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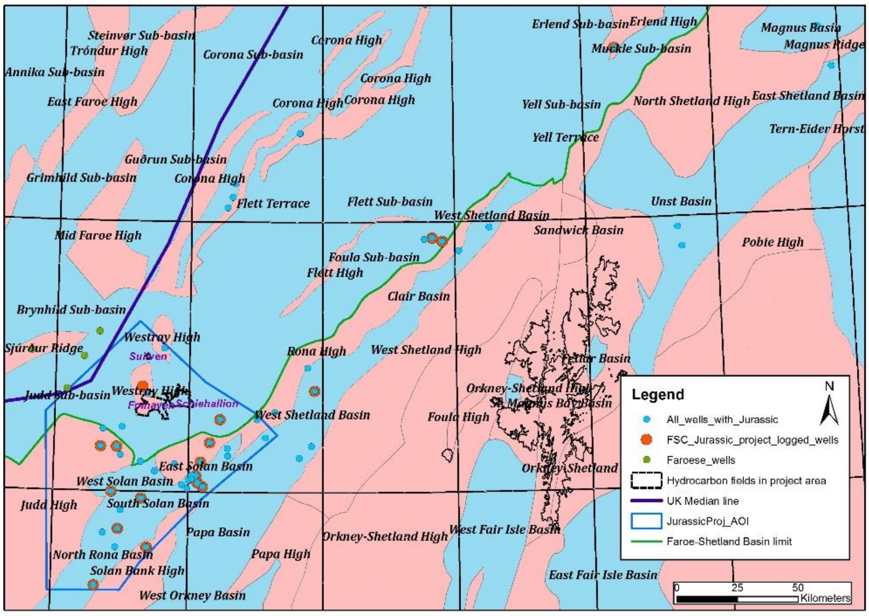
Seismic interpretation and mapping of the Jurassic succession in the SW part of the Faroe-Shetland Basin as part of the Jurassic stratigraphy of the Faroe-Shetland region project.

Energy Systems & Basin Analysis Programme

Commissioned Report CR/18/036



BRITISH GEOLOGICAL SURVEY

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Seismic interpretation and mapping of the Jurassic succession in the SW part of the Faroe-Shetland Basin as part of the Jurassic stratigraphy of the Faroe-Shetland region project.

M.F. Quinn

British Geological Survey, Edinburgh, UK

Keywords

Faroe-Shetland Basin; seismic interpretation; Jurassic mapping.

National Grid Reference

SW corner 999999,999999
Centre point 999999,999999
NE corner 999999,999999

Map

Sheet 999, 1:99 000 scale, Map name

Front cover

Location of study area within the Faroe-Shetland Basin.

Bibliographical reference

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff CF10 3AT

Tel 029 2167 4280 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the result of a study by the British Geological Survey (BGS) on behalf of the Faroe-Shetland Consortium (FSC). The report provides a detailed record of the seismic interpretation and mapping of the Jurassic as part of the Faroe-Shetland Consortium (FSC), Phase 3, Jurassic stratigraphy of the Faroe-Shetland region Project. The aim of this task was to map the extents and thickness of the Jurassic succession within an area of study located over the south-western end of the Faroe-Shetland Basin and adjacent basins. The area of study was defined where the majority of the core descriptions and palynology analyses were carried out. The report includes representative geoseismic profiles, structure contour maps and an isochore map of the Jurassic succession. These outputs are utilised in a final report on the Jurassic project (Andrews et al., 2018) and also form part of the project GIS.

The study is based upon 2D and 3D seismic data provided by the Consortium members and other supporting organisations and a comprehensive dataset of released commercial wells. In addition, reference was made to sedimentological core description and new palynological dating of the Jurassic succession carried out as part of the Jurassic project

Acknowledgements

This report was commissioned by the BGS/Jarðfeingi/Industry Faroe-Shetland Consortium, which includes the following seven oil company sponsors: Chevron, DONG Energy, E.ON, Maersk Oil UK Ltd, Nexen Petroleum, Shell and Total. Following the acquisition of E.ON by Premier Oil, E.ON left the FSC in 2016. The co-funding support and interest of all these companies and their representatives is gratefully acknowledged.

In compiling this report, the author readily acknowledges the assistance of several BGS colleagues including Mike Sankey (seismic data management), Mark Kassyk (well management), Ian Andrews and Vanessa Starcher (review and editing).

Sandy Henderson is acknowledged for compiling and presenting the GIS for this report.

We thank Faroe-Shetland Consortium oil company sponsors for allowing us to access their proprietary seismic data for the purpose of this report. BP, Chevron and Hess are acknowledged for permission to use their seismic data, including the data illustrated in Figures 12-16 and 18-24.

Common Data Access (CDA) Limited is acknowledged for allowing access to released well data for the purpose of this report.

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Summary

This task forms part of the Faroe-Shetland Consortium (FSC), Phase 3, Jurassic stratigraphy of the Faroe-Shetland region Project. The aim of the task was to map the extents and thickness of the Jurassic succession within an area of study located over the south-western end of the Faroe-Shetland Basin and adjacent basins. This report forms a detailed account of the seismic interpretation of the Jurassic in the study area. The area of study was defined where the majority of the core descriptions and palynology analyses were carried out.

The dataset for this task comprised four 3D and five 2D seismic surveys and access to all released commercial wells in and adjacent to the study area. Other tasks within the Jurassic project, one providing new palynology analyses on selected wells, the other, detailed core descriptions and environmental interpretations, contributed useful information during the seismic interpretation.

Seismic interpretation of the Top and Base Jurassic seismic reflectors was carried out over the study area. Other seismic reflectors - Base Cenozoic, Top Upper Cretaceous, Top Lower Cretaceous, Triassic and Top crystalline basement lying above or below the Jurassic succession were also interpreted where necessary to help in the interpretation of the Jurassic succession. Interpretation of the seismic reflectors was constrained by well time/ depth pairs, production of synthetic seismograms and recognition of similar characteristics within the Jurassic seismic package.

Top and Base Jurassic structure maps in Two-Way-Travel-Time (TWTT) were generated, and from these an isochore of the Jurassic succession in metres was produced.

Within the study area, the Jurassic is interpreted to be thin or absent over much of the Judd High and an area on and adjacent to the south-west extension of the Rona High and Flett Sub-basin; it is also thin or absent on the tops of some of the tilted fault blocks within the North Rona Basin. The majority of Jurassic successions in the North Rona, South, West and East Solan basins are of Upper Jurassic age and less than 200 m thick. However, the Jurassic reaches a maximum interpreted thickness of 1426 m within the West Solan Basin where a thick interval of Lower Jurassic sediments are preserved. Due to lack of seismic data and, where present, seismic data that has not been processed deeply enough to image any possible Jurassic, parts of the Judd Sub-basin surrounding the Westray High could not be interpreted using sufficient seismic data to produce mapped surfaces; however it is expected that Jurassic will be present at depth.

In an area west of the Westray High and north of the Judd High, a Jurassic succession has been interpreted on the north-western flank of the Judd High. No wells have been drilled deeply enough to prove a Jurassic succession in this area and interpretation relies on the character of the seismic package. An untested hydrocarbon play has been proposed in this area.

1 Introduction

This task forms part of the Faroe-Shetland Consortium (FSC), Phase 3, Jurassic stratigraphy of the Faroe-Shetland region Project. The aim of the task was to map the extents and thickness of the Jurassic succession within an area of study located over the south-western end of the Faroe-Shetland Basin and adjacent basins. The area of study was defined where the majority of the core descriptions and palynology analyses were carried out.

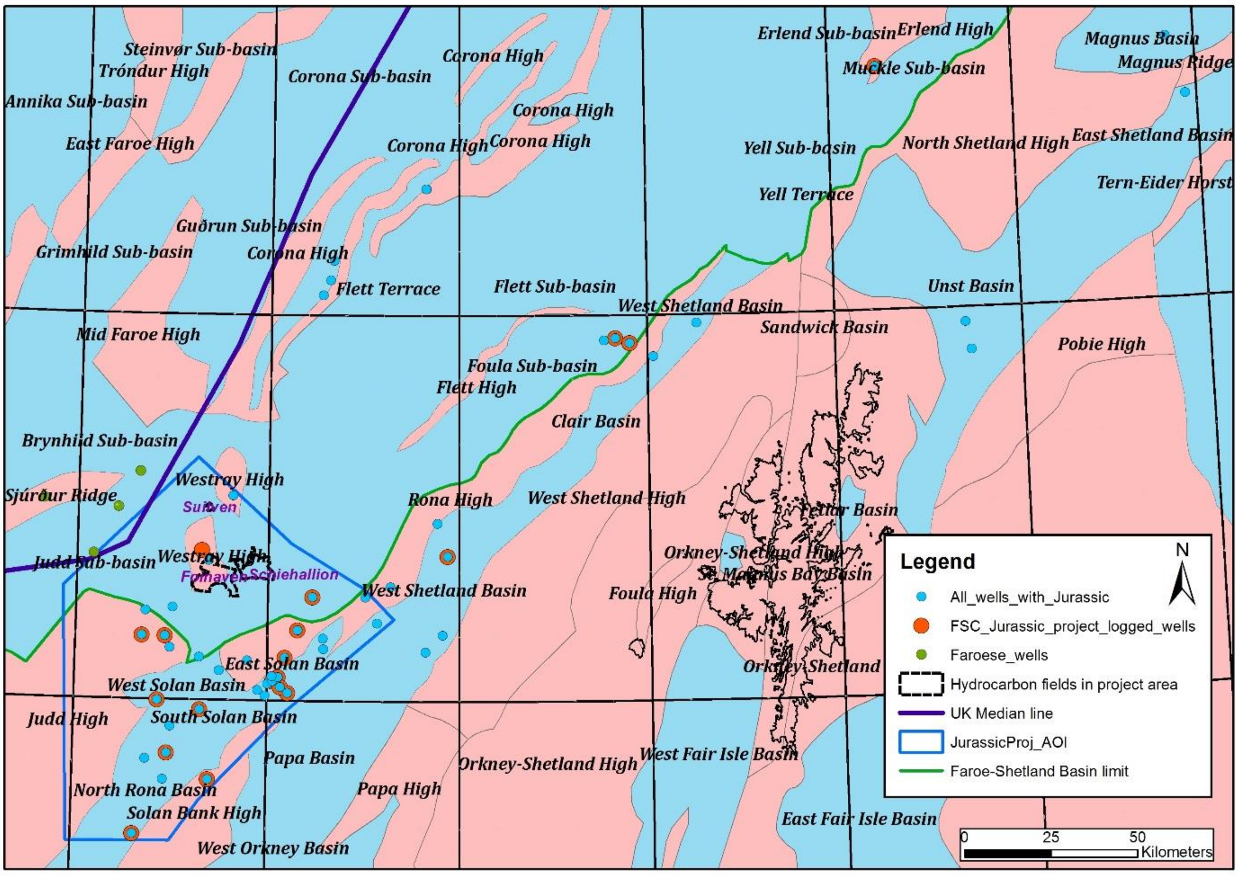

Figure 1. Location of study area (blue polygon) within regional context of Faroe-Shetland Basin. Field and well locations from OGA website, http://data-ogauthority.opendata.arcgis.com/. Background structure from Stoker et al., 2015.

1.1 RATIONALE AND BACKGROUND

The scope and aims of this task followed guidance from sponsors. The aim was to review the regional geometry of the Jurassic succession using commercially available seismic and released well data as well as reference to relevant publications. The top and base of the Jurassic succession were tied to synthetic seismograms generated from selected wells, and this enabled an understanding of the seismic response to the Jurassic lithologies and over- and under-lying successions. Maps of Top and Base Jurassic and an isochore in Two-Way Travel Time (TWTT) were generated; the isochore was also converted to metres.

Early in the task, seismic attribute displays were generated and examined to see if they would provide any additional information on the Jurassic interval. However, results were inconclusive and this was not pursued further.

The study area is located 100 km west of Shetland and includes the southern Westray High and Judd Sub-basin, located within the Faroe-Shetland Basin, and basins and highs to the east of the

Judd High, including the north-eastern part of the latter, parts of the Rona High, Solan Bank High, North Rona Basin and Solan Basins (Figure 1 and Figure 3).

2 Dataset

2.1 SEISMIC DATA

The seismic dataset available for this study comprises four 3D and five 2D surveys (Figure 2). The North Rona, South Solan and part of the West Solan basins have only 2D coverage. There was no seismic data available to the study within parts of the Judd Sub-basin (Figure 2).

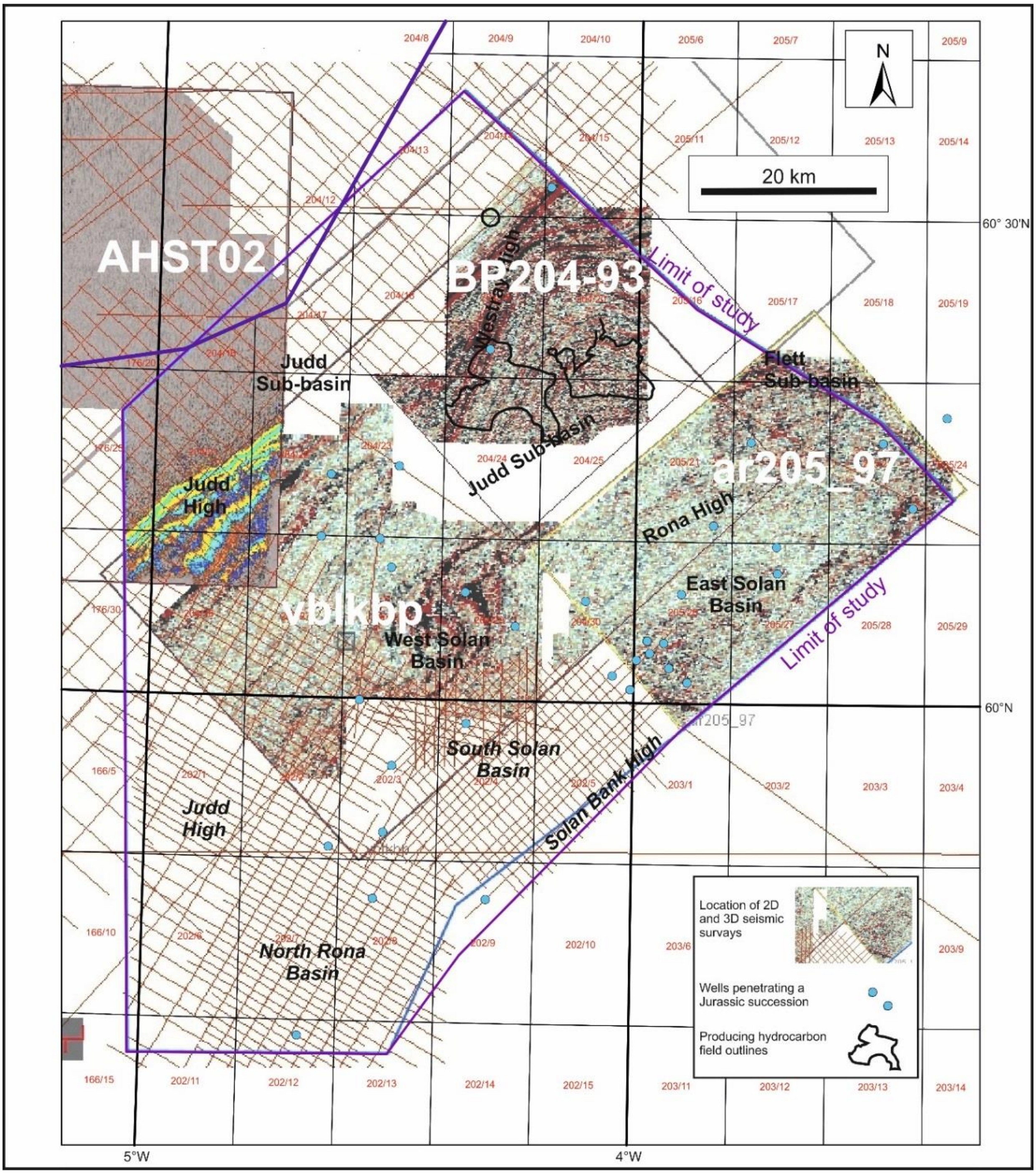

Figure 2. Seismic database available to the study. Field and well locations from OGA website, http://data-ogauthority.opendata.arcgis.com/.

2.2 WELLS

To date, 33 released wells prove a Jurassic succession within the study area (Figure 3 and Table 1). In addition, unreleased wells 205/27- 3 and 3Z, drilled in 2016 by Chrysaor proved reservoir quality Upper Jurassic Solan sandstone (http://ukdigest.canadiandiscovery.com/?q=node/58114). Table 1 details depths and Two-Way-Travel-Time (TWTT) for the released wells.

Figure 3. The study area (blue polygon) showing all wells proving Jurassic and those for which cores were logged and sampled for palynology. Field and well locations from http://data-ogauthority.opendata.arcgis.com/. Structure from Stoker et al., 2015.

3 Interpretation of seismic horizons

In the majority of basins in the study area, Top and Base Jurassic seismic reflectors can be tied directly to at least one well and as a result the interpretation is fairly well constrained. In a small number of other areas it was necessary to make a short jump correlation, or compare seismic character over a relatively short distance; here confidence in presence of a Jurassic succession is moderately high. However, to the north of the Judd High, no wells are present that penetrate below the Cretaceous and here a Jurassic succession has been mapped based on the character of the seismic package and the relationship of that package to the overlying and underlying successions. The confidence of the interpretation in this region is low to moderate.

Where applicable, the Jurassic is mapped as 'thin or absent' as seismic resolution would always allow for a thin occurrence of Jurassic. Within the study area, seven wells prove Jurassic absent (Table 1; Figure 7). The majority of wells (21) in the study area record an Upper Jurassic succession of no more than 100 m. Wells 202/03a- 3 & 202/04- 1, are interpreted by Ritchie and Varming (2011) as proving Upper Jurassic resting on Lower Jurassic. Well 204/19- 9 records Lower Jurassic only. Well 204/22- 1 records Upper and Middle Jurassic Heather Formation resting on an undivided Middle Jurassic succession on the original BP composite log. Ritchie and Varming (2011) restrict the extent of Heather Formation to a late Callovian age with the latter resting on an undivided Middle Jurassic succession; this is the only well in the study area with a possible Middle Jurassic succession (Table 1). It was not possible to interpret any subdivisions within the Jurassic away from these wells due to the generally thin intervals.

Seismic reflectors representing the Top and Base Jurassic where mapped over the study area. The seismic character of the Top and Base Jurassic seismic reflectors is dependent upon the contrast between the physical properties of the Jurassic succession and the overlying or underlying rocks. The top and base of the Jurassic succession are commonly unconformable.

A series of synthetic seismograms were generated in order to gain an understanding of the relationship between seismic character and lithologies present.

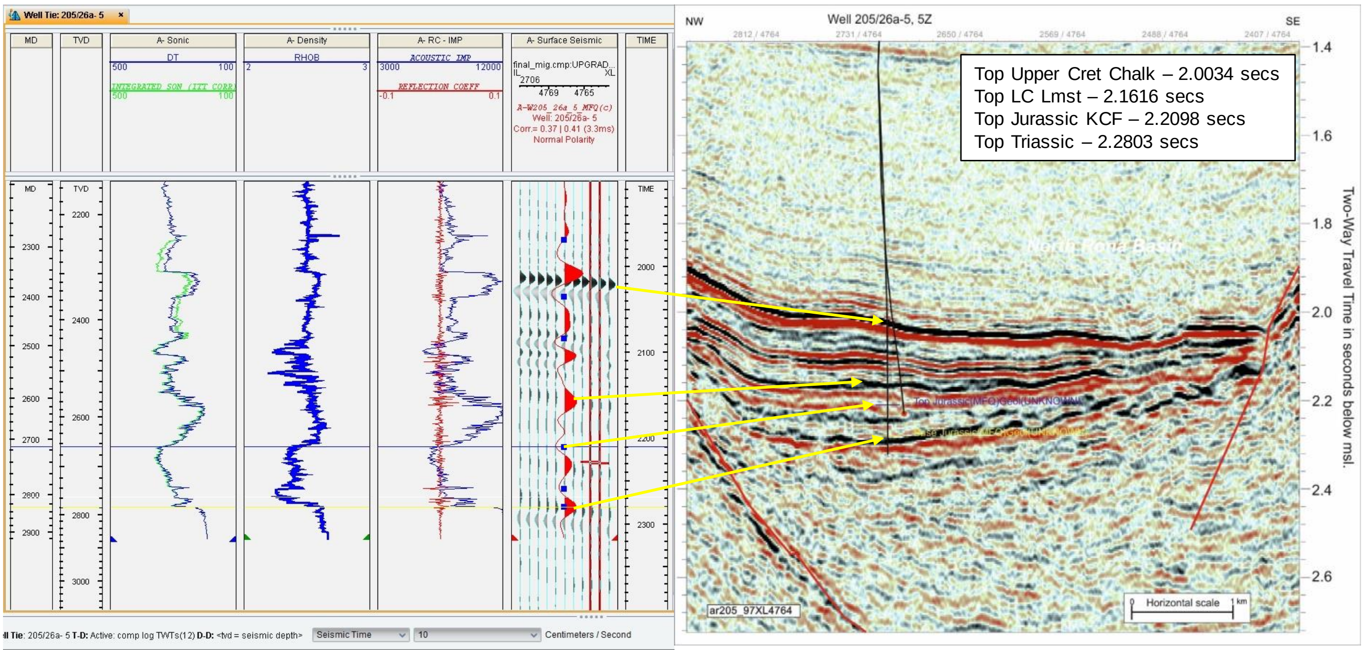

Figure 4. Synthetic seismogram, generated over the Jurassic interval, for Well 205/26a- 5 in the East Solan Basin.

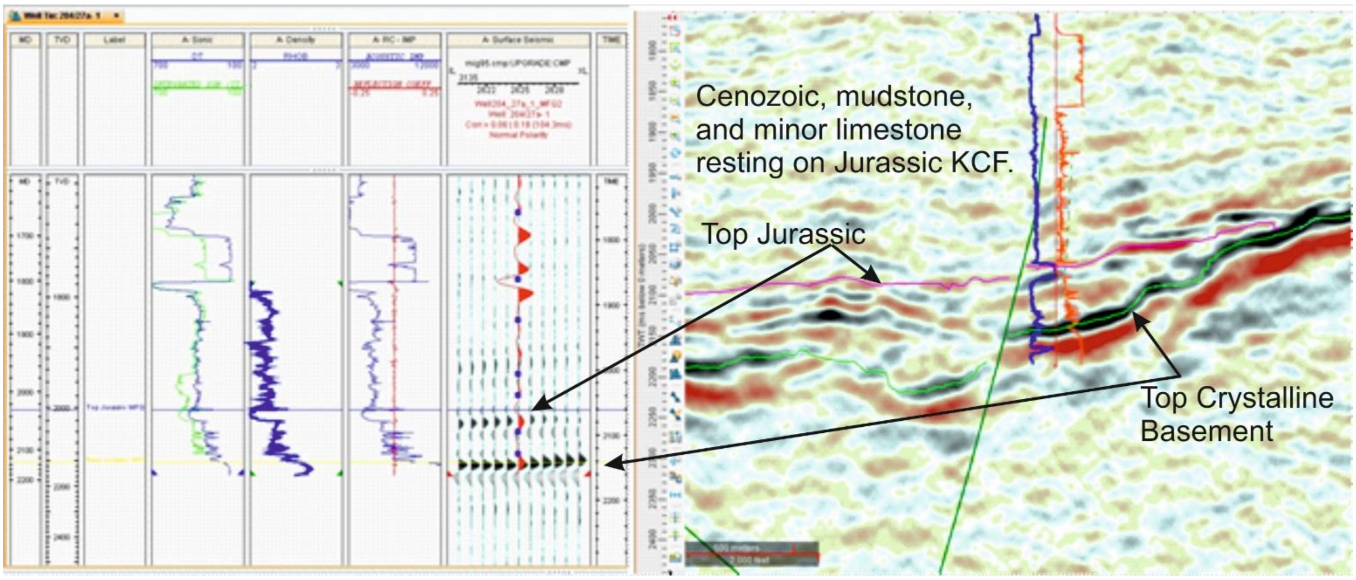

Figure 5. Synthetic seismogram, generated over the Jurassic interval, for Well 204/27a- 1 on the Judd High.

3.1 TOP JURASSIC SEISMIC REFLECTOR

This is defined as the top of the Kimmeridge Clay Formation (KCF) that has an age range of Kimmeridgian (Upper Jurassic) to Late Ryazanian (approximates to Lower Cretaceous, Berriasian age); so the uppermost part of the succession may be Lower Cretaceous, Ryazanian in age. The Top Jurassic reflector is overlain by either a Lower or Upper Cretaceous or Cenozoic succession and is commonly an unconformity. In general, the boundary between the overlying succession and Jurassic succession is marked by a decrease in acoustic impedance that on the seismic data is displayed as a negative reflection and a red trough (Figure 4 and Figure 5).

3.2 BASE JURASSIC SEISMIC REFLECTOR

The Jurassic succession rests unconformably on either Triassic sediments or crystalline basement. In general, the reflector is generated by an increase in impedance, which on the seismic data is displayed as a positive reflection and a black peak.

3.3 DELINEATION OF FAULTS

Faults were interpreted as part of the mapping exercise to aid in mapping Jurassic extents and to help understand the Jurassic distribution. As a result, a structure map of the study area has been generated that is more detailed than the existing FSC Atlas structure map (Stoker et al., 2015). However, mapping of faults was not exhaustive and not all the minor faults have been delineated.

WELL	KB (ft)	Top KCF (MD ft)	Top KCF (TVDSS m)	Top KCF (TVDSS ft)	Top KCF (TWTT)	Top TMJ/ LJ (MD ft)	Top TMJ/ LJ (TVDSS ft)	TOP TMJ/ LJ (TWTT)	Jurassic divisions after Ritchie & Varming 2011 and this study.	Base Jurassic (MD ft)	Base Jurassic (TVDSS m)	Base Jurassic (TVDSS ft)	Base Jurassic (TWTT)	Overlying/ underlying	Jurassic thickness (m)
202/02- 1	31	3766.0	1138.4	3735.0	1.097	3857.0	3826.0	1.123	All UJ	3928.0	1187.8	3897.0	1.137	UC/ Bsmt	49.4
202/03- 1A	98	5243.0	1568.2	5145.0	1.439	5371.0	5273.0	1.472	All UJ	5640.0	1689.2	5542.0	1.522	LC/ Bsmt	121.0
202/03- 2	83	4649.0	1391.7	4566.0	1.348	4803.0	4720.0	1.391	All UJ	4888.0	1464.6	4805.0	1.409	LC/ Bsmt	72.8
202/03a- 3	85	5769.0	1732.5	5684.0	1.591	5854.0	5769.0	1.613	UJ/LJ	*TD in LJ at 2554 (MD m) and 2.062 (TWTT secs)*				LC/ TD in LJ	795.6
202/04- 1	86	5980.0	1796.5	5894.0	1.698	6072.0	5986.0	1.721	UJ/LJ	6514.0	1959.3	6428.0	1.806	LC/ Trias	162.8
202/08- 1	82	5145.0	1543.2	5063.0	1.371				All UJ	5412.0	1624.6	5330.0	1.430	LC/ Bsmt	81.4
202/09- 1	81	2610.0	770.8	2529.0	0.800	2739.0	2658.0	0.840	All UJ	2918.0	864.7	2837.0	0.876	LC/ Trias	93.9
202/12- 1	77	4337.0	1298.4	4260.0	~1.210	4644.0	4567.0	~1.280	All UJ	4990.0	1497.5	4913.0	~1.350	LC/ Trias	199.0
204/15- 2	118	11660.0	3517.1	11539.0	~3.189				All UJ	12427.0	3750.0	12303.0	>3.320	LC/ Bsmt	232.9
204/19- 1	85								*Lower Cretaceous on Triassic*						
204/19- 9	85	*KCF absent*				13835	13751	3.424	LJ	14442.0	4376.3	14358.0	3.521	LC/ Trias	185.0
204/22- 1	85	8048.0	2427.1	7963.0	2.381	8094	8009		UJ/MJ	8901.0	2687.1	8816.0	2.580	Ceno/ Bsmt	260.0
204/23- 1	85	12416.3	3758.6	12331.3	3.240				All UJ	12432.4	3763.5	12347.4	3.244	LC/ Bsmt	4.9
204/25- 1	88								*Upper Cretaceous on Basement*						
204/26- 1A	82								*Lower Cretaceous on Basement*						
204/27a- 1	85	6657.0	2002.8	6571.0	2.030				All UJ	6991.0	2104.9	6906.0	2.104	Ceno/ Bsmt	102.1
204/28- 1	82	6109.0	1837.0	6027.0	1.793				All UJ	6365.0	1915.1	6283.0	1.846	LC/ Bsmt	78.0
204/28- 2	82	7505.0	2262.5	7423.0	~1.977				All UJ	7756.0	2339.0	7674.0	~2.029	LC/ Trias	76.5
204/29- 1	87	5878.0	1765.1	5791.0	1.626				All UJ	5961.0	1790.4	5874.0	1.648	UC/ Trias	25.3
204/29a- 2	85	7178.0	2161.6	7092.0	1.938				All UJ	7294.0	2197.0	7208.0	1.957	LC/ Trias	35.4
204/30- 1	83	6307.0	1897.1	6224.0	1.744				All UJ	6456.0	1942.5	6373.0	1.778	LC/ Bsmt	45.4
204/30a- 2	85	7771.0	2342.1	7684.0	2.028				All UJ	8012.0	2415.2	7924.0	2.081	LC/ Trias	73.2
204/30a- 3	82	9831.0	2418.3	7934.0	2.029				All UJ	10320.0	2473.8	8116.0	2.068	LC/ Trias	55.5
205/16- 1	85								*Lower Cretaceous on Basement*						
205/21- 1a	82	4392.0	1313.7	4310.0	1.260	4405.0	4323.0	1.263	All UJ	4439.0	1328.0	4357.0	1.270	LC/ Bsmt	14.3
205/21a- 4	83								*Upper Cretaceous on Basement*						
205/21a- 5	83								*Lower Cretaceous on Basement*						
205/22- 1a	85	10424.9	3151.6	10339.9	2.620				All UJ	10590.5	3202.1	10505.5	2.644	LC/ Bsmt	50.5
205/23- 1	88	3678.0	1094.2	3590.0	1.094				All UJ	4050.0	1207.0	3960.0	1.191	LC/ Trias	112.8
205/23- 2	76	2186.0	642.8	2109.0	No vel				All UJ	2298.0	677.0	2221.0	No vel	UC/ Trias	34.1
205/25- 1	82	7560.0	2276.9	7470.0	1.819	7810.0	7728.0	1.864	All UJ	7928.0	2391.5	7846.0	1.881	LC/ Trias	114.6
205/26- 1	84	6650.0	2001.3	6566.0	1.770	6820.0	6736.0	1.810	All UJ	6900.0	2077.5	6816.0	1.821	LC/ Bsmt	76.2
205/26a- 2	82	6920.0	2084.2	6838.0	1.782				All UJ	7100.1	2126.9	6978.0	1.814	LC/ Trias	42.7
205/26a- 3	80	7803.0	2352.4	7718.0	2.015				All UJ	8040.0	2424.4	7954.0	2.065	LC/ Trias	71.9
205/26a- 4	81	7807.0	2354.9	7726.0	2.023				All UJ	8104.0	2445.4	8023.0	2.087	LC/ Trias	90.5
205/26a- 5	85	8904.0	2666.4	8748.0	2.210				All UJ	9273.0	2778.3	9115.0	2.280	LC/ Trias	111.9
205/26a- 6	82	8248.0	2488.1	8163.0	2.104				All UJ. Part of Triassic re-interp.	8520.0	2571.0	8435.0	2.158	LC/ Trias	82.9
205/26a- 7	83	8850.0	2435.4	7990.1	No vel				All UJ	9251.0	2532.9	8309.9	No vel	LC/ Trias	97.5
205/27a- 1	80								*Quaternary on Triassic*						
205/27a- 2	104	7235.0	2157.1	7077.0	1.9180				All UJ	7634.0	2272.0	7454.0	1.997	LC/ Trias	114.9

Table 1. Summary of all released wells in study area with Jurassic data, including relationship of Jurassic with overlying and underlying successions. KCF is Kimmeridge Clay Fm. If Middle or Lower Jurassic intervals have been identified on the Composite Log, times and depths are recorded in the table, but the next column ('Jurassic divisions') gives the latest interpretation.

4 Map generation

The key maps produced for this task are TWTT to Top and Base Jurassic and isochore maps of the Jurassic succession in TWTT and metres (Figures 8, 9 and 10). The mapping coordinate system is ED_1950_UTM_Zone_30N, Central Meridian 3W. A One-Way-Travel-Time (OWTT) isochore map was also generated as part of the process in producing an isochore map in metres.

4.1 GENERATION OF SURFACES

The TWTT grids of Top and Base Jurassic were generated in Decision Space using the following gridding parameters:

- Cell size; square, 100 m.
- Least squares algorithm; search radius = 5000 m, refinements = 2, smoothing modulus = 0.5.

The grids were exported to ArcGis (Version 10.3.1) where TWTT contour maps were generated (Figures 8 & 9).

4.2 FAULT AND JURASSIC LIMIT POLYGONS

These were generated in DecisionSpace and exported as shapefiles to the project GIS.

4.3 JURASSIC ISOCHORE

Seismic interpretation of Top and Base Jurassic reflectors and production of gridded surfaces in TWTT made it possible to produce isochore grids of the Jurassic succession in TWTT, OWTT and metres. In order to convert the time isochore to metres a grid of Jurassic interval velocity was produced which ensured that the resultant thickness map tied to the wells.

Using the following procedure, the time isochore was converted to metres:

1. In ArcGis, convert the TWTT isochore map (milliseconds) to OWTT in seconds;
2. At all well locations in study area, the OWTT (from the seismic interpretation) through the Jurassic interval was recorded in an Excel spreadsheet,
    a. Calculate 'apparent interval velocity' (measured thickness (metres) at each well divided by OWTT at well derived from the seismic interpretation);
    b. Import the 'apparent interval velocity' data at each well to ArcGIS as an XYZ data file.
3. Grid the 'apparent interval velocity' points using IDW interpolation option (3D Analyst Tools - Raster Interpolation - IDW) entering following controls (Figure 6):
    a. Output cell size = 100; power 2.5; radius setting = variable; number of points = 3; maximum distance = 40000.
    b. Then toggle 'Environments' and 'Processing extent' and choose the OWTT isochore in the drop-down menu to constrain extents i.e. so that cells generated in Interval Velocity grid coincide exactly with OWTT grid cells.
4. In ArcGis – Toolbox- Raster Math, calculate the product of the 'apparent interval velocity' grid and the OWTT grid derived from the seismic interpretation (of Top and Base Jurassic) to generate a Jurassic isochore in metres that ties to the measured Jurassic thickness at the wells (Figure 10).

It was necessary to generate an 'apparent interval velocity grid' in order to maintain a consistent derivation of thickness for comparison purposes across the area (Figure 6). The 'apparent interval velocity' was calculated from the OWTT derived from the seismic interpretation and the measured thickness of Jurassic at the well. The 'apparent velocity grid' corrects for any difference between the well times and seismic interpretation derived times, the difference due primarily to the resolution of the seismic and the fact that that the Jurassic isochore is thin in places. Applying the ‘apparent velocity grid’ results in the correct Jurassic thickness at each well. Away from wells, the grid will generate Jurassic thicknesses that are comparable with the measured Jurassic thicknesses at wells.

The ‘apparent velocities’ are not true interval velocities of the Jurassic succession as they are not calculated from well derived time/ depth pairs but from measured well thicknesses and times from seismic interpretation. It was noted that a nine ms difference between well times and seismic interpretation could cause a 25-30 m difference between measured and calculated thickness. To ensure consistency between the final depth thickness map and well thicknesses, the seismic times were taken as the primary data source for OWTT. In this project, interval velocities calculated from wells ranged from 2299 to 3825 m/s with a mean of 2937 m/s.

The resultant depth isochore (Figure 10) was produced to be used solely as a regional map.

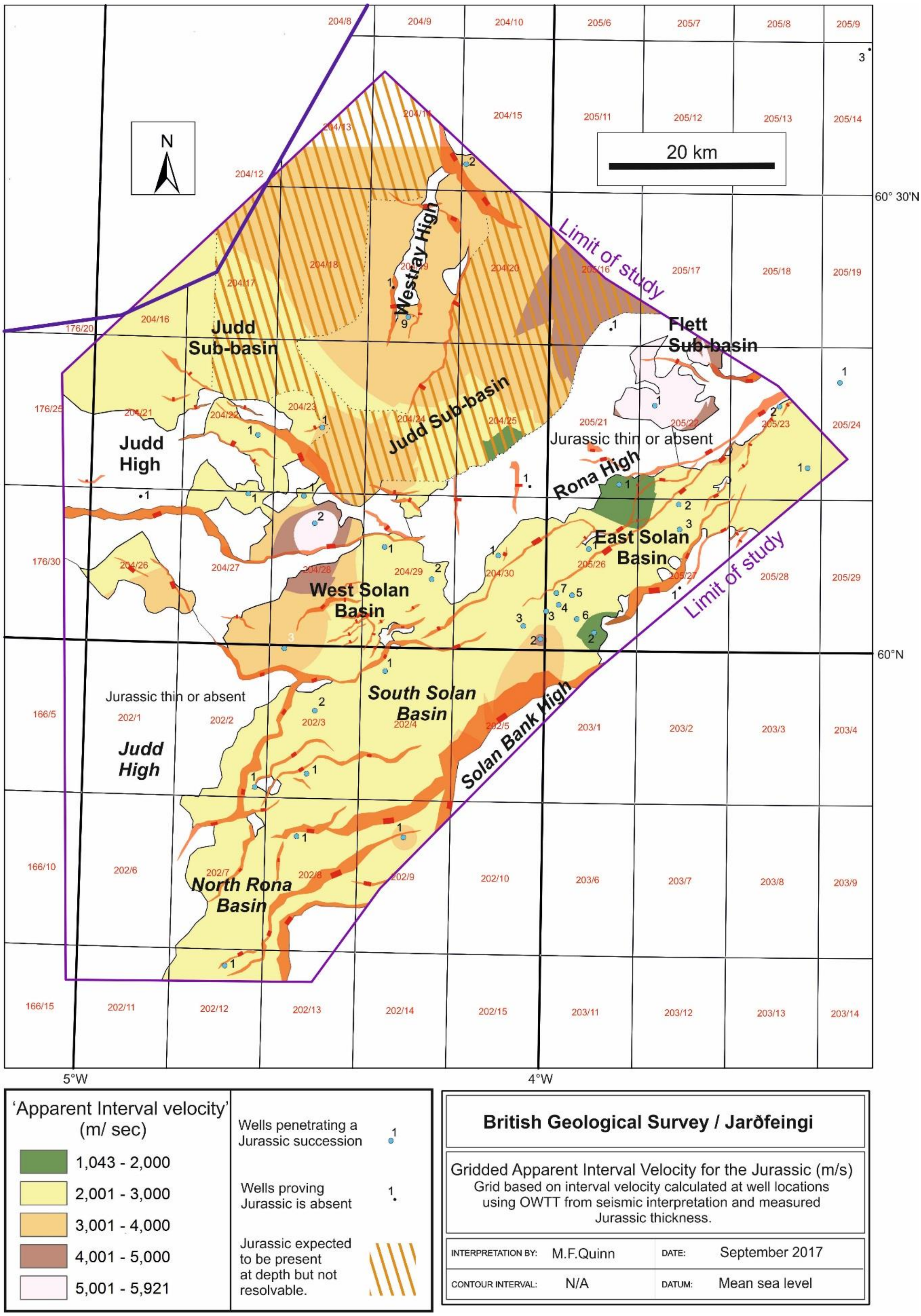

Figure 6. Apparent interval velocity grid of the Jurassic based on interval velocity calculated at well locations using OWTT from seismic interpretation and measured Jurassic thickness. Note that apparent, anomalously high and low velocities result from very thin successions and/or inaccurate well ties caused by uncertain TWTT values.

5 Distribution of Jurassic in the study area

5.1 INTRODUCTION

The majority of wells, proving a Jurassic succession in the study area, show the Jurassic overlain by Lower Cretaceous rocks, often with a limestone lithology near the base. A small number of wells record Upper Cretaceous or Cenozoic sediments resting on Jurassic (Figure 7).

Seven wells prove Jurassic absent (4 with Lower Cretaceous resting on Crystalline Basement; 2 with Upper Cretaceous resting on Basement; 1 with Quaternary resting on Triassic) (Table 1; Figure 7).

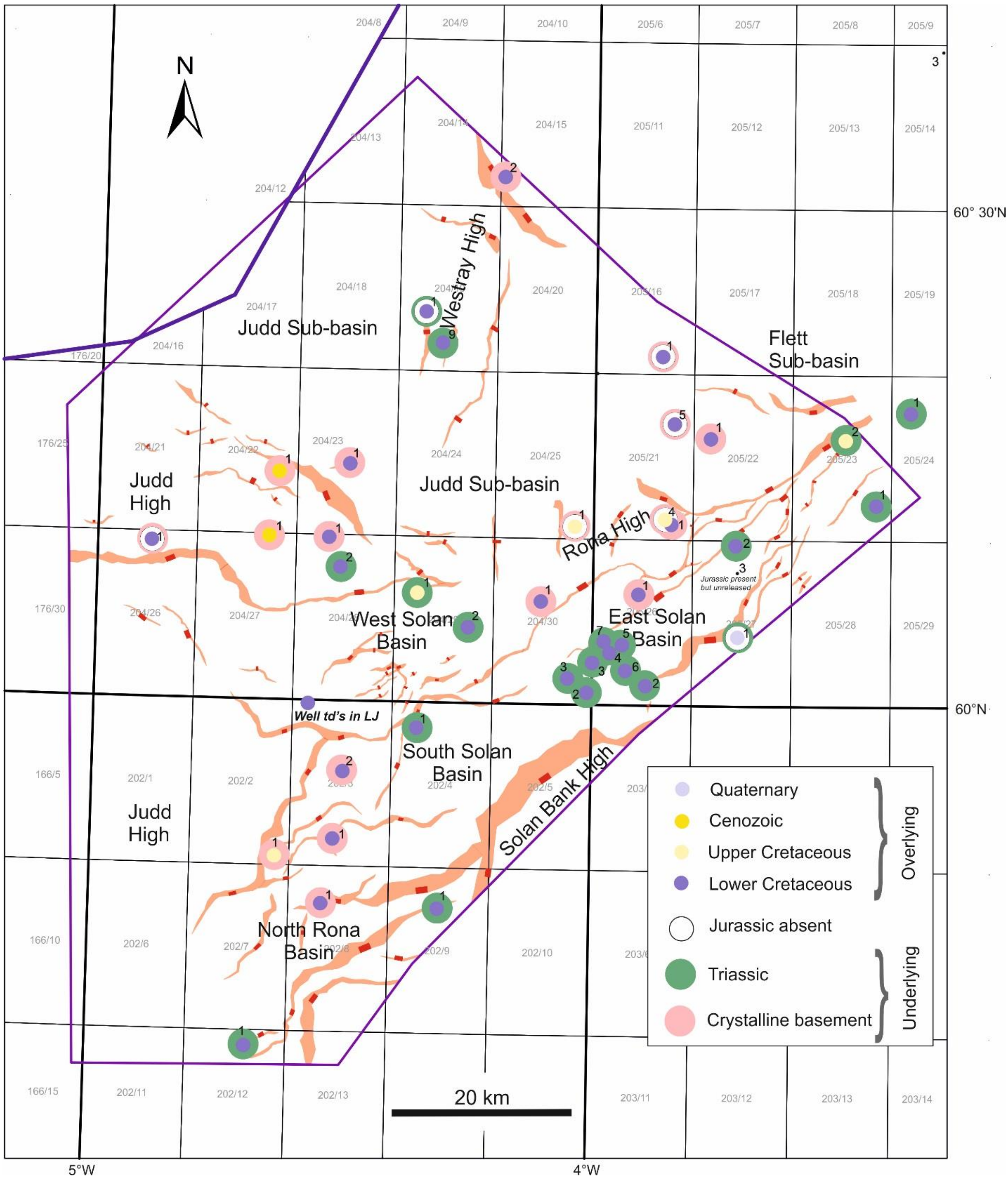

Figure 7. Underlying and overlying successions in relation to the Jurassic succession.

5.1.1 Top Jurassic TWTT map

The Top Jurassic surface (Figure 8) varies in TWTT from approximately 800 ms to over 5200 ms. The shallowest areas occur on parts of the Rona and Solan Bank highs while interpreted Top Jurassic is deepest to the north of the Judd High, in the western part of the Judd Sub-basin.

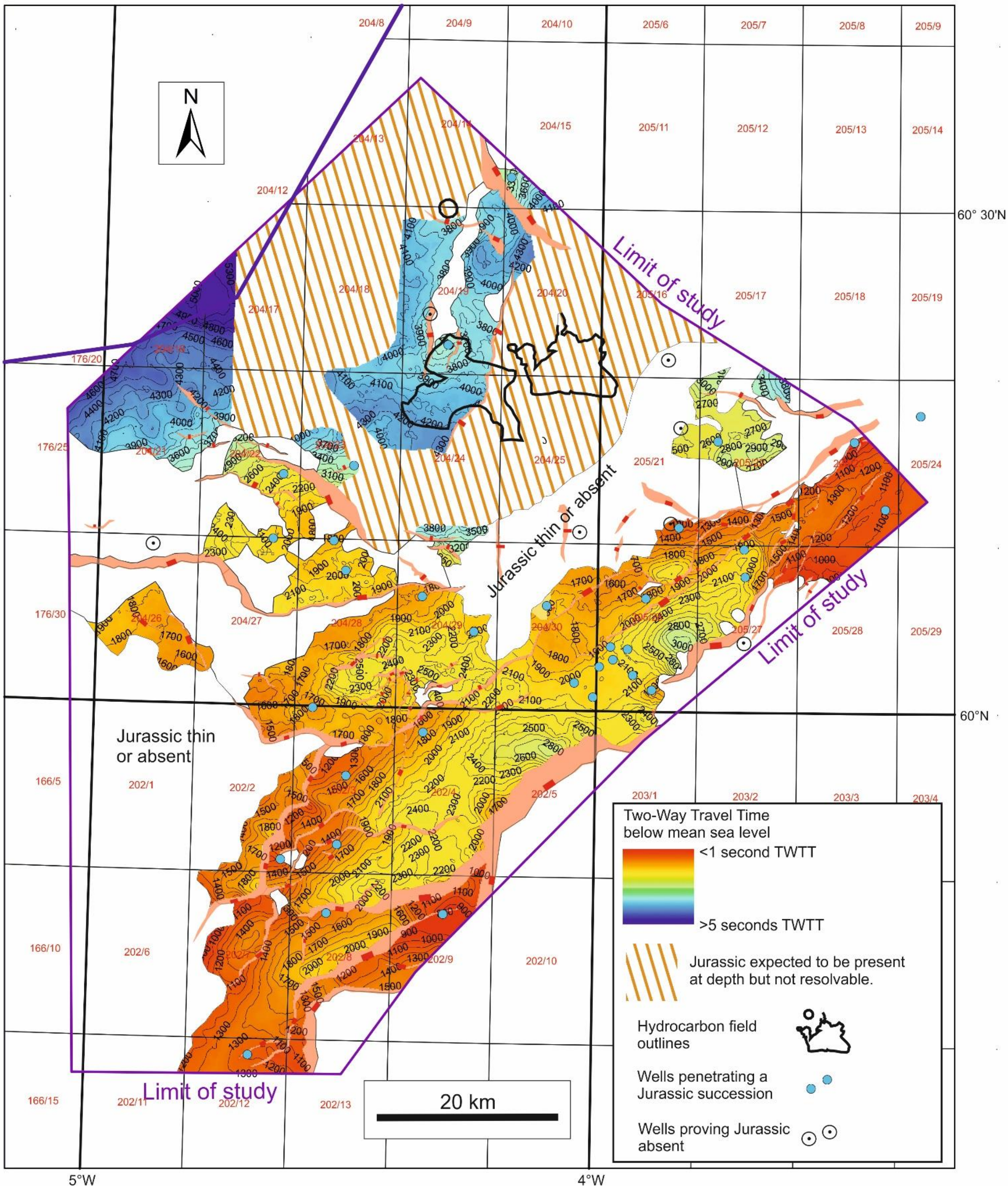

Figure 8. TWTT to Top Jurassic in the study area. The Jurassic is expected to be present over the area defined by diagonal lines but lack of data and greater depth prevented its seismic interpretation.

5.1.2 Base Jurassic TWTT map

The Base Jurassic surface (Figure 9) varies in TWTT from approximately 900 ms to >5400 ms in the western part of the Judd Sub-basin.

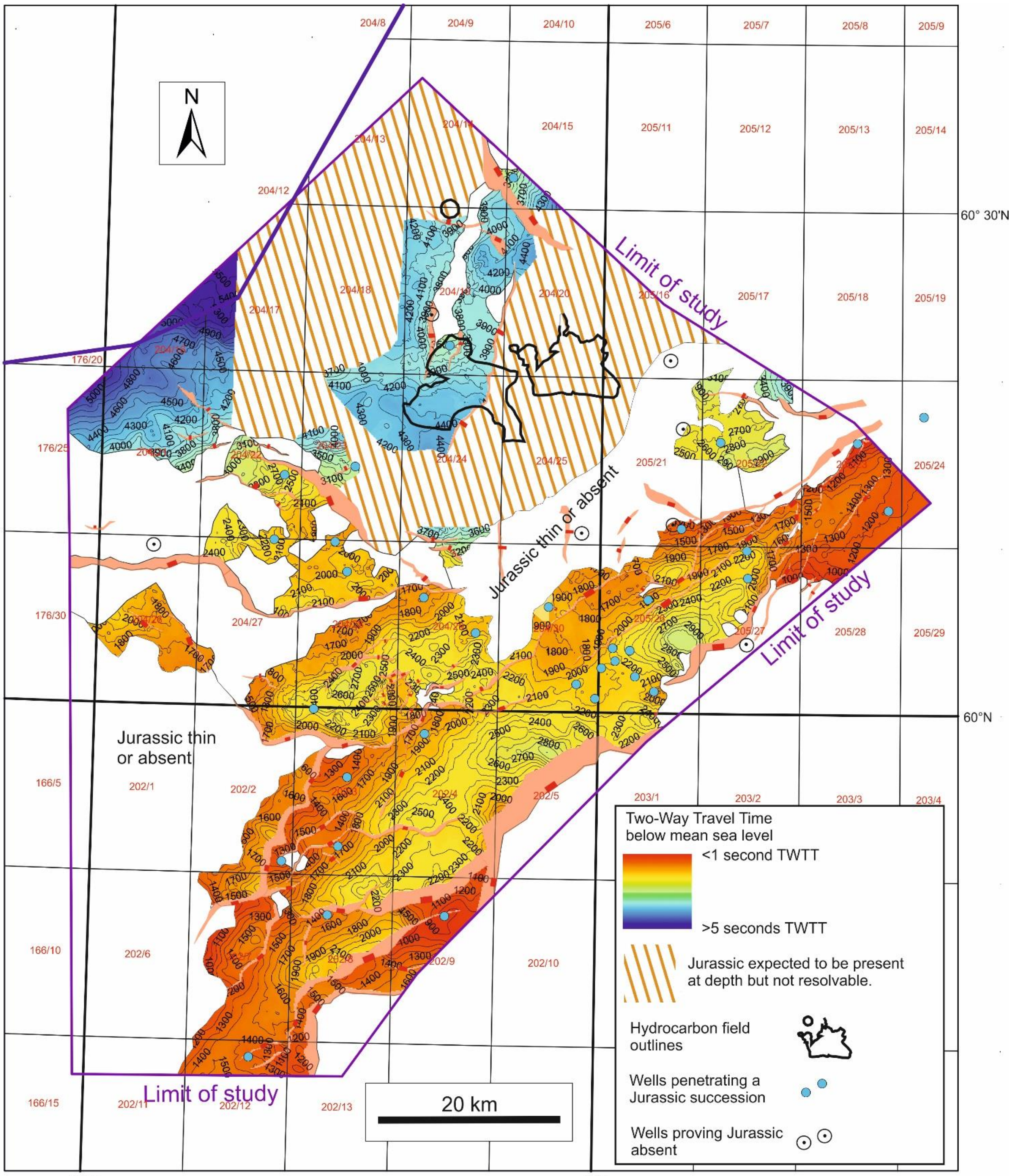

Figure 9. TWTT to Base Jurassic in study area. The Jurassic is expected to be present over the area defined by diagonal lines but lack of data and greater depth prevented its seismic interpretation.

5.1.3 Jurassic isochore in metres

Jurassic thickness (Figure 10) varies from more than 1400 m in the West Solan Basin to less than 200 m in some of the south-westerly marginal basins such as the North Rona Basin.

The Jurassic is thin or absent over much of the Judd High, with a more patchy distribution on the Judd High adjacent to the Judd Sub-basin. Seismic mapping suggests >1400 m total Jurassic thickness in the West Solan Basin. Seismic mapping indicates Jurassic thicknesses of up to 200 m in marginal basins.

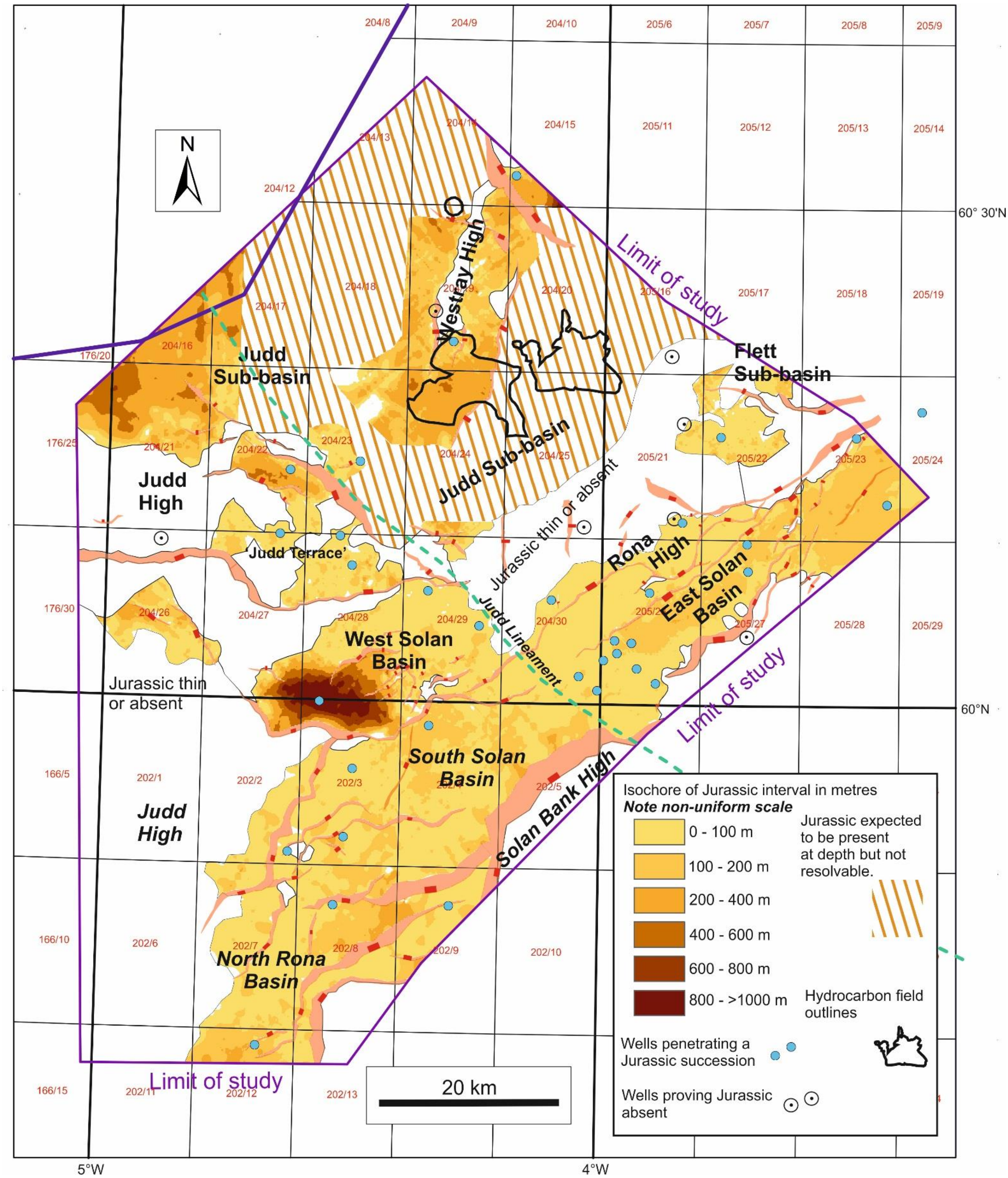

Figure 10. Isochore of the Jurassic interval in the study area. The Jurassic is expected to be present over the area shown by diagonal lines but lack of data and/ or its greater depth prevented interpretation.

5.1.4 Fault throws and orientations

NE-trending faults delineate the North Rona and Solan basins while faults with a more ENE-trend are located within the North Rona Basin. NW-trending faults mark the boundary between the Judd High and Judd Sub-basin. The Judd High itself is divided into faulted terraces, the major faults having a general E-W trend. The West Solan Basin is located at the juxtaposition of the dominantly NE-trend characterising the 'back basins' and E-W trend seen on the Judd High. There is a suggestion of a N-S trend over the Westray High and within the Judd Sub-basin (Figure 10).

The NE- and NW-trending faults tend to have the greater throws. For instance, the NE-trending Otter Bank Fault has throws of 1.5 to 2 seconds TWTT, the NW-trending Judd Fault more than 1 second and the unnamed fault shown in Figure 12 has a 1 second TWTT throw. The ENE-trending faults in the North Rona Basin have throws of 100's of ms.

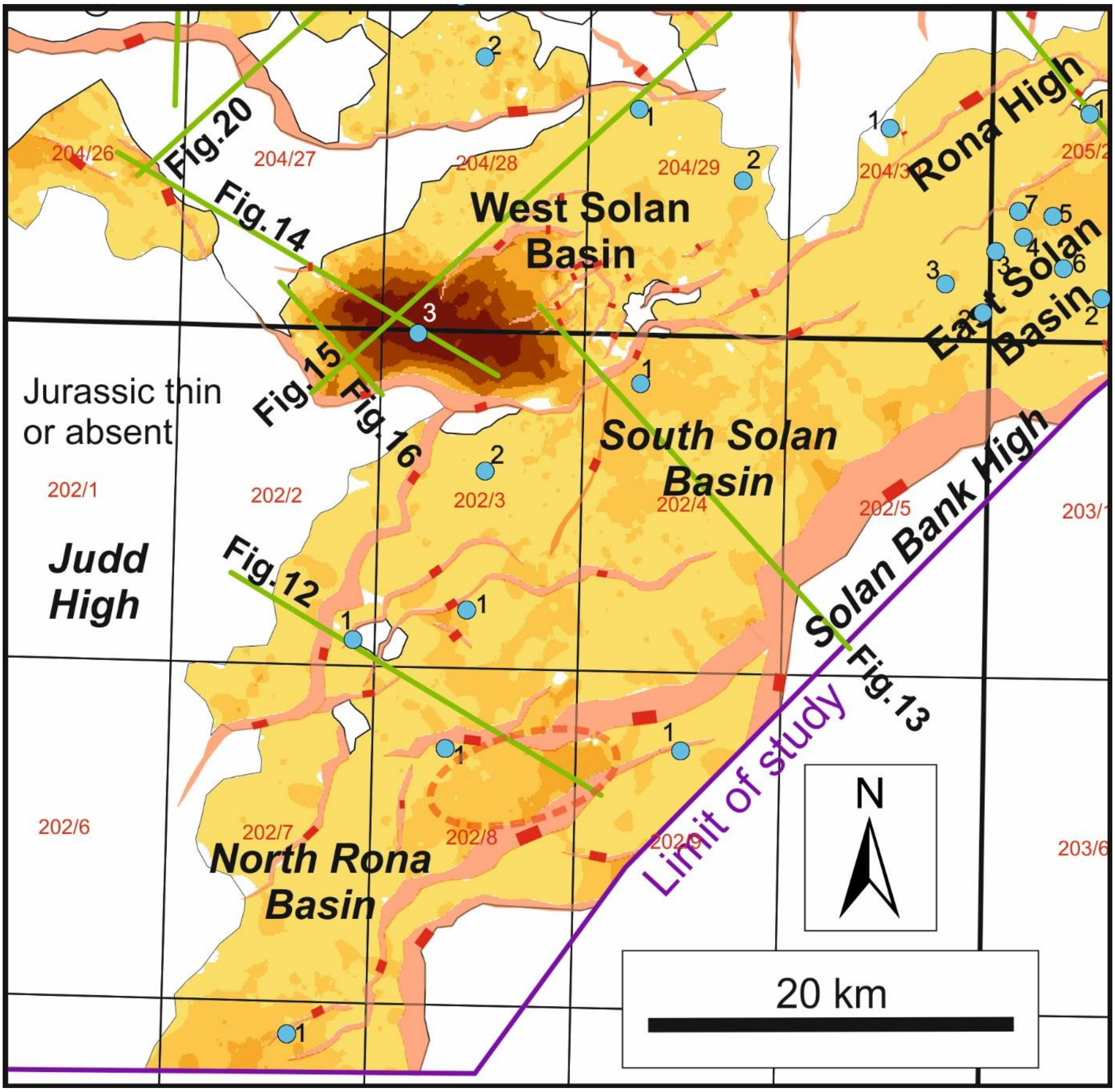

Figure 11. Location of seismic sections in the south-west of the study area. Dashed red oval outline marks thickening of sediments in a possible relay ramp setting referred to in the text below.

5.2 NORTH RONA BASIN

The North Rona Basin is located in the south-western part of the study area and is bounded to the south-east by the Solan Bank High and the north-west by the Judd High (Figure 11). Within the North Rona Basin are several ENE-trending fault blocks many of which have been tested by exploration wells and generally prove relatively thin Jurassic resting directly on crystalline basement.

The seismic section shown in Figure 12 shows a slight increase in thickness of the Jurassic towards the southeast basin bounding fault, though seismic interpretation of top and base reflectors is uncertain. The underlying Triassic and overlying Lower and (especially) Upper Cretaceous do exhibit a wedge-shaped geometry (Figure 12). To the NW, the Jurassic thins and is absent up-dip towards the Judd High.

The majority of wells in the North Rona Basin prove an Upper Jurassic succession, including sands interpreted as Upper Jurassic, resting on Basement. The only exception is well 202/12- 1 that proves an Upper Jurassic succession resting on c.158 m of Triassic sediments (before TD) reflecting its position within the basin itself (Figure 7). The wells with Jurassic resting on Basement are located on, or close to, the crests of tilted fault blocks with significant throws where Triassic sediments were either not deposited, or eroded prior to Jurassic deposition.

Well 202/08- 1 was originally interpreted as Lower Cretaceous Berriasian resting on crystalline basement on the Shell completion log. Subsequent dating by BGS (1984), reinterpreted the Berriasian succession as ‘no younger than Portlandian’ (Portlandian spans the Cretaceous-Jurassic boundary). For this study, the Top Jurassic seismic reflector was picked at top of the KCF (see Section 3.1) at 1.371 secs TWTT, equivalent to a marked increase in the Gamma Log response and marked reduction in interval transit time characteristic of the top of the Kimmeridge Clay Formation (Table 1).

All wells prove a Lower Cretaceous succession resting on Upper Jurassic, except Well 202/02- 1, located on a tilted fault block where Upper Cretaceous onlaps Lower Cretaceous onto the faulted high (Figure 7; Figure 12). There is also evidence of a folded Lower Cretaceous succession in the hanging wall of an ENE-trending fault close to well 202/08- 1 (Figure 11).

The isochore map for this basin shows Jurassic thicknesses of mainly 0-100 m (Figure 11), but a thicker succession, up to 300+ m, has been mapped between two NE-trending faults, SW of the Solan High, that could represent accumulation of sediments on a relay ramp (circled on Figure 11).

5.3 SOUTH SOLAN BASIN

The South Solan Basin appears to be cut by fewer faults than adjacent basins and is located in the hanging wall of a major NE-trending fault, the Otter Bank Fault (OBF), which defines the edge of the Solan Bank High in this area (Figure 10). The seismic section displayed in Figure 13 shows that the Upper Cretaceous succession thickens against the fault indicating some movement of the Otter Bank Fault at this time, however, as Ritchie et al. (2011) observed, this does not appear to be enough to account for the 1.5 sec TWTT displacement of the Top Basement reflector. The underlying Lower Cretaceous, Jurassic and Triassic show no evidence of thickening suggesting that the OBF was a feature in pre-Jurassic times. In some places, recognition of the Top Basement seismic reflector is difficult and hence the intervening Triassic succession, expected to be thin in this area, is difficult to resolve (Figure 13). The Jurassic succession rises towards the north-west culminating on a faulted high that separates this basin from the West Solan Basin to the north-west (Figure 13).

Only one well, 202/04- 1, has been drilled in the South Solan Basin and this proved a Jurassic succession, comprising 28 m of Upper Jurassic (confirmed by palynological analysis of core for this project) and 135 m of Lower Jurassic sediments resting on a 26 m thick Triassic succession and ultimately crystalline basement (Figure 6). A thin Lower Cretaceous limestone (4 m thick) at the base of the Lower Cretaceous succession rests on the Jurassic succession; the Lower Cretaceous succession thins up dip and may be absent towards the tilted fault block crests.

The isochore map shows Jurassic thicknesses in the South Solan Basin of generally <200 m.

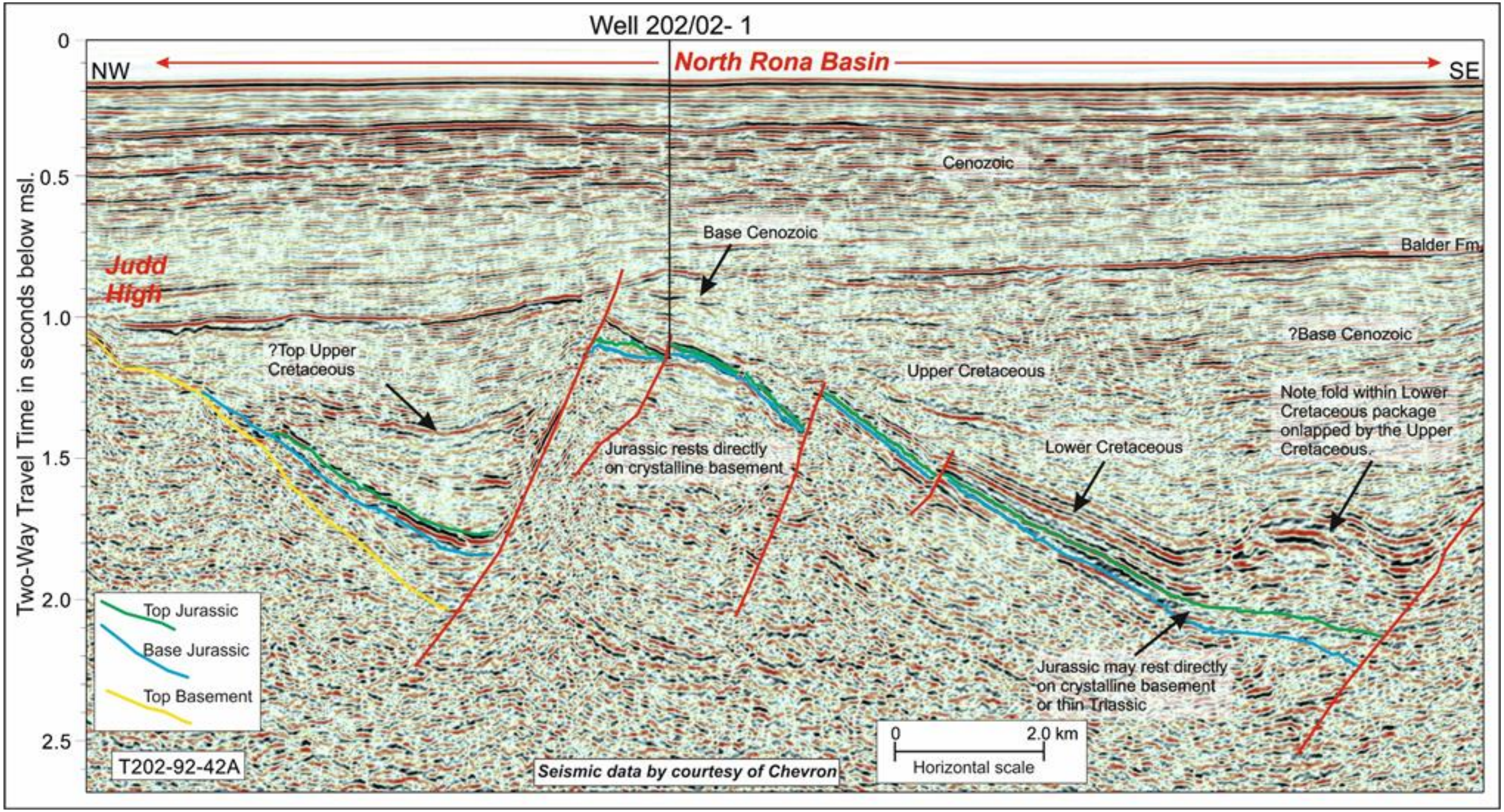

Figure 12. North Rona Basin: NW-SE trending interpreted 2D seismic section showing Jurassic resting directly on crystalline basement on top of a fault block, with a Triassic succession preserved in the hanging wall. Line location shown on Figure 11.

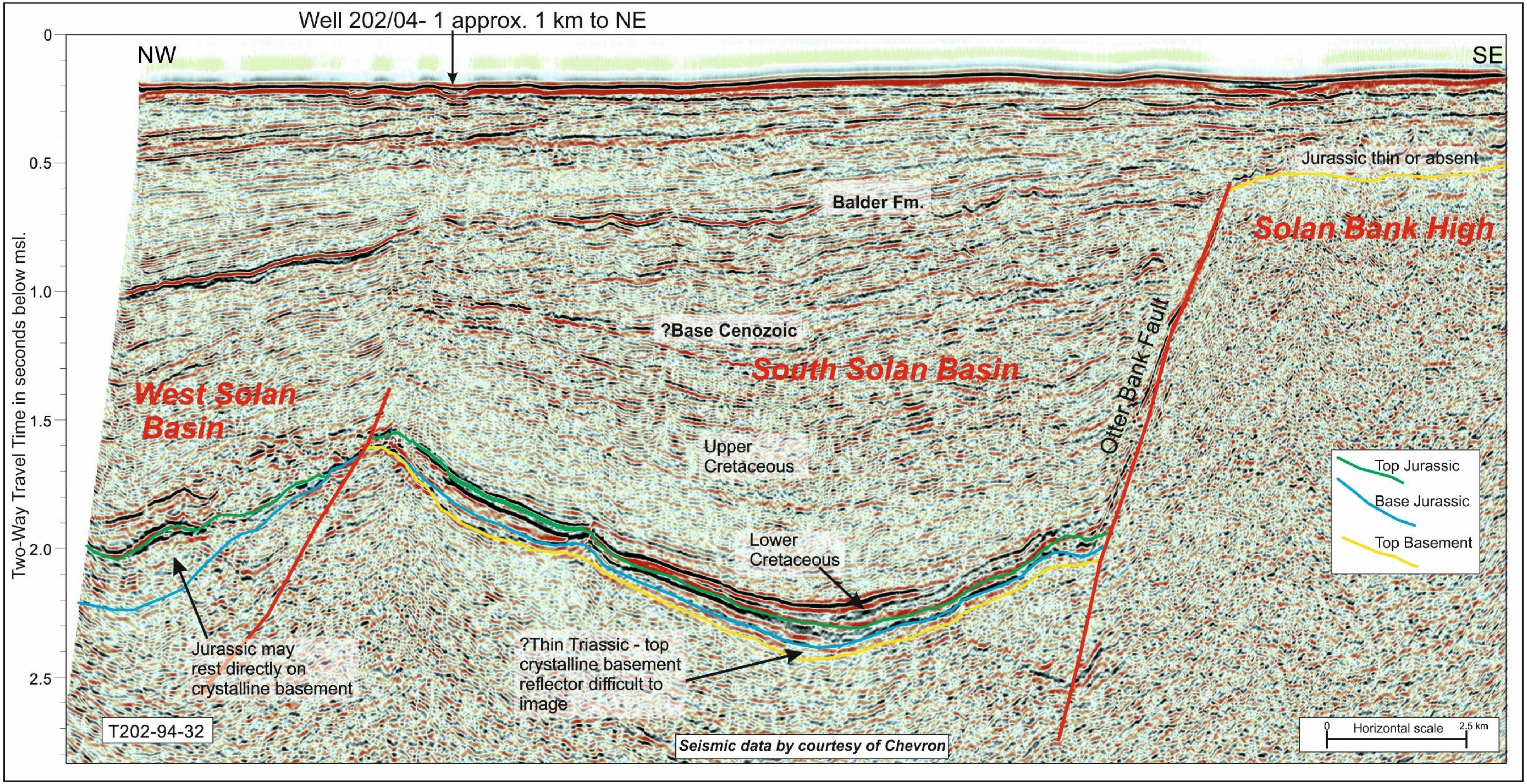

Figure 13. South Solan Basin: NW-SE trending interpreted 2D seismic section showing a Jurassic succession resting on a possible thin Triassic succession. Line location shown on Figure 11.

5.4 WEST SOLAN BASIN

The West Solan Basin, defined by its post-Jurassic succession, trends NE and is 25 km long and 15 km wide (Figure 3; shown also in Figure 2 of Stoker et al., 2015 and Figure 7 of Ritchie et al., 2011). The north-eastern part of the West Solan Basin comprises Upper Jurassic sediments mainly <100 m, while the south-western part has a predominantly Lower Jurassic succession of >500 m that thickens to a maximum interpreted thickness of 1426 m (Figure 14 and Figure 15). The Lower Jurassic succession, its thickness defined on the isochore map is located within the NE-trending West Solan Basin, and forms an E-W trending depocentre, 15 km long and 6 km wide (Figure 10 and Figure 11).

A question remains as to whether the thick Lower Jurassic mapped here is due to localised deposition in an isolated subsiding basin or widespread deposition followed by uplift and erosion resulting in preservation of a Jurassic remnant post-erosion. The basin is located immediately north-west of the South Solan Basin and separated from the latter by a faulted high. The main controlling fault to the thick Jurassic succession runs along its south-eastern and southern edges (Figure 11). The following observations are pertinent to the question:

- In the West Solan Basin, wells 202/03a- 3 and 204/29- 2 prove an Upper Jurassic succession resting unconformably on Lower Jurassic and this, coupled with the interpretation of seismic data in the area, indicates subsequent deposition of a relatively thin Upper Jurassic Kimmeridge Clay Formation blanketed the whole area.
  - If the present-day distribution of Lower Jurassic is due to its preservation after widespread deposition and erosion, it might be expected that there would be more frequent occurrences of Lower Jurassic in some of the other basins beneath the Upper Jurassic succession.
  - However, if uplift was widespread, and significant deep erosion occurred, this would also have resulted in the absence of Lower Jurassic except in a small number of isolated basins.
- The Jurassic depocentre could have formed in a transtensional regime due to strike-slip movement along this controlling fault resulting in deposition of the Lower Jurassic in a subsiding basin;
  - Figure 16 shows apparent onlap of Lower Jurassic sediments onto a Triassic surface within the subsiding basin.

The most likely explanation for the present day distribution of Lower Jurassic in the project area is a combination of widespread deposition, with, in the West Solan Basin, possibly a greater amount of subsidence, deposition and also preservation of sediments in a transtensional setting, followed by extensive widespread deep erosion.

The Top and Base Jurassic TWTT maps (Figures 8 and 9) show culminations, seen in cross-section on seismic lines in Figures 14, 15 and 16, which provide evidence of compression. Timing of compression, from examination of reflector relationships, could have occurred between the end of the Lower Jurassic to end-Lower Cretaceous; Upper Cretaceous reflectors appear to thin and onlap the culminations in Figure 15. More detailed estimation of timing is not possible as the Upper Jurassic and Lower Cretaceous succession is too thin to discern the relationship between these reflectors and the culminations.

Three wells have been drilled in the West Solan Basin all penetrating a Jurassic succession. Well 202/03a- 3 located within the Jurassic depocentre proved 794 m of mainly Lower Jurassic sediments (26 m Upper Jurassic; 768 m Lower Jurassic). Wells 204/29- 1 and 204/29- 2 are located outside the Jurassic depocentre and proved 25 and 35 m of Upper Jurassic respectively (Figure 11).

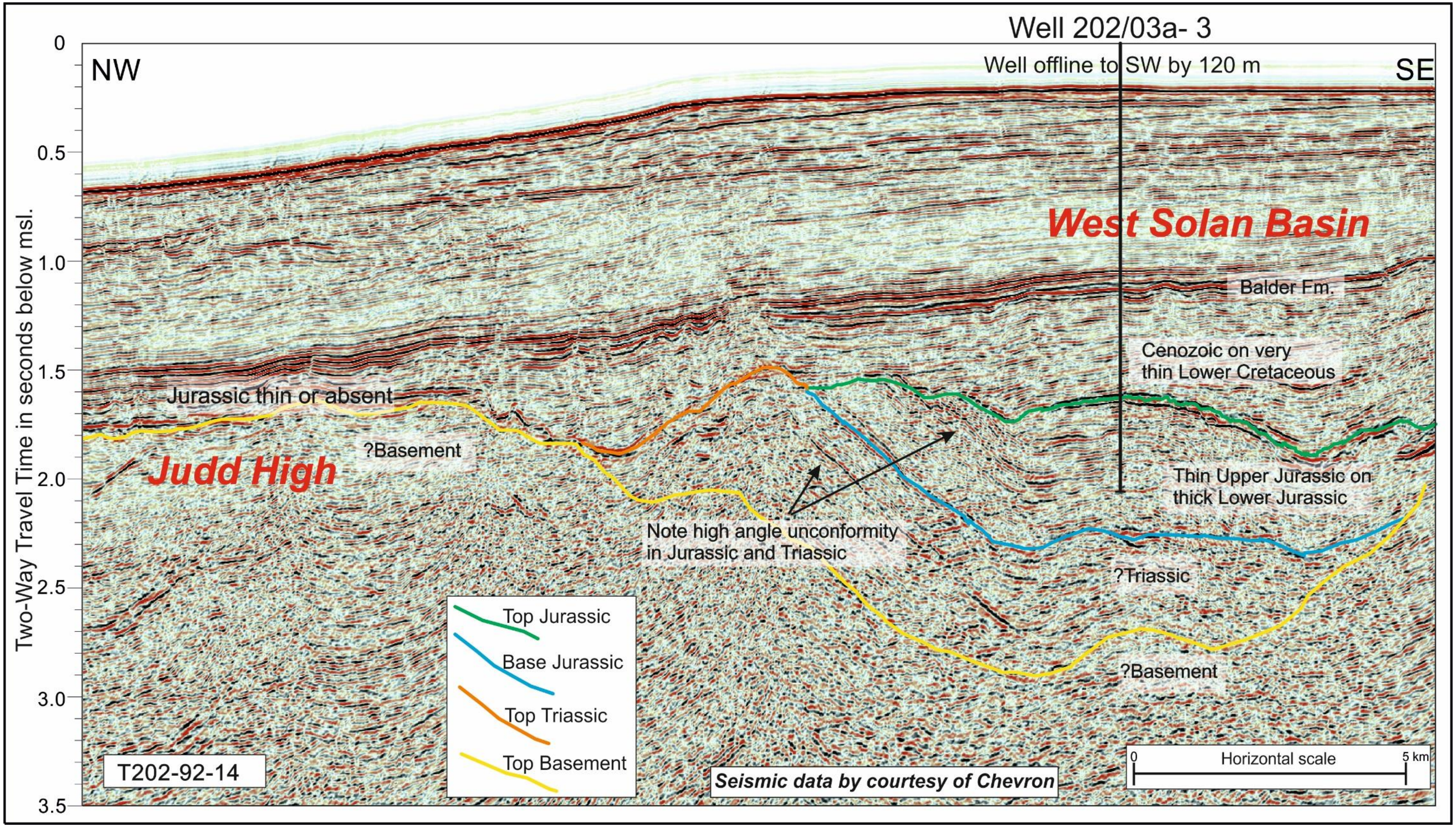

Figure 14. West Solan Basin: NW-SE trending interpreted 2D seismic section showing thick Lower Jurassic sediments resting on a possible thick Triassic succession. Line location shown on Figure 11.

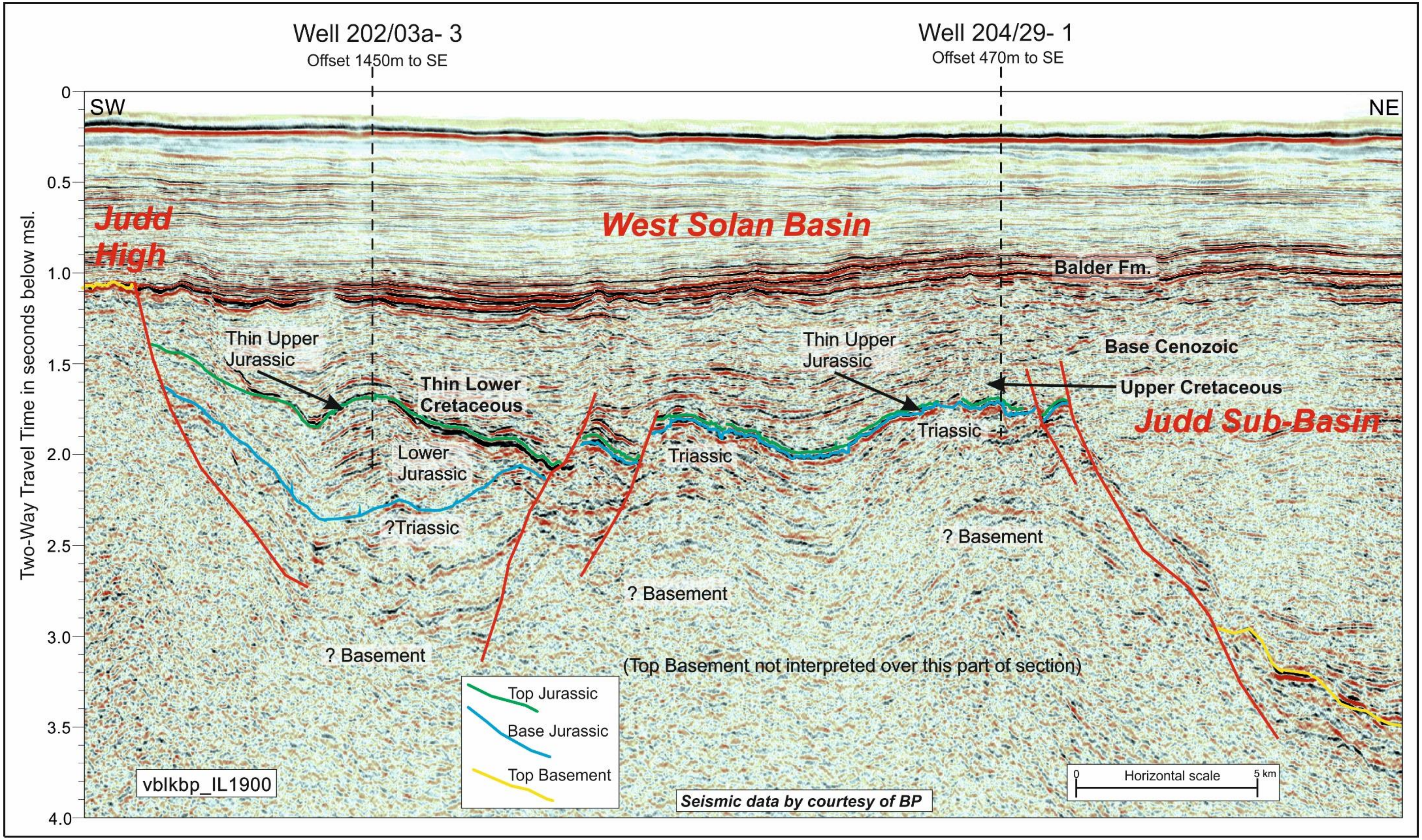

Figure 15. West Solan Basin: SW-NE trending interpreted 3D seismic section showing thick Lower Jurassic sediments resting on a possible thick Triassic succession in the SW with a thin Upper Jurassic succession to the NE. Line location shown on Figure 11.

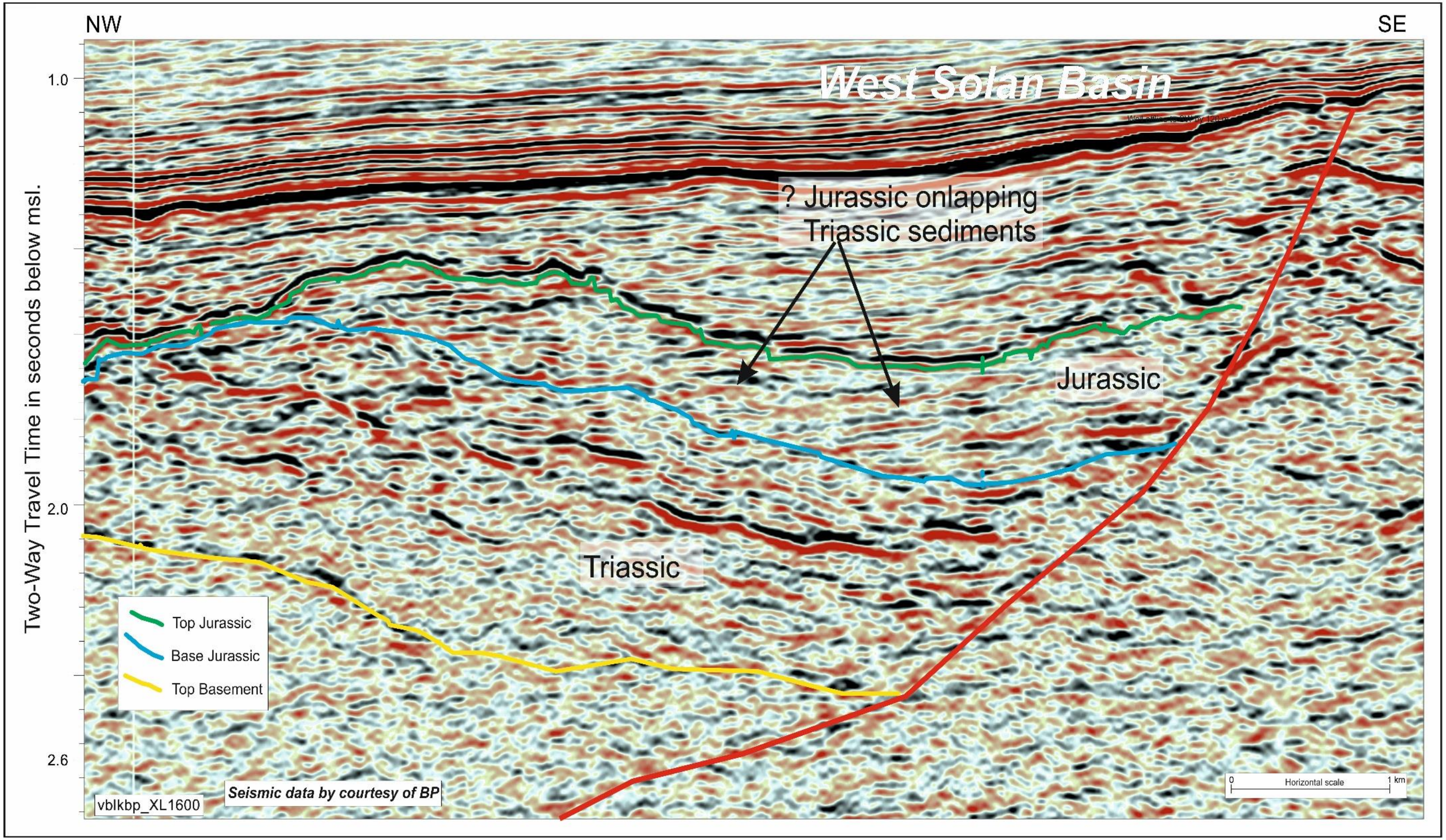

Figure 16. West Solan Basin: SW-NE trending interpreted 3D seismic section showing Lower Jurassic sediments onlapping a thick Triassic succession. Subsidence and/ or compression continued during the Lower Cretaceous (see text). Line location shown on Figure 11.

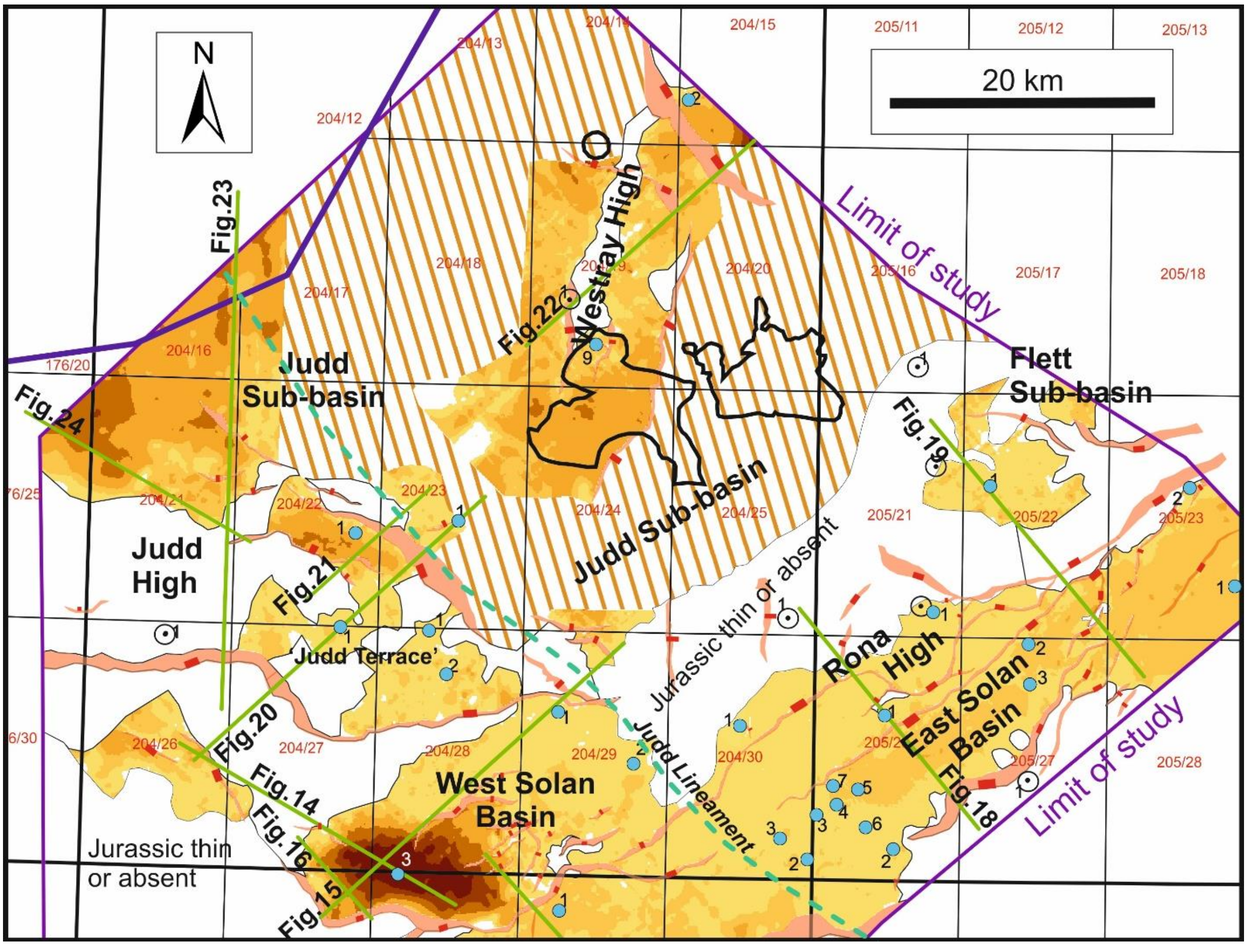

Figure 17. Location of seismic sections in the north of the study area.

5.5 EAST SOLAN BASIN

The NE-trending East Solan Basin is bounded to the south-east by the Otter Bank Fault that exhibits at least 2 seconds TWTT of throw (Figure 18). The Judd Lineament (Figure 3 and 17) defines the south-west boundary of the East Solan Basin and the SW extension of the Rona High forms its north-west boundary (Ritchie et al., 2011). The Jurassic succession comprises Upper Jurassic Kimmeridge Clay Formation including sandstone, the latter forming an oil reservoir for the Solan Field, with a thickness of between 50 and approximately 200 m. There is a major unconformity between the Triassic and relatively thin Upper Jurassic succession.

All wells in the East Solan Basin prove Lower Cretaceous resting on an Upper Jurassic succession that in turn rests on Triassic sandstone. The only exception is well 205/26- 1, located on the higher NW flank of the East Solan Basin (Figure 18), where the Upper Jurassic rests directly on crystalline basement (Figure 7).

5.6 RONA HIGH

The south-western extremity of the Rona High is present within the study area where it separates the East Solan Basin to the SE from the Judd Sub-basin to the NW. In this area the high is cut by a predominately NE-trending series of faults (Figure 10; Figure 17). The Jurassic succession decreases in thickness towards the north-west and is interpreted to be thin or absent along the north-western edge of the Rona High; well 204/25- 1 proved Upper Cretaceous resting on crystalline basement. The crest of the Rona High is punctuated by several predominantly NE-trending faults with relatively small throws (Figure 18).

The isochore indicates that, where present, the Jurassic succession has been interpreted to be <100 m thick.

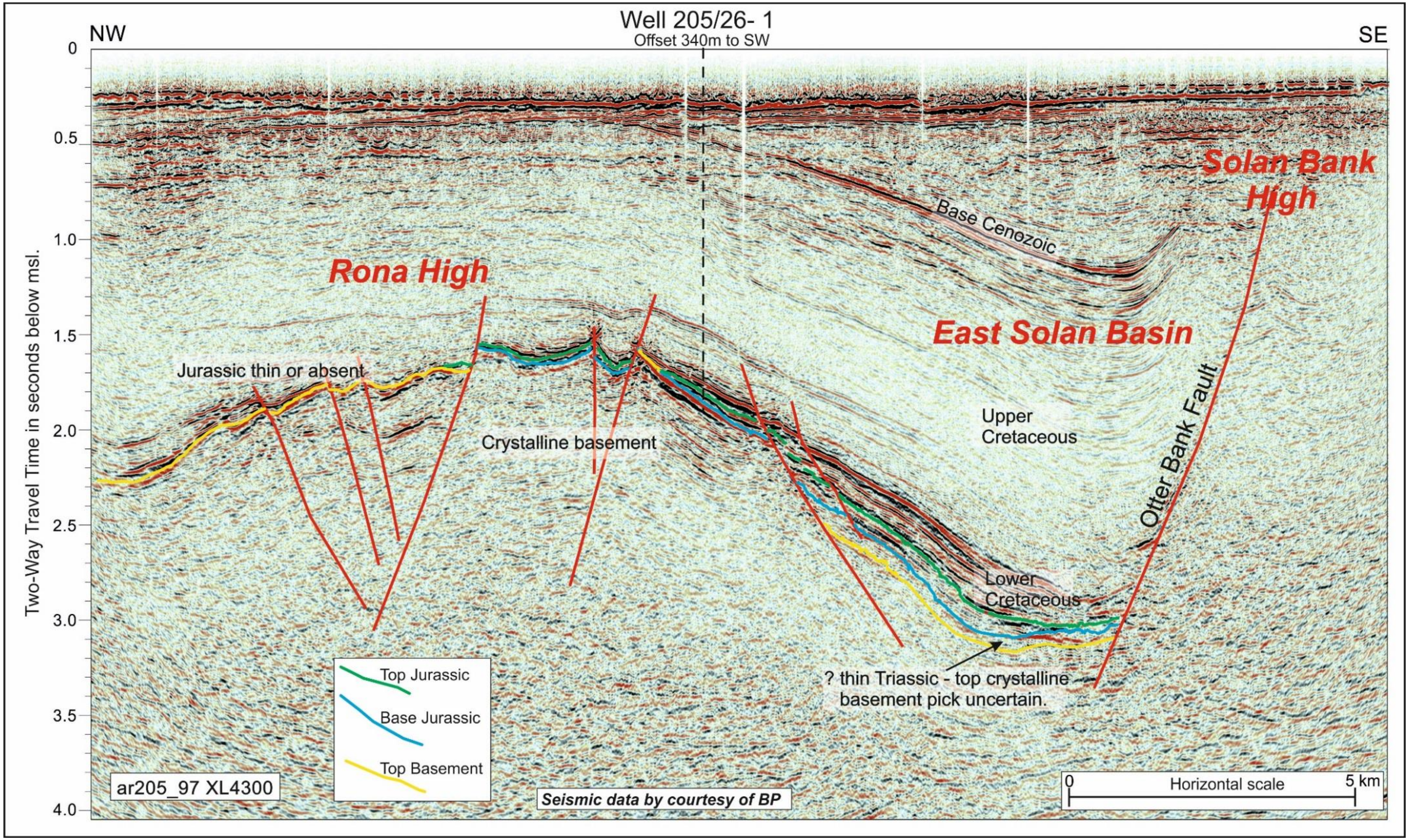

Figure 18. East Solan Basin: NW-SE trending interpreted 3D seismic section showing the Jurassic succession and structure across the Rona High and East Solan Basin. Line location shown on Figure 17.

5.7 SOUTH-WEST FLETT SUB-BASIN

Well 205/22- 1A proved 50.5 m of Upper Jurassic mudstone, limestone, sandstone and conglomerate at a location immediately NW the Rona High (Figure 17; Figure 19). Seismic interpretation shows a restricted area of Upper Jurassic sediments generally less than 100 m and patches around 200 m in thickness.

The restricted nature of the deposit must be due in part to erosion prior to deposition of the Lower Cretaceous, as deep marine mudstones (presumably deposited widely) have been described from a core at the top of the Jurassic succession in well 205/22- 1A (Dodd et al., 2018). The interpretation of the older palaeo-environment from the core as a proximal fan delta/ alluvial cone resting on crystalline basement (Dodd et al., 2018) suggests a local source area and its location immediately NW the Rona High, points to the latter as the likely source for the clastic material.

5.8 JUDD HIGH

The north-eastern part of the Judd High is present within the study area. A NW-trending fault defines its boundary with the Judd Sub-basin. Another, E-W trending fault, with a NNW-trending 'dog-leg' transects the high forming a terrace, referred to here as the 'Judd Terrace', on which five wells have been drilled to date. Distribution of the Jurassic is patchy and is generally between 0 and 200 m thick but on part of the 'Judd Terrace', Jurassic thicknesses have been interpreted to be >400 m thick (Figures 10 and 17).

Four wells prove a Jurassic succession, three prove <100 m but the fourth, well 204/22- 1 proves 246 m of Middle Jurassic Bathonian and Callovian sediments (BP interpretation on composite log) overlain by thin Oxfordian (14 m). Well 204/22- 1 is located on the 'Judd Terrace', closest to the Judd Sub-basin, where the thickest Jurassic is interpreted to be preserved (Figure 21).

In wells 204/22- 1, 204/27a- 1 and 204/28- 1, the Jurassic succession rests directly on crystalline basement however the most southerly well, 204/28- 2, reached total depth in the Triassic after proving 185 m of Triassic sediments. It may be that this well is located in the hanging wall of a fault observed on the seismic data, but not mapped, where the Triassic is preserved; there is a slight difference in the seismic package either side of this fault that may reflect the different crystalline basement and Triassic lithologies.

The fifth well, 204/26- 1, located further to the west and closer to the E-W fault bounding the terrace, proved Jurassic absent with Lower Cretaceous sediments resting on basement.

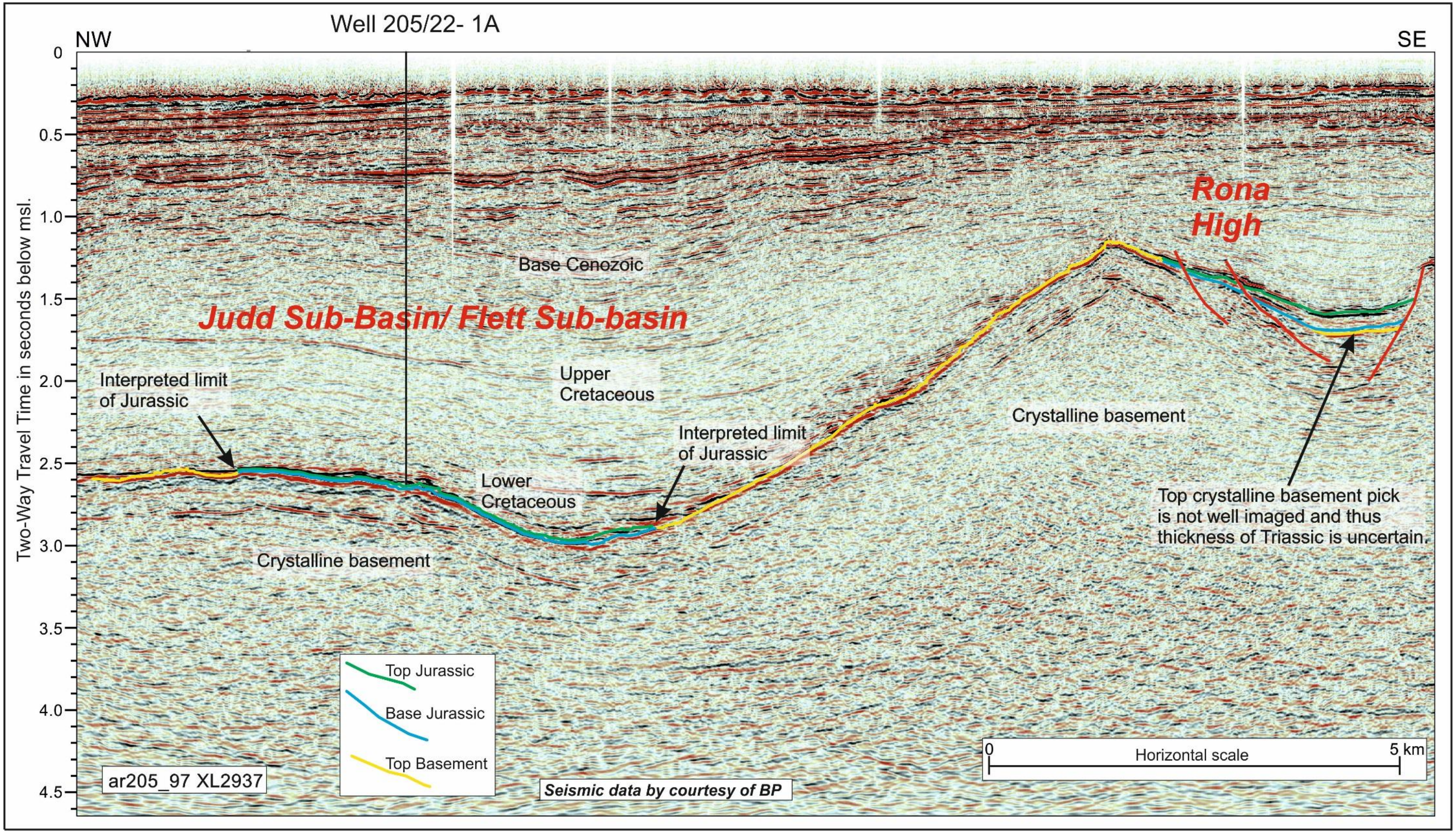

Figure 19. Flett Sub-basin: 3D seismic section showing interpretation of the Jurassic succession in the south-western part of the Flett Sub-basin. Line location shown on Figure 17.

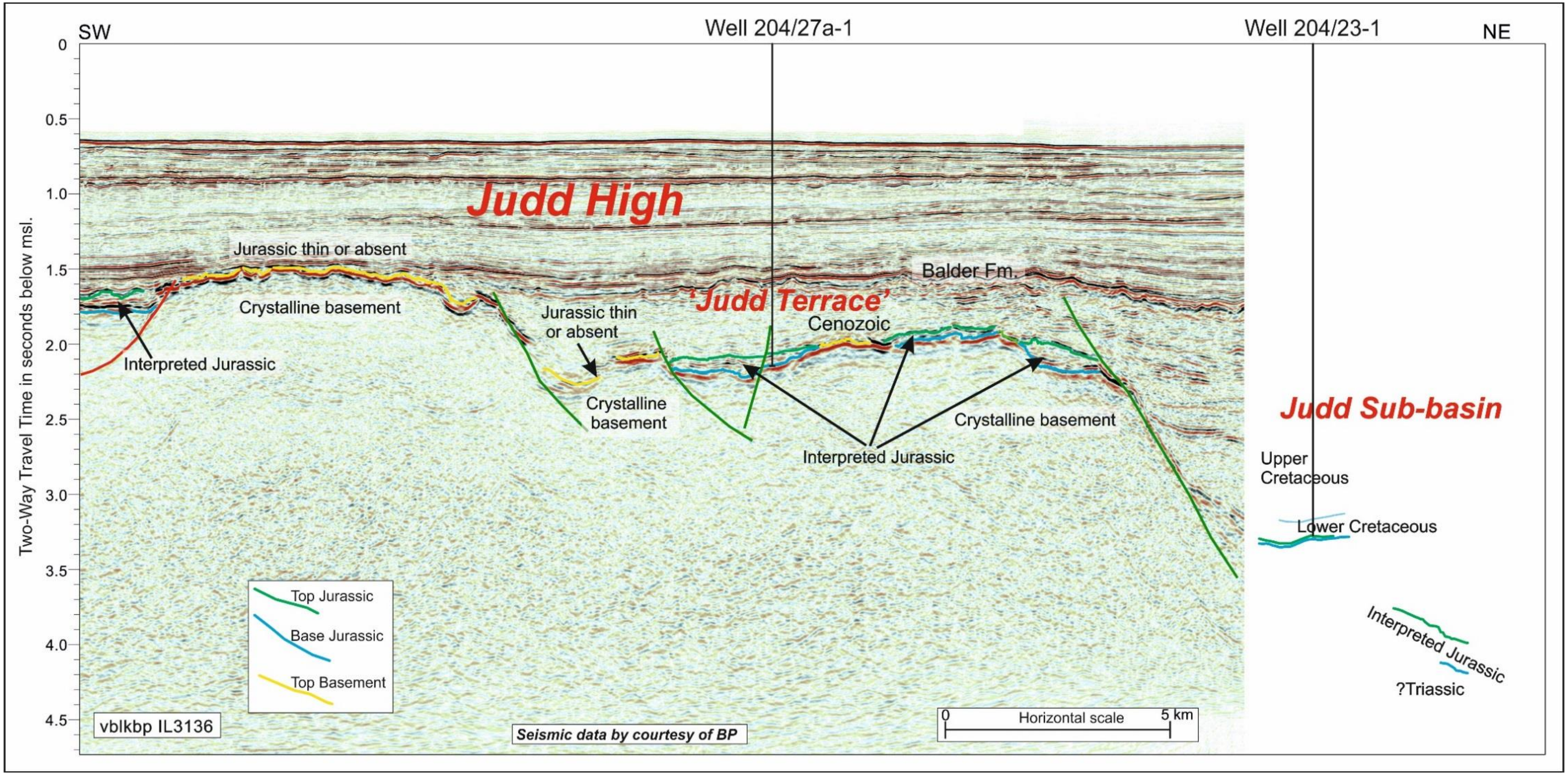

Figure 20. Judd High: NE-SW trending interpreted 3D seismic section showing the Jurassic succession and structure across the 'Judd Terrace'. Line location shown on Figure 17.

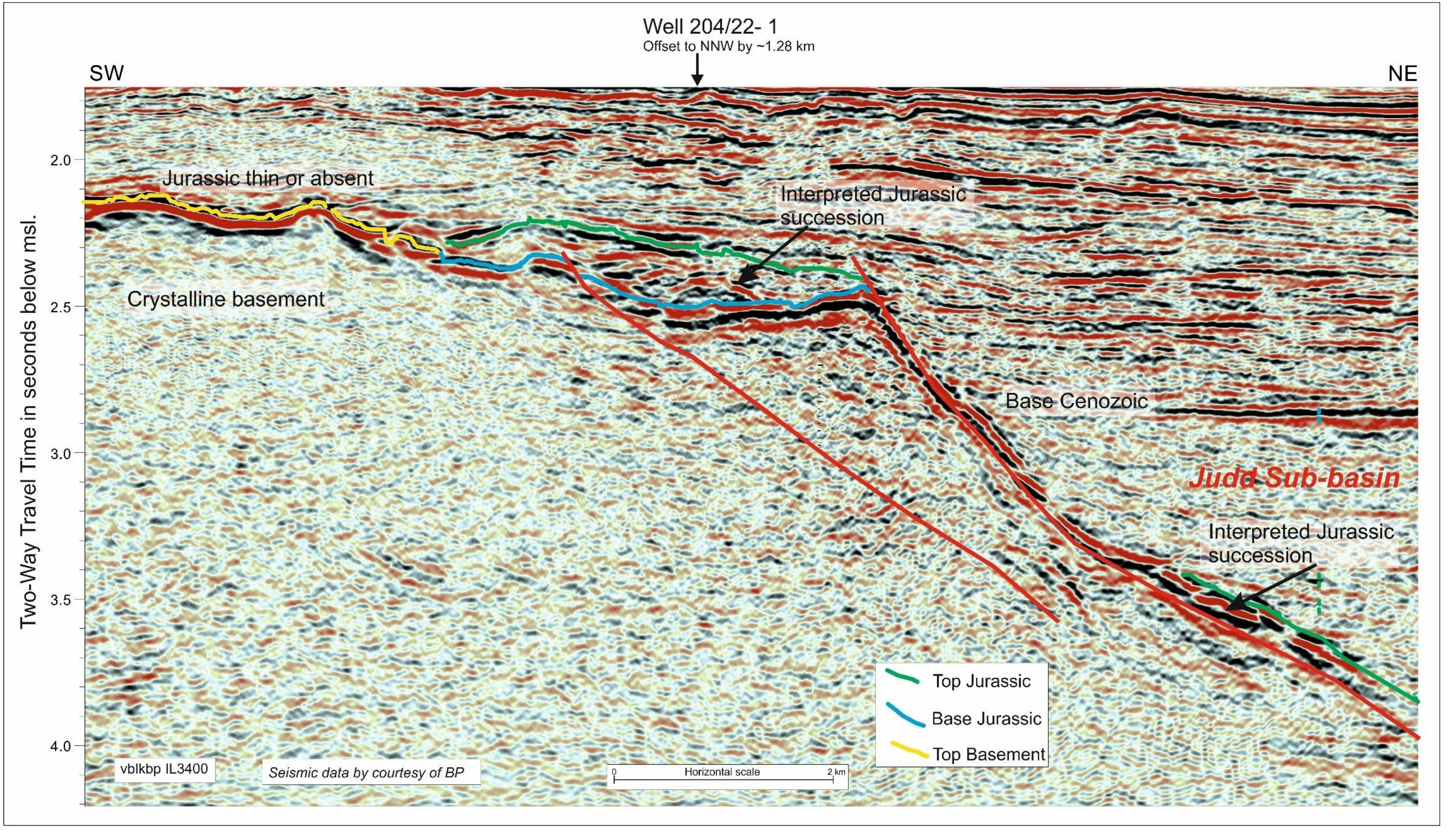

Figure 21. Judd High: NE-SW trending interpreted 3D seismic section showing Jurassic onlapping Judd High. Line location shown on Figure 17.

5.9 WESTRAY HIGH

The Westray High is described by Ritchie et al. (2011) as two small north to NNW-trending intra-basinal highs (Figure 3). The southerly high and the southern part of the northern high lie within the study area. The highs are deeply buried, Well 204/19- 1 drilled just off the crest of the south Westray High, penetrated the base Lower Cretaceous/ Top Triassic boundary at 4263 m TVDSS. The south Westray High is located beneath the Paleocene Foinaven Oil Field and immediately west of the Schiehallion Oil Field. The Jurassic is interpreted to be absent along the crest of the south Westray High (Figure 8) and to thicken eastwards down-dip into the Judd Sub-basin (Figure 10).

One well on the south Westray High, well 204/19- 9, and well 204/15- 2 located on the north Westray High within the study area proved Jurassic successions. Well 204/19- 9 drilled on the eastern flank of the south Westray High, 1.5 km off the crest, proved 185 m of Lower Jurassic sediments overlain by Lower Cretaceous sediments and resting on Triassic. However, it is expected that Upper Jurassic sediments will be present down-dip where the total Jurassic interval is interpreted to be 200-300 m thick but in some areas may exceed 400 m. Well 204/15-2, located on the footwall of a major fault bounding the northern Westray High (Figure 17 and Figure 22), penetrated 233 m of Upper Jurassic siltstone, sandstone and occasional limestone.

5.10 JUDD SUB-BASIN

The study did not have access to sufficient 2D or 3D seismic coverage over much of the Judd Sub-basin to enable mapping of the Top and Base Jurassic. In addition, no commercial wells penetrate far enough into the deeper parts of the Judd Sub-basin to prove the presence of Jurassic. However, the expectation is that a Jurassic succession will be present at depth within the Judd Sub-basin (Ritchie and Varming, 2011) and the limited seismic interpretation in this study supports this view. For instance, seismic interpretation over the Westray High, located in the middle of the Judd-Sub-basin, where a Jurassic succession is proven in well 204/19- 9, shows the Jurassic dipping down to between 4.0 and 4.5 seconds TWTT (approximately 5 to 5.5 km) (Figure 22). Figures 20 and 21 also show a Jurassic succession dipping down into the Judd Sub-basin. Note however, east and south-east of the Westray High close to the Rona High and including part of the Flett Sub-basin, where seismic information is limited, three wells prove Jurassic to be absent and here an area has been mapped as 'Jurassic thin or absent'.

A tentative seismic interpretation within part of the Judd Sub-basin, north of the Judd High and west of the Westray High maps a possible Jurassic succession. Figure 23 shows a Cenozoic seismic package, the base tied to nearby wells 204/21- 1 and 204/16- 1 (that both reach total depth close to the top of the Upper Cretaceous), and a Cretaceous succession characterised by abundant sill intrusions. The Cretaceous appears to onlap a deeper seismic package (Figure 23) suggesting the presence of an older succession, possibly Jurassic, resting on Triassic or basement forming the Judd High. A series of faults cut the Jurassic succession with relatively small displacements throwing into the sub-basin (e.g. Figure 23); the Jurassic succession thins and eventually terminates on the flanks of the Judd High. The Jurassic shows a gradual increase in thickness downdip into the Judd Sub-basin; the Jurassic isochore shows interpreted thickness of >500 m (Figure 10).

The style of the faulting is reminiscent of the Jurassic succession that thins onto the NW flank of the Rona High (see Figures 22 and 24 in Quinn et al., 2014 and Haszeldine et al., 1987). The Jurassic succession on the Rona High includes Upper Jurassic sandstone, and in the project area, Upper Jurassic sands have been proved in many wells. For instance, well 204/27a- 1, 15 km to the SE, proved more than 70 m of Upper Jurassic Rona Sandstone. Dodd et al. (2018)

predicts the presence of a clean well sorted marine sandstone, the Rona Sandstone Member (R4) and Solan Sandstone Member (R6) on the northern flank of the Judd High. The Solan Sandstone Member is a proven hydrocarbon reservoir in the East Solan Basin.

The interpretation of the Jurassic on the northern flank of the Judd High forms an untested hydrocarbon play where Jurassic reservoir sands pinchout up-dip, are faulted and rotated, and are sourced down-dip by a thickening Upper Jurassic succession.

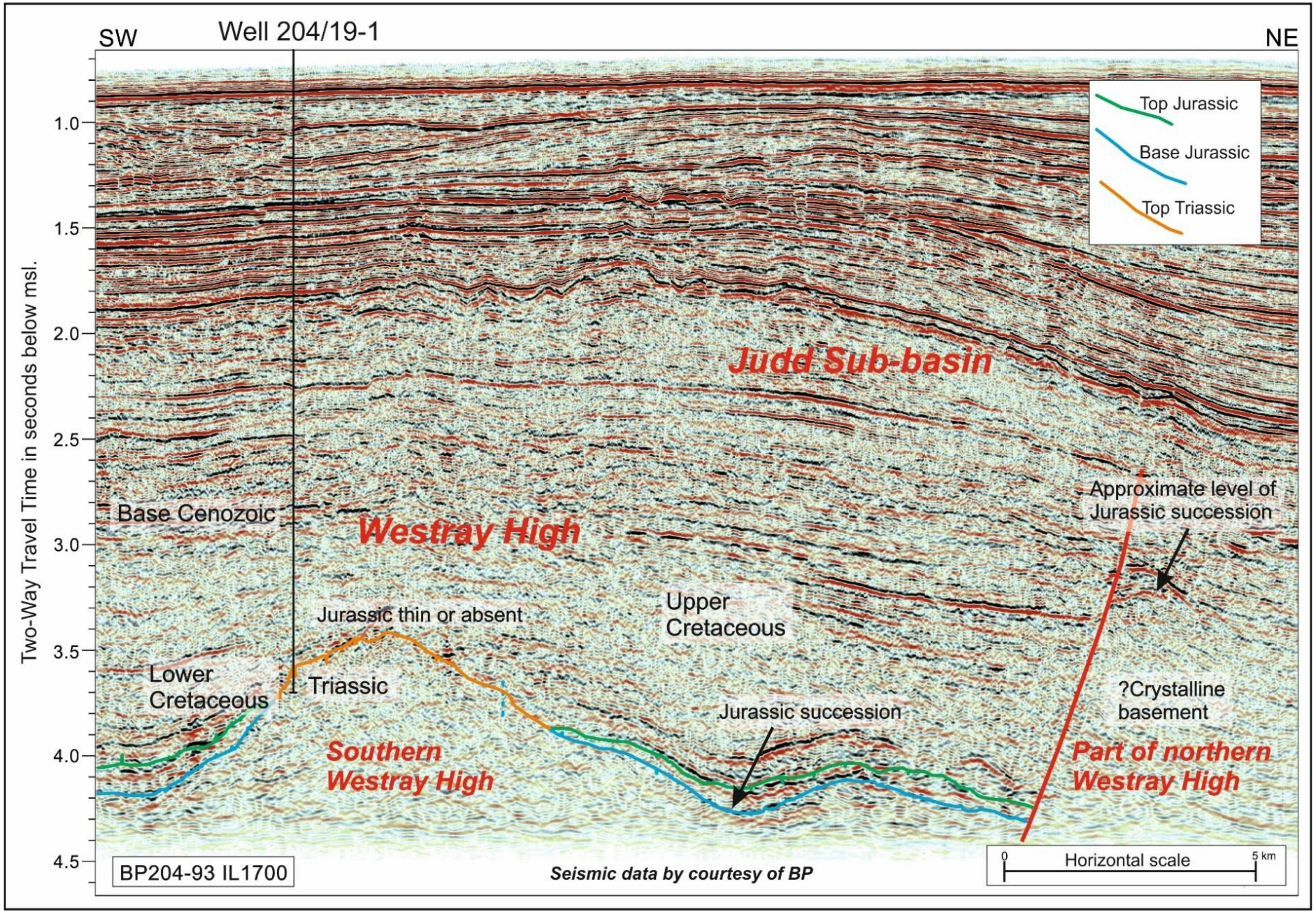

Figure 22. Westray High: NE-SW trending seismic section showing interpretation of Jurassic succession. Line location on Figure 17.

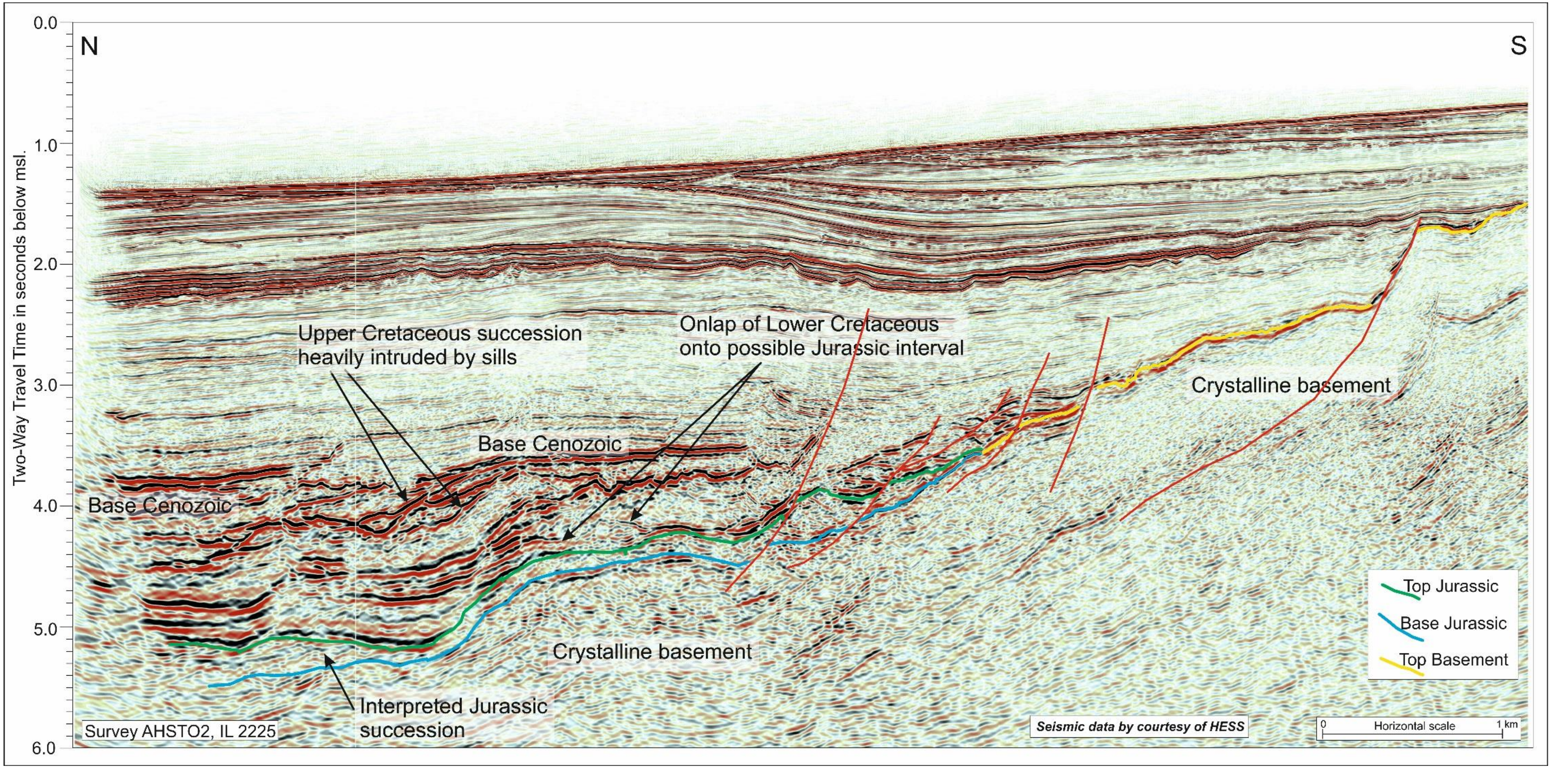

Figure 23. Judd Sub-basin: 3D seismic section showing interpretation of the Jurassic succession on the northern flank of the Judd High. Note numerous sill intrusions predominantly within the Cretaceous interval. Line location shown on Figure 17.

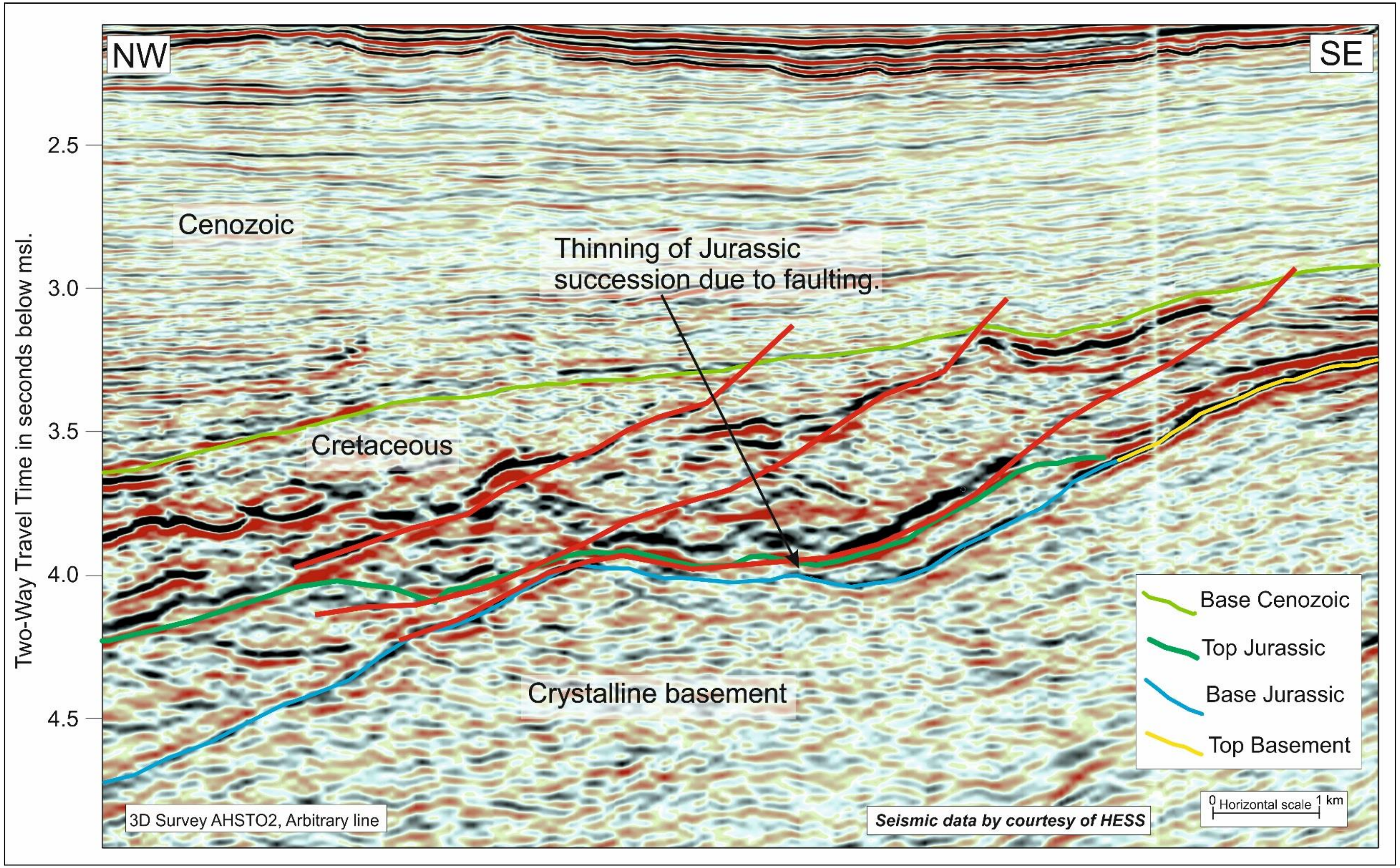

Figure 24. Judd Sub-basin: Arbitary NW-SE trending seismic section from 3D survey AHST02 showing interpretation of the Jurassic succession on the northern flank of the Judd High. Line location shown on Figure 17.

6 Conclusions

6.1 SEISMIC RESPONSE

- Top Jurassic boundary generally shows a decrease in impedance resulting in a negative or 'soft' reflection;
- Base Jurassic boundary generally shows an increase in impedance resulting in a positive or 'hard' reflection;
- Synthetic seismograms have helped in the understanding of the seismic response to the Jurassic succession;
- Preliminary amplitude extraction failed to produce anything meaningful but further investigation may prove useful.

6.2 THE JURASSIC SUCCESSION

The Lower Cretaceous, Upper Cretaceous or Cenozoic rests unconformably on Jurassic succession:

- Lower Cretaceous succession is observed to onlap the Jurassic in many places.

The Jurassic rests unconformably on Triassic sandstones or Lewisian basement:

- Interpretation suggests that the Jurassic in the marginal basins was deposited on an eroded Triassic/Lewisian surface with minimal syn-sedimentary fault activity and relief;

Total Jurassic thickness, recorded in wells, is generally less than 200 m over project area:

- The Kimmeridge Clay Formation is generally less than 100 m thick;
- Well 202/03a- 3 (West Solan Basin) reached total depth in the Lower Jurassic proving 794 m of Jurassic (770 m of this being Lower Jurassic).

Jurassic does not appear to thicken significantly adjacent to faults in the hanging wall, evidence suggests Upper Jurassic rifting not widespread, perhaps confined to specific faults/basins.

- Seismic mapping away from Well 205/22- 1A (SW Flett Sub-basin) provides evidence for the Rona High acting as a sediment source for fan deltas during early part of Upper Jurassic.
- West Solan Basin – the very thick (>1200 m) Lower Jurassic succession may be due to transtension on a NW-trending fault in E-W extensional regime that was prevalent during the Jurassic.
    - The Lower Jurassic succession in the West Solan Basin may be a remnant of widespread deposition during early Jurassic times followed by extensive erosion prior to Upper Jurassic deposition.

Questions arising from interpretation.

- Would equivalent thicknesses of Jurassic occur in hanging wall of NW-trending Judd Fault?
- Is Middle Jurassic absent in the area?
    - Middle Jurassic recorded in composite logs in the area, is generally interpreted as Upper Jurassic by Ritchie and Varming (2011). Ritchie and Varming (2011) did record an 'Undivided' Middle Jurassic succession in well 204/22-1; this is the only well in the study area that proves a potential Middle Jurassic succession.

- Is the Upper Jurassic thicker and more prevalent W and NW of the Westray High and Judd High and thinner and more patchy to SE?
    - Based on the limited mapping in the Judd Sub-basin north of the Judd High and west of the Westray High that interprets a thickening (northward) Jurassic succession.
    - The proven thin or absent occurrences of Jurassic east of the southern Westray High (where mappable).

6.3 IMPLICATIONS FOR HYDROCARBON EXPLORATION

- The Upper Jurassic, Kimmeridge Clay Formation source rock has been mapped over a large part of the study area.
    - In the Judd Sub-basin, where it is expected to be most deeply buried and mature, it has been mapped at more than 5.2 seconds TWTT. However, lack of seismic data available for this study and at the depth required to resolve the succession, meant that a detailed map could not be produced; the presence of KCF at even greater depths is expected. Upper Jurassic thicknesses have been mapped at more than 500 m.
    - The main KCF source kitchen for the existing Foinaven and Schiehallion hydrocarbon fields may be located to the west of the Westray High.
    - In the North Rona and Solan basins the Upper Jurassic reaches a maximum depth of around 3 seconds TWTT with thicknesses generally of 250 m or less.
- Well penetrations prove Jurassic sandstone/ seal couplets are present in the study area. Core descriptions have identified a range of reservoir quality sandstones.
    - Thickening of the Jurassic succession in the North Rona Basin between ENE-trending faults adjacent to the Solan Bank High provides greater potential for the presence of suitable reservoirs.
- The interpretation of the Jurassic on the northern flank of the Judd High forms an untested hydrocarbon play where Jurassic reservoir sands pinchout up-dip, are faulted and rotated, and are sourced down-dip by an thickening Upper Jurassic succession.

6.4 RECOMMENDATIONS FOR FUTURE WORK

- Focus on mapping structure and the Jurassic succession on the northern flank of the Judd High to evaluate the possible hydrocarbon play identified in this study.
- Investigate further using amplitude analysis to highlight variation within the Jurassic seismic package.
- Extend mapping of the Jurassic north-eastwards onto Corona High and Flett Sub-basin.
- Extend interpreted presence of Jurassic from northern flank of Judd High north-westwards into the Faroese sector.
- Herries et al. (1999) shows Late Jurassic isochron may indicate presence of Solan Sandstone where greater than ~50 ms TWTT;
    - compare % sand recorded in wells with the isochore generated by seismic interpretation - is isochore also related to sand presence

7 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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