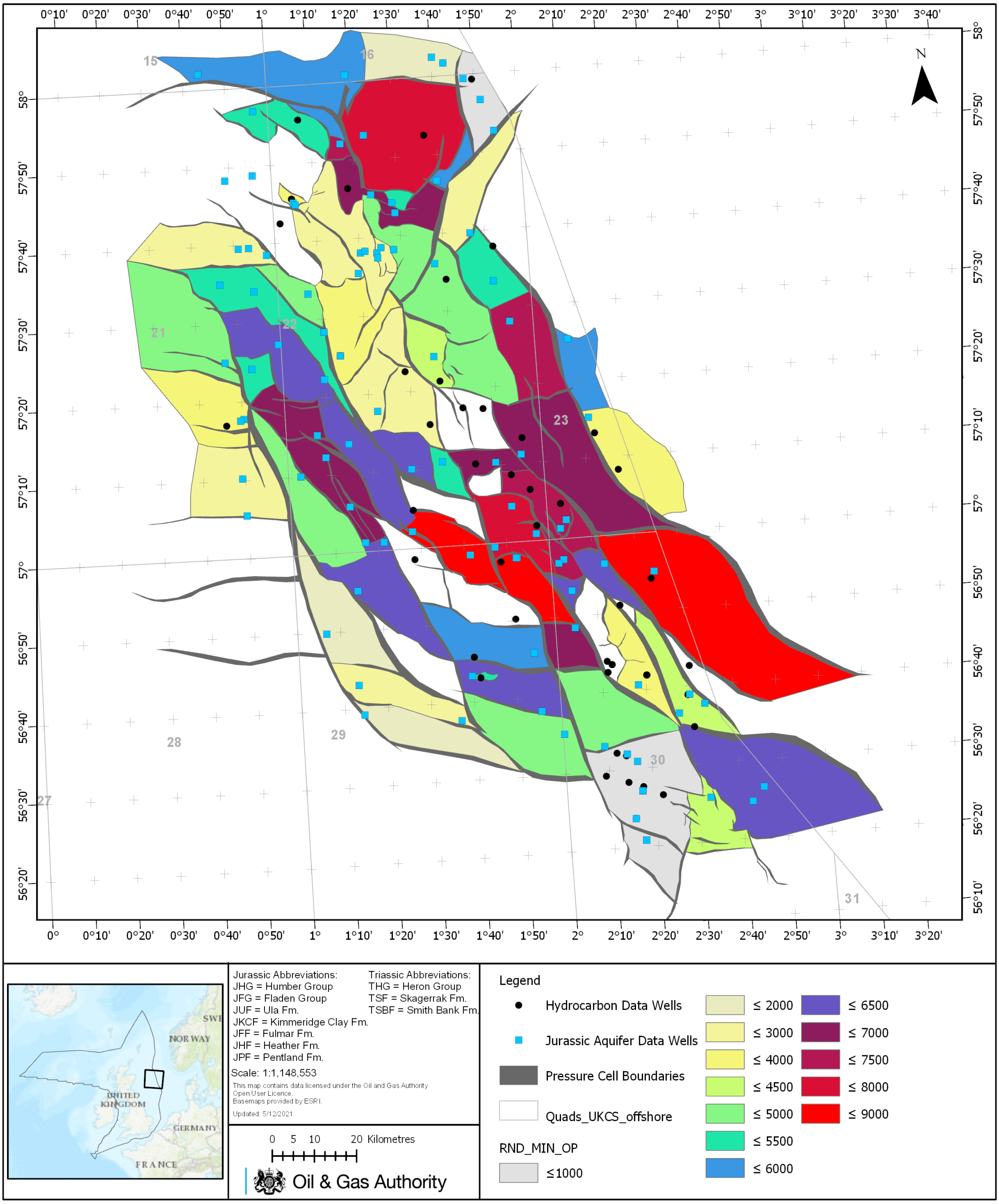

Figure 4: The Jurassic pressure cell map is based on aquifer data from 103 wells and has only a few gaps.

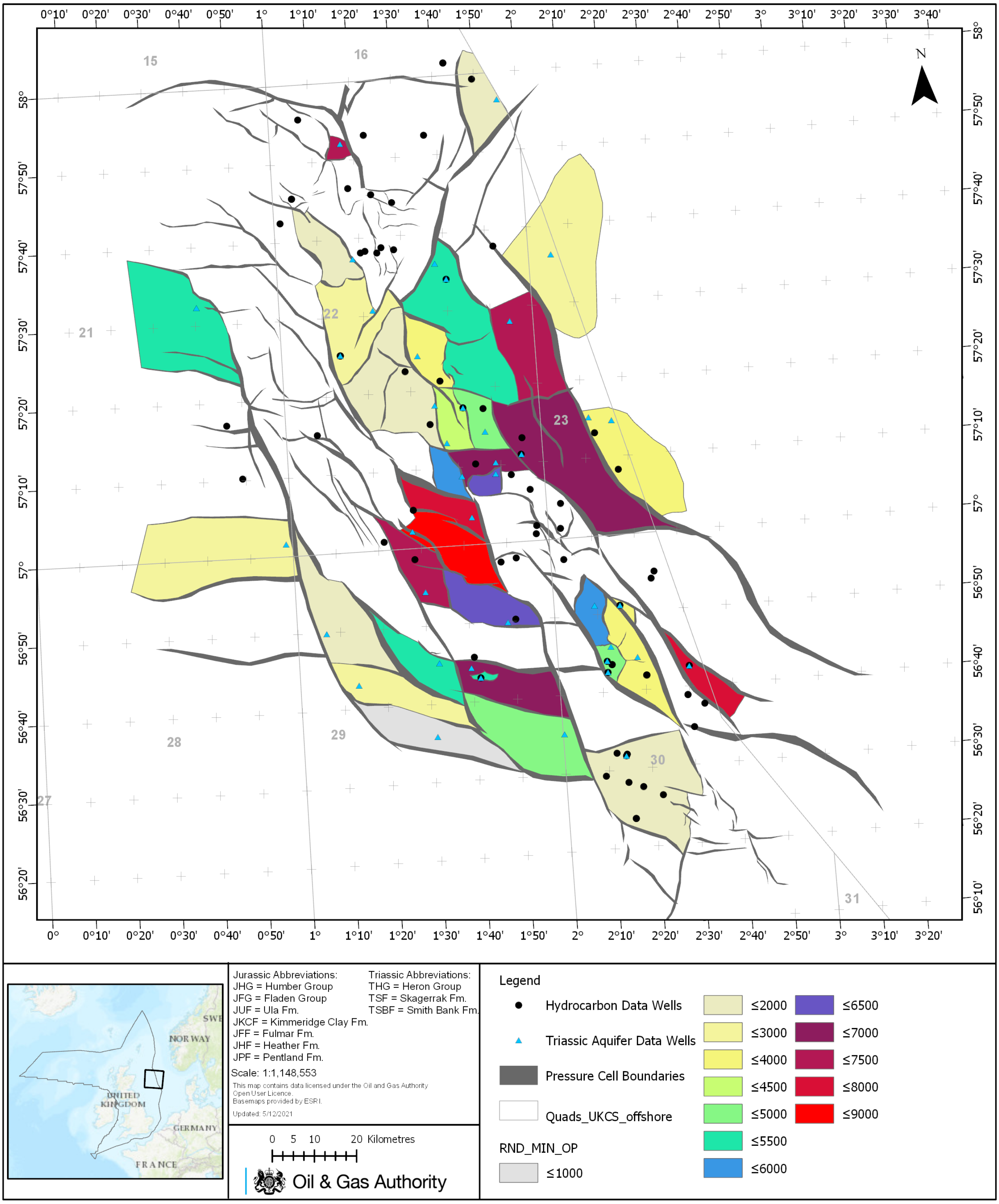

Figure 5: The Triassic pressure cell map is based on aquifer data from 44 wells. Coverage of the HPHT core area is impacted by the small amount of data available and only about half of the interpreted pressure cells could be populated with a Triassic aquifer overpressure.

Fisher Bank Basin and surrounding areas

The highest overpressures in the Fisher Bank Basin are recorded in its centre, in well 22/02- 2 ranging from 7902 to 8010 psi in the Jurassic Fulmar Formation (Figure 6, Figure 7). The cells bordering the Fisher Bank Basin to the East have lower overpressures between 2800 psi in the south (Jurassic Heather Formation in well 22/14a- 2, Figure 6, Figure 7) and 1131 psi closer to the Jæren High (Jurassic Humber Group in well 22/05b- 9).

Pressure cell containing well 22/02- 3 (Cell ID: 2)

The Ikon Science dataset contains a mudweight-derived data point from the Jurassic Heather Formation for well 22/02- 3. Additional RFT data for the Triassic Skagerrak Formation is added to the dataset from the NDR (File ID: 233270598, Table 1). It is assumed that both data points are taken in water-bearing intervals.

The overpressure of 7355 psi for the Jurassic Heather Formation is taken from the Ikon Science dataset and the fluid type is reclassified as water. A standard water gradient is fitted to the Triassic RFT data, resulting in an overpressure of 7390 psi (Figure 6, Figure 8)

This pressure cell is characterised by overpressures between 7360 and 7390 psi.

Pressure cell containing well 22/02- 2; 22/04b- 6 (Cell ID: 13)

This pressure cell contains the MacLeod discovery well 22/02- 2, which discovered gas condensate in the Jurassic Fulmar Formation in 1983. The Ikon Science dataset records two RFT data points in the Fulmar Formation which are classified as "poor" quality, all other data points are classified as "invalid". Comments in the test summary outline that the formation was tight in some instances (NDR File ID 131819558, Figure 9).

Using the two poor quality RFT data points from well 22/02- 2 the hydrocarbon pressure gradient is extrapolated to a high case contact (*ca.*16950 ft TVDSS) and a low case contact (*ca.*16595 ft TVDSS) derived from legacy operator interpretations held by the OGA. An assumed gas condensate pressure gradient of 0.2 psi/ft yields overpressures of 8010 psi and 7902 psi at the high case and low case contacts, respectively (Figure 6, Figure 9).

The objective of well 22/04b- 6 ("White Bear") was the Fulmar Formation, which was absent. The well did encounter a secondary sand in the Kimmeridge Clay Formation. The formation was found to be tight and did not yield a good test result. There were no shows above the oil-based mud, but it is still assumed that the test was carried out in a gas-bearing section (NDR File ID: 235510504; 235510507). The mud weight used for the Kimmeridge Clay Formation was 17.3 ppg suggests an overpressure of 8620 psi in well 22/04b- 6[5]. Using mud weight to calculate overpressure can lead to overestimation of overpressure and this value is not used for analysis. Since no hydrocarbon or water gradient is visible in the scattered pressure data for this well, this well is not used for the pressure cell analysis.

The resulting pressure cell covers a range of 7900 – 8010 psi overpressure. However, the mud weight in well 22/04b-6 suggests that the maximum overpressure in this cell could be as high as 8620 psi.

Pressure cell containing wells 22/12a- 2; 22/12b- 4 (Cell ID: 6)

The fluid type for well 22/12a- 2 is reclassified as water since no clear indication of hydrocarbons are evident in the composite log. The RFT data from the Triassic Heron Group shows a pressure gradient which fits an aquifer overpressure between 1506 and 1538 psi reasonably well (Figure 6, Figure 10).

The RFT data recorded in well 22/12b- 4 shows a clear water gradient. Ikon Science recorded an overpressure of 2150 psi which is used for this pressure cell analysis.

This pressure cell is characterised by overpressures between 1510 and 2150 psi.

Pressure cell containing wells 22/12a- 1; 22/12a- 8 (Cell ID: 7)

Well 22/12a- 1 found oil in the Jurassic Fulmar Formation in 1987 and the discovery was later developed as the Howe field. The RFT data recorded in the Ikon Science dataset tested the oil-bearing section of the formation and the overpressure is determined through extrapolation of the pressure gradient to a contact. An ODT for the Howe field at 10330 ft TVDSS is used for the analysis. Ikon Science determined an oil gradient of 0.311 psi/ft from the RFT

[5] Formula used for calculation: Hydrostatic pressure [psi] = 0.052 x Mud Weight [ppg] x True Vertical Depth [ft] (from Schlumberger's oilfield glossary, https://glossary.oilfield.slb.com/Terms/h/hydrostatic_pressure.aspx).

data. The analysis yields an overpressure of 2118 psi for well 22/12a- 1 (Figure 7, Figure 11), although this likely overestimates the aquifer overpressure slightly for this well.

The RCI data recorded in well 22/12a- 8 shows a clear water gradient. Ikon Science recorded an overpressure of 2094 psi which is used for this pressure cell analysis.

This pressure cell is characterised by overpressures between 2090 and 2120 psi.

Other pressure cells in the Fisher Bank Basin and surrounding areas

No additional well data analysis was carried out on these pressure cells in the Fisher Bank Basin and surrounding area:

- Pressure cell containing wells 15/29c- 16; 16/27a- 3 (Cell ID: 3)
- Pressure cell containing wells 16/28- 5; 16/29a- 8; 16/29a- 13; 16/29a- 13Z (Cell ID: 20)
- Pressure cell containing wells 22/04- 3; 22/05a- 1; 22/05b- 9; 22/05b- 12; 22/05a- 13 (Cell ID: 14)
- Pressure cell containing wells 21/05b- 4; 22/01a- 4 (Cell ID: 1)
- Pressure cell containing well 21/10- 7 (Cell ID: 5)
- Pressure cell containing wells 22/07- 1; 22/07- 2 (Cell ID: 4)
- Pressure cell containing well 22/08a- 4 (Cell ID: 10)
- Pressure cell containing well 22/08a- 3 (Cell ID: 11)
- Pressure cell containing well 22/09- 5 (Cell ID: 12)
- Pressure cell containing wells 22/10a- 2; 22/14a- 2 (Cell ID: 90)
- Pressure cell containing wells 22/06a- 14Z; 22/06a- 14; 22/06c-B2; 22/06a- 15 (Cell ID: 91)
- Pressure cell containing wells 22/13a- 2; 22/13a- 8; 22/13a- 4 (Cell ID: 8)
- Pressure cell containing well 22/13b- 5 (Cell ID: 9)

Overpressure values for the pressure cells are derived from the analysis carried out by Ikon Science.

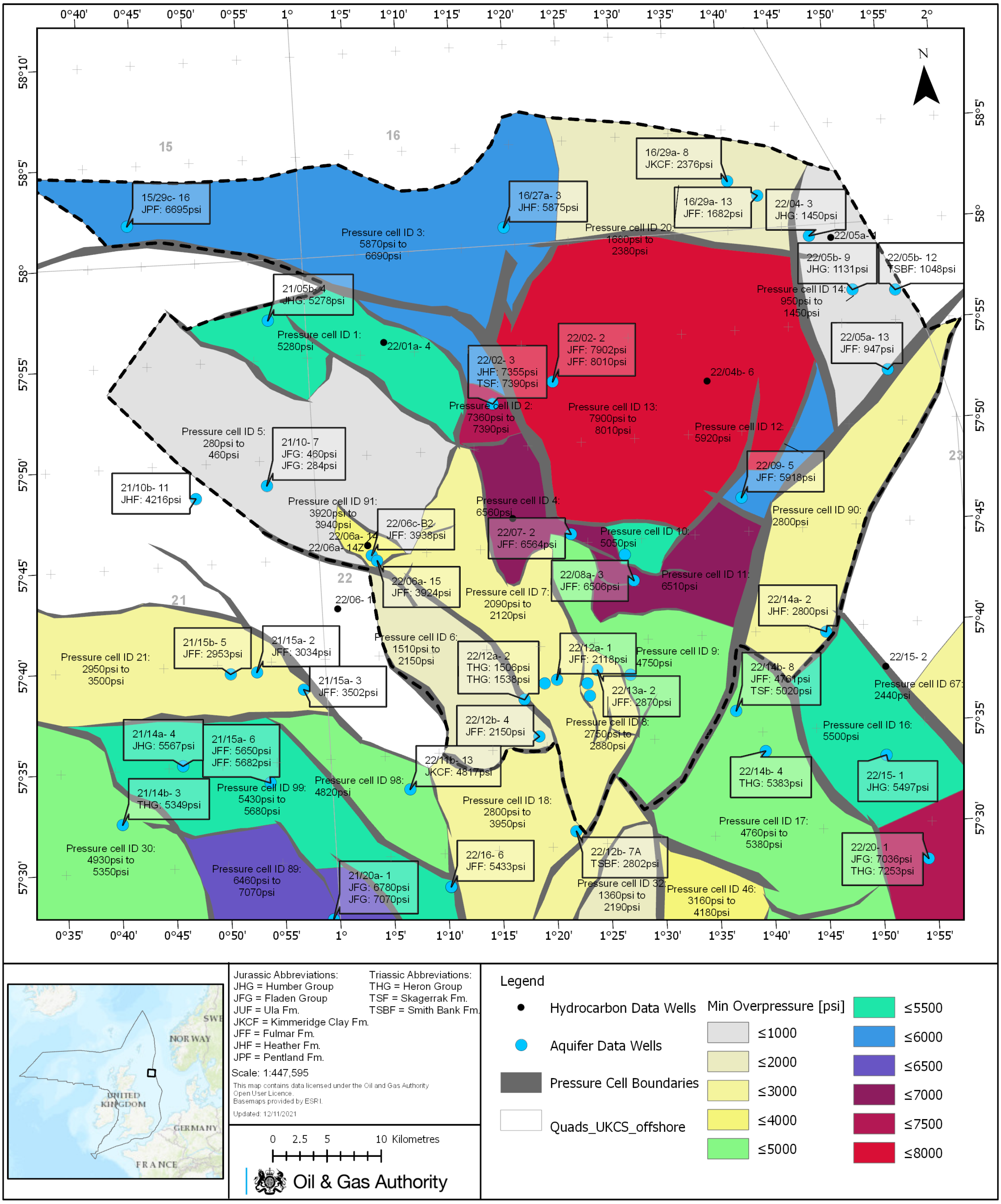

Figure 6: Combined Jurassic/Triassic pressure cell map showing the Fisher Bank Basin and surrounding areas

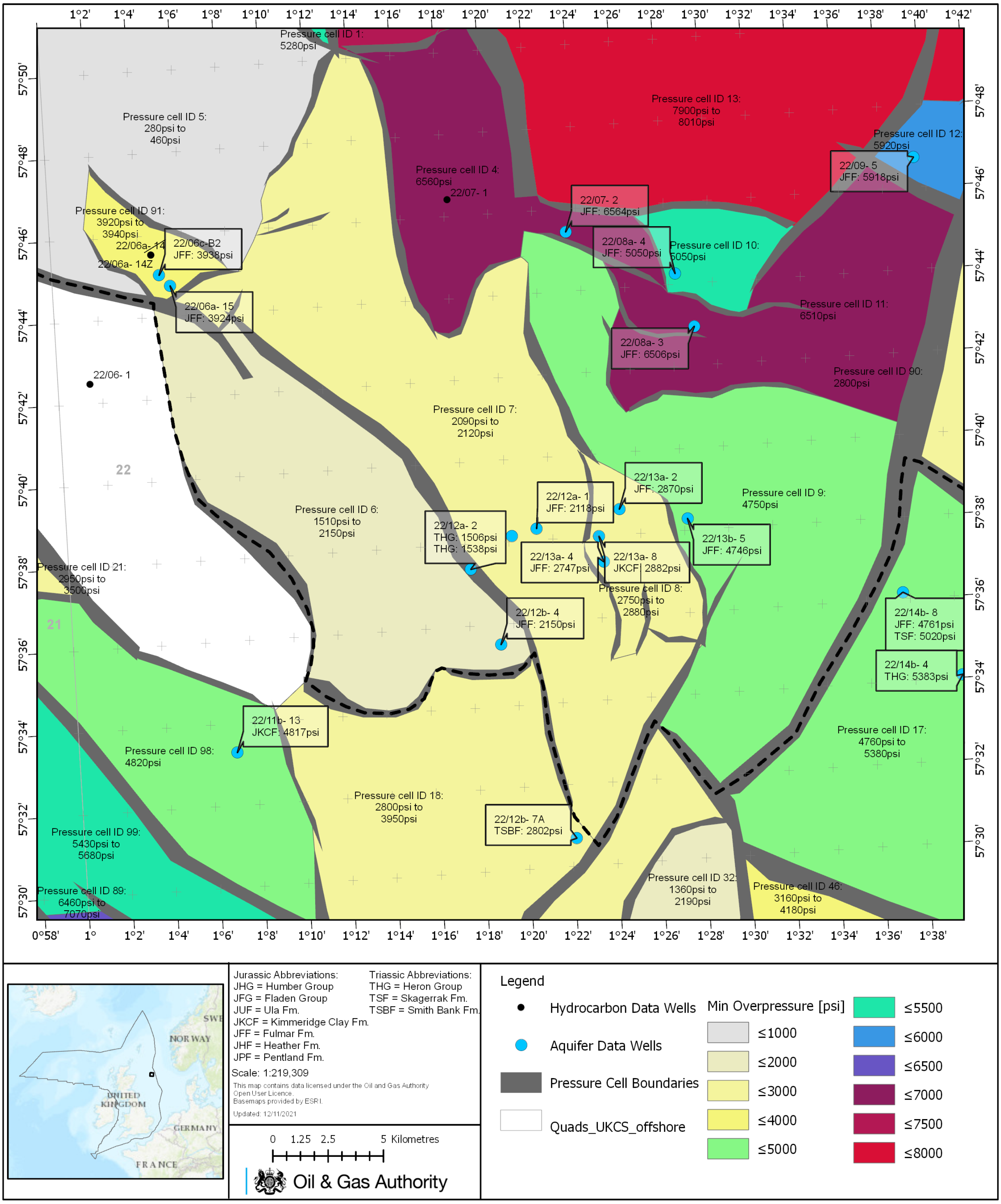

Figure 7: Combined Jurassic/Triassic pressure cell map showing the southern part of the Fisher Bank Basin area.

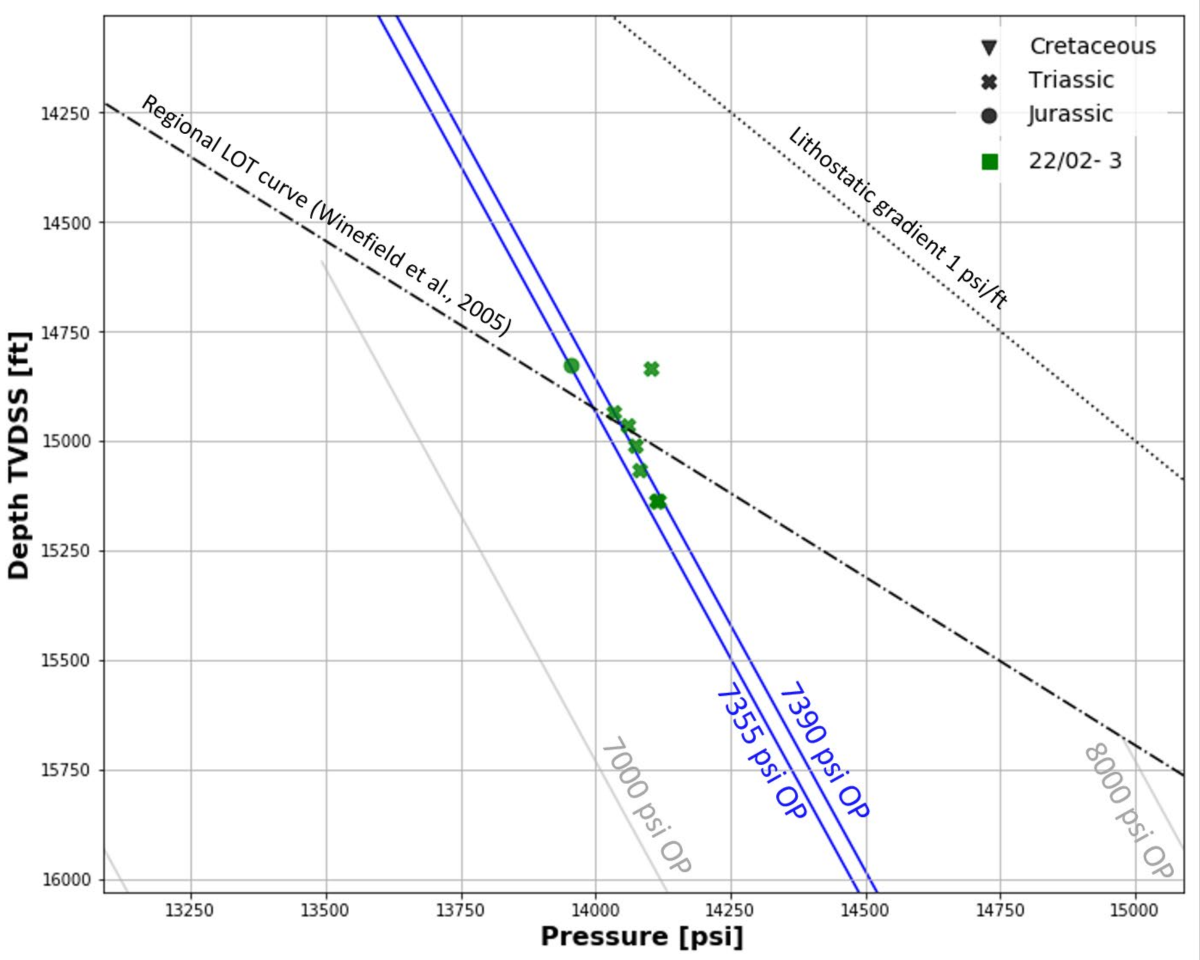

Figure 8: Depth vs pressure plot for well 22/02- 3

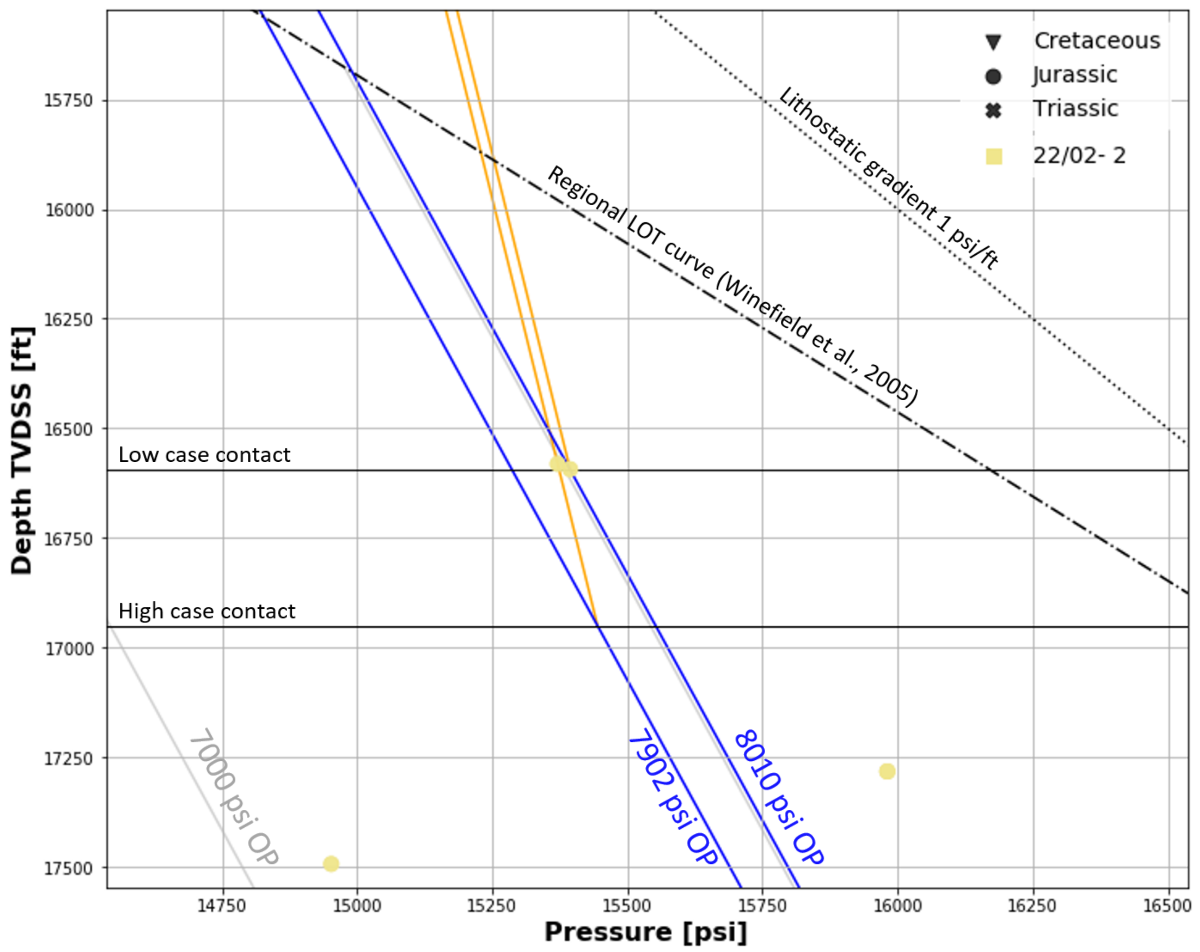

Figure 9: Depth vs pressure plot for well 22/02- 2

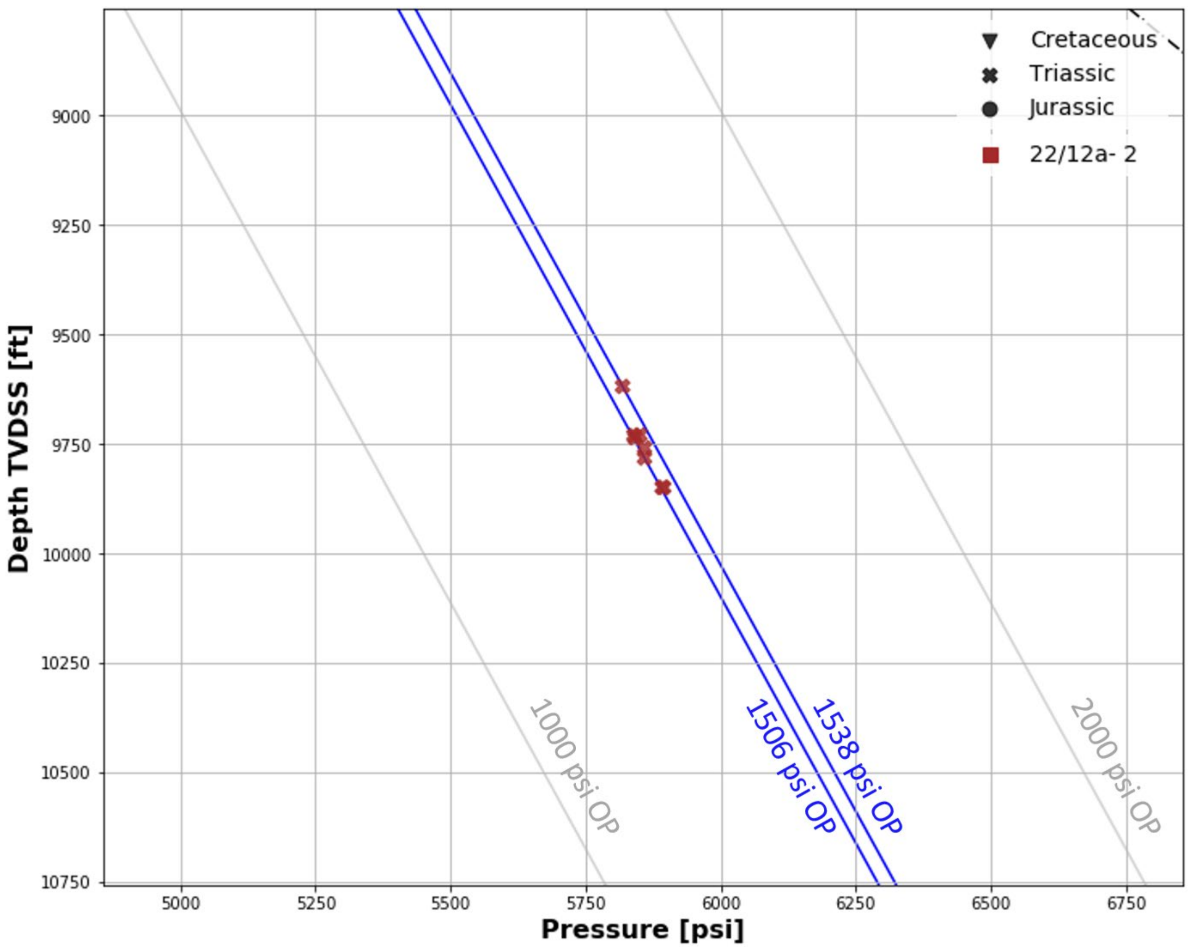

Figure 10: Depth vs pressure plot for well 22/12a- 2

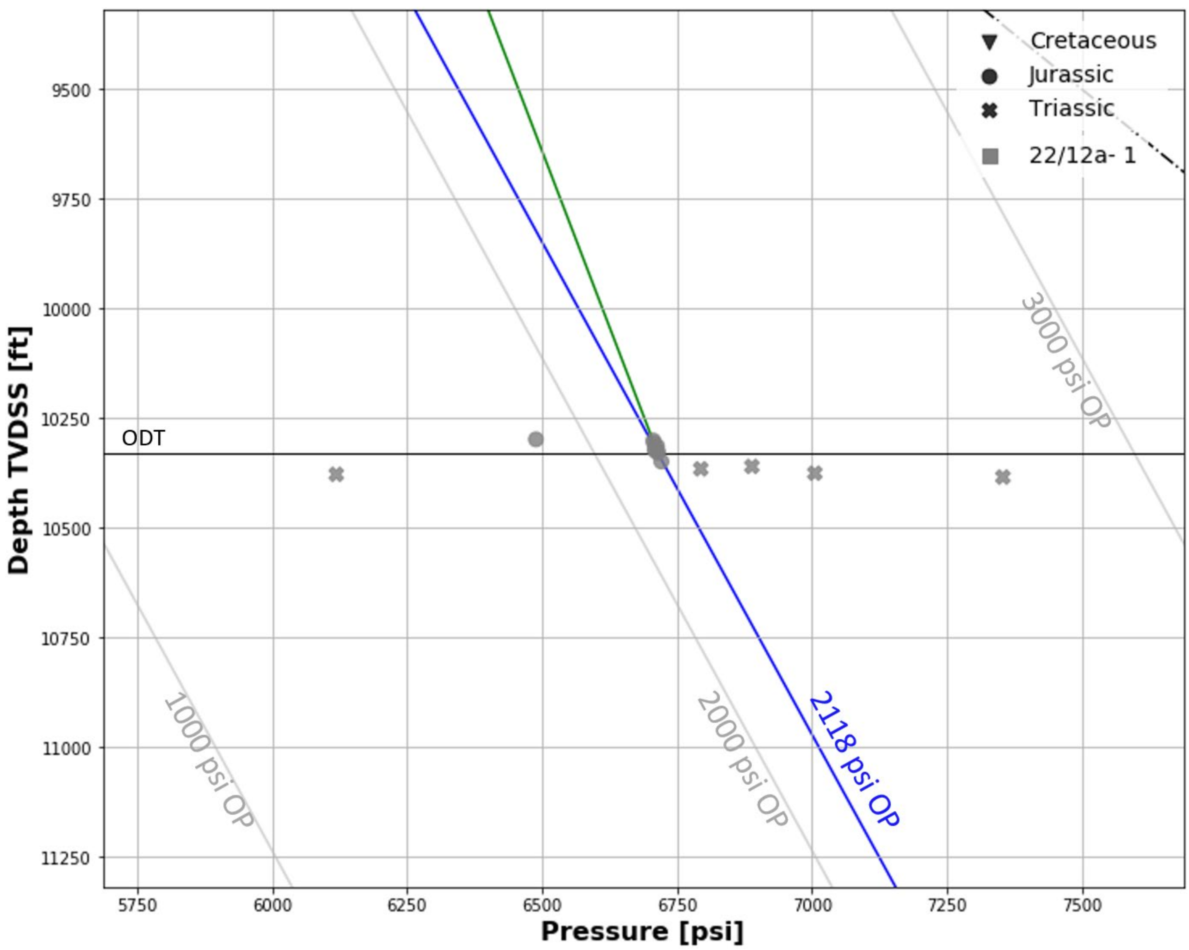

Figure 11: Depth vs pressure plot for well 22/12a- 1

West Forties Basin

The West Forties Basin is divided into 6 pressure cells between the Forties-Montrose High (FMH) to the East and the West Central Shelf to the West. Overpressure values from the Jurassic Fulmar Formation are higher in the deeper part of the basin and lower closer to the FMH. Overpressure decreases from 7070psi in well 21/20a- 1, in the south of the area bordering the Western Graben, to 2953psi in well 21/15b- 5 at the north-western end of the West Forties Basin (Figure 12). The Fulmar Formation is developed in two sandstone intervals in the area, divided by a shale unit. The lower and upper Fulmar sands can have different aquifer overpressures regimes in the studied wells, demonstrating they are not in communication.

Pressure cell containing wells 21/14b- 2; 21/14b- 3; 21/19- 3 (Cell ID: 30)

Well 21/14b- 3 has two pressure data points from kicks in the Cretaceous Valhall Formation and the Triassic Heron Group recorded in the Ikon Science dataset. The kick in the Triassic is recorded just below a cored interval. The core report shows high oil saturation up until the base of the core, which has been interpreted as an ODT in this well (13094 ft TVDSS). Despite the oil saturation evident in the core, this well is not classified as a discovery. The overpressure for the Triassic Heron Group is determined using the ODT and extrapolating to it using a standard oil gradient of 0.3 psi/ft. This yields an overpressure of 5349 psi for well 21/14b- 3 (Figure 12, Figure 13).

Well 21/19- 3 discovered oil in the Jurassic Fulmar Formation in 1990. This discovery was then appraised and developed as the Mallard field. High case and low case OWC's were assumed for the Mallard field (12970 and 12720 ft TVDSS, respectively). The overpressure is determined using a standard oil gradient of 0.3 psi/ft and extrapolating this from the pressure data to the high and low case contacts. Overpressures between 4928 and 4961 psi are determined for the Jurassic Fulmar Formation in well 21/19-3 (Figure 14).

Well 21/14b- 2 has data recorded from the hydrocarbon-bearing interval of the Cretaceous Cromer Knoll Group in the Ikon Science dataset. This data is not used for the pressure cell analysis.

This pressure cell is characterised by overpressures between 4930 and 5350 psi.

Pressure cell containing wells 22/11b- 13 (Cell ID: 98)

In well 22/11b- 13 a small oil column was encountered in the upper Jurassic Fulmar Formation sandstone (Macdui discovery), with water pressures measured in the lower Fulmar sandstone. The upper and lower Fulmar sandstones are separated by a mudstone in this well but may be in communication laterally. Assuming an oil gradient of 0.3 psi/ft for the upper Fulmar Formation data points and fitting a standard water gradient (0.445 psi/ft) to the lower Fulmar Formation data points, an OWC may be inferred at 13590 ft TVDSS. The resulting overpressure for the Jurassic Fulmar Formation in well 22/11b- 3 is 4820 psi (Figure 12, Figure 15). It is however not known if the sands are in communication or are pressured differently as is the case in wells 21/20a- 1 and 22/16a- 2 to the south.

This pressure cell is characterised by an overpressure of 4820 psi.

Pressure cell containing wells 21/14a- 4; 21/15a- 6; 22/16- 6; 22/16- 6Z (Cell ID: 99)

The Dalziel discovery, well 22/16- 6, encountered oil in the Jurassic Fulmar Formation. In addition to the Ikon Science dataset DST data from the NDR was added for this well (File ID: 257265624). The data fits a standard oil gradient of 0.3 psi/ft and is analysed using an OWC of 13720 ft TVDSS. These inputs yield an overpressure of 5433 psi for well 22/16- 6 (Figure 12, Figure 16). The sidetrack 22/16 -6Z was water-wet and penetrated an older interval of the Jurassic Fulmar Formation than well 22/16- 6. XPT pressure data following a standard water gradient of 0.445 psi/ft was added to the Ikon Science dataset from the NDR (File ID: 244964758). This older Jurassic Fulmar Formation interval has an overpressure of 5650 psi (Figure 12, Figure 17). The interpreted aquifer overpressure in well 22/16-6 is therefore significantly lower than that measured in the water-wet sidetrack 22/16- 6Z, suggesting that these Jurassic Fulmar Formation intervals are not in communication (Figure 18).

A pressure data point derived from mud weight recorded in the Ikon Science dataset for well 21/14a- 4 is reclassified as water. The well completion report mentions rising background gas levels in the Kimmeridge Clay Formation but there are no clear indicators for a hydrocarbon column (NDR File ID: 1794015). The overpressure value of 5567 psi, determined through fitting a standard water gradient to the data point, is used as aquifer overpressure for the pressure cell analysis (Figure 12, Figure 19). However, the confidence level in this data point is low.

The RFT pressure data in well 21/15a- 6 is scattered and only few data points lie on a shared water gradient. The composite log (NDR File ID: 1709349) and test log (NDR File ID: 1884479) show that there were a few issues encountered (tight test/seal failure) whilst testing the Jurassic Fulmar Formation especially below 14210ft. An overpressure between 5650 and 5682 psi is determined for well 21/15a- 6 (Figure 20).

This pressure cell is characterised by overpressures between 5430 and 5680 psi.

Pressure cell containing wells 21/20a- 1; 22/16a- 2 (Cell ID: 89)

Although there were minor oil shows and increasing gas levels in the Upper Jurassic of well 21/20a- 1, the well is considered dry. A LOT data point in the Ikon Science dataset is reclassified to be from a water-bearing interval. An additional fluid test data point was added from information found on the NDR (File ID: 1764780, Table 1). The data points record pressure from two separate sandstone intervals separated by a siltstone package and a standard water gradient (0.445 psi/ft) was fitted to the data points. The overpressure for the upper Fulmar sandstone is determined at 6780 psi and the lower Fulmar sandstone is pressured at 7070 psi (Figure 12, Figure 21, Figure 22).

Like 21/20a- 1, well 22/16a- 2 only encountered weak shows in the Upper Jurassic, is reclassified as water-bearing and a standard water gradient (0.445 psi/ft) is therefore used for the analysis (NDR File ID: 1967653). The two data points in the Fulmar Formation record pressures in an upper sand package and a lower sand package separated by a siltstone/mudstone interval. The upper Fulmar sandstone has an overpressure of 6455 psi whereas the lower Fulmar sandstone has a higher overpressure of 7060 psi (Figure 12, Figure 23, Figure 24).

The difference in overpressure between these two Fulmar Formation sand intervals suggests that the two sands are not laterally connected and that stratigraphic pinch-out likely plays a role in confining the pressure conditions in the sands.

The resulting pressure cell covers a range of 6460 – 7070 psi overpressure. The ‘cell’ however is characterised by a stratigraphically separated pressure regime with a lower Fulmar range of 7060 – 7070 psi overpressure and an upper Fulmar range of 6455 - 6780 psi overpressure.

Pressure cell containing well 21/20b- 4Z (Cell ID: 24)

Well 21/20b- 4Z discovered oil in two levels of the Jurassic Fulmar Formation (discovery “Christian”). Additional data from the NDR is added to the Ikon Science dataset which shows two distinct oil gradients in these two Fulmar Formation intervals (NDR File ID: 96680308, Figure 25). Two ODT’s are applied to well 21/20b- 4Z: 13520 ft TVDSS for the upper sands and 13790 ft TVDSS for the lower sands. A standard oil gradient of 0.3 psi/ft is applied to the data and the overpressures are interpolated using the oil gradient and contact depth. For the Fulmar Formation interval first encountered in the well an overpressure of 5214 is determined, whereas the second encountered Fulmar Formation interval is pressured at 5619 psi overpressure (Figure 12, Figure 25).

This pressure cell is characterised by overpressures between 5210 and 5620 psi.

Other pressure cells in the West Forties Basin

No additional well data analysis was carried out on the pressure cell containing wells 21/15b- 5; 21/15a- 2; 21/15a-3 (Cell ID: 21) in this area. Pressure data was available from the aquifer and overpressures for this pressure cell are derived from the analysis carried out by Ikon Science.

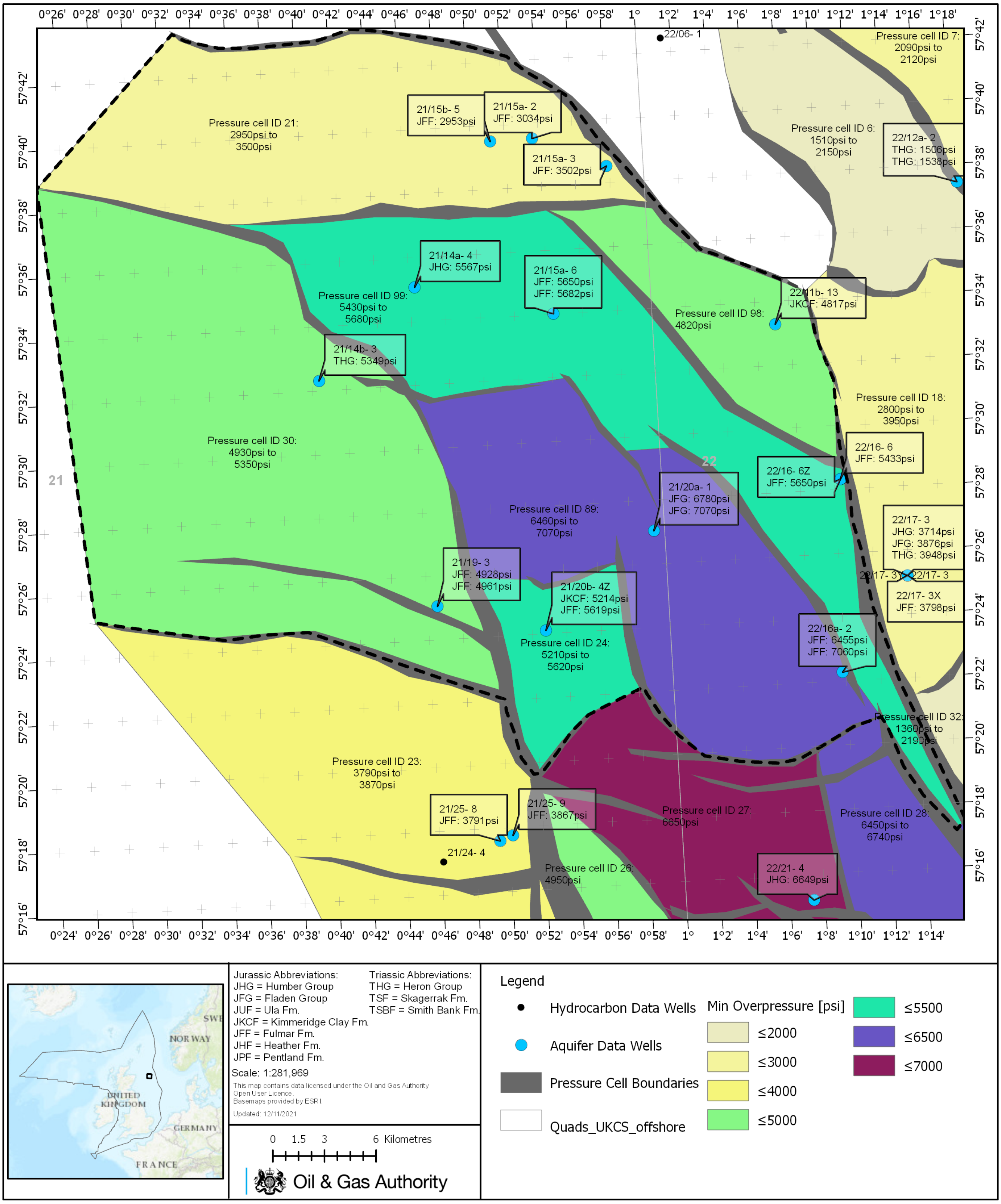

Figure 12: Combined Jurassic/Triassic pressure cell map showing the West Forties Basin area

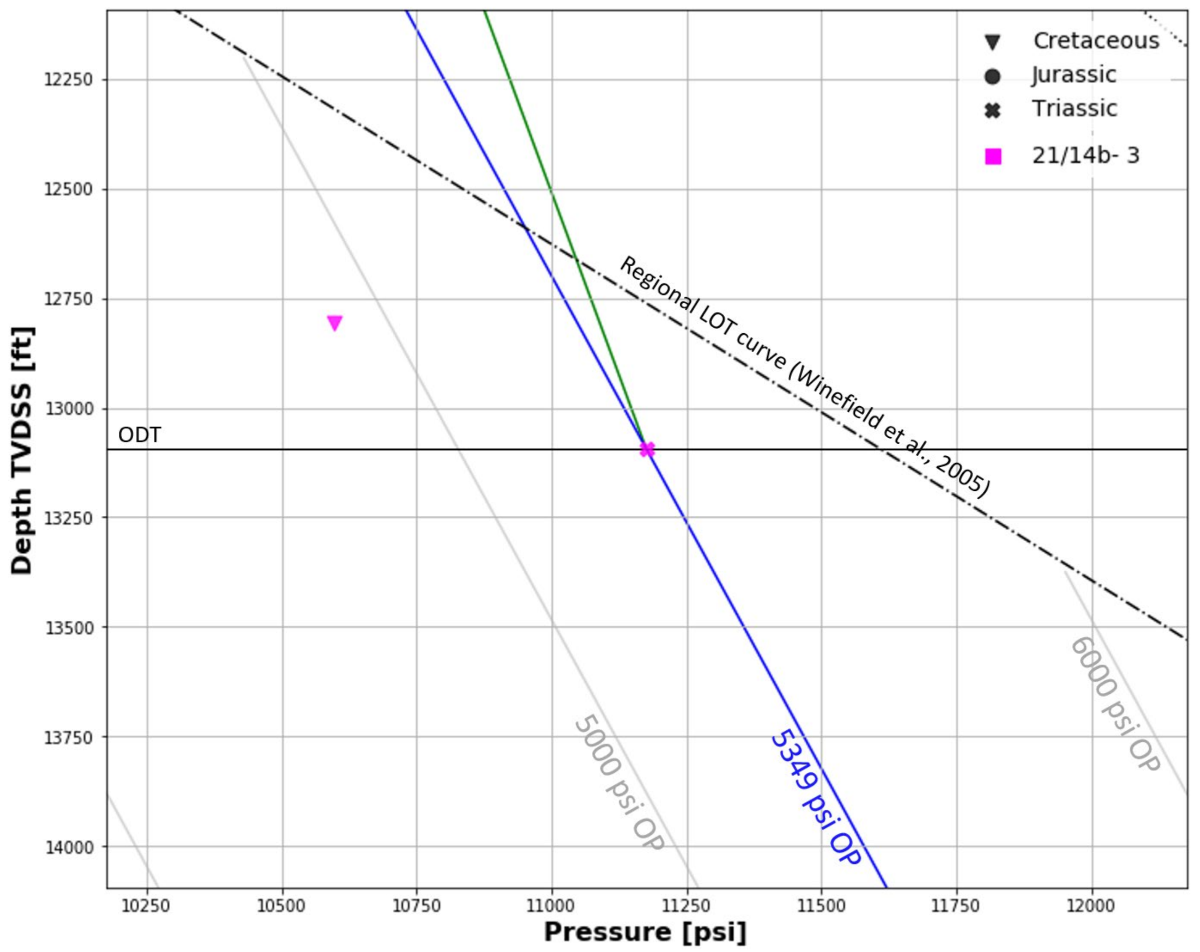

Figure 13: Depth vs pressure plot for well 22/14b- 3

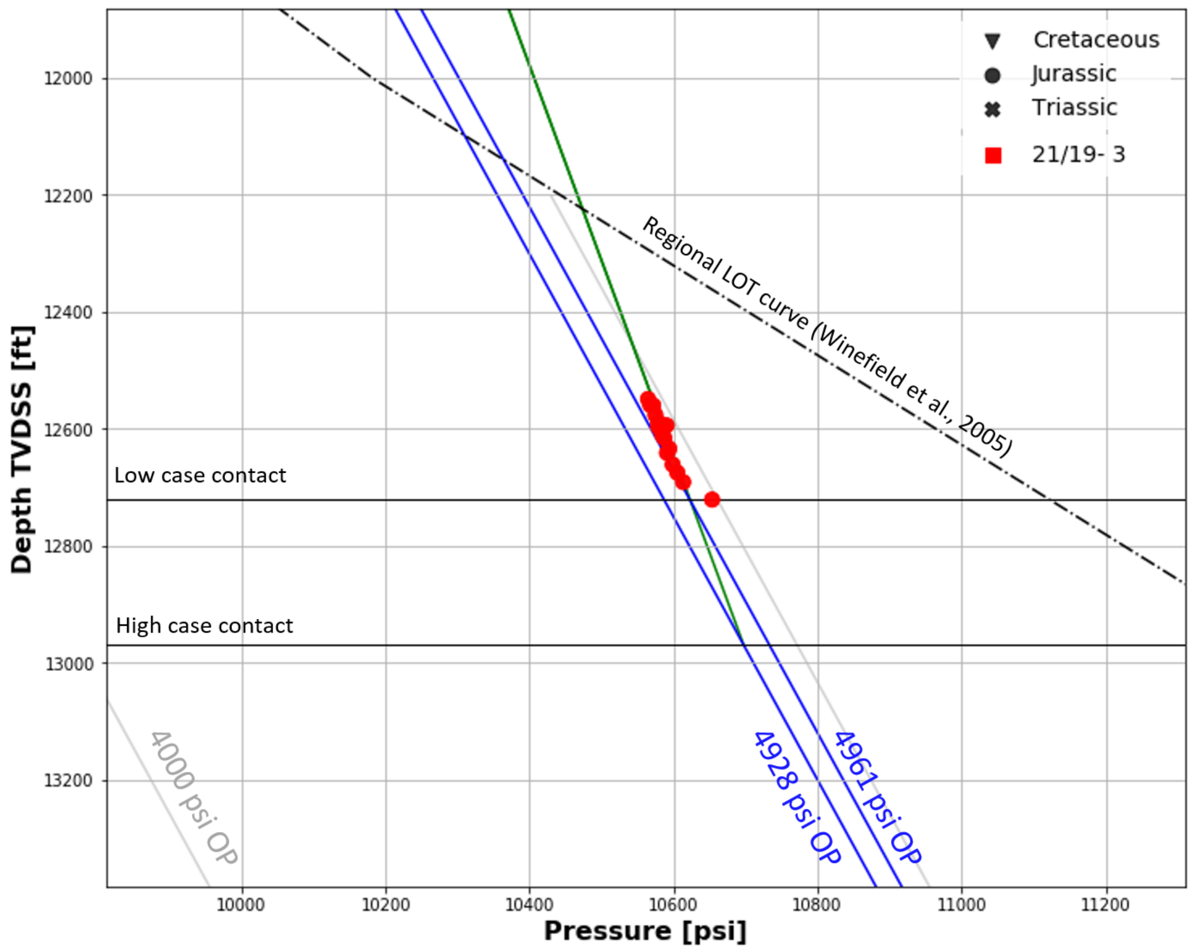

Figure 14: Depth vs pressure plot for well 21/19- 3

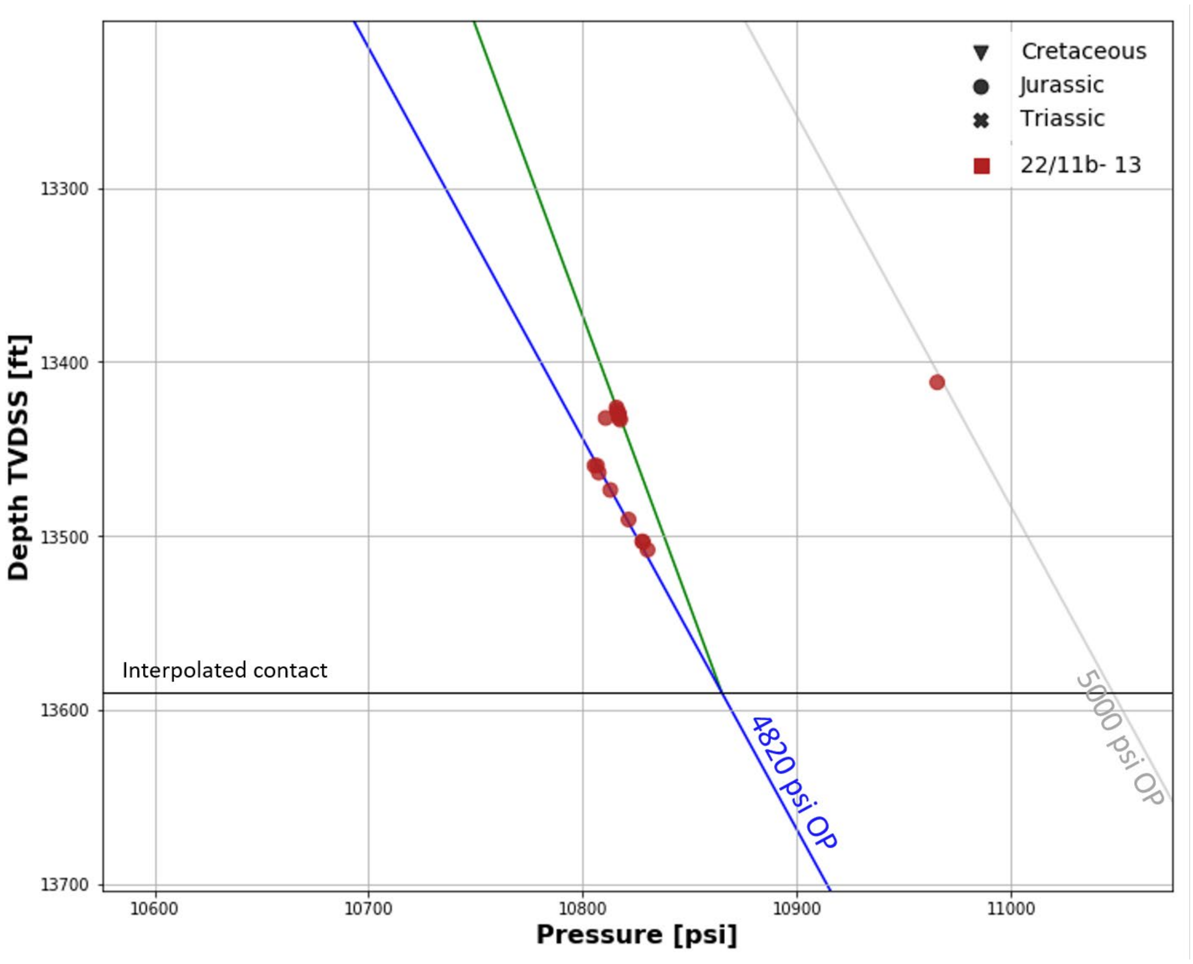

Figure 15: Depth vs pressure plot for well 22/11b- 13

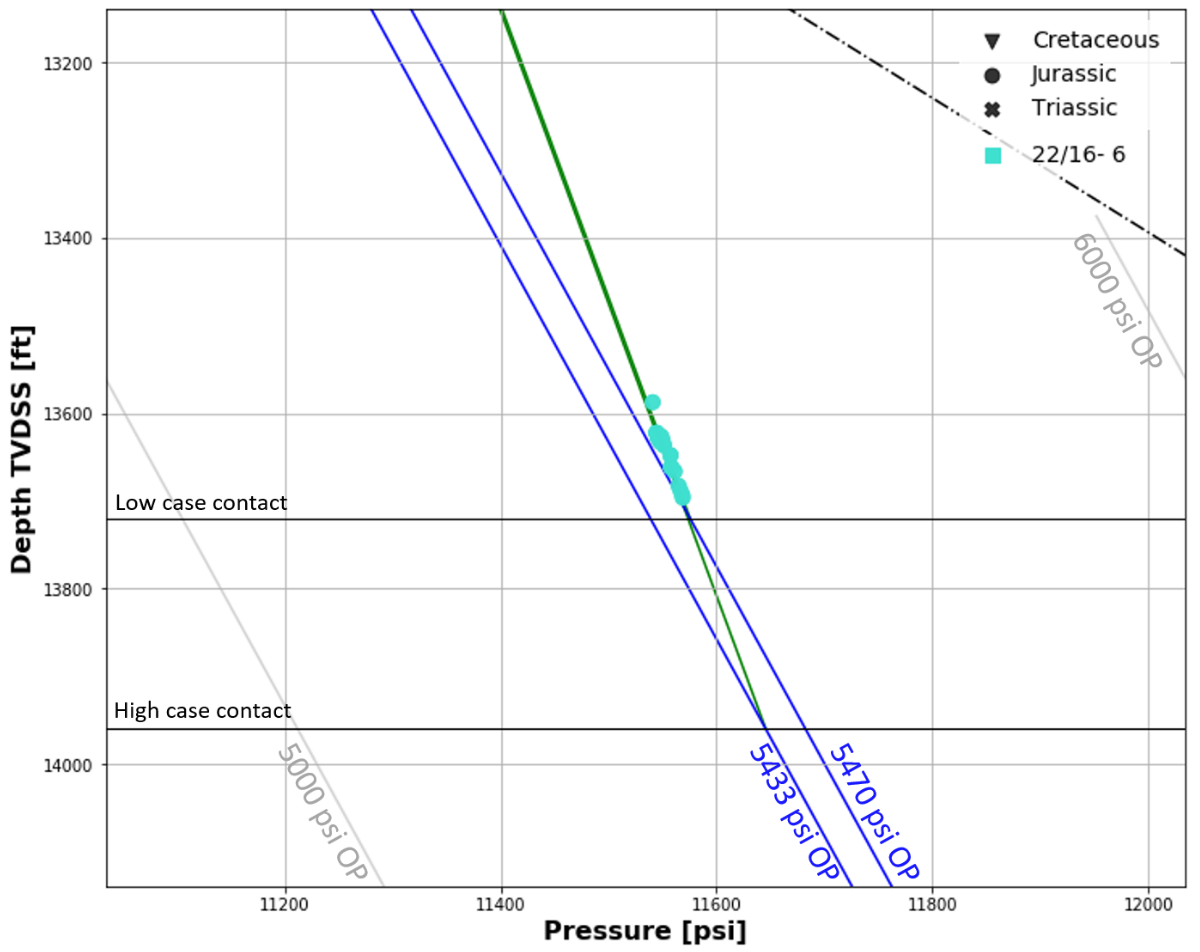

Figure 16: Depth vs pressure plot for well 22/16- 6

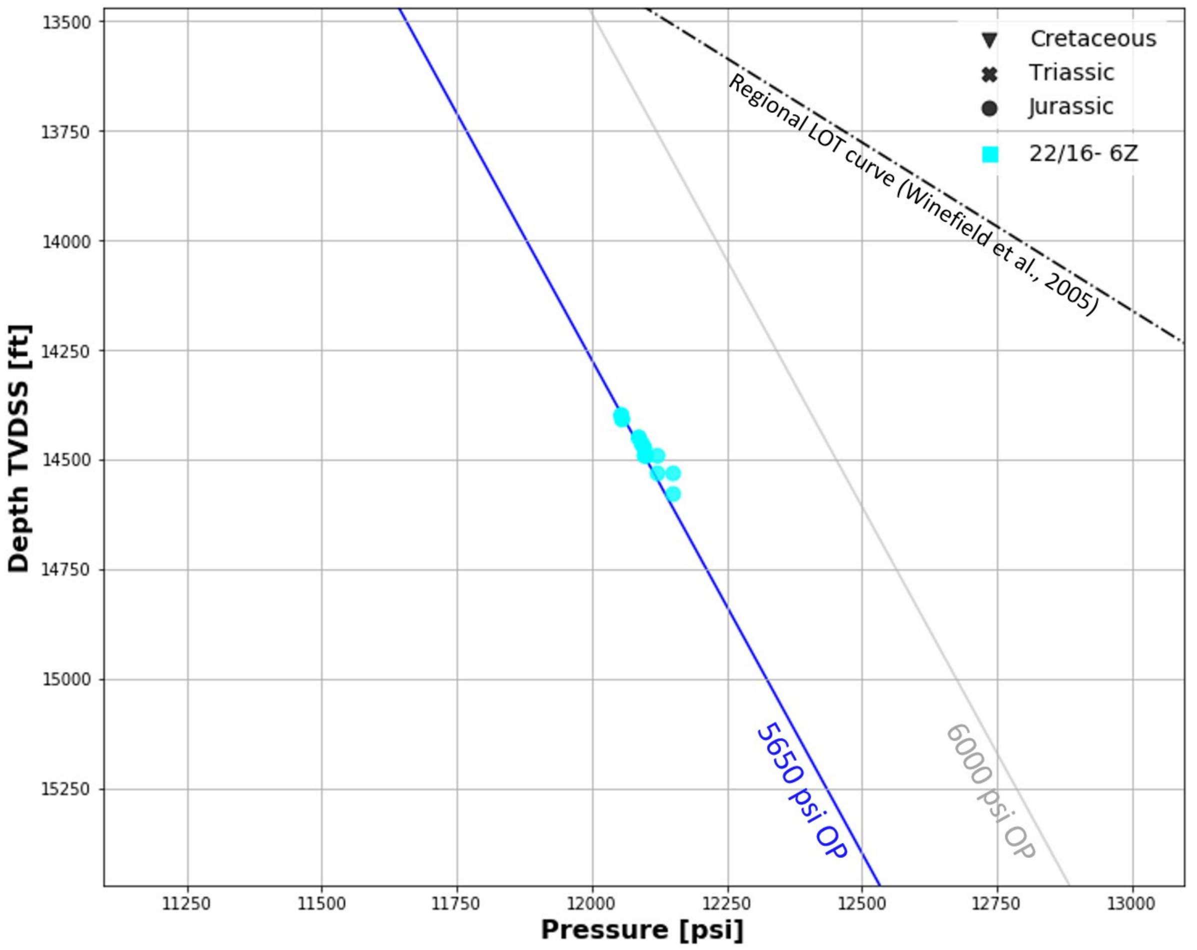

Figure 17: Depth vs pressure plot for well 22/16- 6Z

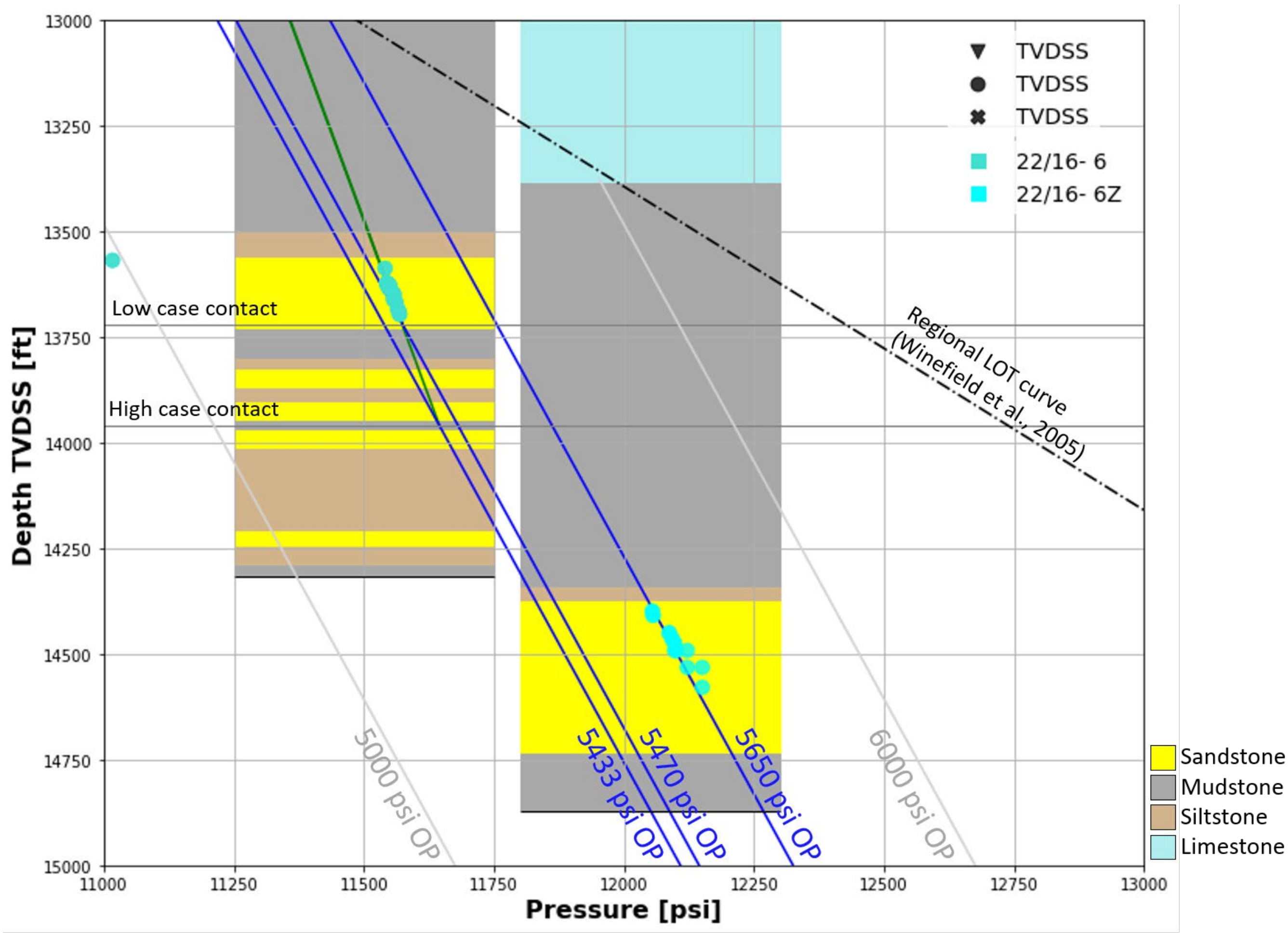

Figure 18: Depth vs pressure plot for well 22/16- 6 and 22/16- 6Z with the lithology log shown alongside the pressure data for both wells. The Fulmar Formation sandstones encountered by each well are of different ages and have different overpressures. The side-track 22/16- 6Z has been drilled in a more basinwards location than well 22/16- 6.

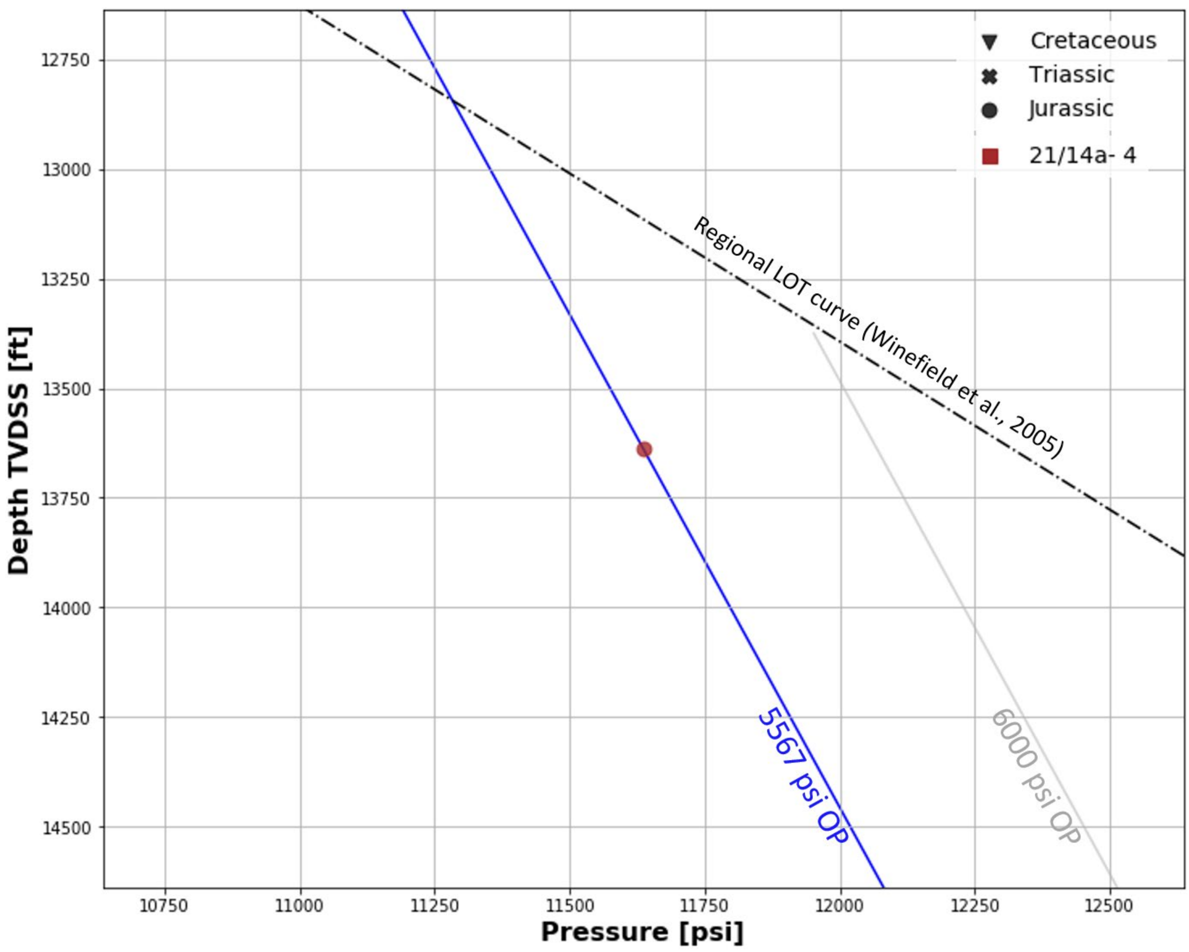

Figure 19: Depth vs pressure plot for well 21/14a- 4

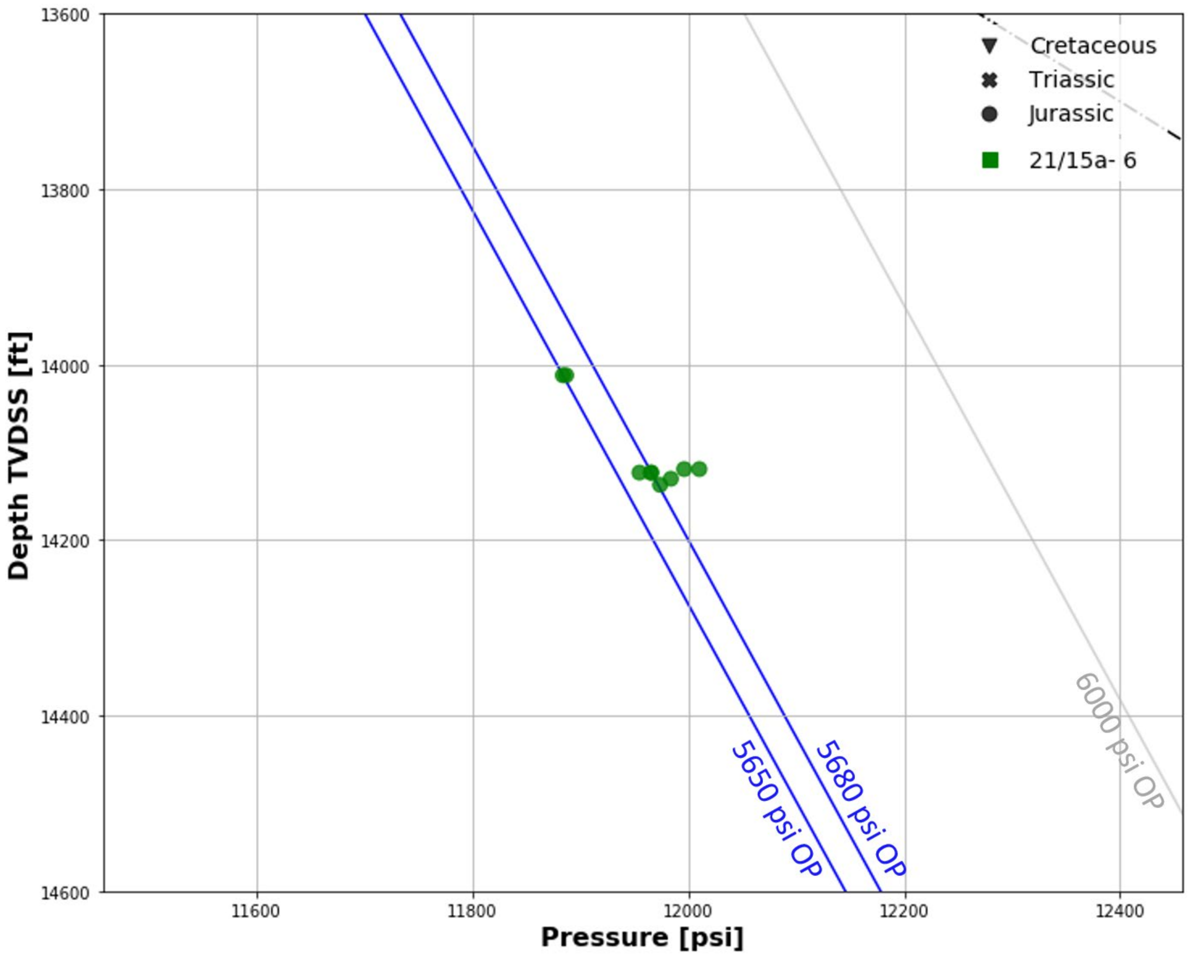

Figure 20: Depth vs pressure plot for well 21/15a- 6

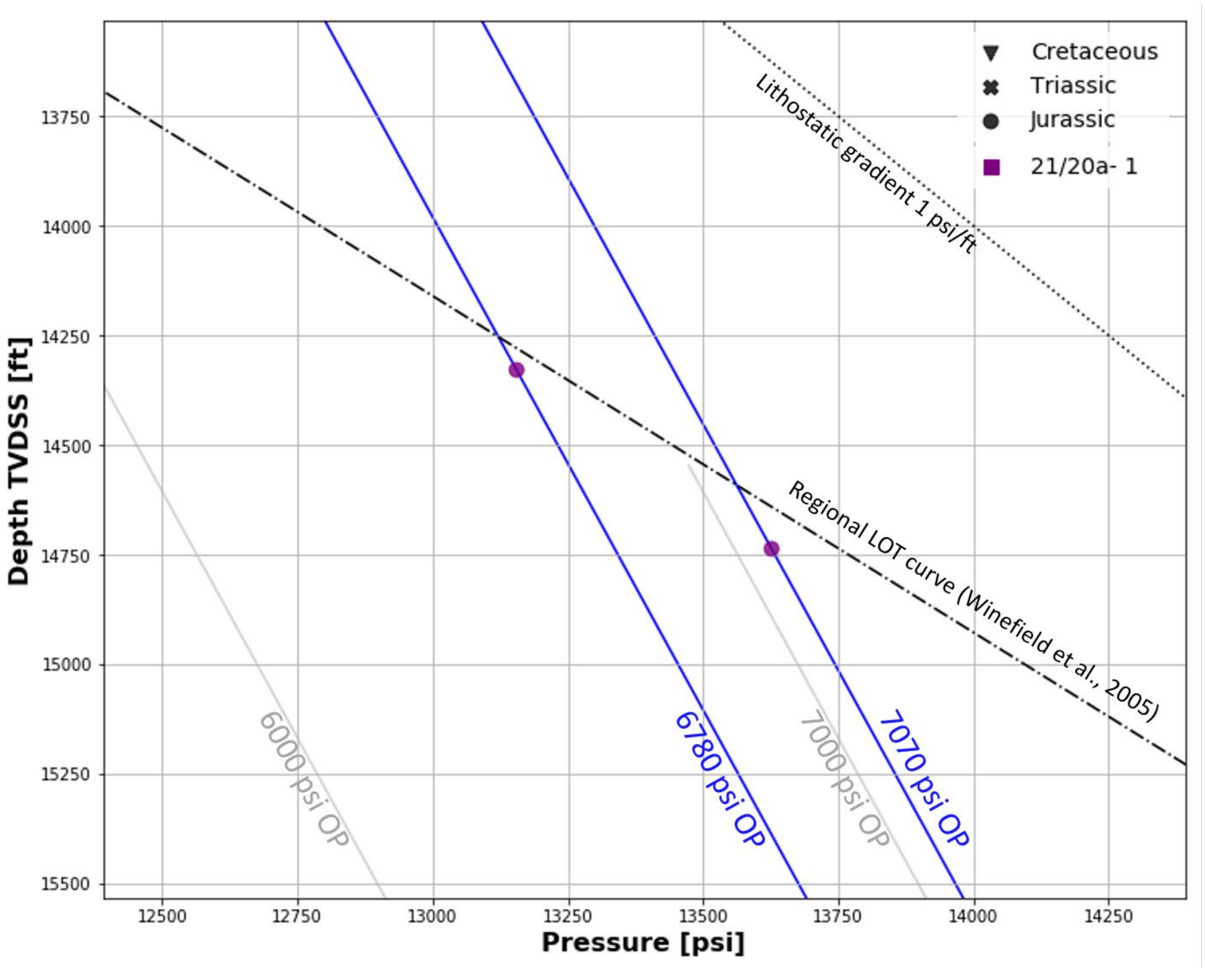

Figure 21: Depth vs pressure plot for well 21/20a- 1

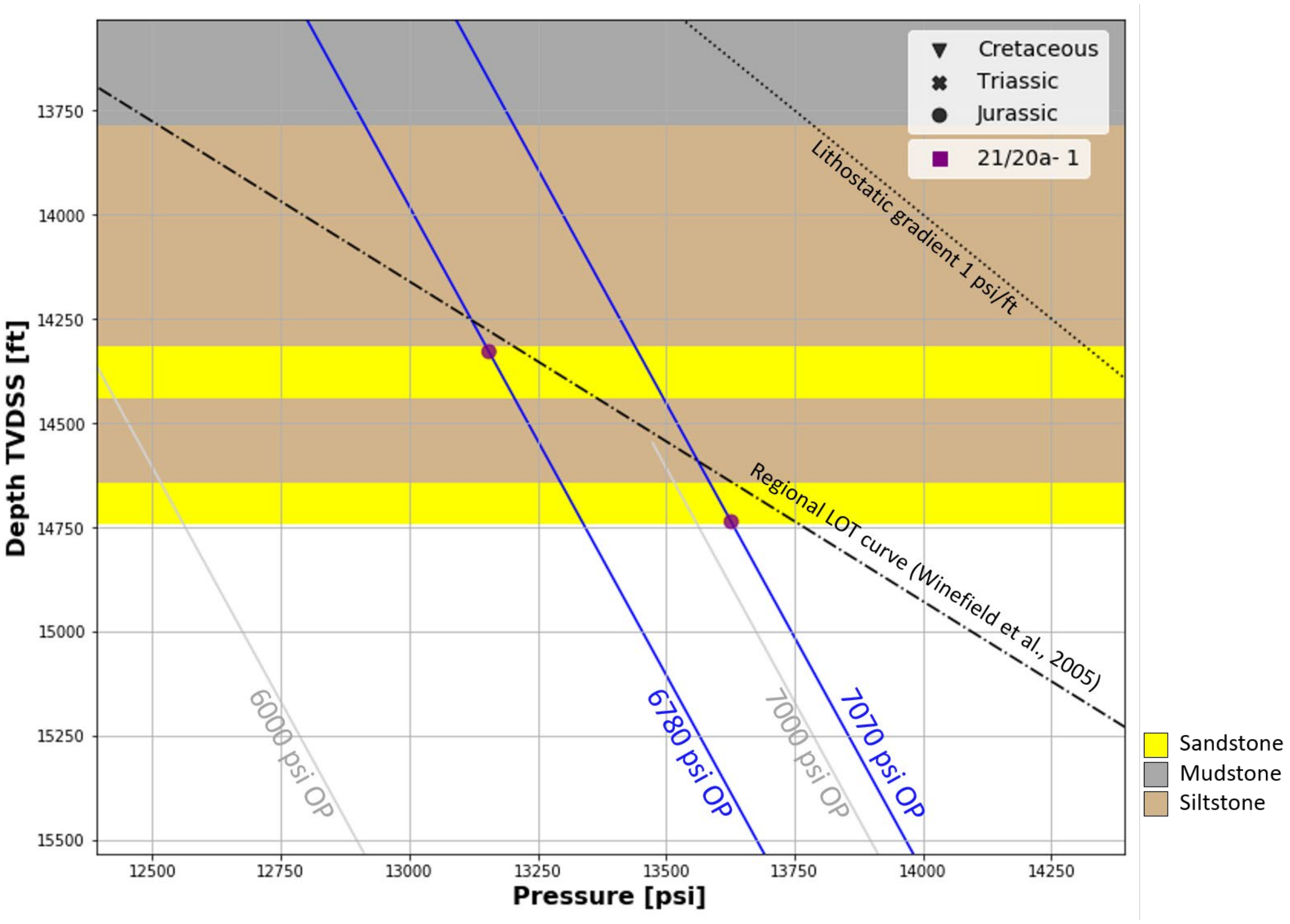

Figure 22: Depth vs pressure plot for well 21/20a- 1 with the lithology log shown alongside the pressure data. Both Fulmar Formation sand intervals have different overpressures and a stratigraphic control on the difference is likely.

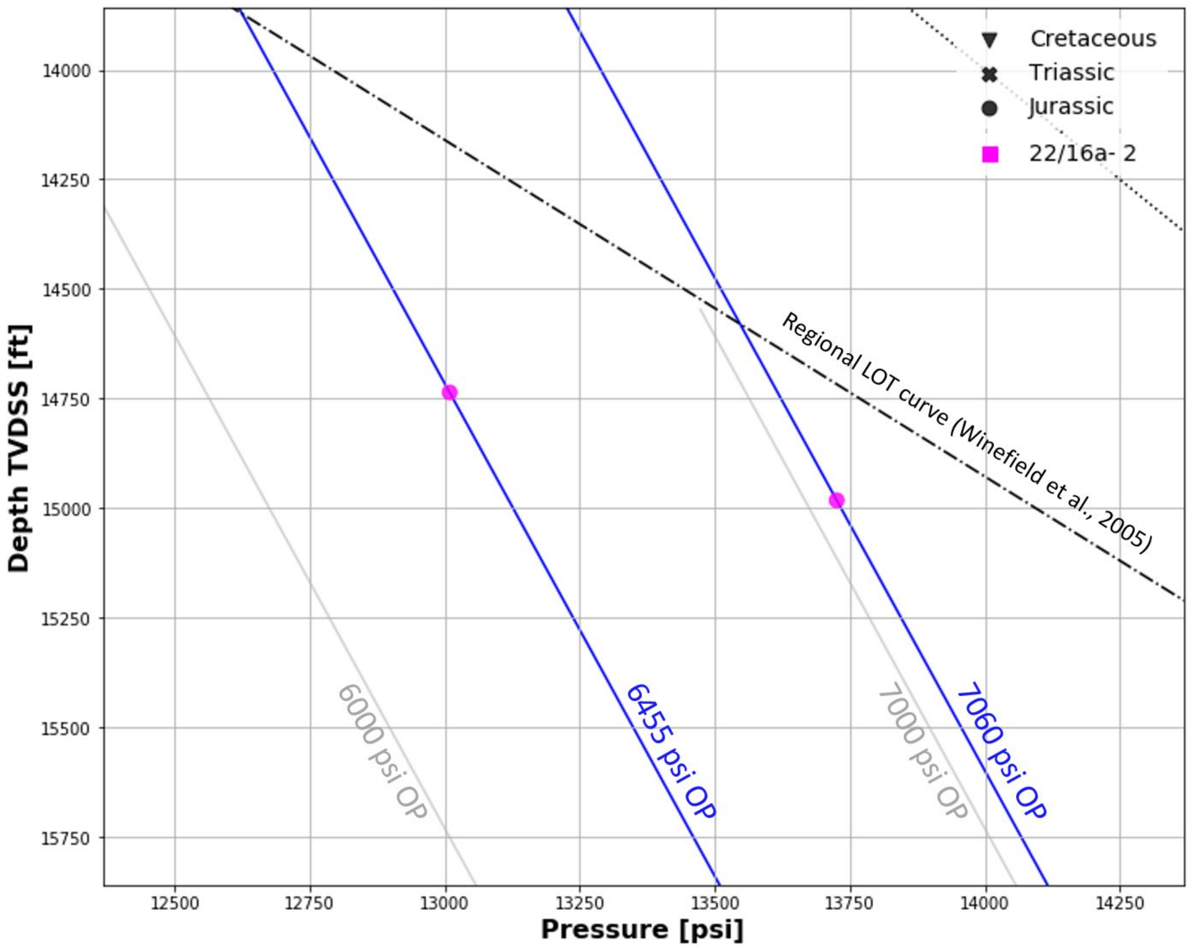

Figure 23: Depth vs pressure plot for well 22/16a- 2

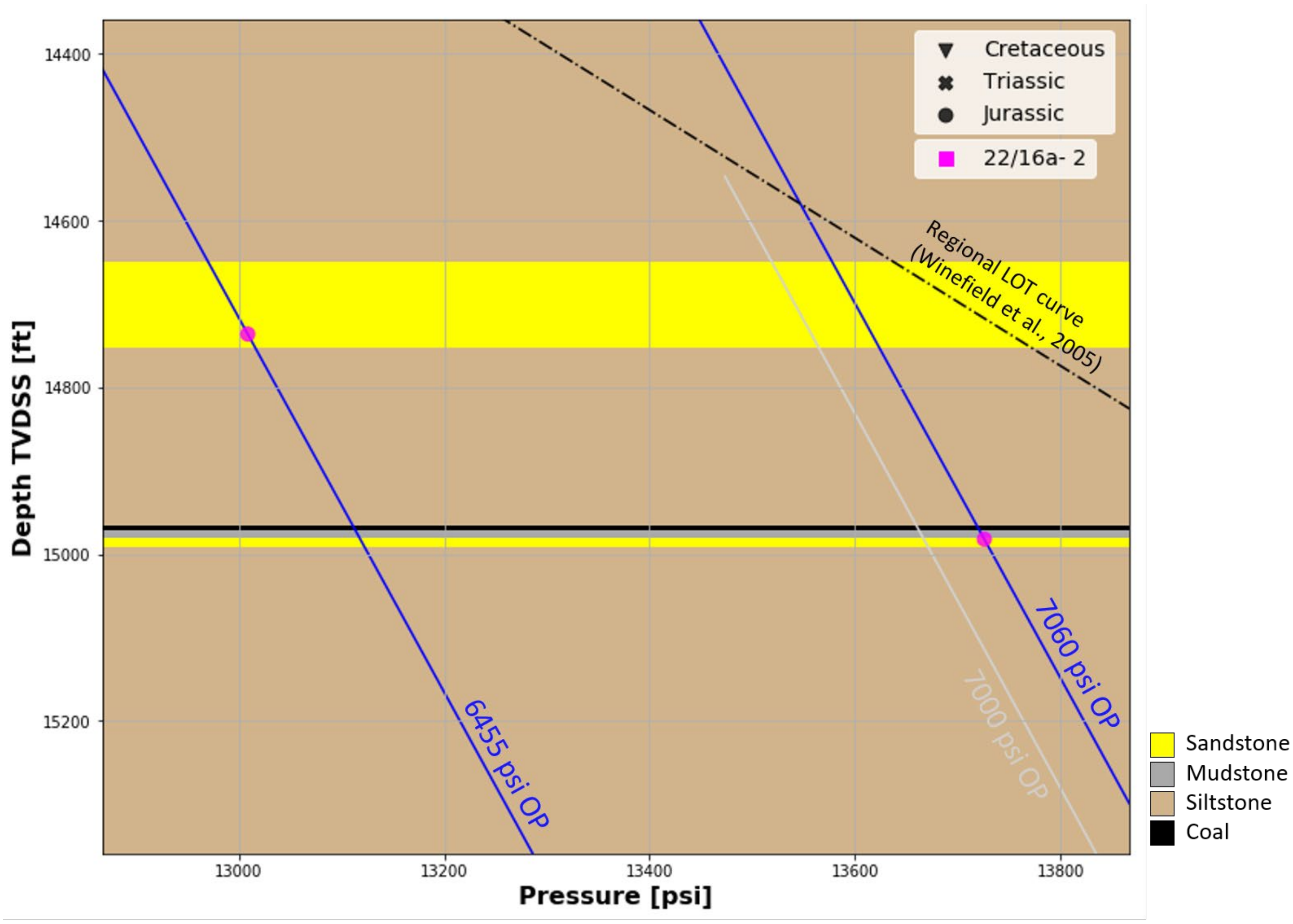

Figure 24: Depth vs pressure plot for well 22/16a- 2 with the lithology log shown alongside the pressure data. Both Fulmar Formation sand intervals have different overpressures and a stratigraphic control on the difference is likely.

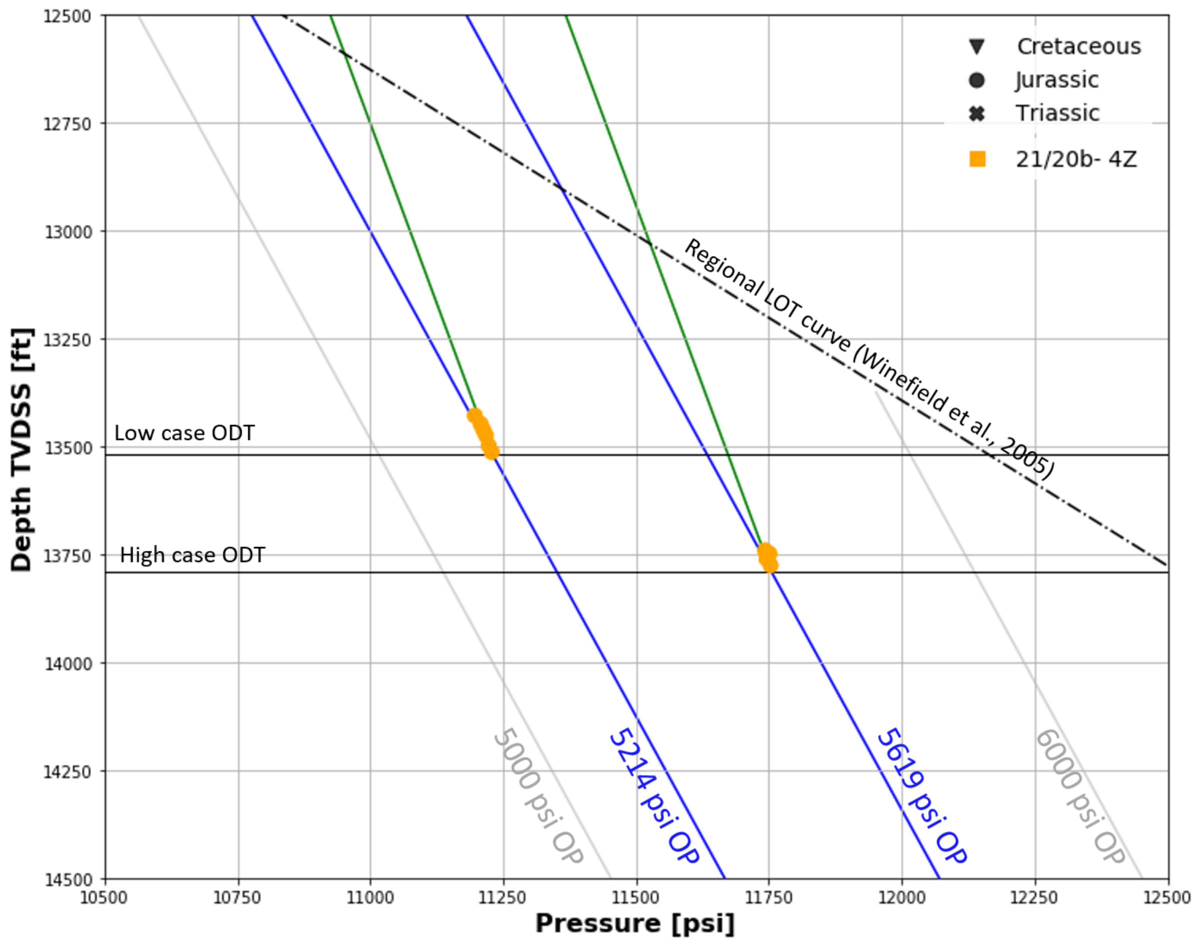

Figure 25: Depth vs pressure plot for well 21/20b- 4Z

Forties-Montrose High and East Forties Basin

On the Forties-Montrose High the magnitude of overpressure is low, but it increases in a stepwise manner across the adjacent fault terraces. Overpressure values from the Jurassic lie around 2000 psi in the pressure cell containing well 22/22a- 7 and reach almost 4000 psi in the pressure cell containing wells 22/17- 3 and 22/17- 3X (Figure 26). Closer to the East Central Graben overpressure increases significantly (e.g. 7253 psi in the Triassic Heron Group, well 22/20- 1).

Pressure cell containing wells 22/12b- 7A; 22/17- 3; 22/17- 3X; 22/17- 3Y; 22/17- 3Z (Cell ID: 18)

While the fluid type for the pressure data taken in well 22/12b- 7A was “unknown”, the resistivity log does not show any signs of hydrocarbons in the ‘Smith Bank Formation’ and the data is interpreted to have come from a water bearing sand. The overpressure of 2802 psi for well 22/12b- 7A determined by Ikon Science is therefore included in the pressure cell analysis (Figure 26).

Ikon Science have determined overpressures from pressure measurements in the water-bearing interval of the Humber Group (3714 psi), Fladen Group (3876 psi), and Heron Group (3948 psi) in well 22/17- 3. Well 22/17- 3X also has pressure data from the water-bearing Fulmar Formation for which Ikon Science have determined an overpressure of 3798 psi (Figure 26). These overpressure values are used in the pressure cell analysis without any alterations. Both 22/17- 3Y and 22/17- 3Z have data recorded only in hydrocarbon-bearing intervals and are not used for the pressure cell analysis.

The resulting pressure cell includes a combined overpressure range of 2800 – 3950 psi overpressure, but it is clear the Fladen Group and Fulmar sands are not in communication.

Pressure cell containing wells 22/18- 4; 22/22a- 7; 22/23a- 2; 22/23b- 4 (Cell ID: 32)

Well 22/22a- 7 discovered the Shaw oil field in 2009 which was appraised through two sidetracks (22/22a- 7Y and 22/22a- 7Z). An OWC for the Shaw field at 11100 ft TVDSS is used for the analysis, derived from Baldwin, 2020. Ikon Science determined an oil gradient of 0.28 psi/ft from the RFT data. The Jurassic Fulmar Formation is divided into two intervals in the well with the upper Fulmar displaying very slightly higher overpressure (2190 psi) than the lower Fulmar (2185 psi, Figure 26, Figure 27).

Wells 22/18- 4 and 22/23b- 4 have pressure data recorded from the hydrocarbon-bearing Triassic Heron Group. No aquifer overpressure was recorded or interpolated for these wells but the hydrocarbon pressure data yields overpressures of 2249 psi for 22/18- 4 and 3139 psi for 22/23b- 4. Ikon Science have determined an aquifer overpressure of 1365 psi in the Triassic Heron Group in well 22/23a- 2 which was used for the pressure cell analysis (Figure 26). Wells 22/18- 4 and 22/23b- 4 would benefit from further analysis to determine the Triassic Heron Group aquifer overpressure. The data from well 22/23a- 2 suggests that the Triassic may have a lower overpressure than the Jurassic in this area. This difference in overpressure is observed in the neighbouring pressure cell 46, where the Triassic Heron Group has an overpressure of 3158 psi in well 22/18- 5 whilst the Jurassic Kimmeridge Clay Formation has a significantly higher overpressure of 4179 psi.

The resulting pressure cell covers a range of 1360 – 2190 psi overpressure. Further analysis would be beneficial for the wells in this pressure cell to confirm the overpressure difference between the Jurassic and the Triassic.

Other pressure cells in the East Forties Basin

No additional well data analysis was carried out on these pressure cells in the East Forties Basin:

- Pressure cell containing wells 22/18- 5; 22/18c- 8; 22/19- 1 (Cell ID: 46)
- Pressure cell containing wells 22/14b- 8; 22/14b- 4; 22/19c- 7 (Cell ID: 17)
- Pressure cell containing well 22/15- 1 (Cell ID: 16)
- Pressure cell containing wells 22/20- 1 (Cell ID: 45)
- Pressure cell containing wells 22/24b- 9; 22/24a- 2 (Cell ID: 38)
- Pressure cell containing wells 22/24b- 8; 22/24c- 11 (Cell ID: 39)

Overpressure values for these pressure cells are derived from the analysis carried out by Ikon Science.

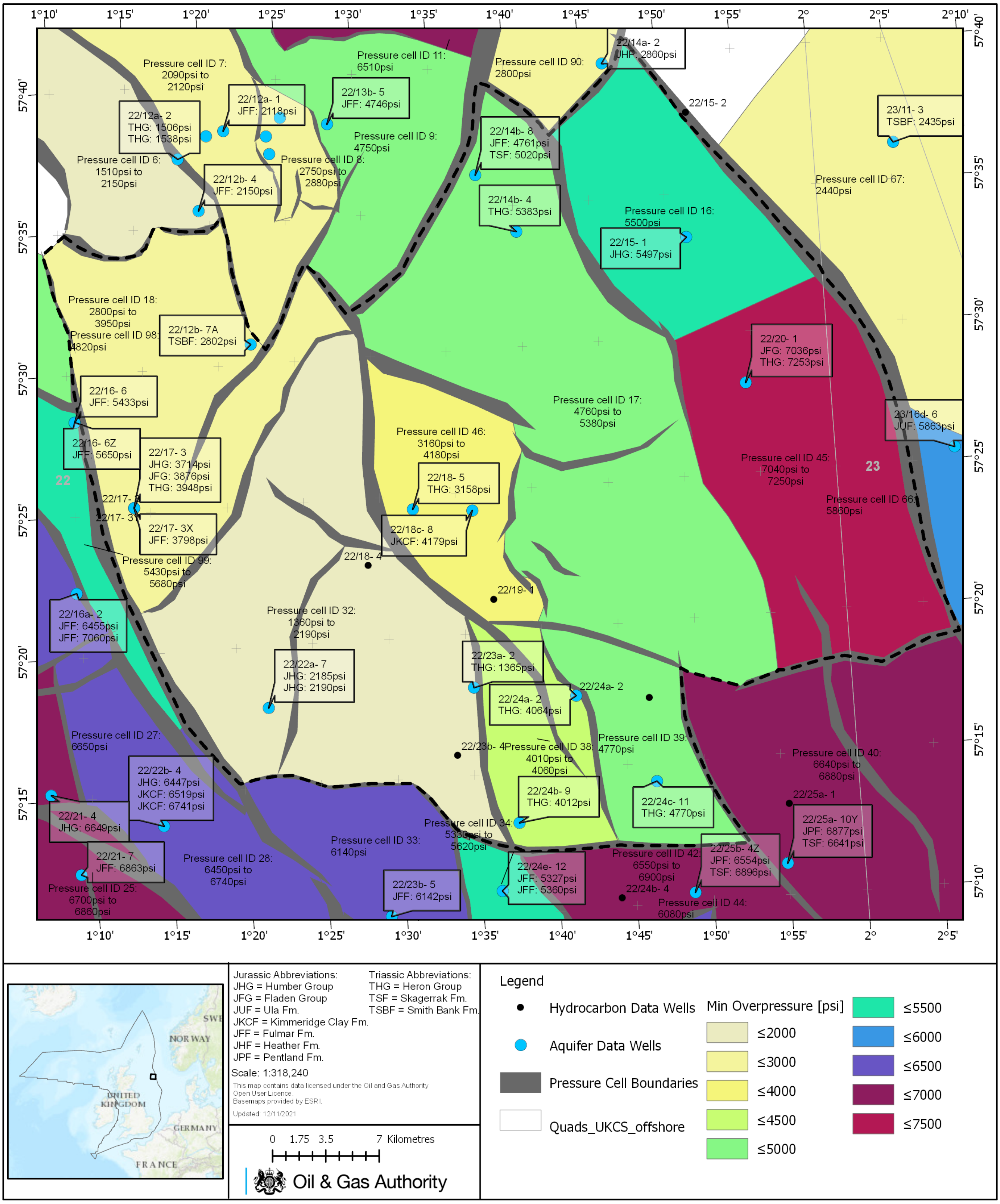

Figure 26: Combined Jurassic/Triassic pressure cell map showing the Forties-Montrose High and East Forties Basin area

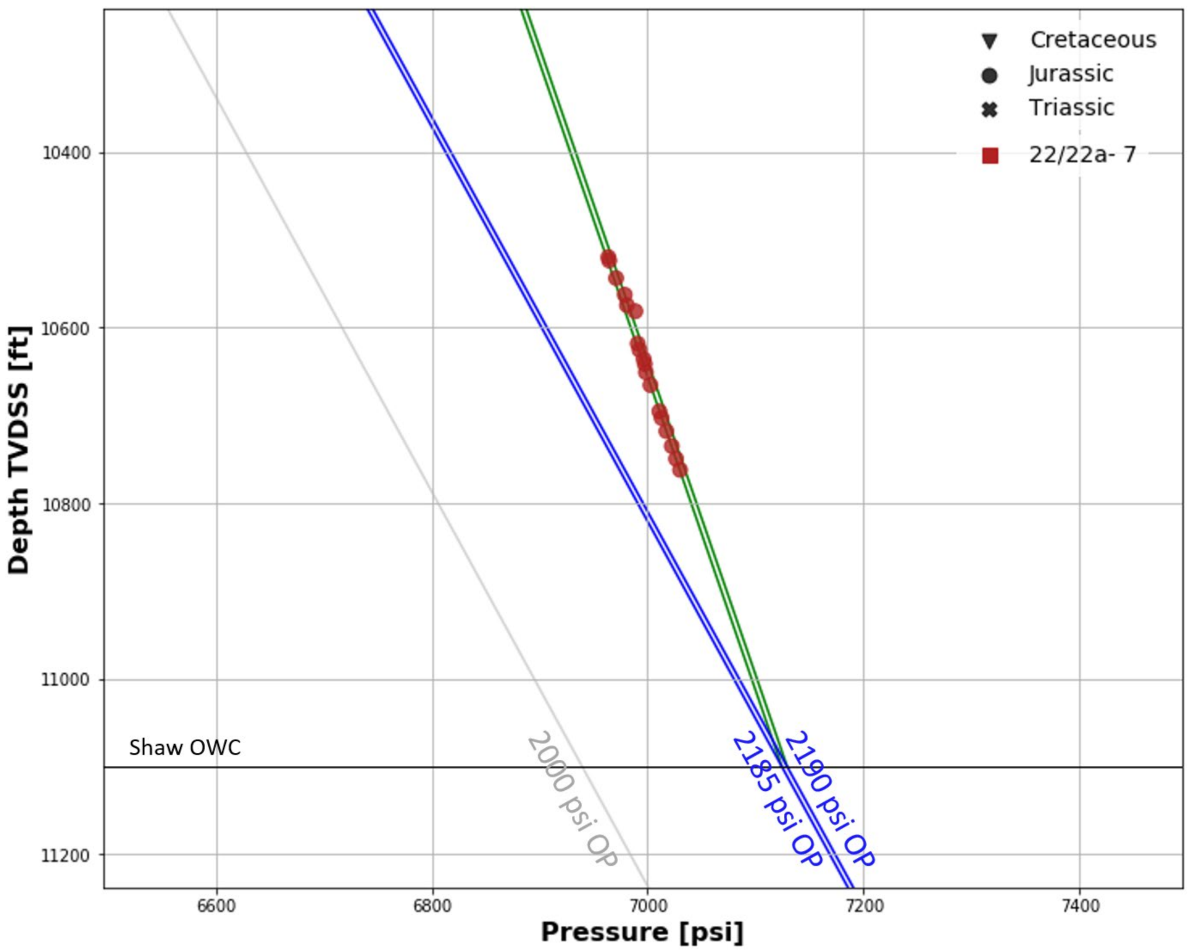

Figure 27: Depth vs pressure plot for well 22/22a- 7

Western margin of the Jæren High

The Jæren High approaches hydrostatic. In the north, the Triassic Smith Bank Formation records an overpressure as low as 2435 psi (Figure 28). No additional well data analysis was carried out on the pressure cells at the western margin of the Jæren High. Overpressure values for these pressure cells are derived from the analysis carried out by Ikon Science.

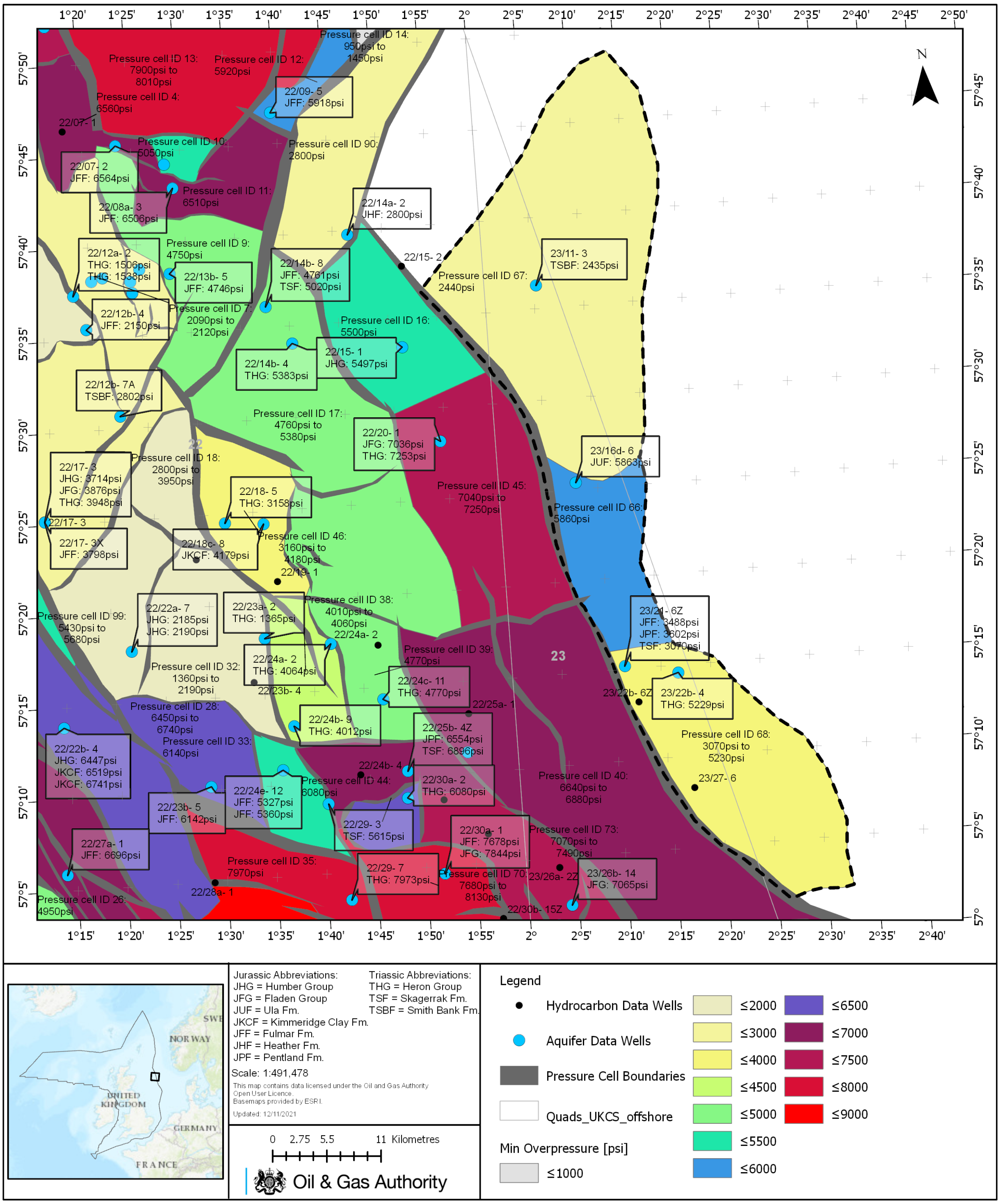

Figure 28: Combined Jurassic/Triassic pressure cell map showing the Jæren High area

West Central Shelf and West Central Graben

The West Central Graben pressure cells have overpressures of around 6500 psi to 6800 psi (Figure 29). The maximum overpressure in this area is recorded in the Jurassic Fulmar Formation in well 22/21- 7 (6863 psi). The overpressure reduces stepwise towards the West Central Shelf. The pressure cells on the West Central Shelf record overpressures of around 2200 psi in the south and overpressures of around 3800 psi in the north (wells 21/25- 8 and 21/25- 9).

Pressure cell containing wells 21/25- 8; 21/25- 9; 21/24- 4 (Cell ID: 23)

The Teal discovery well 21/25- 8 discovered oil in the Jurassic Fulmar Formation. It is possible to discern an oil and an aquifer gradient in the available FMT data. The contact between both lies at approximately 10830 ft TVDSS, which coincides with the base of a typical hydrocarbon separation of neutron porosity and density in the composite log of 21/25- 8 and is marked in the log (NDR File ID: 1709434). The resulting overpressure is 3791 psi (Figure 29, Figure 30).

Well 21/25- 9 (also within the Teal field) has pressure data recorded from water-bearing intervals and Ikon Science have determined an overpressure of 3867 psi for this well.

This pressure cell is characterised by overpressures between 3790 and 3870 psi.

Pressure cell containing wells 21/25- 2; 21/30- 19 (Cell ID: 22)

Well 21/25- 2 discovered oil in the Middle Eocene Tay Formation. This was later developed as the Guillemot West field. Oil was also recovered from the Jurassic during pressure testing, but the accumulation was not appraised or developed (NDR File ID: 1699427). Additional RFT data from the Jurassic Fulmar Formation is added to the Ikon dataset from files available through the NDR (File ID: 1905512). The additional RFT data shows an oil gradient above 8320 ft TVDSS and a water gradient below this depth. The overpressure derived from this water gradient is 2200 psi (Figure 29, Figure 31).

Ikon Science have determined an overpressure of 2166 psi from pressure measurements in the water-bearing interval of the Fulmar Formation in well 21/30- 19. This value is used in the pressure cell analysis.

This pressure cell is characterised by overpressures between 2170 and 2200 psi.

Pressure cell containing well 22/21- 4 (Cell ID: 27)

Well 22/21- 4 (“Helen”) discovered oil in the Jurassic Humber Group (Kimmeridge Clay Formation). The structure is likely breached with the data points in the hydrocarbon leg intersecting the regional LOT curve of Winefield et al. (2005). The hydrocarbons encountered in the well are therefore likely residual. An OWC can be interpreted to be at 14125 ft TVDSS, with the lowermost data point representing a water-bearing interval. Fitting a standard oil gradient to the data and extrapolating this down to the contact yields an overpressure of 6650 psi (Figure 29, Figure 32).

This pressure cell is characterised by an overpressure of 6650 psi.

Other pressure cells in the West Central Shelf and West Central Graben

No additional well data analyses were carried out on these pressure cells in the West Central Shelf and Graben:

- Pressure cell containing well 21/30- 18 (Cell ID: 31)
- Pressure cell containing wells 22/21- 7; 22/27a- 1; 22/27a- 4Z (Cell ID: 25)
- Pressure cell containing wells 22/21- 2; 22/26a- 2 (Cell ID: 26)
- Pressure cell containing wells 22/22b- 4 (Cell ID: 28)

Overpressure values for the pressure cells are derived from the analysis carried out by Ikon Science.

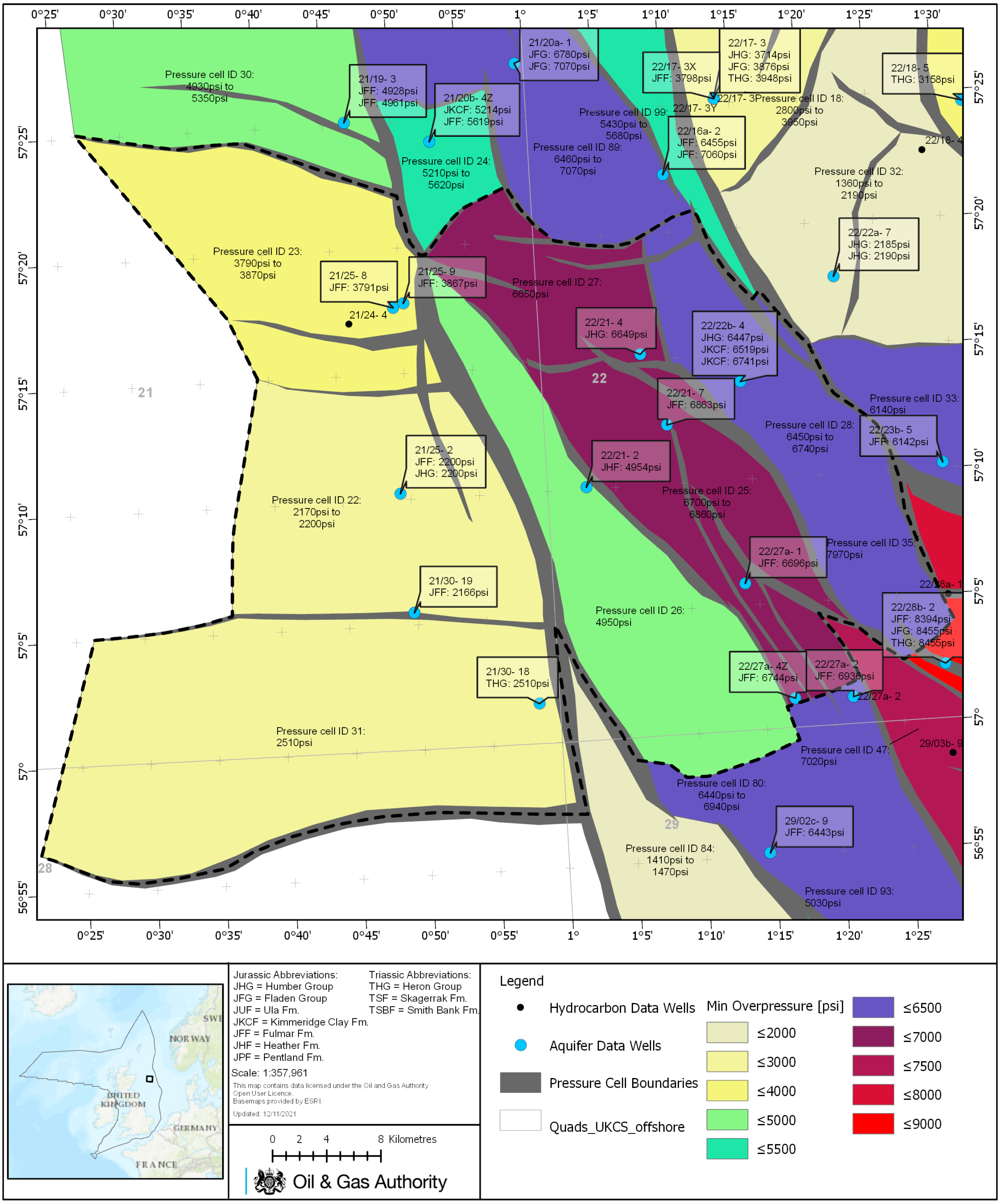

Figure 29: Combined Jurassic/Triassic pressure cell map showing the West Central Shelf and West Central Graben area

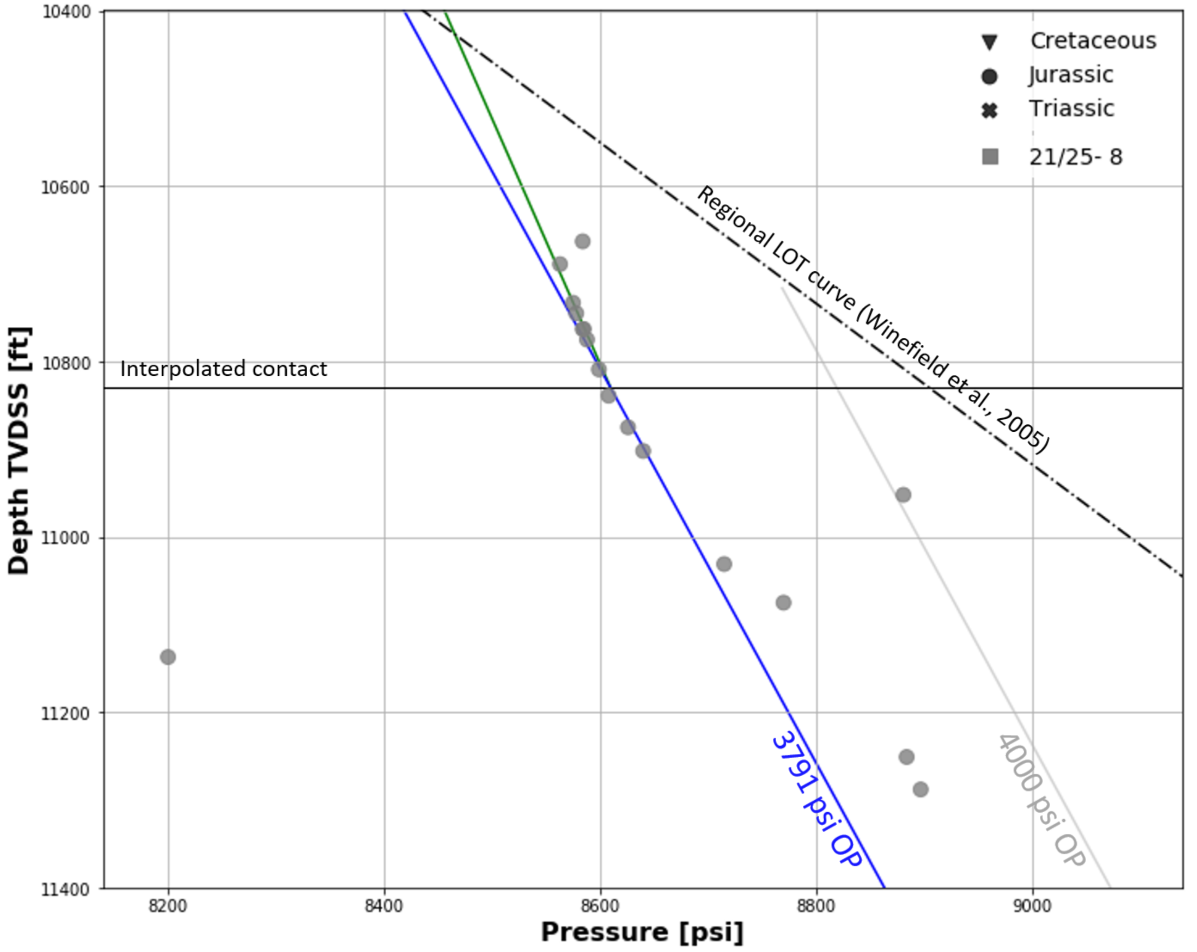

Figure 30: Depth vs pressure plot for well 21/25- 8

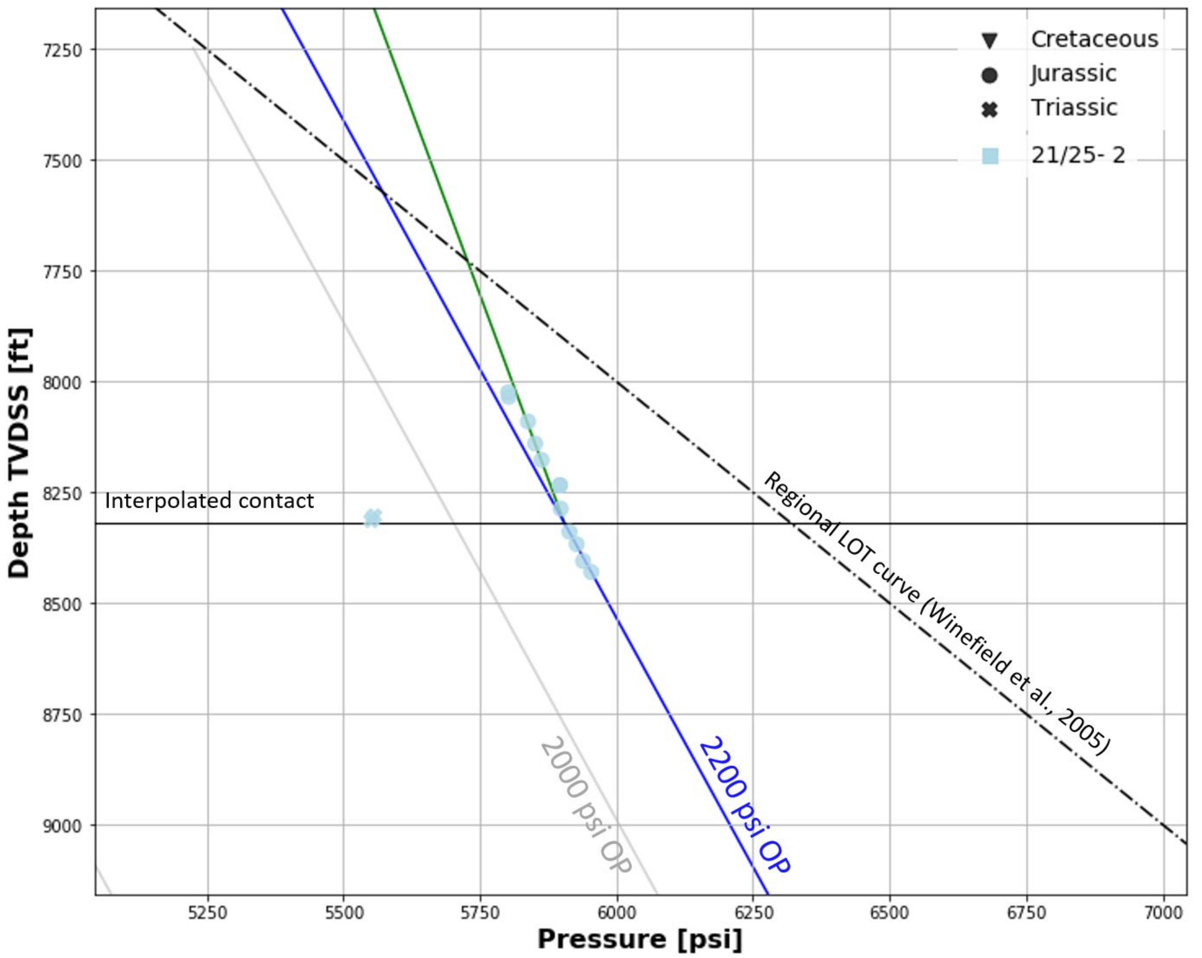

Figure 31: Depth vs pressure plot for well 21/25- 2

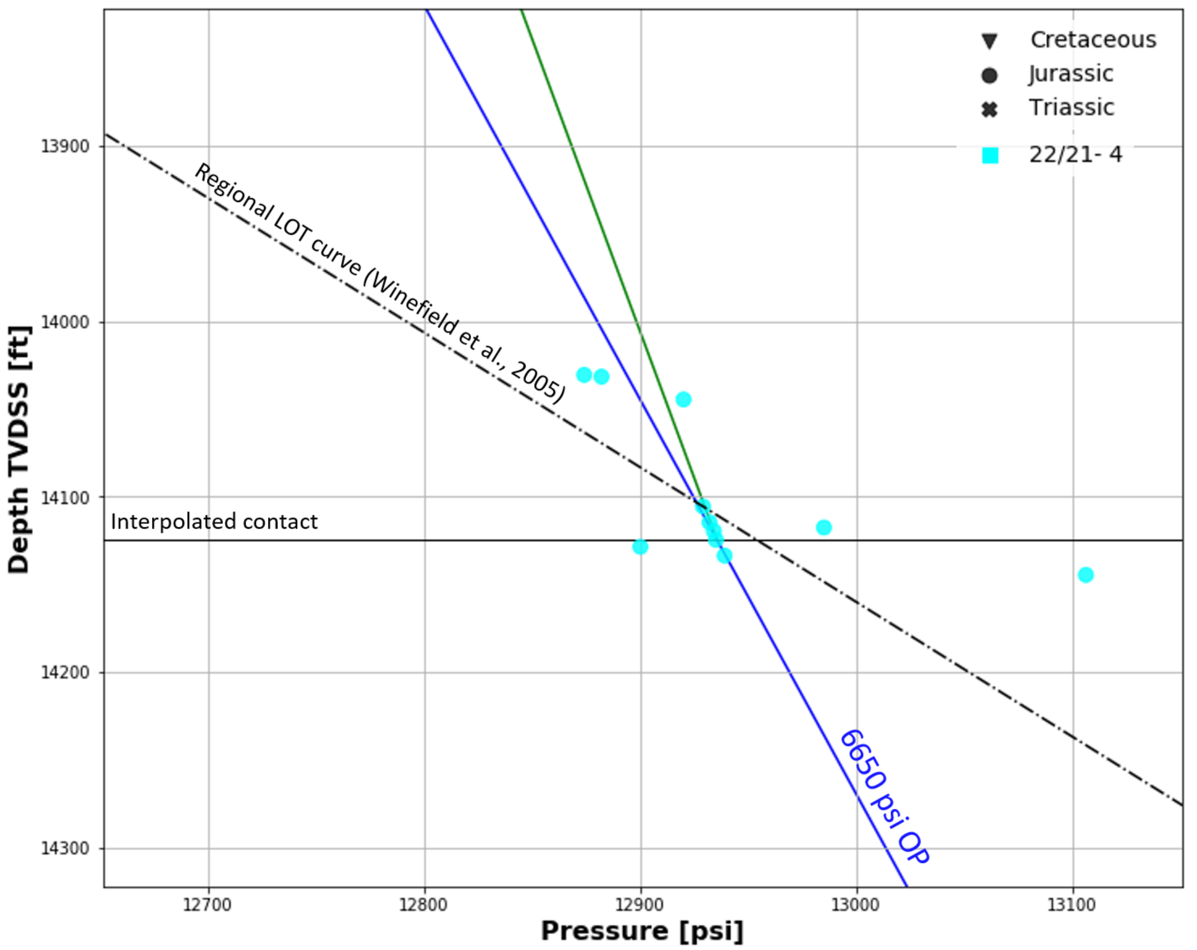

Figure 32: Depth vs pressure plot for well 22/21- 4

Central Graben

The highest overpressures are recorded in the Central Graben. In well 29/04b- 3Z the highest overpressure in the study area is reached at 9093 psi in the Jurassic Fulmar Formation (Figure 33). The surrounding pressure cells have overpressures in the range of 7000 psi to 8500 psi.

Pressure cell containing wells 22/24e- 12; 22/29- 3 (Cell ID: 34)

Well 22/24e- 12 discovered oil in the Jurassic Fulmar Formation ("Seagull North"). Pressures in the shallower Fulmar sand interval follow a standard oil gradient. Some tests encountered a tight Fulmar Formation in both intervals but especially in the deeper, water-bearing sand interval in which the pressure measurements do not follow a clear gradient. The ODT for 22/24e- 12 is determined to lie at 13663 ft TVDSS assuming a hydrocarbon column of 115 ft in the well. In the relinquishment report for licence P1621 the Seagull field OWC (13860 ft TVDSS) is applied to this discovery assuming that the Fulmar Formation is juxtaposed to the Triassic Skagerrak Formation and both are in communication. Extrapolating the standard oil gradient fitted to the pressure measurements down to these contacts yields overpressures of 5360 psi and 5327 psi respectively (Figure 33, Figure 34).

The pressure data recorded for well 22/29- 3 in the Triassic Skagerrak Formation is very scattered and no clear gradients are visible. This well is situated within the Seagull oil field. Applying the Seagull field OWC of 13860ft TVDSS a low confidence fit to an oil gradient above the contact and a water gradient below the contact can be achieved. The resulting low confidence overpressure lies at 5615 psi (Figure 33, Figure 35).

This pressure cell is characterised by overpressures between 5330 and 5620 psi.

Pressure cell containing wells 22/28b- 2; 29/04b- 3Z (Cell ID: 37)

Well 29/04b- 3 has been drilled at the edge of a 4-way dip closure at Cretaceous Hod Formation level ("Hodrian" described in relinquishment report P2047) and discovered minor amounts of oil. The drill pipe got stuck in the Jurassic section, was plugged back and then side-tracked through the 9 7/3" casing in the Cretaceous (29/04b- 3Z). The Jurassic was found to be dry at this location. The pressure data is reclassified as taken in the water leg and the overpressure of 8742 psi in the Kimmeridge Clay Formation and 9093 psi in the Fulmar Formation determined by fitting a standard water gradient to the data is used in the pressure cell analysis (Figure 33, Figure 36).

The RFT data recorded in well 22/28b- 2 is derived from the water leg in the Jurassic Fulmar Formation and Fladen Group as well as in the Triassic Heron Group. Ikon Science interpret overpressures of 8394 psi, 8455 psi, and 8455 psi for these intervals, respectively. These data were used in the pressure cell analysis.

This pressure cell is characterised by overpressures between 8390 and 9090 psi.

Pressure cell containing wells 29/05b- H1; 29/05b- 6Z; 29/05b-F7Z (Cell ID: 49)

All wells within this cell have penetrated the Franklin field which produces condensate from the Jurassic Fulmar Formation. The MDT data in well 29/05b-F7Z are fitted to a gas condensate gradient of 0.17 (determined by Ikon Science). A GDT at a depth of 19570 ft TVDSS is used for the analysis. Extrapolating the hydrocarbon gradient down to the contact depth yields an aquifer overpressure of 8065 psi (Figure 33, Figure 37).

The RFT data recorded in well 29/05b- 6Z provides a clear gas and a water gradient. Ikon Science recorded an overpressure of 8226 psi for the water gradient in this well which is used for this pressure cell analysis (Figure 33). Well 29/05b- H1 shows scattered data, assumed to be derived from the oil-bearing interval, without clear fluid gradients in the pressure data. No further analysis was carried out for this well.

This pressure cell is characterised by overpressures between 8060 and 8230 psi.

Other pressure cells in the Central Graben

No additional well data analysis was carried out on these pressure cells in the Central Graben:

- Pressure cell containing well 22/23b- 5 (Cell ID: 33)
- Pressure cell containing wells 22/24b- 4; 22/25b- 4Z (Cell ID: 42)
- Pressure cell containing wells 22/25a- 1; 22/25a- 10Y (Cell ID: 40)
- Pressure cell containing well 22/30a- 2 (Cell ID: 44)
- Pressure cell containing wells 22/30a- 17; 22/30a- 16; 23/26a- 2Z; 23/26b- 14; 23/26b- 15 (Cell ID: 73)
- Pressure cell containing wells 22/28a- 1; 22/29- 7 (Cell ID: 35)

- Pressure cell containing wells 22/30a- 1; 22/30b- 15Z; 22/30c- G11; 22/30b- 11; 29/04d- 4 (Cell ID: 70)
- Pressure cell containing wells 30/01a- 11; 30/01f- 8 (Cell ID: 72)

Overpressure values for the pressure cells are derived from the analysis carried out by Ikon Science.

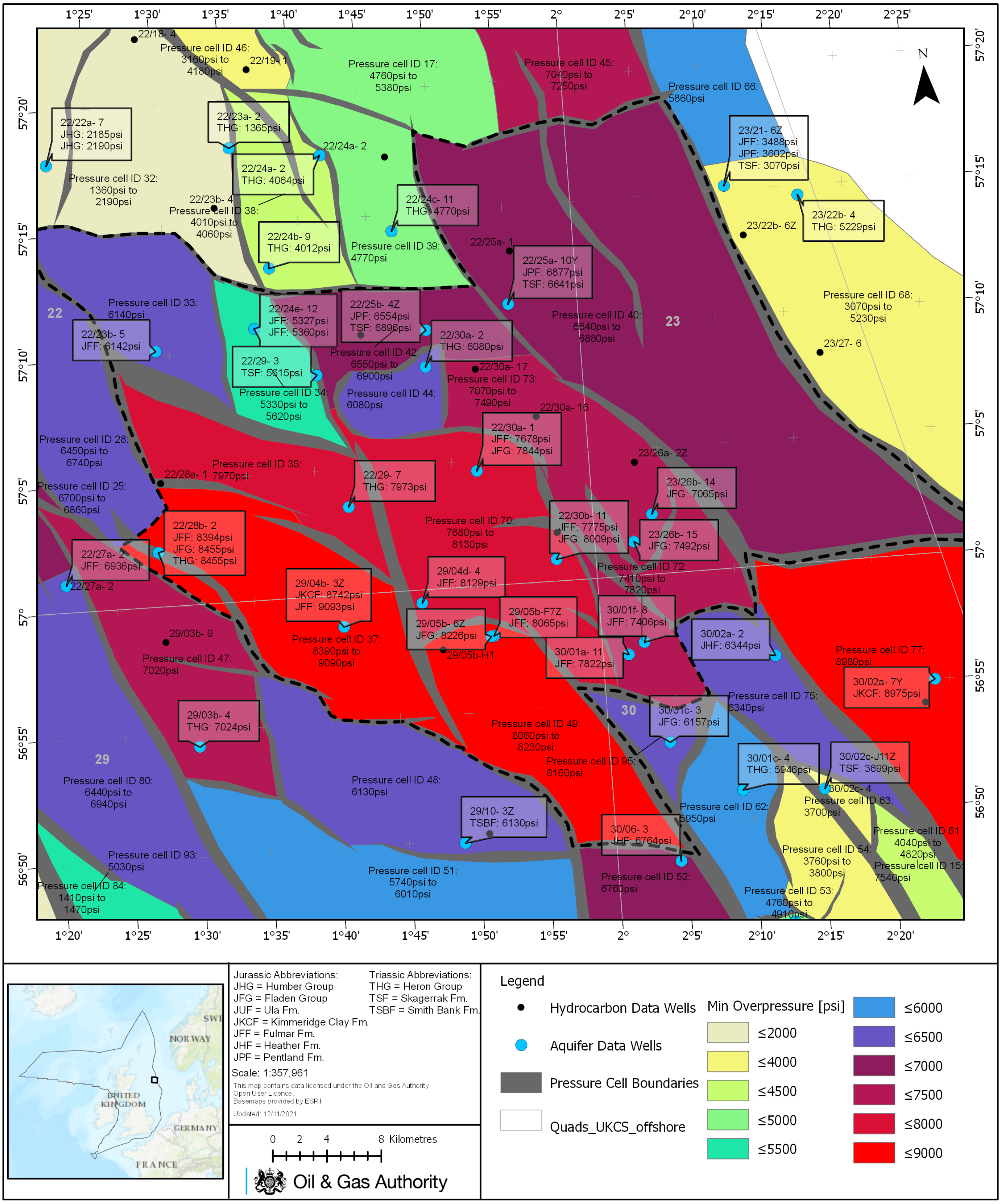

Figure 33: Combined Jurassic/Triassic pressure cell map showing the Central Graben area

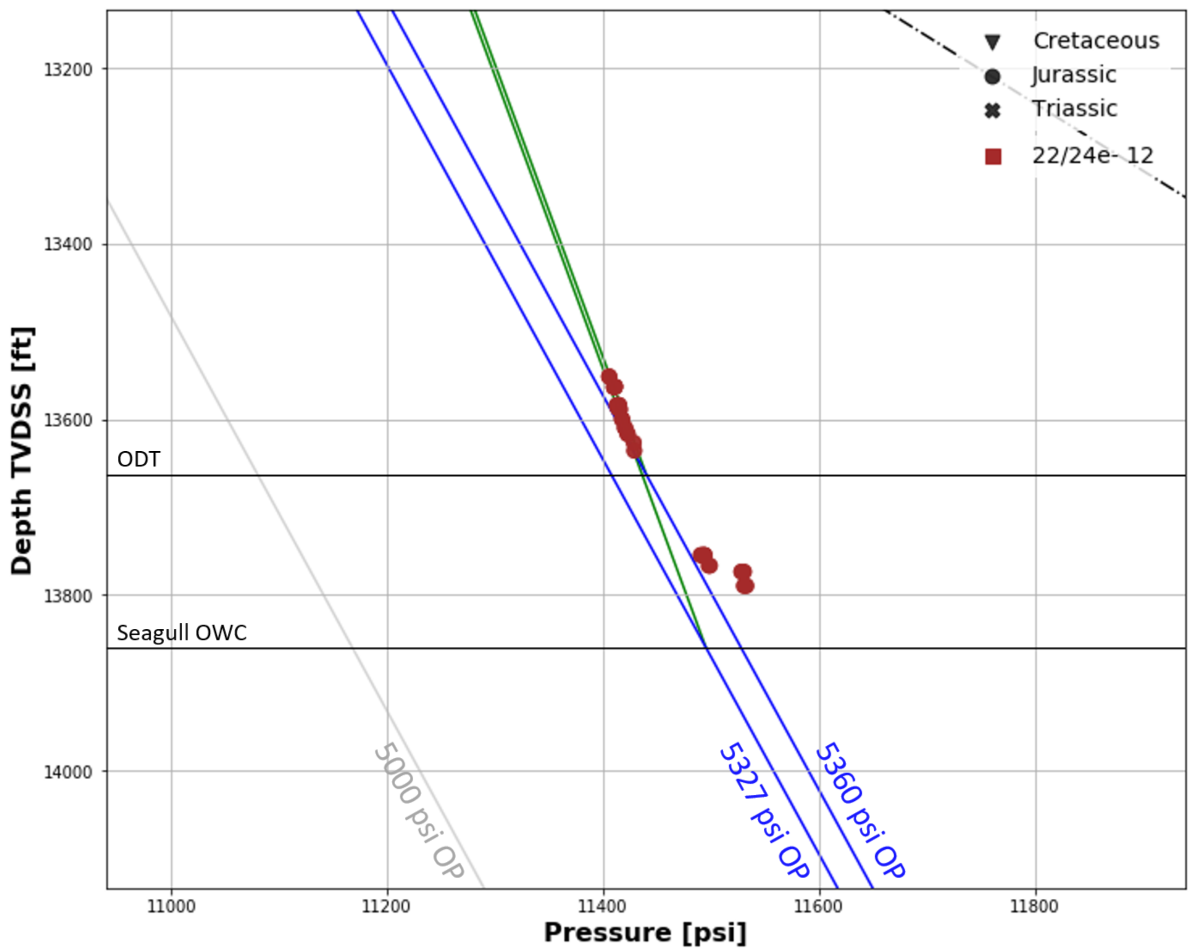

Figure 34: Depth vs pressure plot for well 22/24e- 12

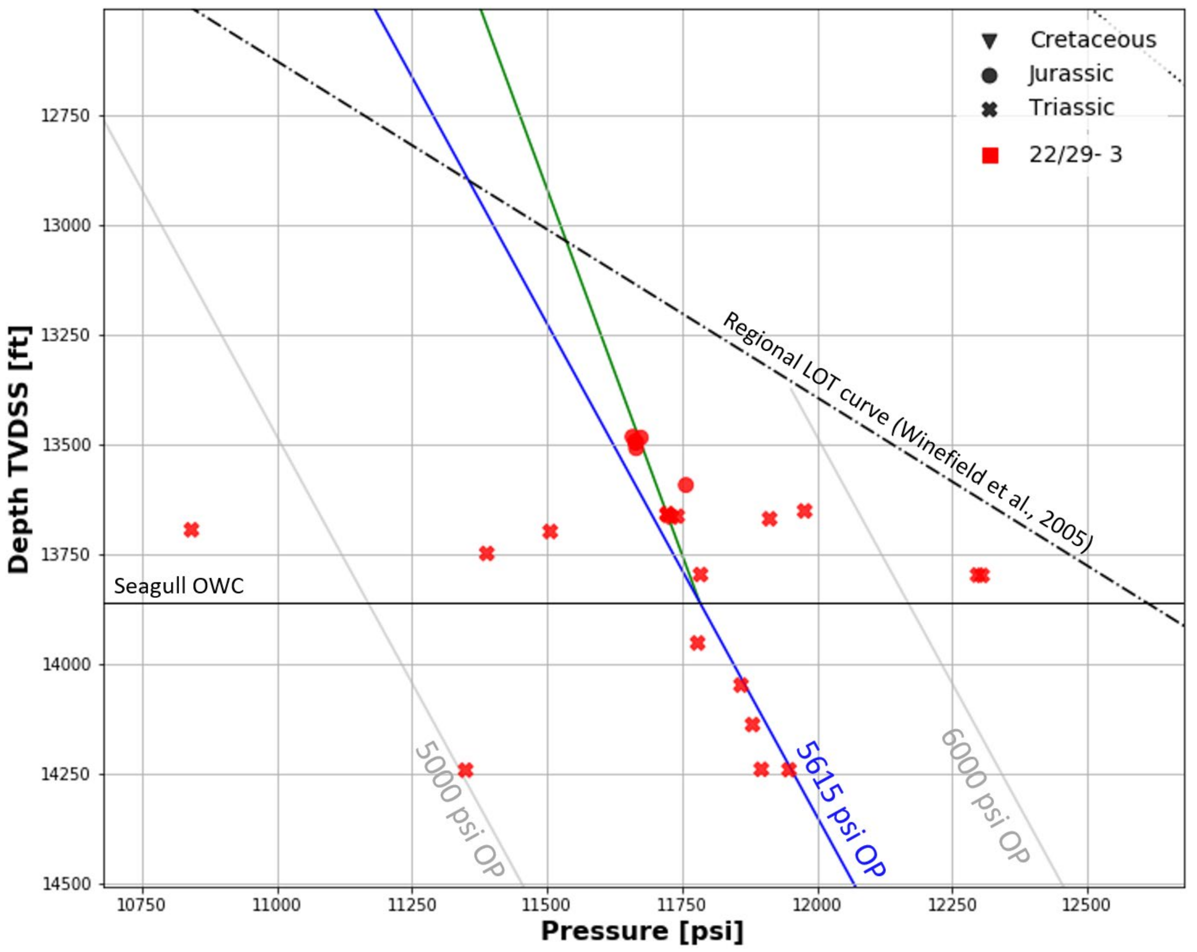

Figure 35: Depth vs pressure plot for well 22/29- 3

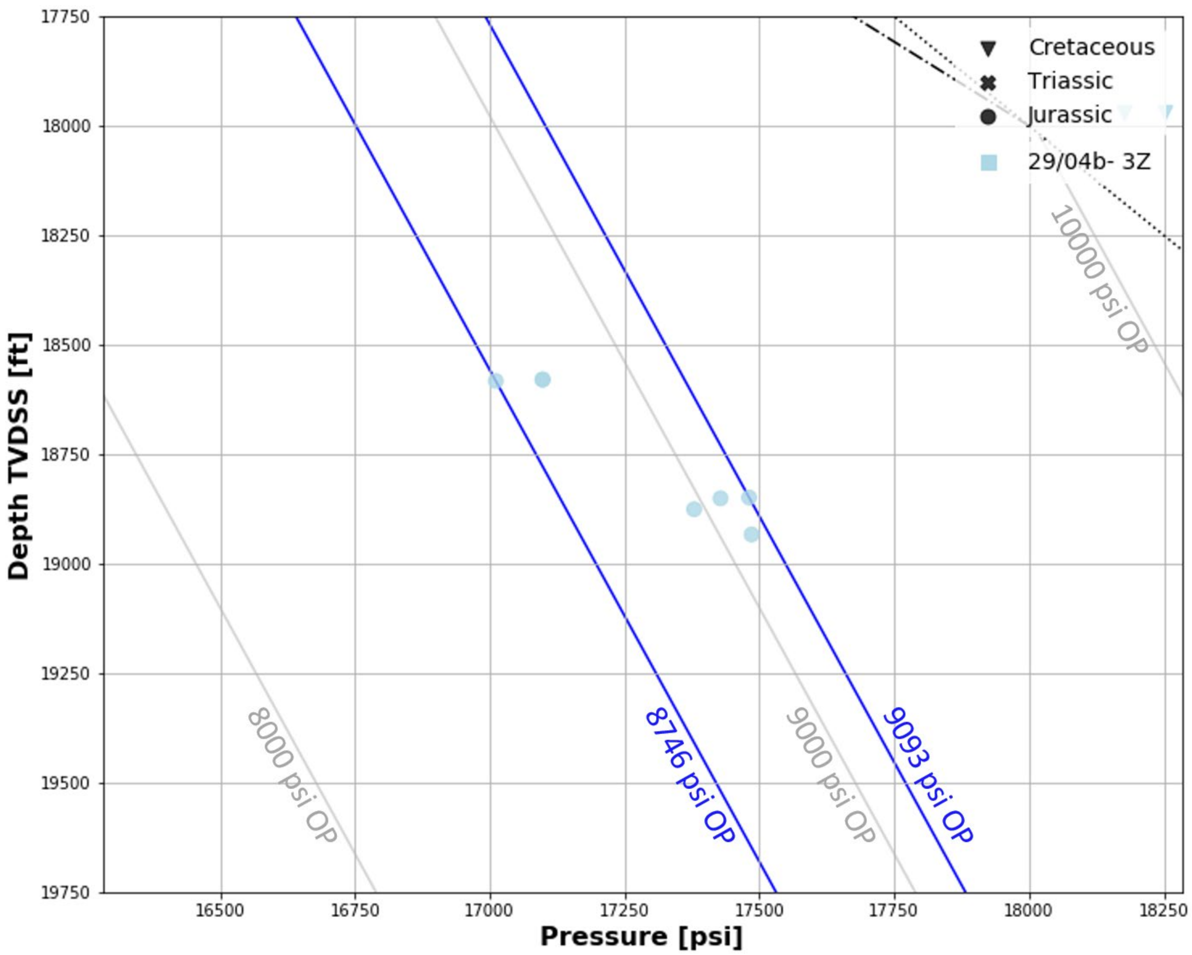

Figure 36: Depth vs pressure plot for well 29/04b- 3Z

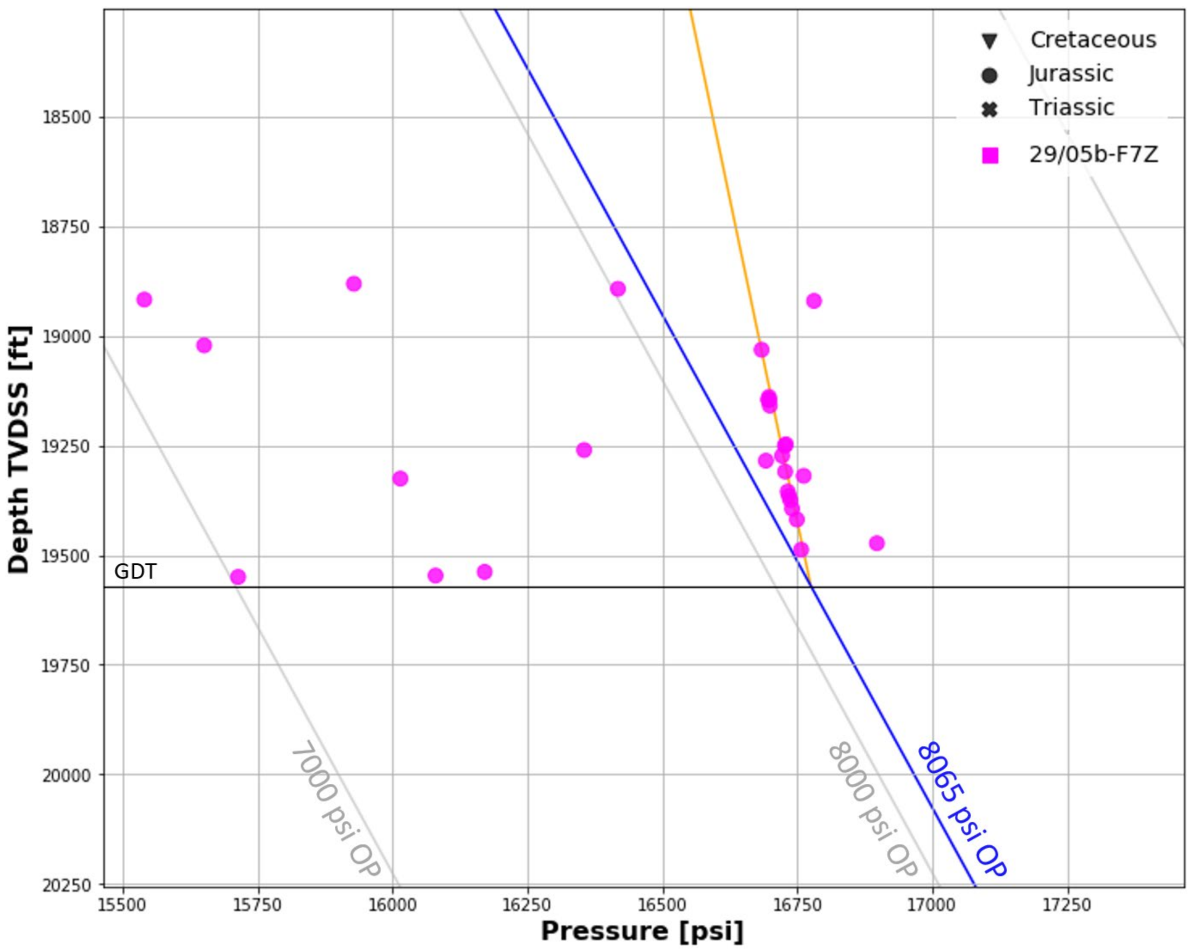

Figure 37: Depth vs pressure plot for well 29/05b-F7Z

South-west Central Graben

The South-west Central Graben shows a clear stepwise increase in overpressures across fault terraces, from near hydrostatic at the margin to between 6000 psi and 7000 psi overpressure in the basin. (Figure 38).

Pressure cell containing wells 29/06a- 3 (Cell ID: 84)

Oil was discovered in the Jurassic Fulmar Formation by well 29/06a- 3 ("Centurion"). The discovery has not been further matured but an ODT has been identified at 11072 ft TVDSS in this well (Relinquishment Report P1627). Using this contact and extrapolating through the Jurassic RFT data points along an oil gradient of 0.35 psi/ft yields an overpressure of 1409 psi. Well 29/06a- 3 did not find hydrocarbons in the Triassic Heron Group and the data is therefore reclassified as coming from a water-bearing interval. The Triassic Heron Group is assigned an overpressure of 1467 psi (Figure 38, Figure 39).

This pressure cell is characterised by overpressures between 1410 and 1470 psi.

Pressure cell containing wells 22/27a- 2; 29/02c- 9 (Cell ID: 80)

Well 22/27a- 2 discovered the "Deep Banff" gas condensate accumulation in the Jurassic Fulmar Formation. The lowermost RFT data point in the Jurassic Fulmar Formation lies below the OWC (16210.0 ft TVDSS, Relinquishment Report P114 and P224). This point is reclassified as being taken in the water-bearing interval and results in an overpressure of 6936 psi. Ikon Science also recorded pressure data from a kick in the gas-bearing Kimmeridge Clay Formation of well 22/27a- 2 which was not used to characterise the pressure cell (Figure 38, Figure 40).

The MDT data recorded in well 29/02c- 9 is assumed to be taken in the water leg with only residual oil shows noted during drilling. Ikon Science recorded an overpressure of 6443 psi for this well which is used for this pressure cell analysis.

This pressure cell is characterised by overpressures between 6440 and 6940 psi.

Pressure cell containing wells 30/11c- 6C (Cell ID: 56)

The "Romeo" discovery well 30/11c- 6C found oil both in the Jurassic and in the Triassic. The Jurassic Fulmar Formation was encountered at a greater depth than anticipated and was developed in thin oil-bearing sand intervals (Relinquishment Report P1666). A series of ODT's is given for the Fulmar Formation interval: 13783 ft TVDSS as definite ODT as well as 13874 ft TVDSS and 13940 ft TVDSS as possible ODT. Oil-bearing sands were also encountered in the Triassic Skagerrak Formation with an ODT of 14787 ft TVDSS and a possible WUT of 14817 ft TVDSS identified in the relinquishment report. Applying a standard oil gradient to the RCX data and extrapolating down to the given contacts yields a minimum and maximum overpressure of 4950 psi and 5294 psi of for the Jurassic (Figure 38, Figure 41) and a minimum and maximum overpressure of 4999 psi and 5042 psi for the Triassic intervals (Figure 42).

This pressure cell is characterised by overpressures between 4950 and 5290 psi.

Other pressure cells in the South-west Central Graben

No additional well data analysis was carried out on these pressure cells in the South-west Central Graben:

- Pressure cell containing wells 29/03b- 9; 29/03b- 4 (Cell ID: 47)
- Pressure cell containing wells 29/05a- 5; 29/10- 3Z (Cell ID: 48)
- Pressure cell containing well 29/08a- 3 (Cell ID: 93)
- Pressure cell containing wells 29/09c- 8; 29/15- 2 (Cell ID: 55)
- Pressure cell containing wells 29/09b- 6; 29/09b- 2 (Cell ID: 94)
- Pressure cell containing wells 29/07- 4; 29/14c- 5 (Cell ID: 82)
- Pressure cell containing wells 29/12- 2; 29/13b- 1 (Cell ID: 78)

Overpressure values for the pressure cells are derived from the analysis carried out by Ikon Science.

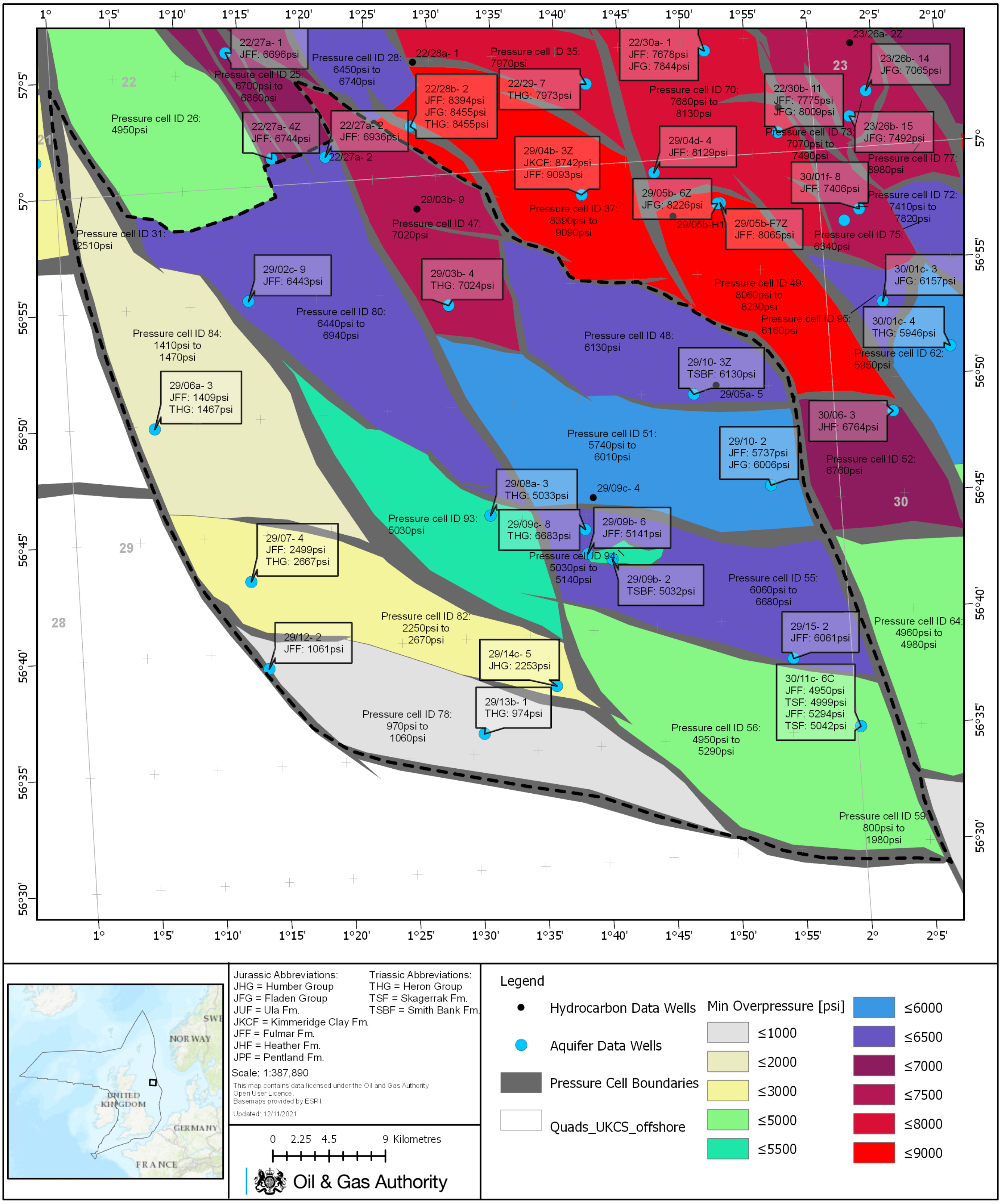

Figure 38: Combined Jurassic/Triassic pressure cell map showing the south-west Central Graben

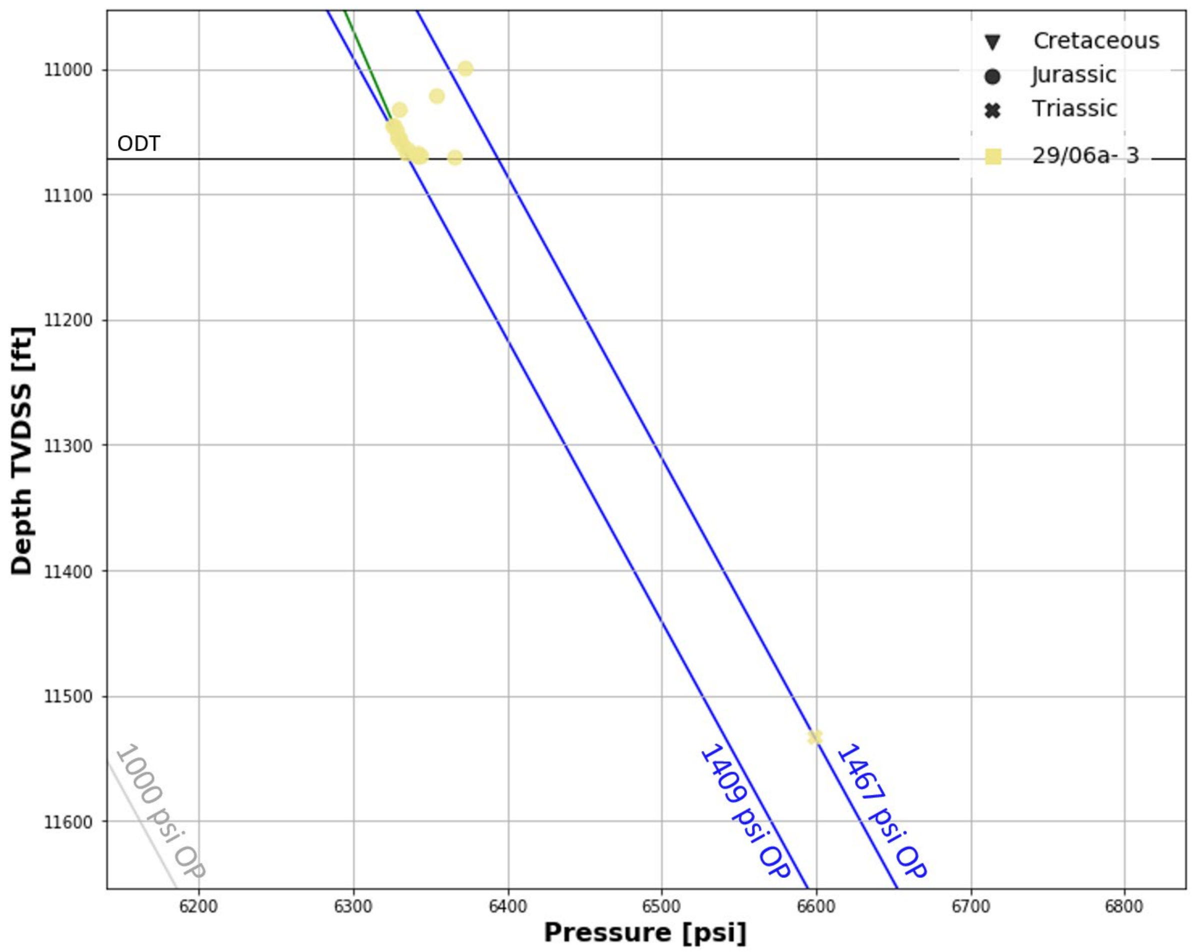

Figure 39: Depth vs pressure plot for well 29/06a- 3

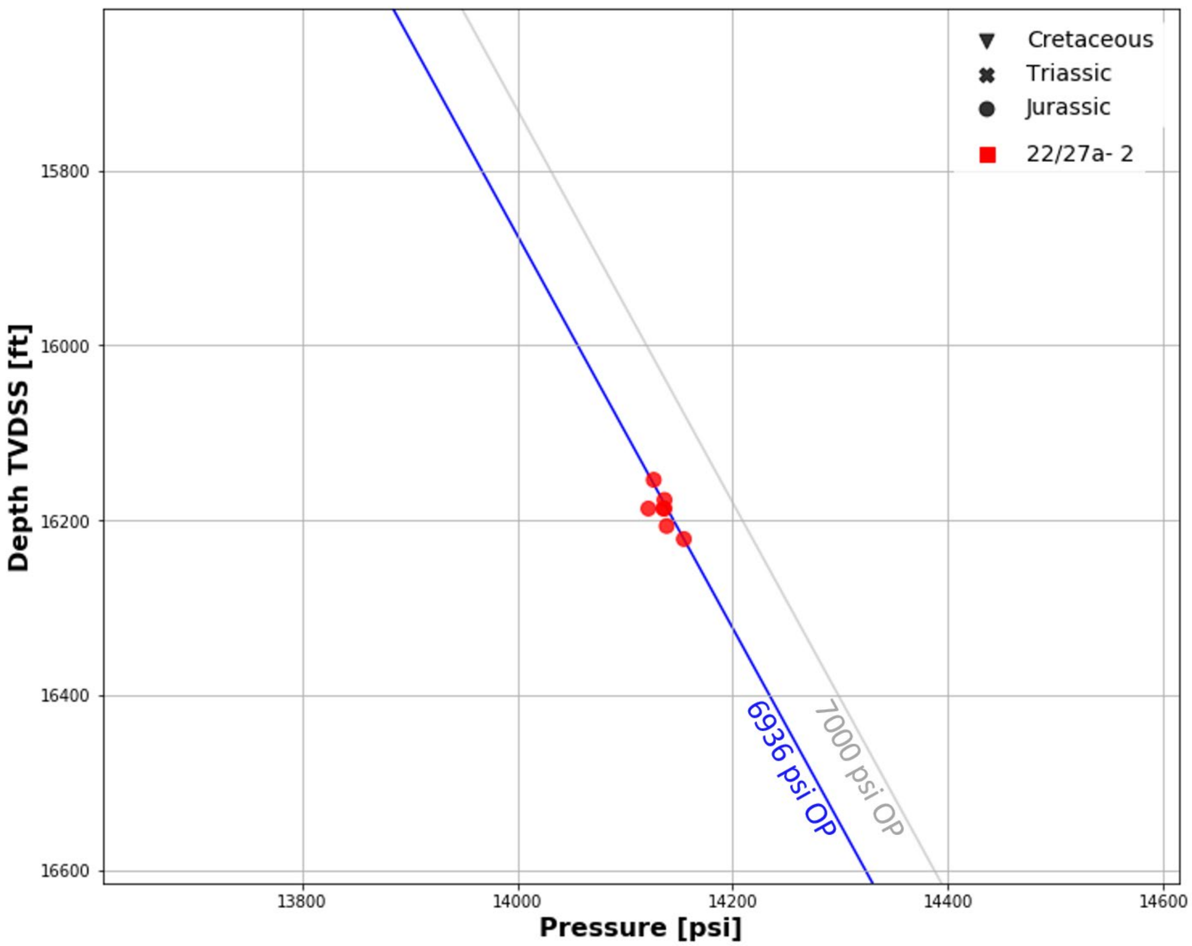

Figure 40: Depth vs pressure plot for well 22/27a- 2

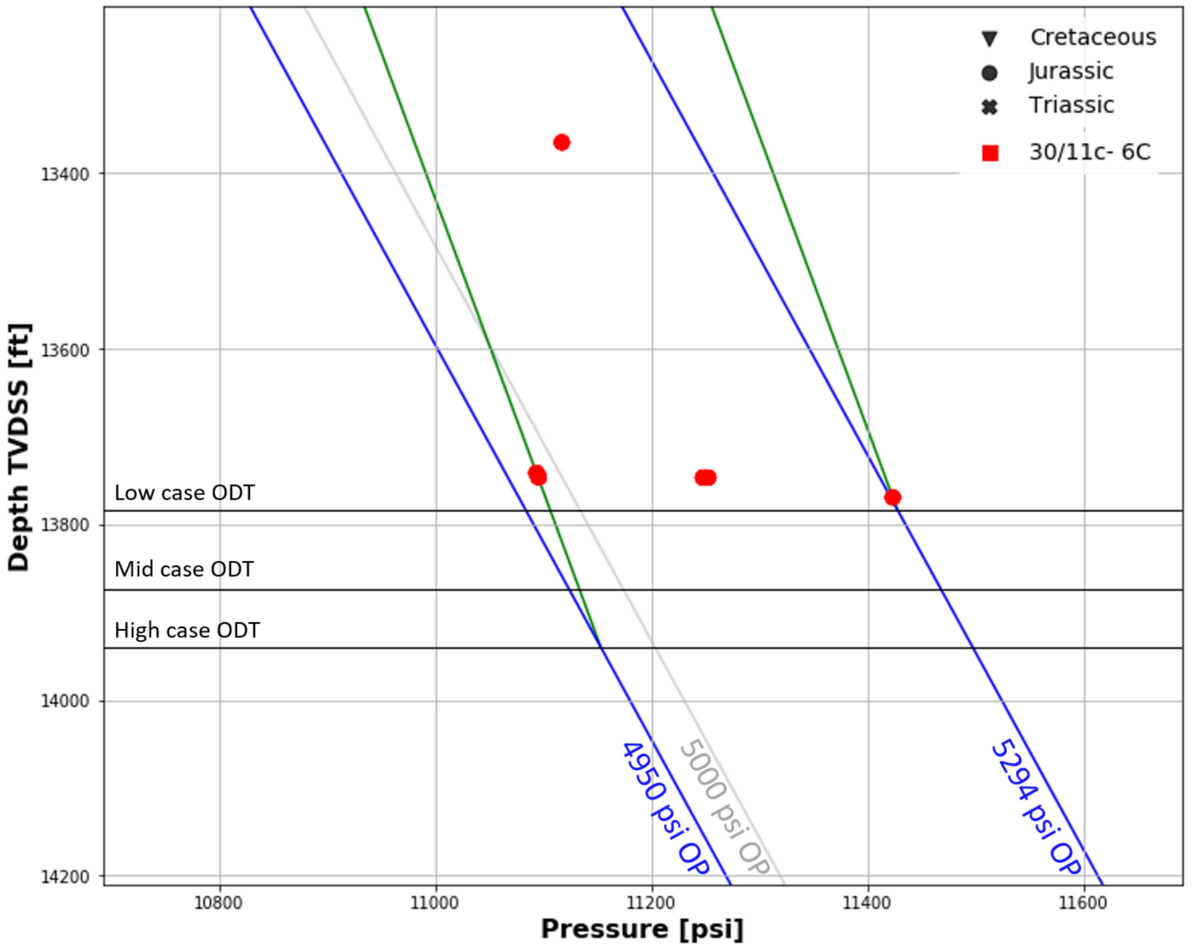

Figure 41: Depth vs pressure plot for well 30/11c- 6C, Jurassic data

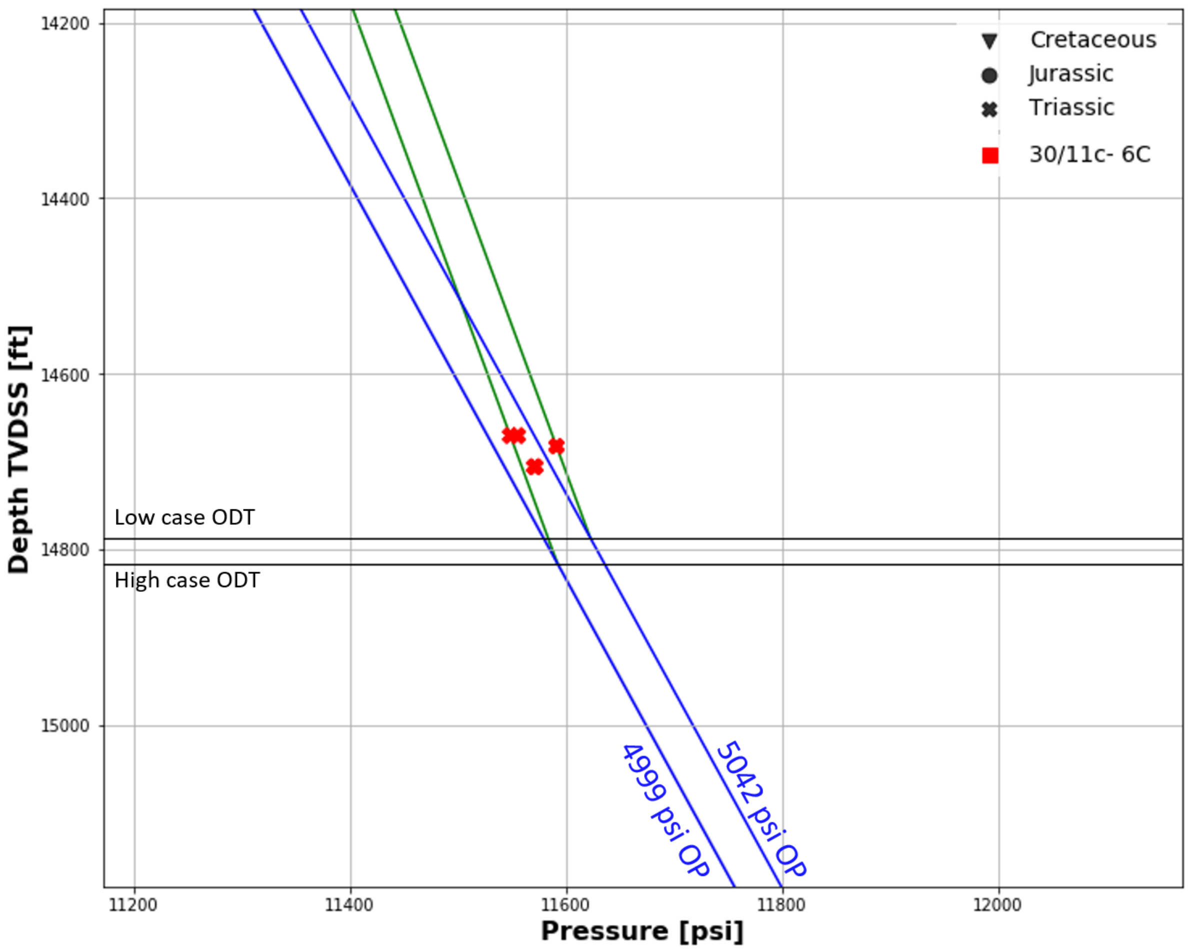

Figure 42: Depth vs pressure plot for well 30/11c- 6C, Triassic data

Josephine High and bordering basins

On the Josephine High, relatively low overpressures are interpreted, especially in the south (e.g. well 30/07a- 9 with 3762 psi overpressure in the Triassic Heron Group, Figure 43).

East of the Josephine High lies the south-eastern arm of the east Central Graben (Briefflab Basin) which has overpressures almost as high as in the centre of the Central Graben. The Jurassic Kimmeridge Clay Formation records an overpressure of 8975 psi in well 30/02a- 7Y in this area.

South of the Josephine High overpressures are lower, and measured pressures are close to the expected hydrostatic pressure. In the southernmost wells on the study area, 30/17a- 15 and 30/7a- 15Z overpressures of only 347 psi and 352 psi respectively are recorded (Figure 43).

Pressure cell containing wells 30/06- 7; 30/06- 7Y; 30/07a-S2; 30/07a-S4; 30/06- 6; 30/07a-10 (Cell ID: 53)

Well 30/06- 7 penetrates the Jasmine field which produces gas condensate and oil from the Triassic Skagerrak Formation. The MDT data recorded in the Triassic is fitted to a standard condensate gradient of 0.2 psi/ft and the aquifer overpressure is determined using a hydrocarbon contact. A HCDT of 15300 ft TVDSS for well 30/06- 7 is interpreted. The intersect of possible condensate gradients and the HCDT provide an aquifer overpressure of between 4878 psi and 4910 psi (Figure 43, Figure 44).

The RFT data recorded in well 30/07a- 10 shows a clear a water gradient in the Triassic Heron Group. Ikon Science recorded an overpressure of 4755 psi for the water gradient in this well which is used for this pressure cell analysis (Figure 43). The MDT data recorded in well 30/06- 6 displays a clear gas condensate gradient in the upper section of the Triassic Skagerrak Formation which was not analysed further. In the lower section of the Triassic Skagerrak Formation, it is assumed that the data was taken in the water leg based on well reports. Ikon Science recorded an overpressure of 4840 psi for these data which is used for this pressure cell analysis (Figure 43). No additional analysis was carried out for wells 30/06- 7Y, 30/07a-S2, and 30/07a-S4 which have data recorded in the hydrocarbon leg.

This pressure cell is characterised by overpressures between 4760 and 4910 psi.

Pressure cell containing wells 30/11b- 4 (Cell ID: 64)

The “Appleton Beta” discovery well 30/11b- 4 found gas condensate in the Jurassic Fulmar Formation. Ikon Science determined a gas condensate gradient for the recorded MDT data of 0.249 psi/ft. Two tentative HCDT depths were determined from the composite log for this well (NDR File ID: 1778499) at 14339 ft TVDSS and 14429 ft TVDSS. The intersect of the condensate gradients and HCDT depths provides an overpressure range of 4980 psi to 4963 psi (Figure 43, Figure 45).

This pressure cell is characterised by overpressures between 4960 and 4980 psi.

Pressure cell containing wells 30/13- 3; 30/13- 6; 30/13- 2; 30/13b- 10; 30/13b- 10Z; 30/13a-9; 30/14- 1 (Cell ID: 61)

Wells 30/13- 3 and 30/13- 6 both penetrate the oil-bearing Jurassic Heather Formation. This discovery is known as “Jacqui” or “Austen”. Well 30/13- 3 has an ODT of 13720 ft TVDSS and well 30/13- 6 has an ODT of 13410 ft TVDSS. Well 30/13- 3 shows multiple oil gradients with increasing pressure magnitude. Standard oil gradients of 0.3 psi/ft are fitted to this data. Using the oil gradients and the ODT an overpressure range of 4711 psi to 4823 psi is interpreted. In well 30/16- 3 an oil gradient of 0.387 psi/ft was determined by Ikon Science. Using this oil gradient and the ODT for this well an overpressure range of 4709 psi to 4715 psi is determined for the well (Figure 46, Figure 47). The range is due to the scatter of the data.

Mudweight pressure data is available from the water-bearing Jurassic Humber Group in well 30/13- 2. Ikon Science interpret an overpressure of 4044 psi for this well which is used for this pressure cell analysis (Figure 43). The data for wells 30/13b- 10, 30/13b- 10Z, and 30/13a- 9 are derived from oil-bearing intervals, no further analysis was carried out for these wells and they were not used for the pressure cell interpretation. Well 30/14- 1 has data recorded for the Cretaceous which was not used for analysis.

This pressure cell is characterised by overpressures between 4040 and 4820 psi.

Other pressure cells on the Josephine High and in bordering basins

No additional well data analysis was carried out on these pressure cells in the South-west Central Graben:

- Pressure cell containing wells 30/01c- 3 (Cell ID: 95)

- Pressure cell containing wells 30/01c- 4 (Cell ID: 62)
- Pressure cell containing wells 30/02a- 2 (Cell ID: 75)
- Pressure cell containing wells 30/06- 3 (Cell ID: 52)
- Pressure cell containing wells 30/07a- 9; 30/07a-P23; 30/07a-P24; 30/07a- 6 (Cell ID: 54)
- Pressure cell containing wells 30/02c-J11Z; 30/02c- 4 (Cell ID: 63)
- Pressure cell containing wells 30/08- 3 (Cell ID: 15)
- Pressure cell containing wells 30/02a- 7; 30/02a- 7Y; 30/02a- 6 (Cell ID: 77)
- Pressure cell containing wells 30/12b- 6; 30/12b- 10; 30/12b- 4; 30/12b- 3; 30/16- 6; 30/17b- 9; 30/17b- 2; 30/17b-A42; 30/17b-A34W; 30/17b-A34X; 30/17b- 5; 30/17a- 14Z; 30/17a-J9; 13/17a-J14 (Cell ID: 59)
- Pressure cell containing wells 30/18- 3 (Cell ID: 96)
- Pressure cell containing wells 30/19a- 5; 30/19a- 5X; 30/19a- 6 (Cell ID: 60)
- Pressure cell containing wells 30/17a- 15; 30/17a- 15Z (Cell ID: 97)

Overpressure values for the pressure cells are derived from the analysis carried out by Ikon Science.

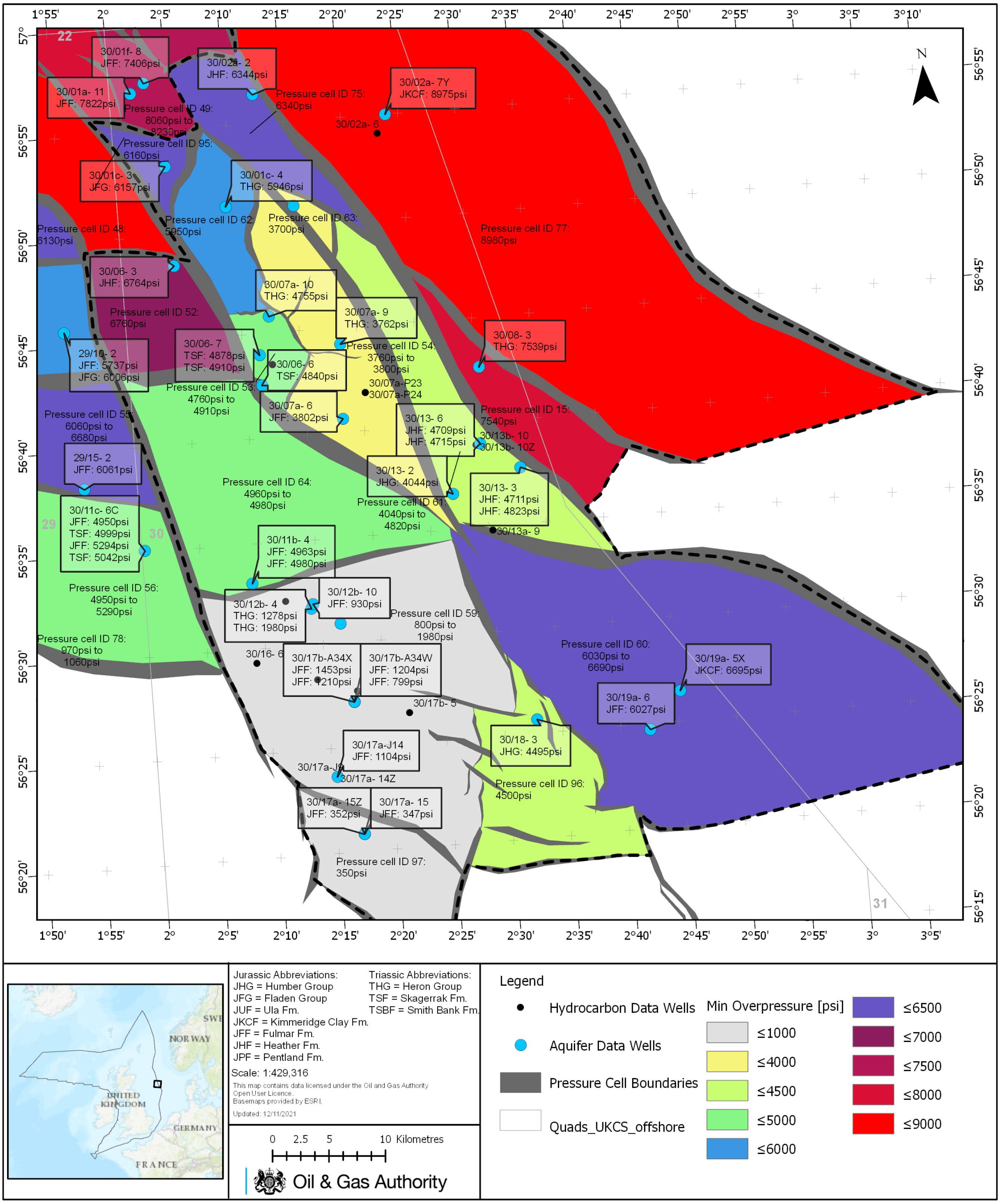

Figure 43: Combined Jurassic/Triassic pressure cell map showing the Josephine high area

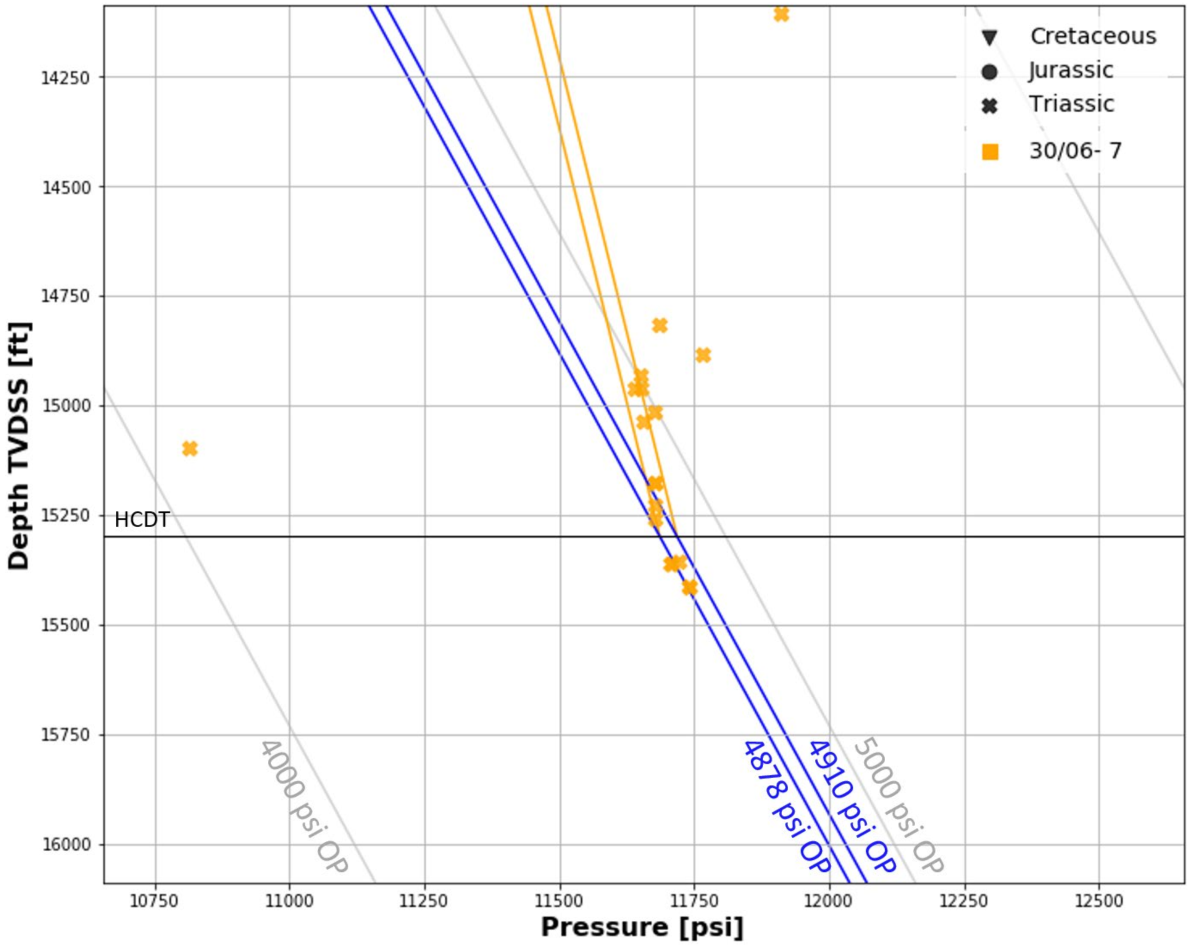

Figure 44: Depth vs pressure plot for well 30/06- 7

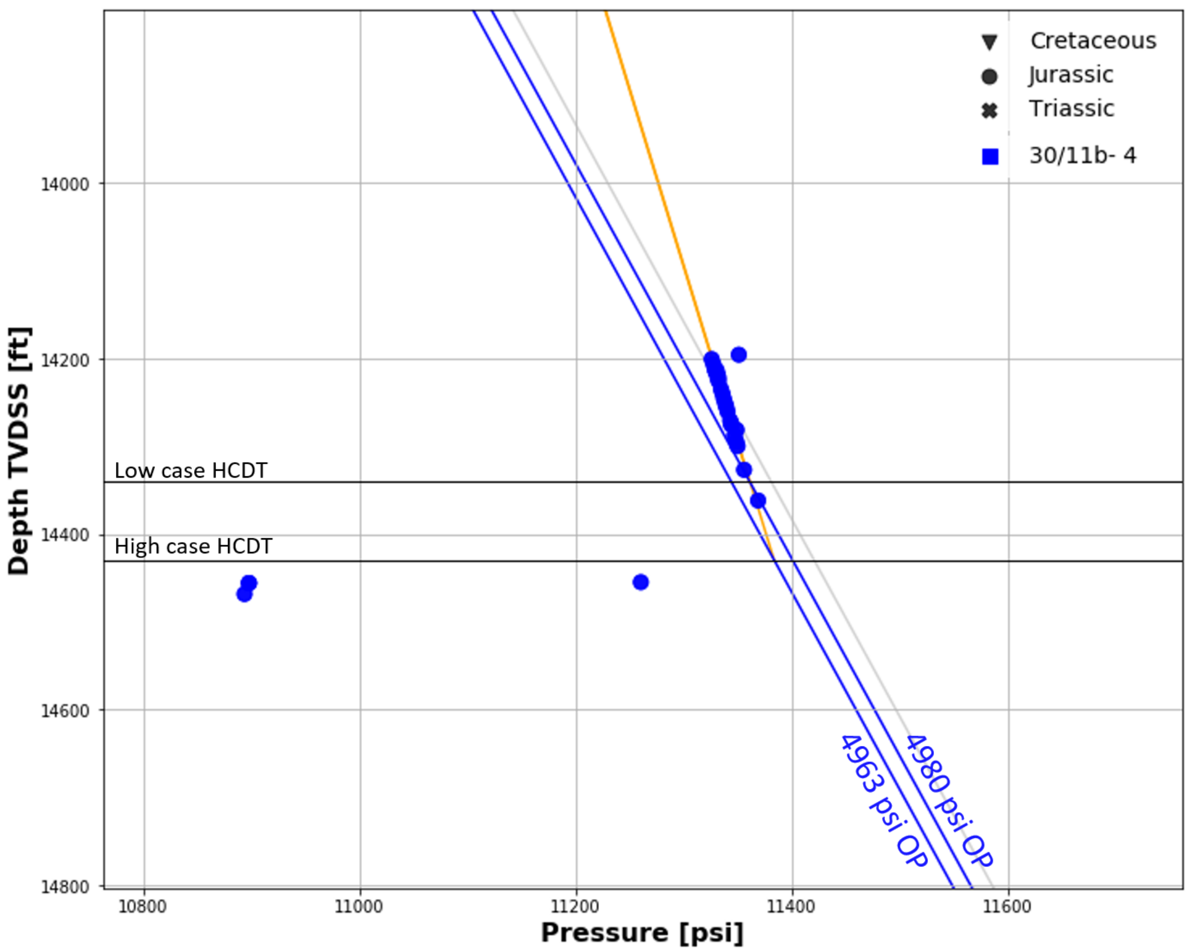

Figure 45: Depth vs pressure plot for well 30/11b- 4

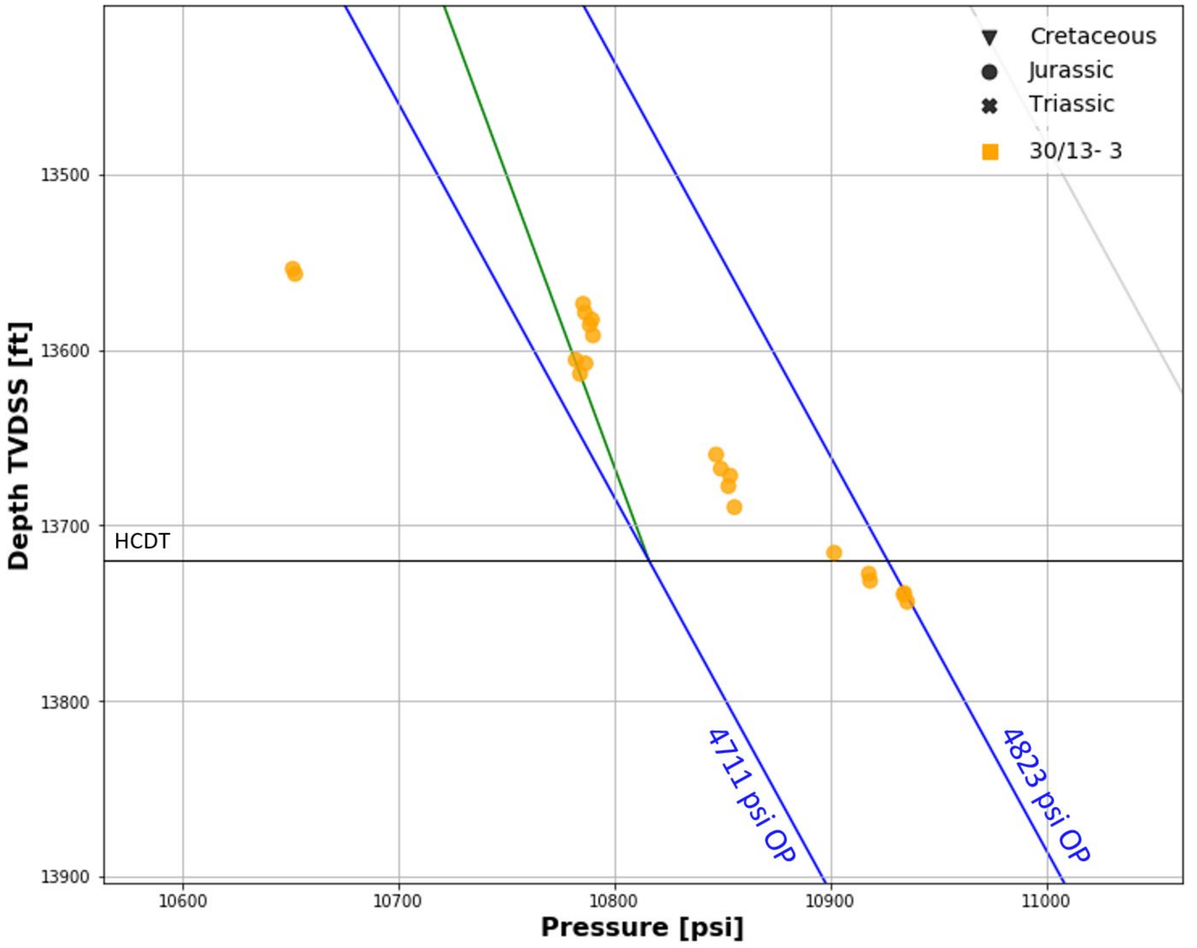

Figure 46: Depth vs pressure plot for well 30/13- 3

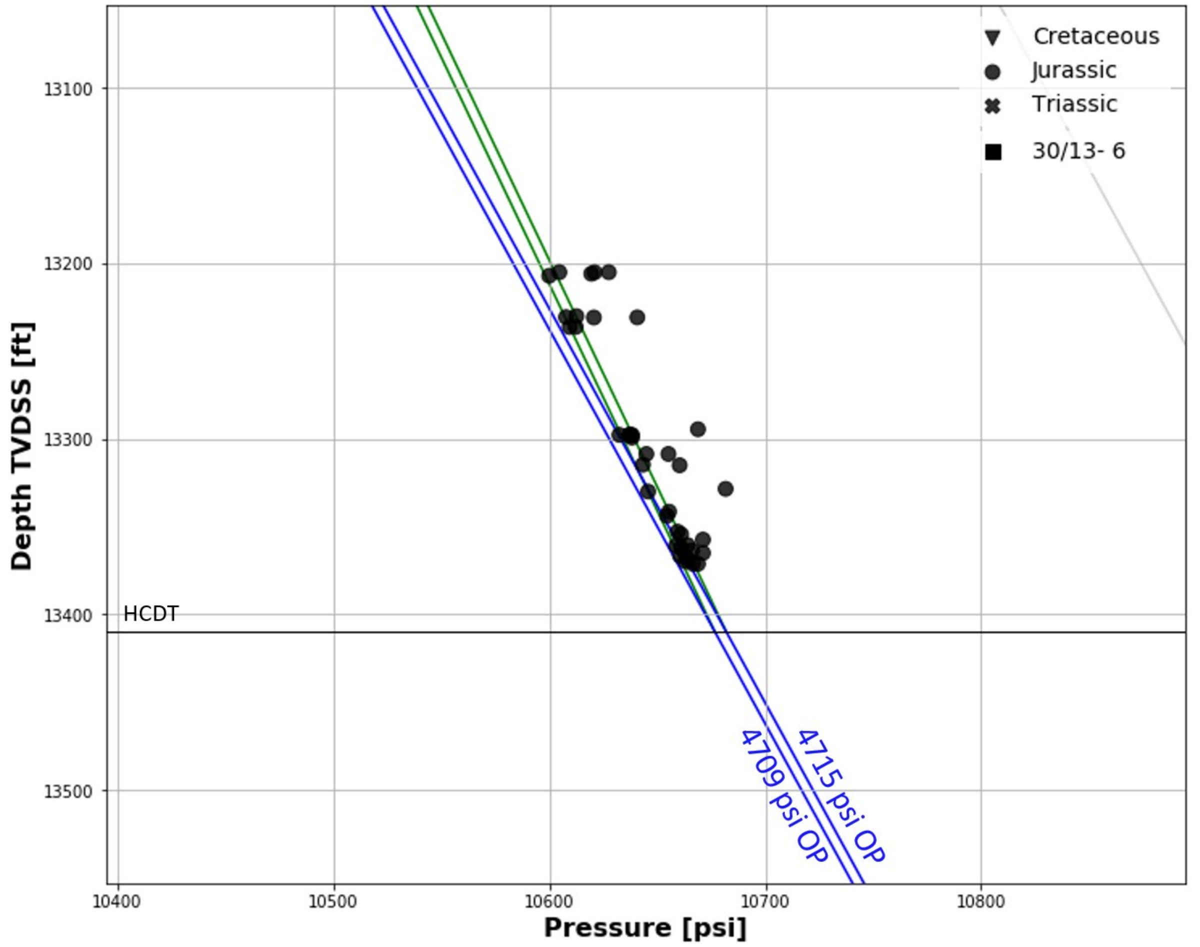

Figure 47: Depth vs pressure plot for well 30/13- 6

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Appendix 1: Regional HPHT Pressure Database

Study by Ikon Science Limited

Proposal Number | 0002716v2 / ITT-NEO-003-2020

Regional HPHT Pressure Database Study

Technical Report for New European Offshore (NEO)

21 January, 2021

Sam Green — Technical Manager, Wells – EA & ME
Steve Edmond — Data Services Manager

William Slade — Senior Business Development Manager

Contents

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Changes Record

Rev.	Comments	Date	Reviewed by
0	Initial submission	21 Jan, 2021	Sam Green
1	Updated the overpressure database to add fluid type interpretations to all data points where these were not present Update the report to discuss how the fluid types were interpreted / recorded	5 Mar, 2021	Sam Green
2	Minor updates to the fluid type definitions to reflect aquifer data more accurately	10 Mar, 2021	Sam Green

Scope of Work

The primary aim of this study is to provide a quality-controlled high pressure high temperature (HPHT) database for the selected wells the Area of Interest as defined by NEO (Figure 1), the focus is on the Jurassic interval but where this interval is missing, or was not pressure tested, then data from the overlying Cretaceous (Pre-Chalk) or underlying Triassic have been included.

Data Sourcing & Loading

There are 194 wells in total included in the study. The wells are split such that 72 wells were taken from the CGG pressure database (as supplied by NEO) and 122 were sourced from the UK National Data Repository (NDR). The wells in the CGG database were checked against the NDR database for additional data, such as LOT, FIT, and mudweights, and downloaded where available/necessary. In a few wells, there were minor errors in the CGG database, i.e., incorrect units, which were corrected during the importation process. For all wells, particular focus was applied to finding sources of reservoir pressure data and their build-up pressure plots taken during testing. Additionally, accompanying information such as the well headers, well tops, deviation surveys, and well test data were downloaded in a similar manner from either NDR or the Oil & Gas Authority's (OGA) Open Data repository.

Process Raw Data

All pressure data, either reservoir pressure data or Leak-Off Tests (LOTs) and Formation Integrity Tests (FITs) LOT/FIT data, were assessed for magnitude and quality subject to what reporting is available from the NDR. A standardised criteria for assessing reservoir pressure data was used to assign a quality flag to all data including the CGG data to produce a unified pressure database.

Overpressure Interpretation

All wells were interpreted on a single-well basis, with overpressures calculated relative to a consistent hydrostatic gradient of 0.445 psi/ft in all wells, and all gradients calculated using the same statistical method of fitting. All overpressure values were assigned a category value, based on the quality of the fit and/or the fluid type derived from gradients established, where possible.

Database Creation

The database was exported in the following formats .xlsx, .csv. The output formats include the following information, available in the requested depth references (MD(RKB), TVD and TVDSS):

- Basic Well Header Information
- Well Picks
- Fluid and Well Test Data
- Formation Integrity Data
- Mud-Weights (where required)
- Fluid Gradients
- Fluid Overpressures
- Quality Flags
- Category Values

Area of Interest

The initial well list for this study was defined by NEO; during the data loading Ikon Science identified, and communicated to NEO, those wells with a lack of key data and substitutes included to build a final list of 194 wells as shown on the map below.

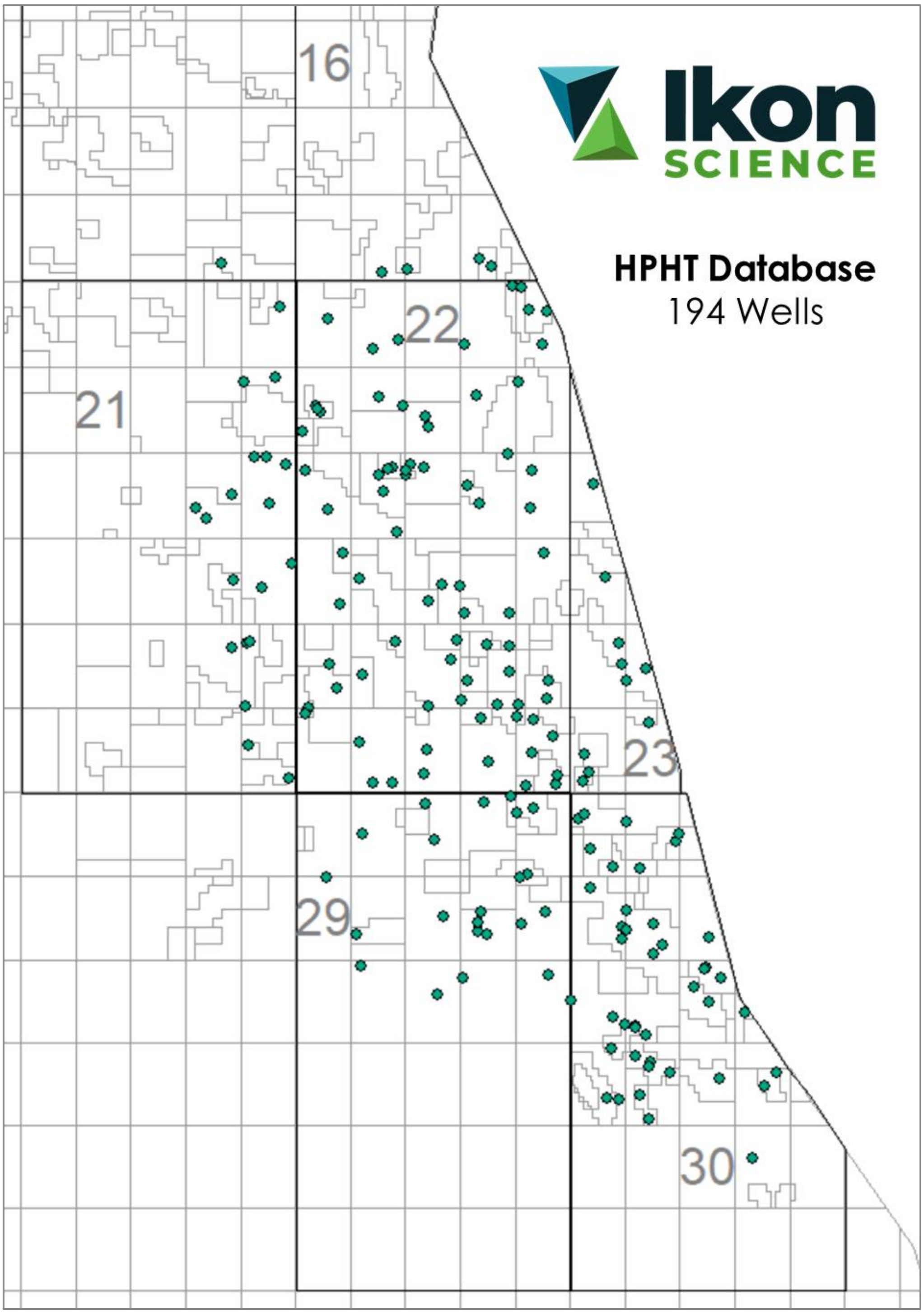


Figure 1 Map of Quads 15, 16, 21, 21, 22, 23, 29, 30 Central North Sea showing the location of the 194 wells in this study

Stratigraphic Naming Scheme

The stratigraphic tops in the study have been taken from the OGA Collated Well Tops database, where wells in this study were not included in the OGA database the reported tops in the well report were standardised against the matching entry in the OGA database.

To make the overpressure data in this study easier to compare regionally, the stratigraphic tops have been simplified to their main geological formation. Where no formation was specified then the group name is used. Time equivalent formations, e.g., Kimmeridge Clay, Fulmar, and Heather can all be Volgian-Oxfordian in age, have been kept separate.

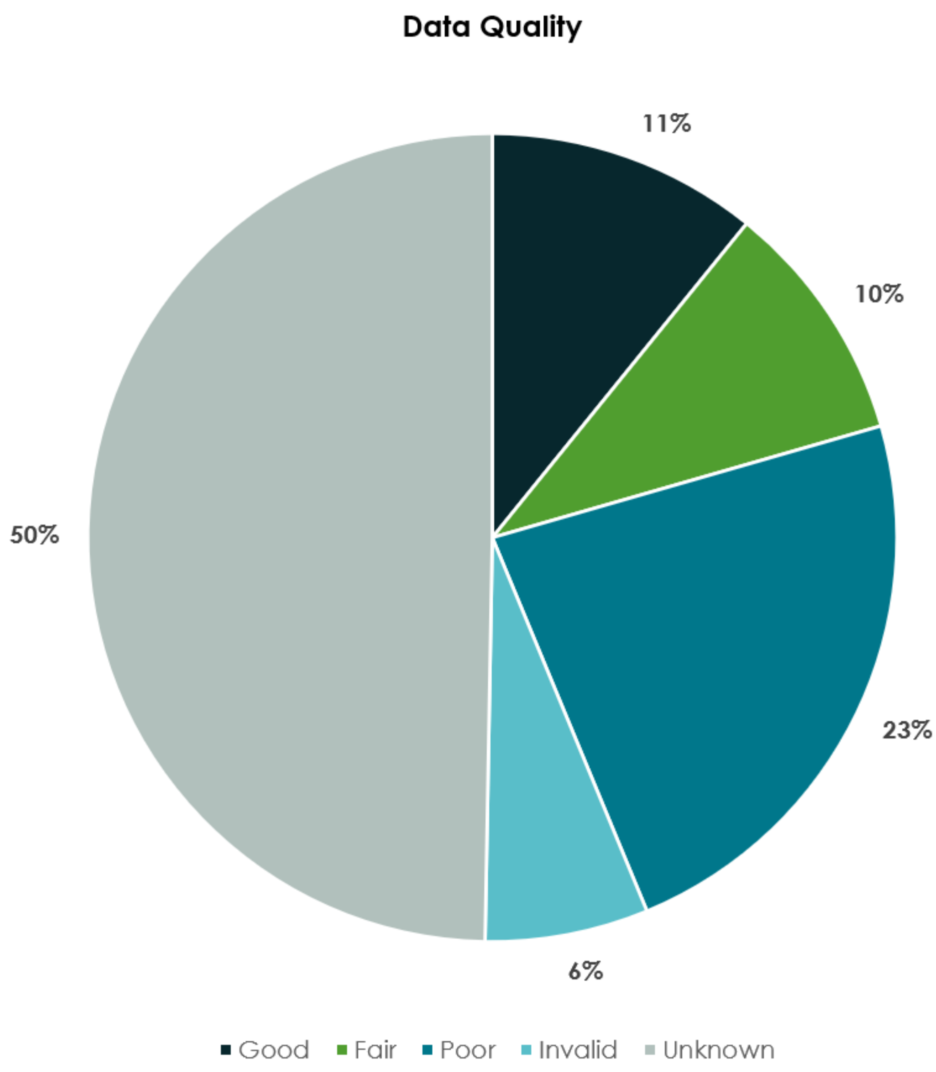
The table below shows the stratigraphic scheme below the Chalk Group.

Geological Period	Unified Well Top	OGA Well Top
Cretaceous Pre-Chalk	Cromer Knoll Group	Cromer Knoll
	Britannia Sandstone Formation	Britannia Sandstone
	Sola Formation	Sola
	Valhall Formation	Valhall
Jurassic	Humber Group	Humber
	Kimmeridge Clay Formation	Ribble Sandstone
		Kimmeridge Clay
		Kimmeridge Sands
	Fulmar Formation	C Sand
		Fulmar
		Fulmar B
		Fulmar B Zone
		Fulmar C
		Fulmar Equivalent
		Fulmar Formation
		Fulmar Member
		Fulmar Sandstone
		Fulmar Zone A
		Fulmar Zone C
		Lower B Sand
		Lower Fulmar
		Lower Fulmar B
		Upper B Sand
		Upper Fulmar
		Lower Fulmar Member
		Middle Fulmar Member
	Heather Formation	Heather
		Freshney Sandstone
		Jacqui Sandstone Member
	Jackdaw Sandstone	Jackdaw Sandstone
	Fladen Group	Fladen
	Hugin Formation	Hugin A
		Hugin B
	Pentland Formation	Pentland
		Pentland Sandstone Member
		Rattray Volcanics
	Ula Formation	Ula
Triassic	Heron Group	Heron
	Skagerrak Formation	Skagerrak
		Joanne Sandstone
		Joanne Sandstone Member
		Jonathan Mudstone Member
		Josephine Sandstone
		Judy Sands
	Smith Bank Formation	Smith Bank
Permian	Rotliegend Group	Rotliegend
	Zechstein Group	Zechstein
Devonian	Old Red Group	Old Red

Data Quality

Every individual pressure data point recorded in each well in the study has had a quality flag assigned, based on interpretation of the pressure build-up plots where the data allow. As the data vary in age, and tool type used, a pragmatic approach was needed to assign a standardised criteria for all the data. Examples of each category are presented in Appendix 1.

Quality	Definition	
Good	Pressure data that have stabilised during build-up to an accuracy of less than a psi for at least 1 minute, i.e., the pressure build-up has stabilised at the first, second, or third decimal place depending on the age and accuracy of the tool	
Fair	Pressure data that are either stable to the nearest single psi value for at least one minute, or are building pressure at the second or third decimal place for at least one minute, and are, therefore, consistently rounded to the same single psi value	
Poor	Pressure data that are still building in magnitude at a rate that indicates that the magnitude, to the nearest single psi value, will increase over the duration of the test, i.e., have not stabilised	
Invalid	Pressure data that are not representative of the true pressure magnitude; this may be due to a variety of factors as described below but are universally captured as "Invalid"	
	Supercharging	In tight formations (low permeability) the pressure of the mud filtrate may not have dissipated from within the formation, leading to pressure readings more than the formation pressure
	Dry Test	In tight formations (low permeability) the reservoir fluid is unable to flow into the tool in time such that a pressure build-up can be measured
	Seal Failure	A failure in the packer around the probe such that the tool only reads the pressure of the mud column and not the formation
	Tool Failure	Mechanical failure of the tool
Unknown	Pressure data for which there are no build-up plots available in the well reports; comments regarding test quality that may exist in the reports are not used as these cannot be verified and will not be consistent across all the data	



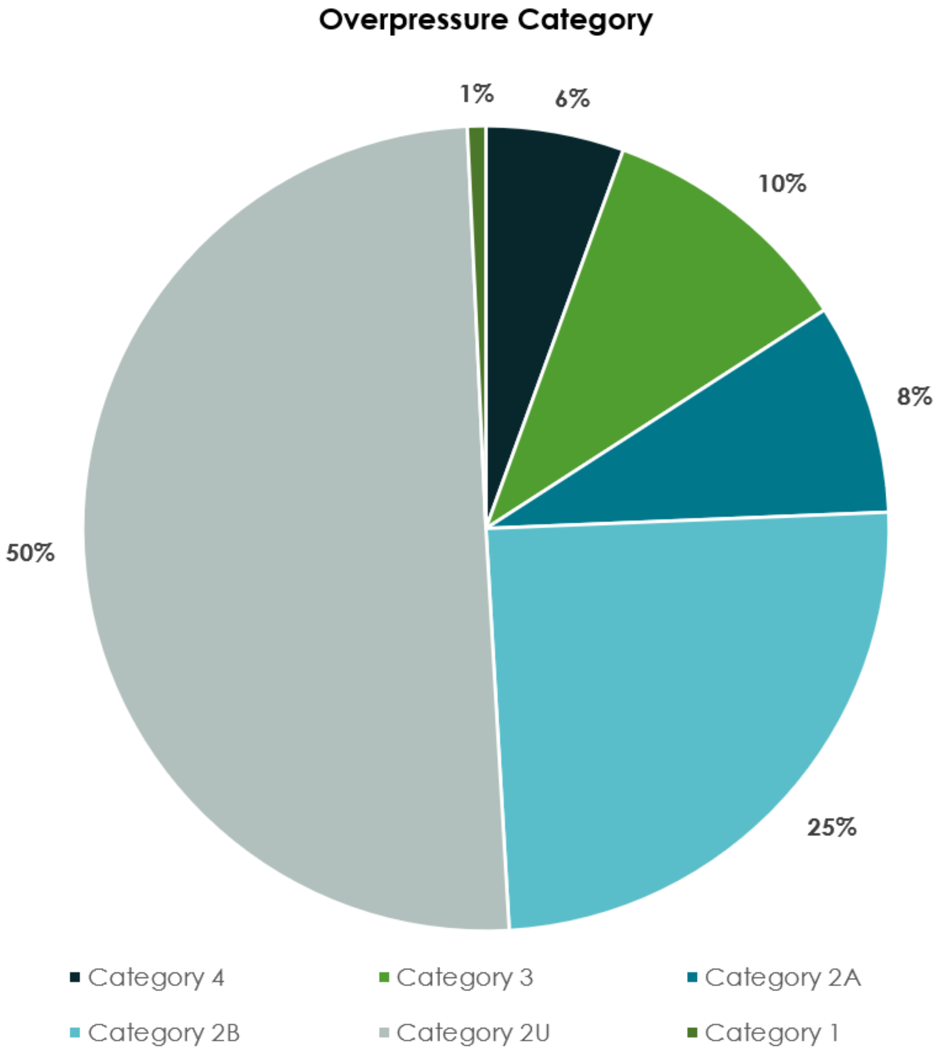
Quality	Total
Good	340
Fair	305
Poor	729
Invalid	205
Unknown	1561

Overpressure Categories

Every overpressure data point in the study has had a category assigned, based on interpretation of the fluid gradients, where the data allow. The magnitude of overpressure is relative to a gradient of 0.445 psi/ft from sea-level to TD with a surface pressure of 14.69 psi.

Where multiple aquifers were present in a single well each gradient has been recorded, but where the same gradient represents multiple reservoirs only one value was recorded. Examples of each category are presented in Appendix 2.

Category	Definition	
4	Well data display a very clear aquifer gradient with little or no scatter in the data. Category 4 values are the highest confidence values.	
3	Represents a well in which the pressure data generate a low uncertainty aquifer gradient but some minor scatter is observable.	
2	Category 2 is assigned when the overpressure data are of lower reliability. It has also been further divided into Categories 2A, 2B and 2U, as follows:	
	2A	Aquifer data: Examples of Category 2A values include wells where there are only a small number of points with no clear gradient, two points only or a single point but the logs indicate water.
	2B	Hydrocarbon data: A hydrocarbon gradient or a single pressure measurement point identified as hydrocarbon using a resistivity log.
	2U	Unidentified fluid type: A gradient with marginal data is present, single point or several but no gradient can be fitted and there is no resistivity log to confirm the fluid type present (i.e., aquifer or hydrocarbon).
1	Category 1 data are assumed to be depleted, i.e., they show pressure less than hydrostatic pressure gradient of 0.445 psi/ft and regardless of the pressure gradient or pressure point type (aquifer/hydrocarbon) or quality.	



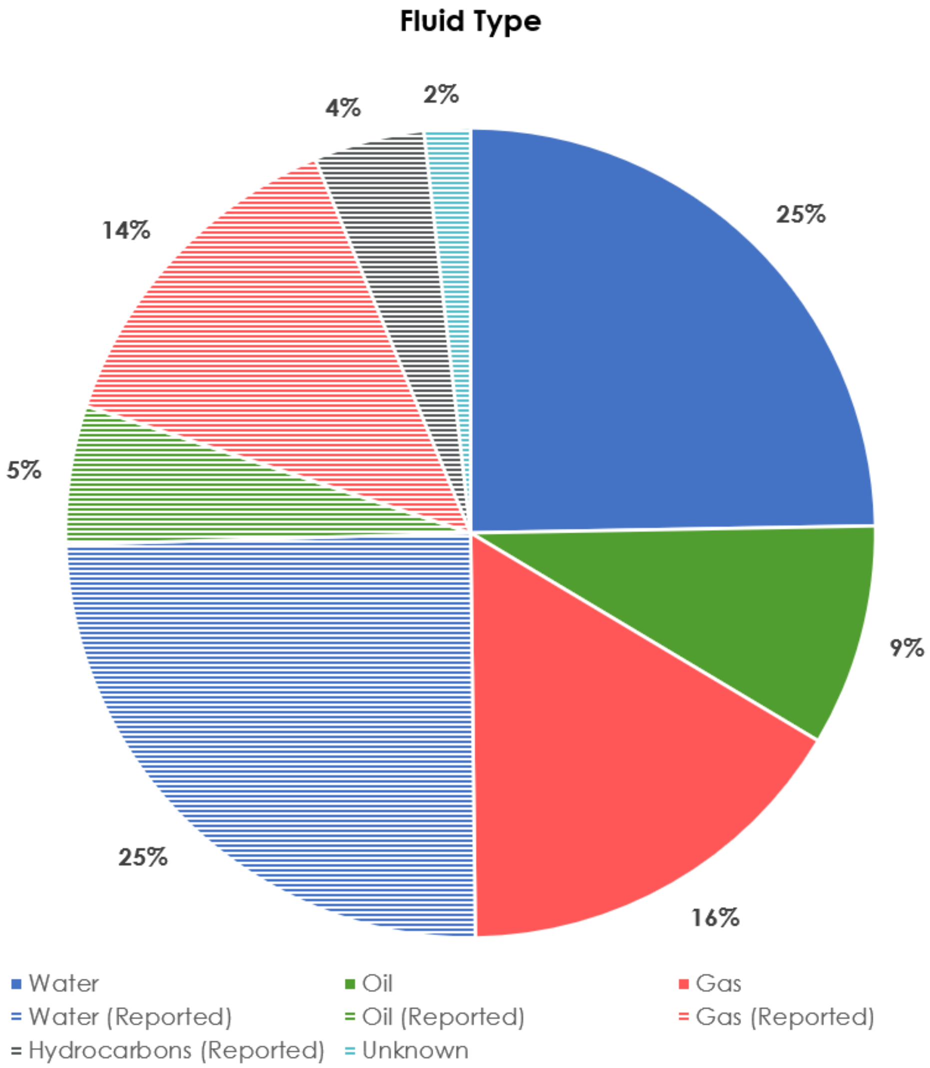
Category	Total
4	15
3	28
2A	23
2B	67
2U	136
1	2

Fluid Types

Every overpressure data point in the study has had a fluid type assigned; if possible, this is based on interpretation of the fluid gradients from the measured pressure data, however, this is not always possible due to a lack of data or scatter in the data which does not allow for a confident gradient to be fitted. Where a fluid type could not be determined then the well documentation was reviewed, and a fluid type assigned following the criteria below.

The fluid types assigned are associated with the specific overpressure values and intervals in the delivered database and may not reflect the primary fluid status of the well associated with the target reservoirs.

Quality	Definition
Water	Defined as a gradient in the range of 0.43 – 0.54 psi/ft to capture aquifers from fresh water to hyper-saline. For 5 data points, the interpreted gradient was in the range of 0.40 – 0.43 psi/ft and these data were initially assigned as oil but were edited to be water as heavy oils are not present in the study area. It is more likely that the fluid gradient was reduced as a function of the in-situ temperature (aquathermal expansion) causing a false interpretation.
Oil	Defined as a gradient in the range of 0.30 – 0.43 psi/ft.
Gas	Defined as a gradient < 0.30 psi/ft. No attempt was made to clarify between gas and gas condensates.
Water (Reported)	Water was reported, interpreted, or inferred in the well documents but cannot be verified from the pressure data available
Oil (Reported)	Oil was reported, interpreted, or inferred in the well documents but cannot be verified from the pressure data available
Gas (Reported)	Gas was reported, interpreted, or inferred in the well documents but cannot be verified from the pressure data available
Hydrocarbons (Reported)	Hydrocarbons were reported, interpreted, or inferred in the well documents but the specific type cannot be verified from the documents or the pressure data available
Unknown	No fluid type was discussed in the well documents



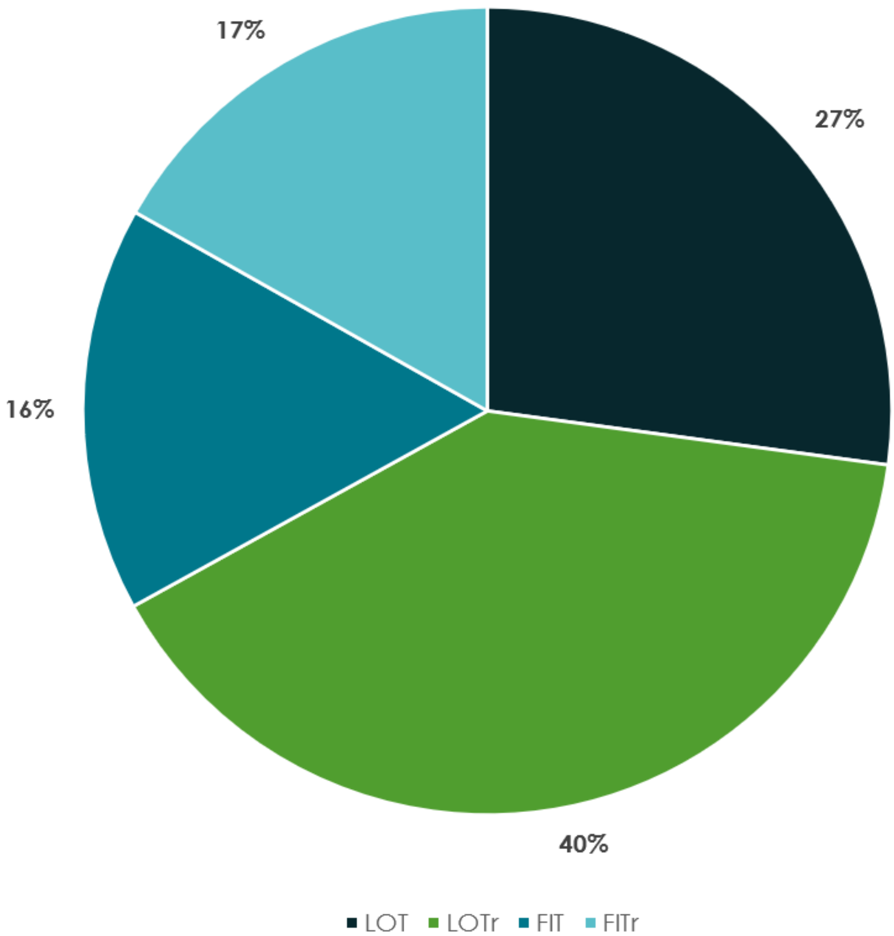
Fluid Type	Total
Water	67
Oil	24
Gas	44
Water (Reported)	67
Oil (Reported)	15
Gas (Reported)	37
Hydrocarbons (Reported)	12
Unknown	5

Fracture Pressure Data

All Leak-Off Tests (LOTs) and Formation Integrity Tests (FITs) have been recorded based on information available in the well reports and other documentation available from the NDR.

Name	Definition
LOT	The build-up plot clearly shows a break in slope consistent with the initiation of a fracture in the wellbore wall. The pressure, and the equivalent mudweight, were then interpreted from the plot and updated relative to the reported values where necessary.
LOTr	The test was reported as a Leak-Off Test but the build-up plot for the test was not available, so the reported values and test type are used.
FIT	The build-up plot clearly shows no break in slope indicative of a fracture in the wellbore wall. The pressure, and the equivalent mudweight, were then interpreted from the plot and updated relative to the reported values where necessary.
FITr	The test was reported as a Formation Integrity Test but the build-up plot for the test was not available, so the reported values and test type are used.

Fracture Pressure Test Type



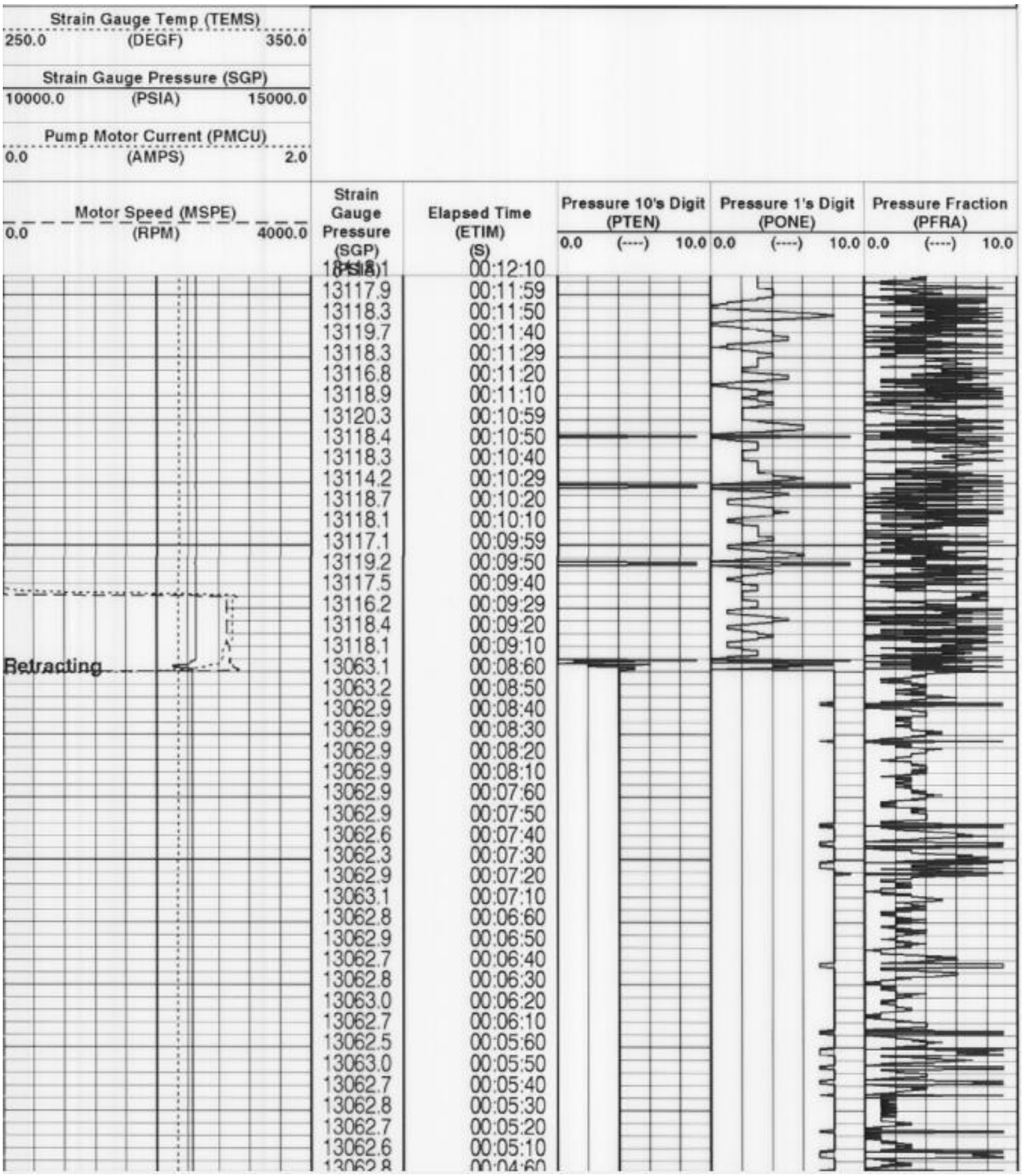
Test Type	Total
LOT	92
LOTr	135
FIT	55
FITr	57

Appendix 1: Data Quality Examples

Good

Well: 22/21-7

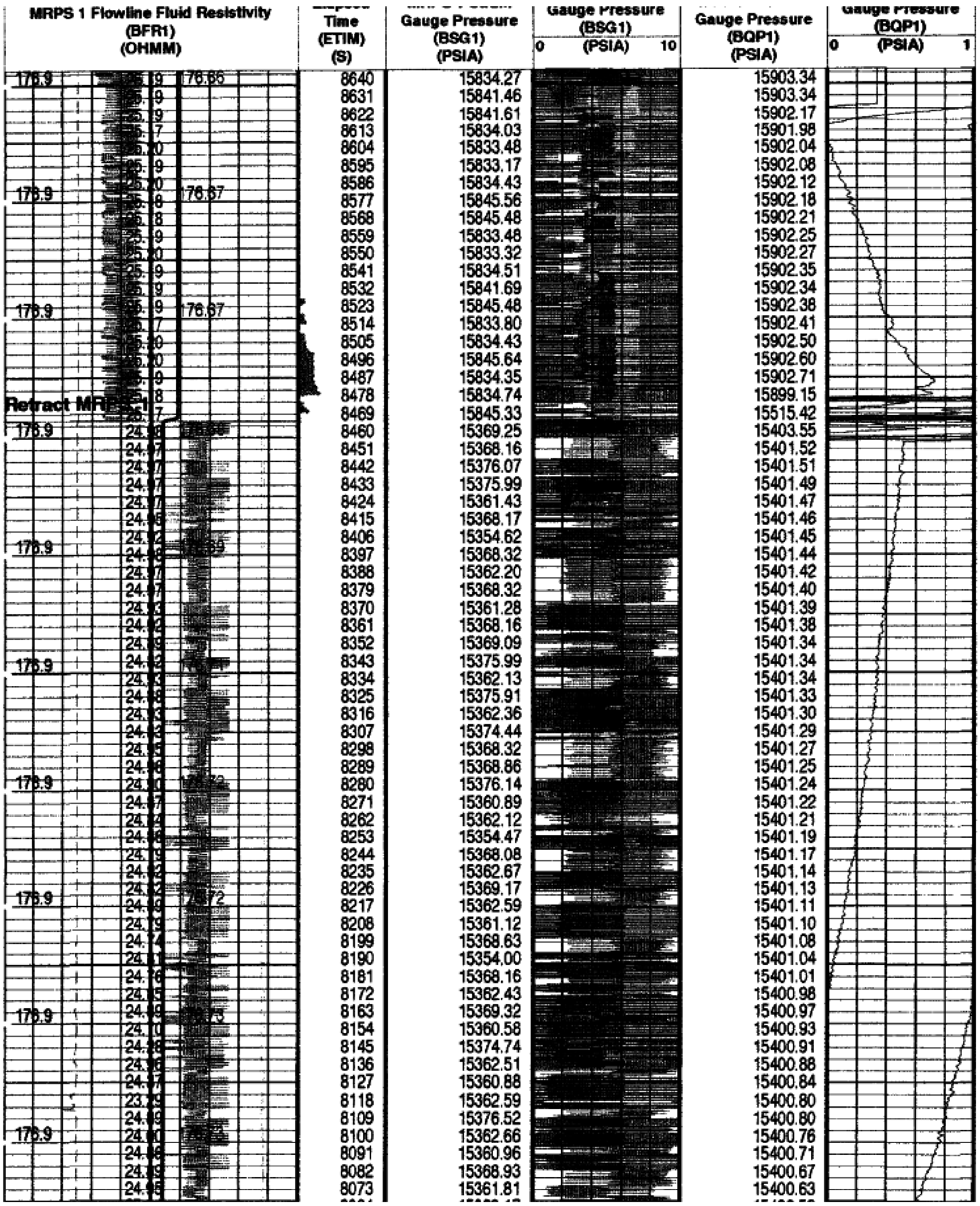
The pressure build-up shows a stable value of 13062.9 psi over the last minute of the test before the packers were retracted.



Fair

Well: 22/29-7

The pressure build-up (Quartz Gauge: BQP1) shows the magnitude is building slowly, at a rate of approximately 0.1 psi/minute over the last 5 minutes of the test. Therefore, the pore pressure is likely to increase slightly beyond the final test value but not by a significant amount.

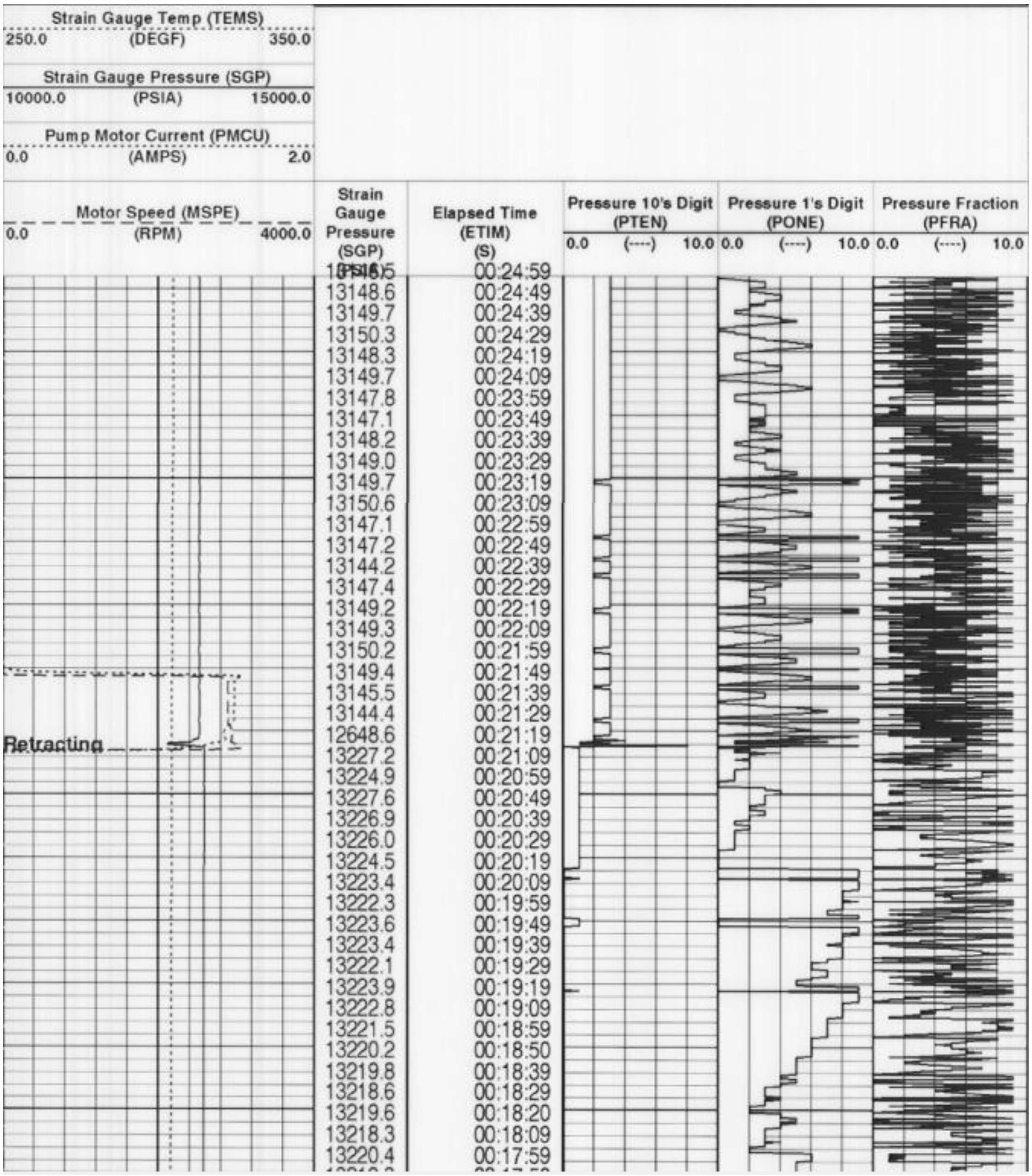


Time (ETIM) (S)	Gauge Pressure (BSG1) (PSIA)	Gauge Pressure (BQP1) (PSIA)
8640	15834.27	15903.34
8631	15841.46	15903.34
8622	15841.61	15902.17
8613	15834.03	15901.98
8604	15833.48	15902.04
8595	15833.17	15902.08
8586	15834.43	15902.12
8577	15845.56	15902.18
8568	15845.48	15902.21
8559	15833.48	15902.25
8550	15833.32	15902.27
8541	15834.51	15902.35
8532	15841.69	15902.34
8523	15845.48	15902.38
8514	15833.80	15902.41
8505	15834.43	15902.50
8496	15845.64	15902.60
8487	15834.35	15902.71
8478	15834.74	15899.15
8469	15845.33	15515.42
8460	15369.25	15403.55
8451	15368.16	15401.52
8442	15376.07	15401.51
8433	15375.99	15401.49
8424	15361.43	15401.47
8415	15368.17	15401.46
8406	15354.62	15401.45
8397	15368.32	15401.44
8388	15362.20	15401.42
8379	15368.32	15401.40
8370	15361.28	15401.39
8361	15368.16	15401.38
8352	15369.09	15401.34
8343	15375.99	15401.34
8334	15362.13	15401.34
8325	15375.91	15401.33
8316	15362.36	15401.30
8307	15374.44	15401.29
8298	15368.32	15401.27
8289	15368.86	15401.25
8280	15376.14	15401.24
8271	15360.89	15401.22
8262	15362.12	15401.21
8253	15354.47	15401.19
8244	15368.08	15401.17
8235	15362.67	15401.14
8226	15369.17	15401.13
8217	15362.59	15401.11
8208	15361.12	15401.10
8199	15368.63	15401.08
8190	15354.00	15401.04
8181	15368.16	15401.01
8172	15362.43	15400.98
8163	15369.32	15400.97
8154	15360.58	15400.93
8145	15374.74	15400.91
8136	15362.51	15400.88
8127	15360.88	15400.84
8118	15362.59	15400.80
8109	15376.52	15400.80
8100	15362.66	15400.76
8091	15360.96	15400.71
8082	15368.93	15400.67
8073	15361.81	15400.63

Poor

Well: 22/21-7

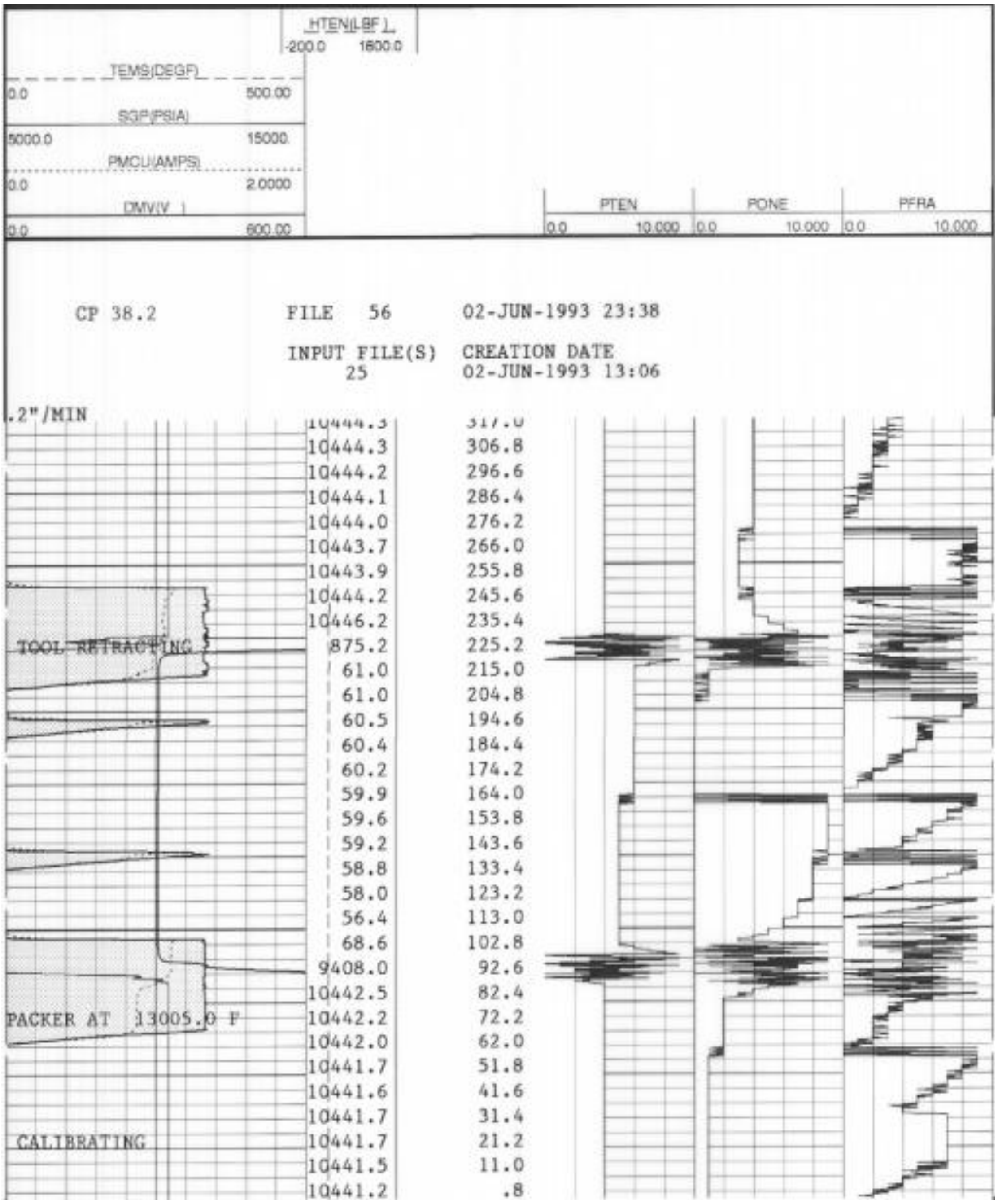
The pressure build-up shows a pressure value that is still building, from 13223.4 psi to 13227.6 psi (approximately 4 psi), over the last minute of the test before the packers were retracted, therefore, the pressure is likely to increase above a 1 psi threshold before it stabilises.



Invalid

Well: 22/21-7

The build-up plot shows that the pore pressure never builds up to true reservoir pressure, known as a Dry or Tight

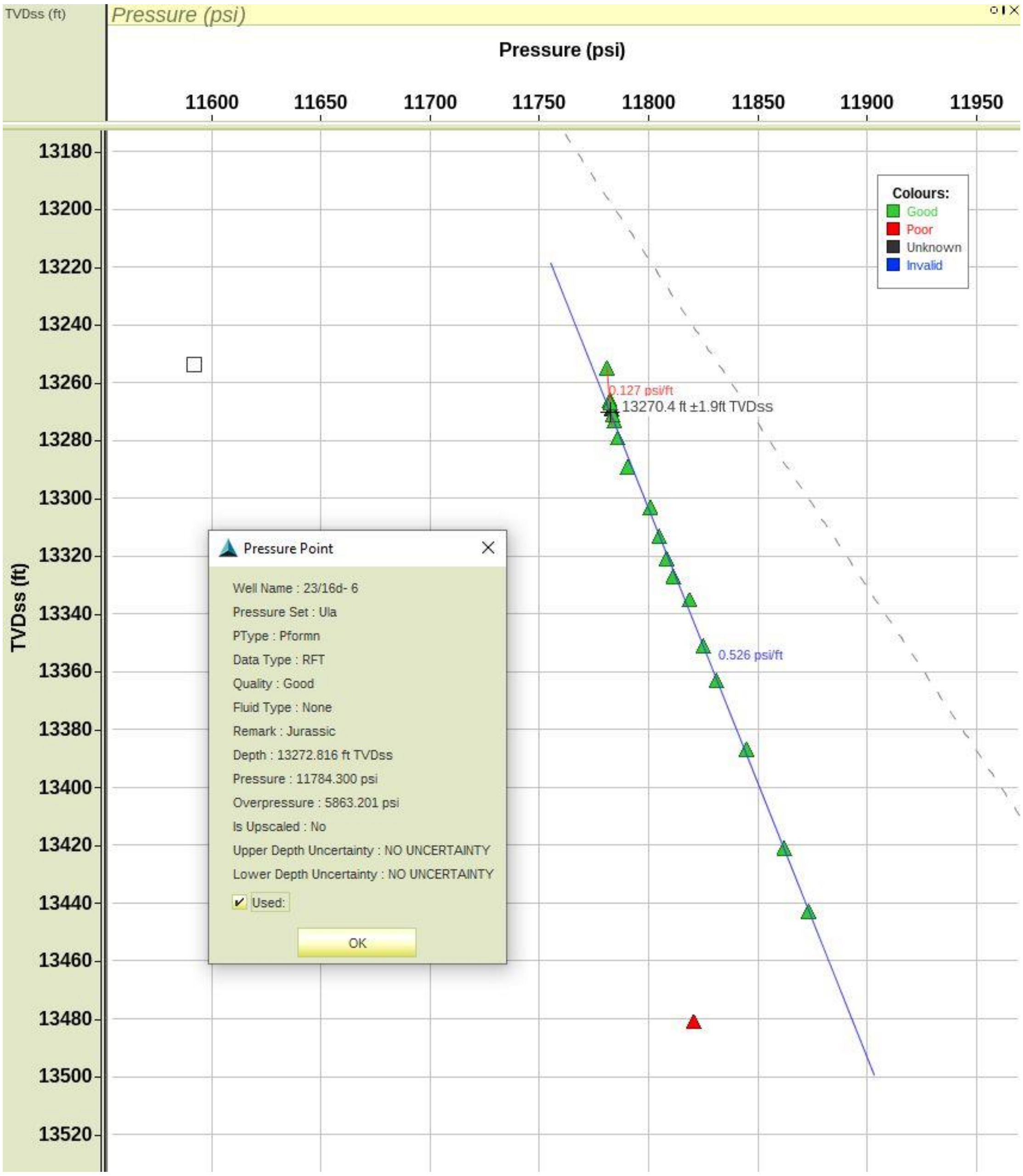


Appendix 2: Overpressure Category Examples

Category 4

Well: 23/16d-6

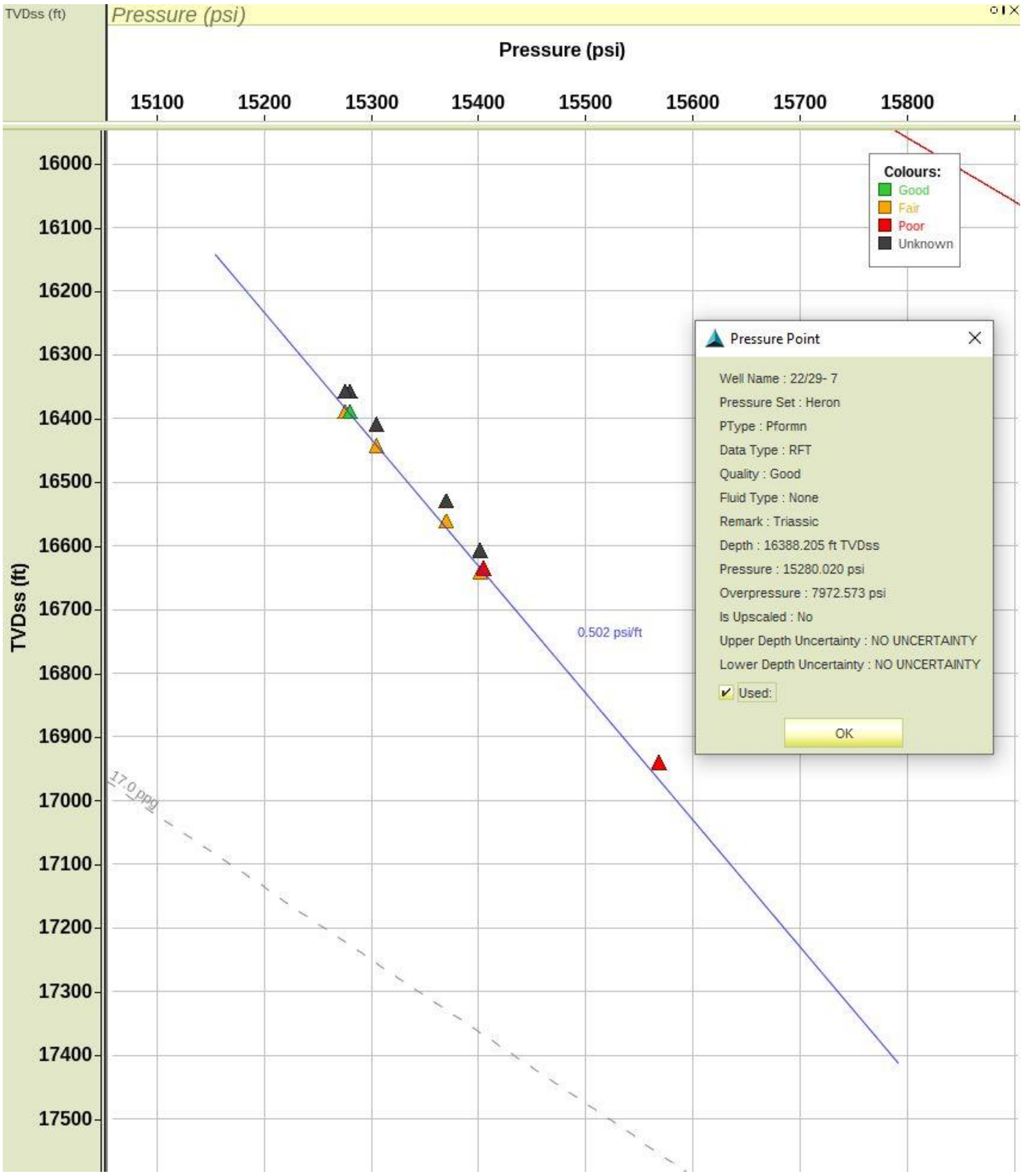
The aquifer gradient is clearly defined by a significant amount of RFT data, all of which have been classified as Good.



Category 3

Well: 22/29-7

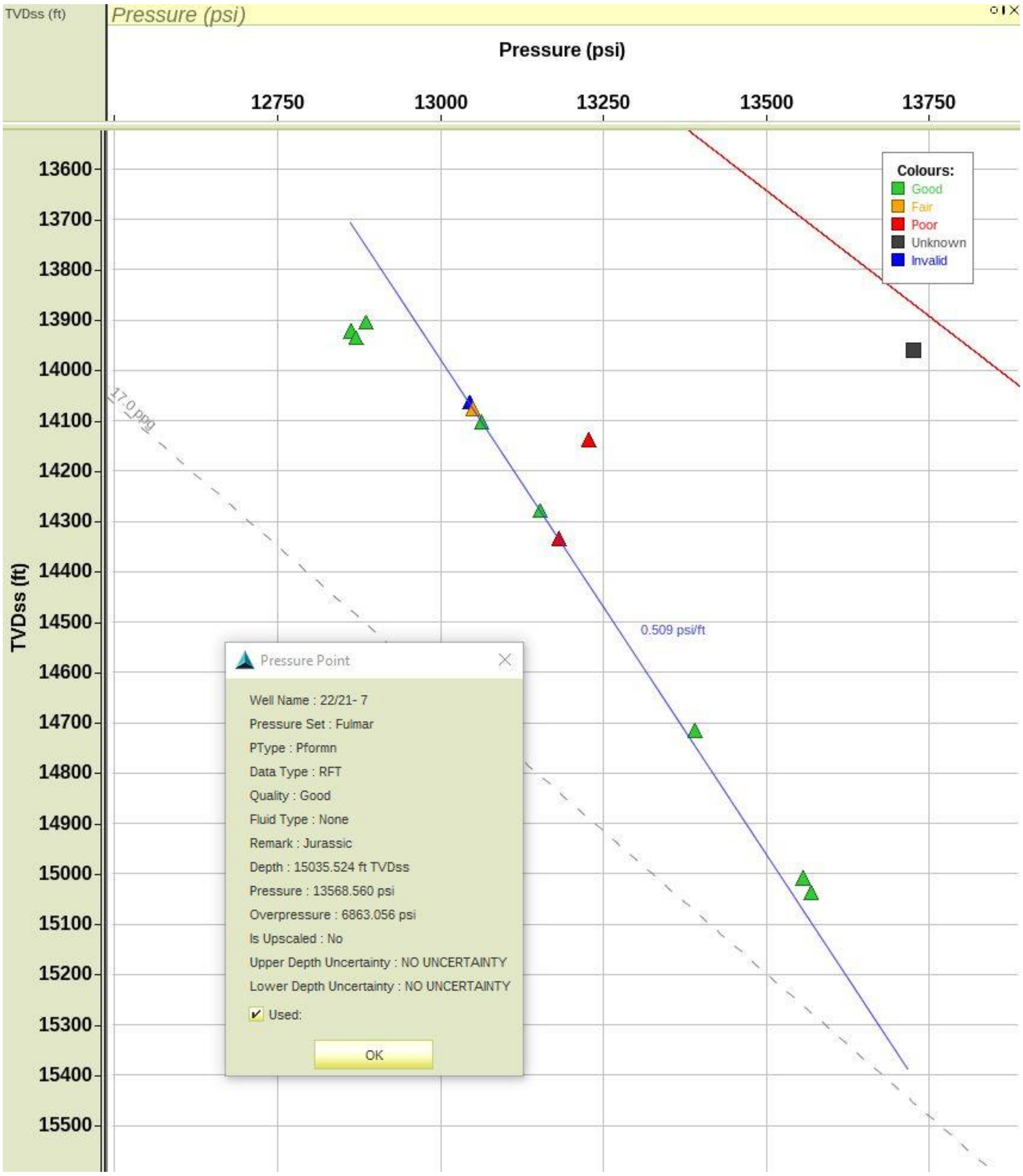
The aquifer gradient is defined by a reasonable amount of RFT data, which have mixed classifications from Good to Poor. Only Good and Fair quality data were used to define the gradient but the small amount of scatter makes this a Category 3 value.



Category 2A

Well: 22/21-7

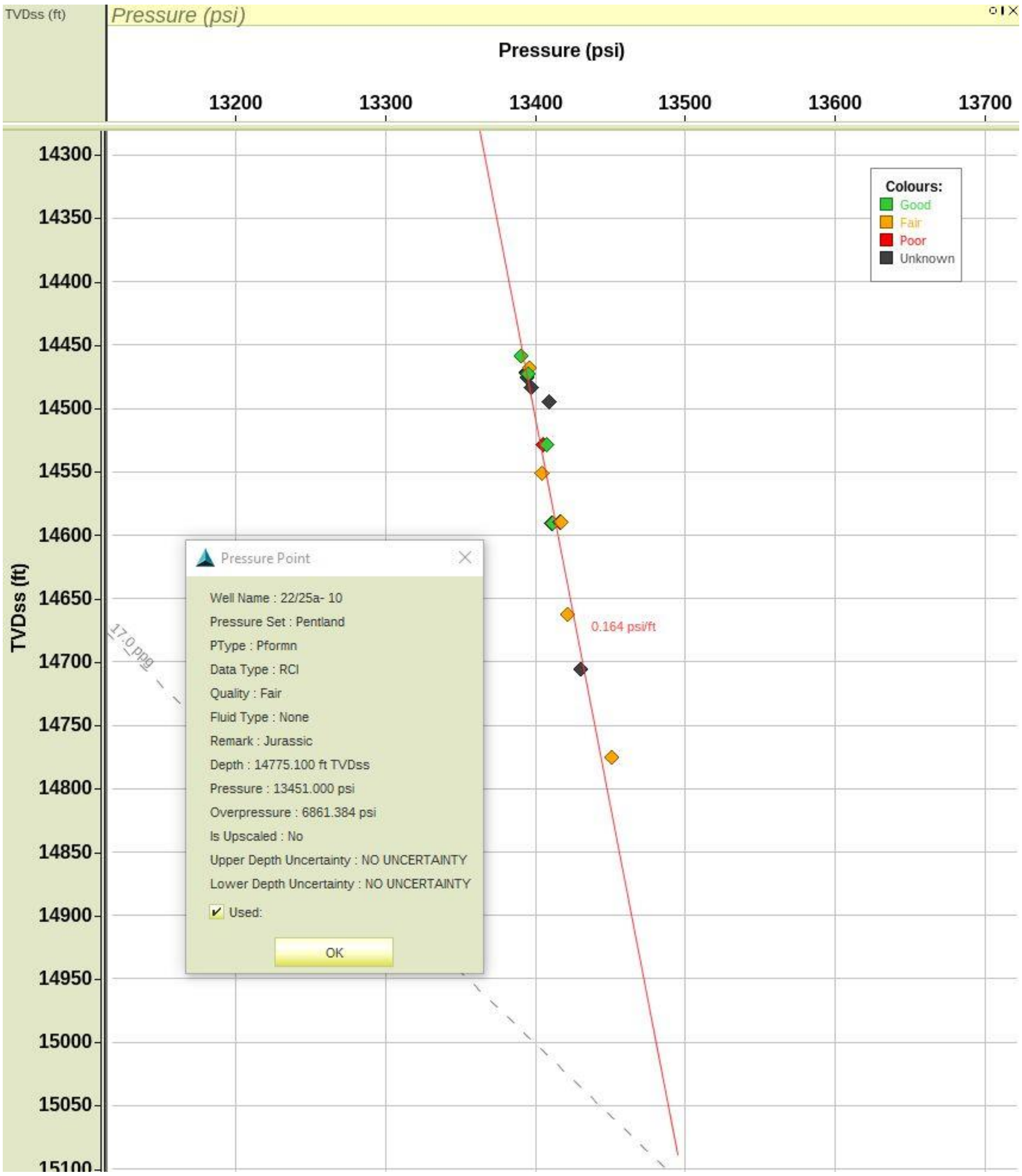
The aquifer gradient is defined by a reasonable amount of RFT data, which have mixed classifications from Good to Poor. Only Good and Fair quality data were used to define the gradient (ignoring the data at ~13900 ftTVDss) but the amount of scatter makes this a Category 2A value.



Category 2B

Well: 22/25a-10

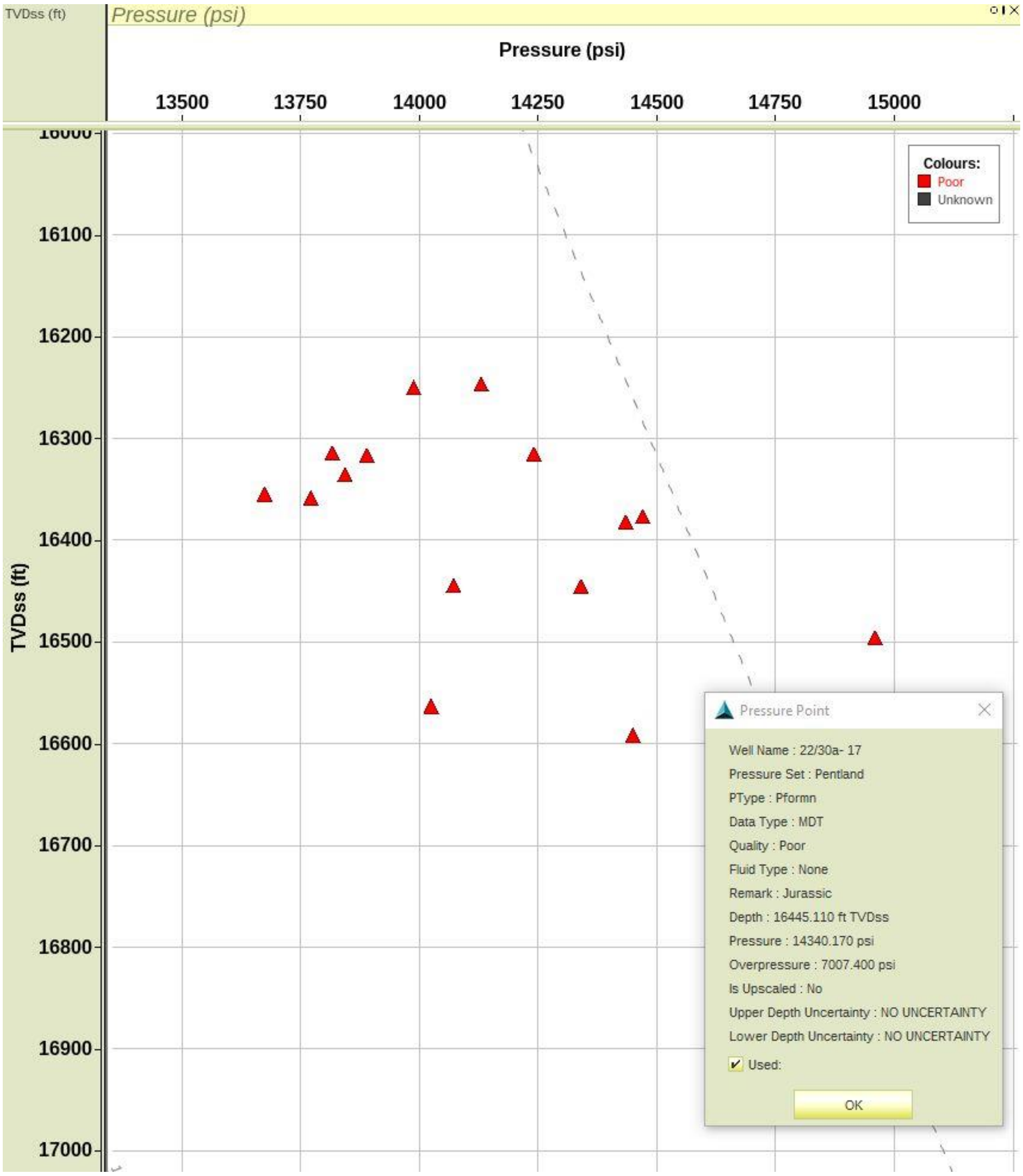
The hydrocarbon gradient is defined by a reasonable amount of RFT data, which have mixed classifications from Good to Poor. As no aquifer gradient can be defined this must be a Category 2B value irrespective of how the gradient fits to the data.



Category 2U

Well: 22/30a-17

No gradient can be defined from a cluster of data, which makes this a Category 2U value. In some wells there may be a single data point (e.g., a single pressure test), or a pressure from mudweight data if no valid tests are present which are also Category 2U values.



Category 1

Well: 16/27a-3

The shallow DST data are underpressured, i.e., the magnitude of the reported pressure is less than hydrostatic (0.445 psi/ft), which makes them a Category 1 value.