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First results of studies on the separation of the Bowland-Hodder shale unit from coal mining activity in the East Midlands

Renewables, Energy Storage & Clean Coal Programme

BGS Commissioned Report CR/17/078

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/17/078

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Key words

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Foreword

This report is the published product of an initial appraisal by the British Geological Survey (BGS) of the separation distance of the Bowland-Hodder unit from the deepest coal mining in the East Midlands part of the Yorkshire-Nottinghamshire-Derbyshire coalfield.

Acknowledgements

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Summary

The British Geological Survey (BGS) has undertaken for the Oil and Gas Authority (OGA) an initial study in the East Midlands region on the separation distance between coal mining activity (worked Coal Measures of late Carboniferous, Westphalian age) and the (deeper) main shale resource (the Bowland-Hodder shale unit of late Dinantian to Namurian age). This work has focussed on the region in and around the two proposed IGas shale gas sites at Spring Road and Tinker Lane (the only two sites with planning consent at the time of this study). The area lies in the southern area of the Gainsborough Trough, a major Early Carboniferous depocentre controlled by a southerly dipping, down-to-the-south syndepositional normal fault some distance (~20 km) to the north of the area of interest and within which an important, thick sequence of shale beds were deposited.

This initial phase of work has been undertaken using the following datasets:

1. The Coal Authority's (CA) coal mine plans for the East Midlands and South Yorkshire region
2. A map of the top of Bowland-Hodder shale unit (noting that the industry may find deeper strata within the unit more prospective)
3. Non-exclusive 2D seismic reflection lines acquired across the region during various phases of hydrocarbon exploration (noting that the industry have detailed 3D seismic data not included in this study)
4. Released hydrocarbon exploration borehole information available from the UKOGL website and again drilled during the various phases of hydrocarbon exploration across the region

The principal aim was to use CA data in order to inform the OGA of a provisional view of the separation distance between potential shale activity and existing (historic) coal mining activity in the East Midlands area, before detail analysis is provided by the industry as part of an application for consent to activity. This would be in two phases:

1. Immediate requirement, to take one seismic line (e.g. UKOGL regional line) across the basin and populate it with a 'base of mine workings' line. This is to be used for public engagement purposes
2. Longer term, to undertake a more rigorous study to add a 'base mine workings' surface to the existing 3D model and hydrocarbons database

For the first stage, a map of the deepest coal has been calculated based upon mine plan data licensed from the CA and from which both the vertical distance to the top of the shale resource and also the lateral distance between mined coal and the IGas sites has been calculated. The vertical separation map illustrates that the minimum vertical separation (distance) between the two levels of interest is just over 310 m to the south of the study area, increasing to over 1300 m to the northwest of the study area.

The deepest mined coal map was then 'time-converted' using a regional velocity curve derived from boreholes across the coalfield area. In this way, the areas of mined coal can be displayed as a 'pick' on the 2D seismic lines acquired in the region and available to the study.

In the region of main interest, around the two proposed IGas sites, the mapping demonstrates the following:

- That in the ground between the Tinker Lane and Springs Road sites and to the west, these coals have been mined
- That no known coal mines exist immediately beneath either of the proposed IGas sites at Tinker Lane or Springs Road

- That the Tinker Lane site lies some 840 m away from the nearest mined coal levels, which lie to the N. To the south and east no areas of mined coal exist
- That the Springs Road site lies over 2700 m away from the nearest mined coal levels, which lie to the NW. No mined coal lies to the northeast, east, or southeast of the site.

1 Introduction

The British Geological Survey (BGS) has undertaken for the Oil and Gas Authority (OGA) an initial study in the East Midland region on the separation distance between coal mining activity (worked Coal Measures of late Carboniferous [Westphalian] age) and the (deeper) main shale resource, the Bowland-Hodder shale unit of Dinantian – Namurian age, which comprises the Hodder Mudstone Formation and the Bowland Shale Formation. In particular, this focuses on the region in and around the two proposed IGas shale gas sites at Springs Road and Tinker Lane in north Nottinghamshire and marginal southeastern parts of South Yorkshire (Figure 1). The area lies in the southern reaches of the Gainsborough Trough, a major early Carboniferous (Dinantian) depocentre (see below).

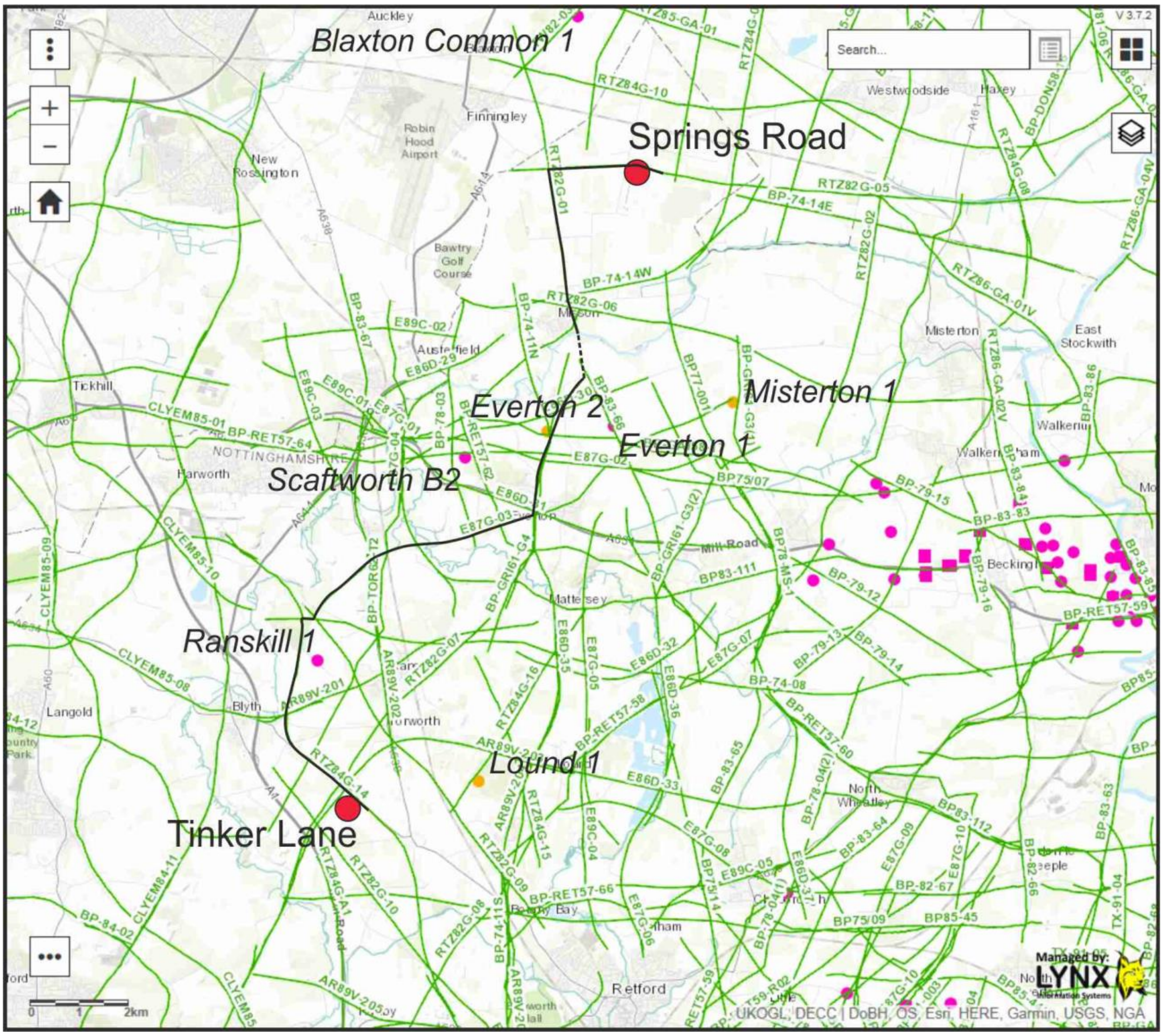

Figure 1. Location map for the two sites of interest (IGas's Tinker Lane and Springs Road sites: red circles) and the main hydrocarbon exploration boreholes (pink & orange dots, italicised) referred to in the study. Composite line location for Figure 11 &Figure 12 shown in black, with short jump-tie indicated by dashed line. Note the location of the Scaftworth B2 well, which is indicated on Figure 2. Figure adapted from UKOGL online map (https://ukogl.org.uk/).

1.1 STRUCTURAL AND STRATIGRAPHIC SETTING OF STUDY AREA

The area of interest lies within the Gainsborough Trough (GT), one of a number of major, narrow, fault bounded depocentres developed across central Britain during Dinantian and Namurian times (Figure 2; e.g. Fraser & Gawthorpe, 1990, 2003). The GT forms the northern of two main depocentres that comprise the East Midlands province, the other being the Widmerpool Gulf (Fraser & Gawthorpe, 1990, 2003). It developed as a generally northerly-tilted half graben, controlled to the north by the Askern-Spital Fault, a major southerly-dipping, normal down-to-the-south fault zone, across which a four-fold increase in the thickness of the Dinantian (EC1-EC6) is interpreted from regional seismic interpretations (Fraser & Gawthorpe, 2003).

The study area lies in the southern half of the GT, with the sequences thinner and shallower than further north, where they deepen and thicken into the Askern-Spital Fault zone. Within the GT up to 3000 m (10,000 ft) of the Bowland-Hodder shale unit are thought to have been deposited (Andrews, 2013). However, of the many wells drilled within the region, few reached sufficient depths to record more than 50 ft (15 m) of net shale in the Early Carboniferous section (Andrews, 2013), and within the main depocentre, Fraser & Gawthorpe (2003) report that no borehole penetrations exist below the top Dinantian (EC6).

Fraser & Gawthorpe (2003) describe the major control on the stratigraphy as being provided by the Grove-3 borehole (refer Figure 2) which, to the south of the area of study, penetrated a complete, but condensed, Dinantian section upon ?Charnian metamorphic basement on the southern flank of the half graben. To the east, boreholes in the Gainsborough-Beckingham Oilfield provide limited stratigraphic control, with the Gainsborough 2 borehole having penetrated through Permian sediments to the Upper Bowland Shale (Fraser & Gawthorpe, 1990, 2003; Vincent & Andrews, 2013).

Major rifting occurred in the Gainsborough Trough during EC1 (late Devonian-Courceyan) and EC3 (Arundian-early Holkerian) times, with both the EC1 and EC3 sequences exhibiting classic wedge-shaped geometries, typical of syn-rift sedimentation (Fraser & Gawthorpe, 2003).

The overlying Silesian (Namurian and Westphalian) sequences were deposited during a period of generally post-rift subsidence during which active faulting was much reduced. Namurian strata show thickening into the GT, which is attributed to three processes (Fraser & Gawthorpe, 2003):

(i) the infill of existing pre-Namurian bathymetry remaining from syn-rift faulting

(ii) differential compaction

(iii) localized Namurian tectonic activity

The earliest Namurian sediments in the half graben were organic-rich mudstones, deposited in relatively deep water, which at the end Dinantian in the centre of the basin is estimated to have been 300 m deep (Steele, 1988). The subsequent fill of the basin has been one of progressive advance of the Kinderscout, Ashover and Chatsworth-Crawshaw shallower water delta systems which infilled the trough from the north (Steele 1988). This culminated in the deposition of extensive coal deposits in the Westphalian, which on seismic reflection data, are represented by packages of strong, laterally continuous, high amplitude reflections (see Figure 11 & Figure 12).

Mild reactivation of extensional faults occurred in some areas of the basin during late Namurian times, particularly in the eastern Gainsborough Trough, with footwall unconformities generated and thick sandstones deposited in the hangingwall (Rough Rock and equivalent). Westphalian strata represent deposition during the latter stages of the post-rift subsidence phase, although localized inversion also took place along the Askern-Spital and Nettleham Faults, forming the West Firsby, Glentworth, Nettleham and Welton oilfields and local unconformities (Fraser & Gawthorpe, 1990, 2003).

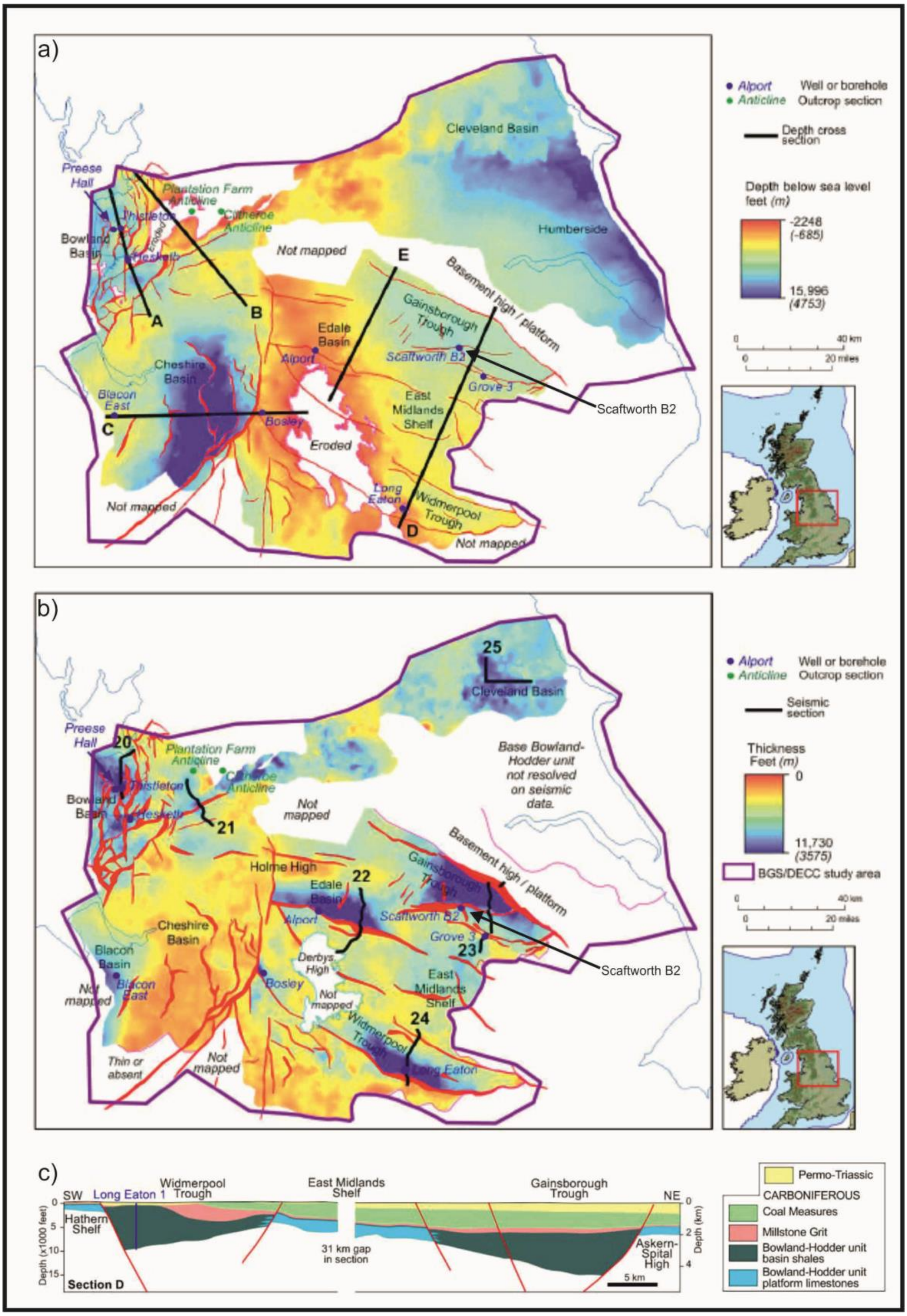

Figure 2. General maps of the main Carboniferous basins in central Britain, development of the Bowland-Hodder shale unit and cross section of Gainsborough and Edale basins, showing basin architecture (compiled from Andrews, 2013). Note: Scaftworth B2 well within the area of interest is highlighted for locational purposes (refer Figure 1). a) Depth (ft) to the top of the Bowland-Hodder unit, central Britain, b) thickness (ft) of the Bowland-Hodder unit, central Britain, c) generalised depth cross-section across the Gainsborough Trough and Edale Basin (for location, refer part [a]).

1.2 COAL MINING AND AVAILABLE DATA

This study has been undertaken by licensing the Coal Authority's (CA) mined coal database (Figure 3), referencing the Bowland-Hodder shale model (Andrews, 2013) and also interpretation of selected non-exclusive regional 2D seismic lines of varying vintage, and acquired for hydrocarbon exploration across the region.

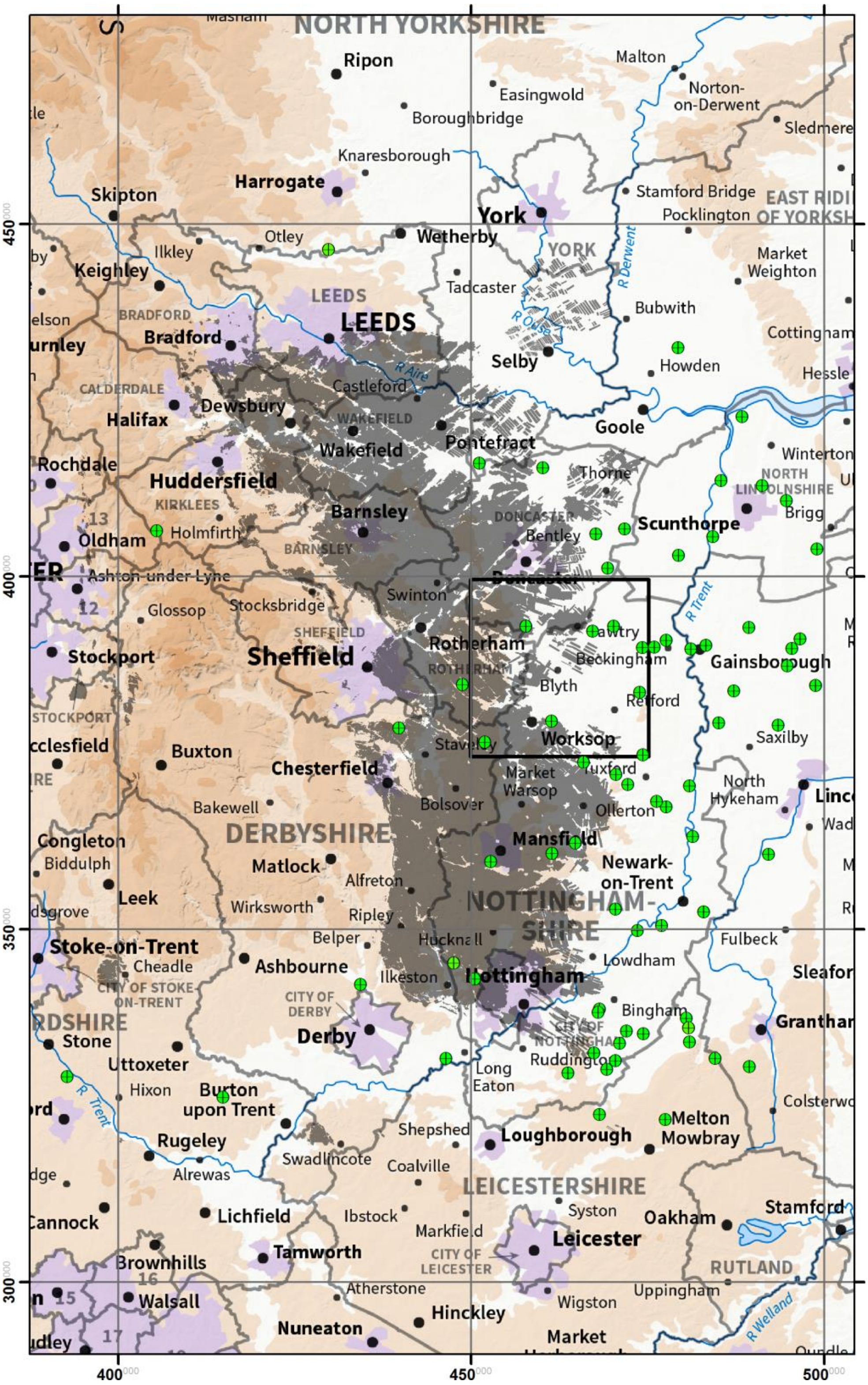

Figure 3. Map illustrating in grey the extent of underground workings in the East Midlands and South Yorkshire coalfields. Green circles show the location of boreholes used to establish the regional relationship between depth and two-way time. The black rectangle shows the extent of the detailed view in Figure 6.

From the CA's database, the main coals mined in this region include (with increasing age [based upon Howard et al., 2009]; Figure 4 & Figure 5):

- Top Hard/Barnsley (Middle Coal Measures, Westphalian B)
- Swallow Wood (Middle Coal Measures, Westphalian B)
- Haigh Moor (Middle Coal Measures, Westphalian B)
- Deep Soft (Lower Coal Measures, Westphalian A)

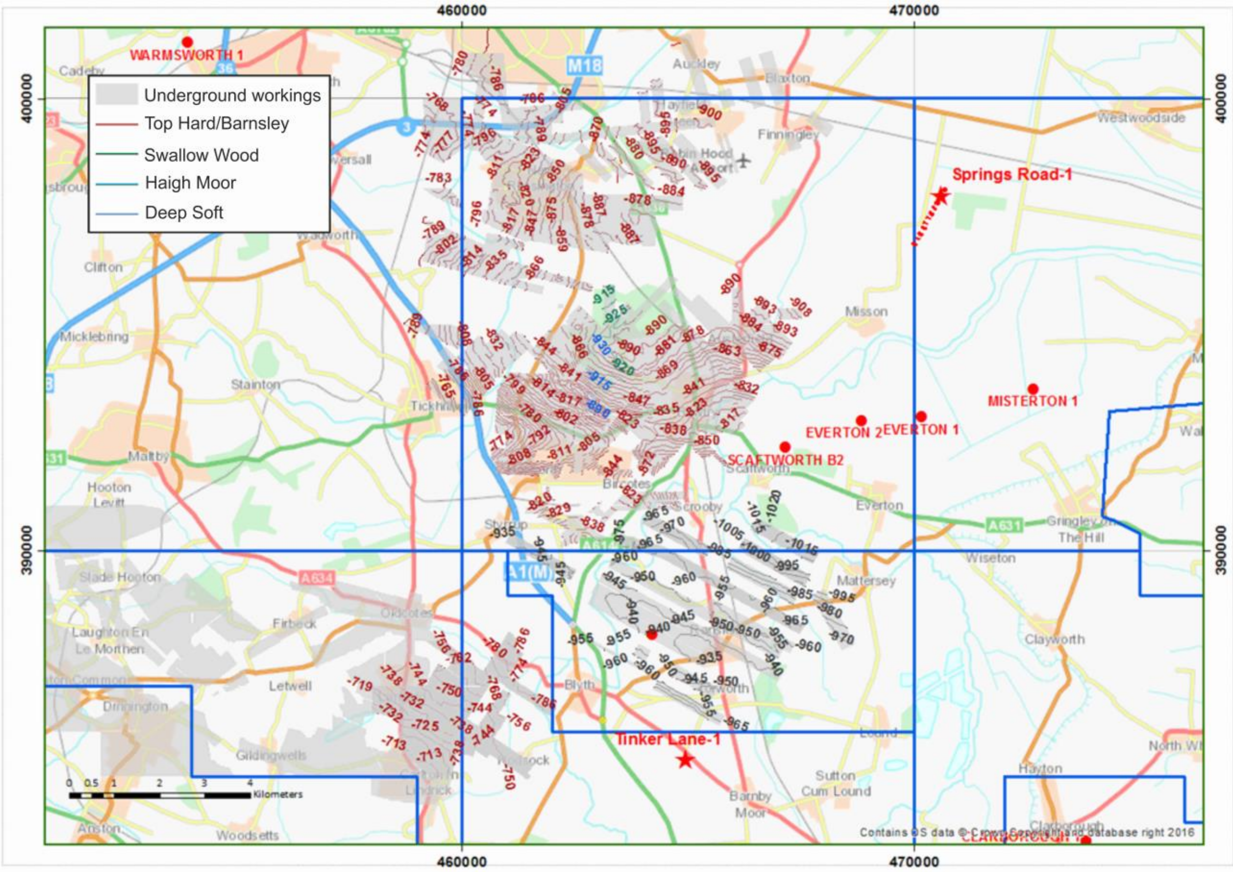

Figure 4. Extracted CA coal mine information on worked coals and their ages between and in the region of the two IGas sites of interest.

Figure 4 illustrates that:

- in the ground between the Tinker Lane and Springs Road sites, these coals have been mined
- mined coal levels do not lie immediately beneath either of the proposed sites at Tinker Lane or Springs Road
- the Tinker Lane site lies some 700-800 m away from the nearest mined coal levels, which lie to the N. To the south and east no mined coal exists.
- the Springs Road site lies over 1700 m away from the nearest mined coal levels, which lie to the SW. No mined coal lies to the north, south or east of the site.

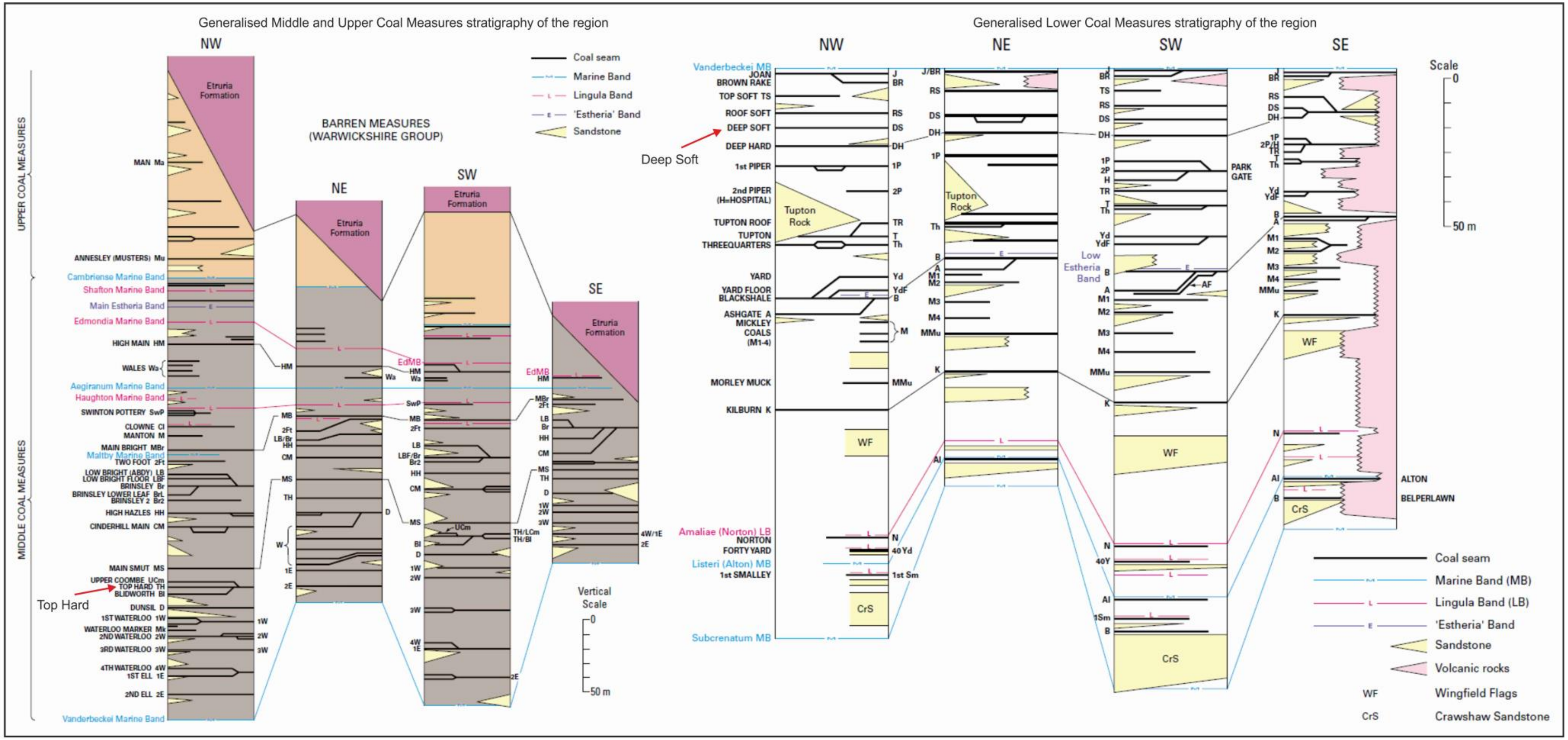

Figure 5. Generalised stratigraphy of the north Nottinghamshire Lower to Upper Coal Measures (from Howard et al., 2009). The Top Hard and Deep Soft coal seams are indicated. The Swallow Wood and Haigh Moor coal seams are of early Westphalian B age and lie between the Top Hard and Deep Soft coal seams, being roughly equivalent to the Waterloo series of seams.

2 Calculation of the deepest mapped mine workings and separation distances to shale resource

As outlined above, the principal aim was to map the base of (deepest) mined existing (historic) coal mining activity in the East Midlands area. This was made possible through the licensing of the Coal Authority's (CA) detailed mine data (Figure 3), which contains information relating to the depths and extents of worked coal seams and shafts sunk for exploration or access purposes.

2.1 CONSTRUCTION OF THE MAP OF DEEPEST MINED COAL AND EXTENT

The available CA data on the extent and depth of underground workings were in the form of a 3-D shapefile containing the limits of all underground workings for the East Midlands/Derbyshire/South Yorkshire coalfields (Figure 3 & Figure 6). The data are divided into 2 km by 1 km rectangles (Figure 6), so that the boundary of each polygon in the shapefile represents either the extent of underground workings or a map sheet boundary. Individual seams are distinguished by a unique code given to every polygon. At a given location within the coalfields there may be several seams stacked at various depths - the problem considered in this work being to generate a regional map of the lowest (deepest) workings from these outline data.

The approach adopted in this study was to bin the data on a regular grid, taking the lowest value in each binning cell and assigning it to the coordinates of the centre of the cell. The dimension of the binning cell was chosen so that each cell could be guaranteed to intersect at least one of the individual outline polygons, and because of the rectilinear structure of the data this value was chosen as 1 km. This set of minimum values was then imported into GOCAD, where a surface mesh was calculated before being converted to a grid and exported. The exported grid was then converted to a suitable format and imported into ArcGIS for further processing.

It should be noted that if the available data were different (for example, contour data were available on each seam) then the binning cell size could be adjusted accordingly.

In terms of alternative approaches to the problem, the 'gold standard' would be to generate a surface model for each worked seam and to find the lowest workings at a given point by interrogation of the individual surface models at that location. The main factor that militates against this is that the large number of individual seams (c. 180) makes the method impractical, although obviously it is in principle possible

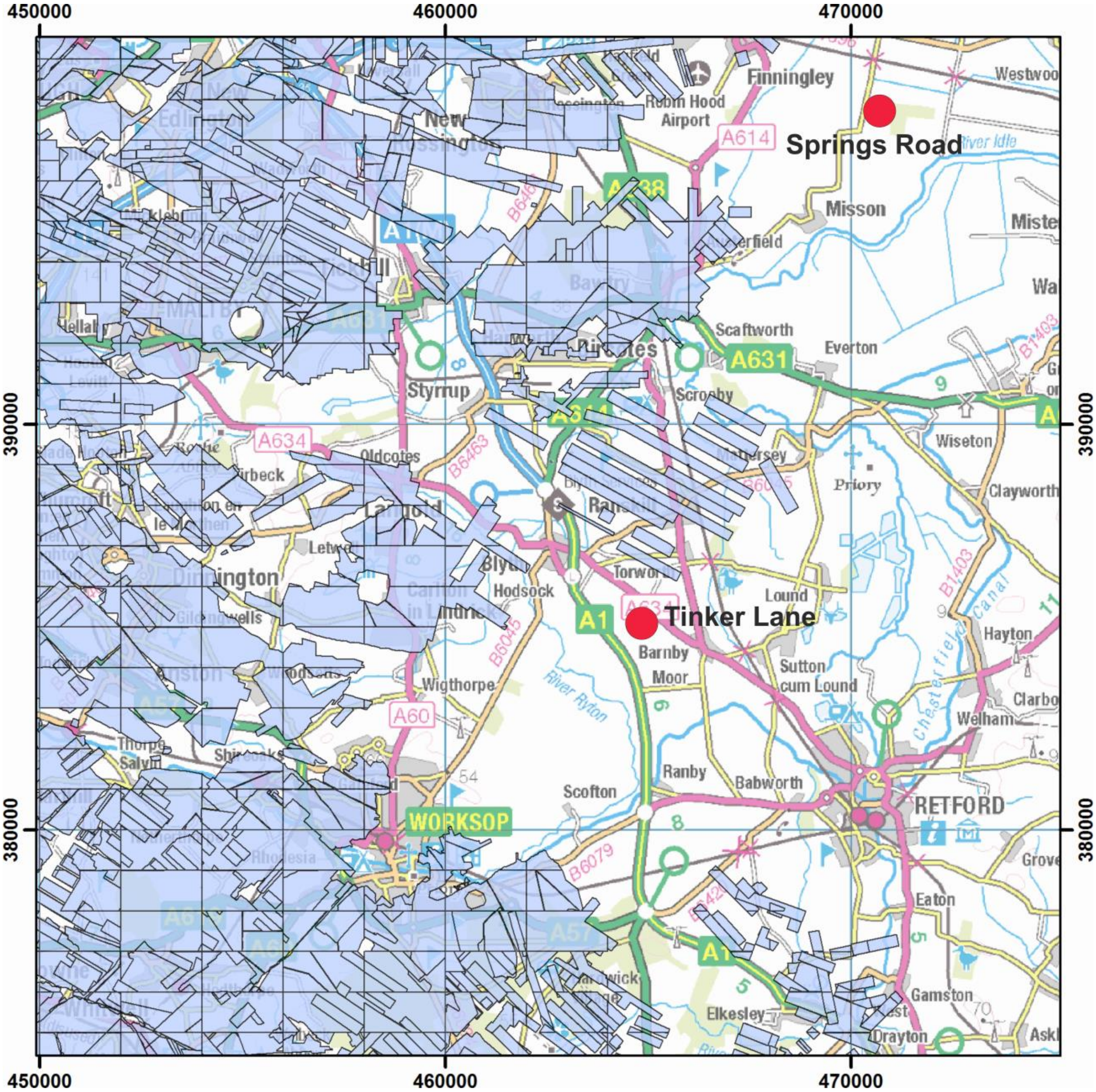

Figure 6. Detail of the underground workings around Blyth, showing the division of the data into 2 km by 1 km rectangles. The relatively confused pattern of polygons is due to the superposition of polygons representing seams at different depth-levels and the rectilinear (2 x 1 km) structure of the data. The location of the two IGas sites of interest are also indicated.

2.2 DEPTH TO TIME CONVERSION

Most legacy and many modern seismic lines are displayed in two-way time travel time (TWTT; below OD) and not depth – exceptions are modern 3D surveys where pre- and post-stack depth migration may be performed, with the output seismic line/data displayed with a depth scale (although results may be stretched back to time to enable comparison with time migrations). During most seismic workstation-based interpretations, borehole information in depth (well formation tops and geophysical logs) is routinely displayed in TWTT. This is achieved where time/depth information is available (from checkshot or VSP surveys) and can convert depth to the time domain, permitting geophysical logs to be displayed on the seismic section during interpretation.

One aim of the Phase 1 work was to display the worked coal levels (in depth below OD) on seismic lines, which are in TWTT. Compared to borehole data, conversion of surfaces in the depth domain to display in the TWTT domain is less frequently undertaken, if at all, and for this study the same time/depth data were used to convert the depth map.

The depth to time conversion was performed by means of deriving a regional curve based upon a crossplot method (Figure 7), using TWTT-depth pairs for all the horizons provided from released wells available from UKOGL (https://ukogl.org.uk/). The crossplot reveals a good overall quadratic relationship between TWTT and depth, although it is evident that a few wells deviate significantly from the regional trend: Ilkeston-1 (green), Weeton-1 (magenta) and Redmile-2 (orange) in Figure 7. The three wells are, however, included in the analysis at this stage as they do not significantly affect the calculated trend. The fitted relationship between TWTT in seconds and depth in metres below OD is calculated as:

$$TWT = c_0 + c_1 d + c_2 d^2$$

Where $c_0 = 2.152757 \times 10^{-2}$, $c_1 = 6.889833 \times 10^{-4}$ and $c_2 = -6.496722 \times 10^{-8}$

Application of this relationship to the depth surface for base of mined coal yielded a time surface that could be imported into seismic interpretation software for display alongside the seismic lines (refer Section 3 and discussions therein).

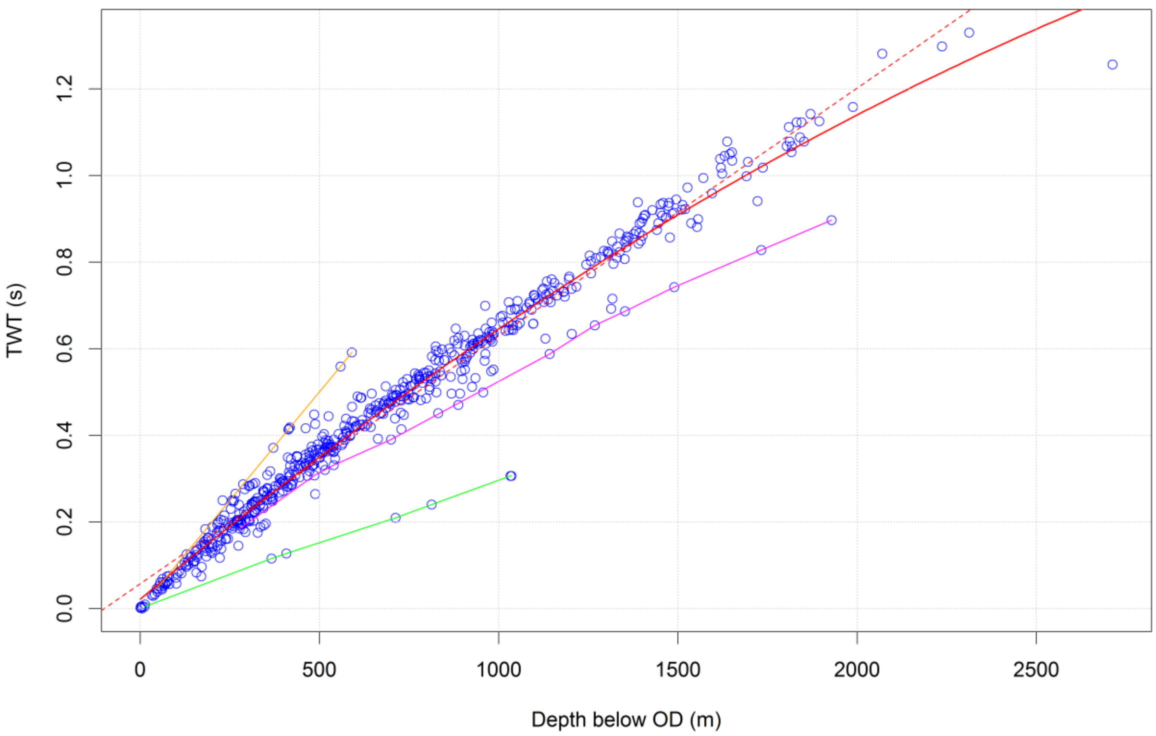

Figure 7. Regional relationship between two-way time (TWT) and depth below OD for wells in the study area. The solid red line illustrates a quadratic trend fitted by least-squares, while for comparison the dashed red line shows the corresponding linear trend. Also shown are curves for three wells that deviate significantly from the regional trend: Ilkeston-1 (green), Weeton-1 (magenta) and Redmile-2 (orange).

2.3 DEEPEST MINED COAL AND SEPARATION BETWEEN MINING AND THE BOWLAND-HODDER SHALE UNIT

The main aim of Phase I of the work was to establish and map the deepest mined coals (including shafts) in the region of the two IGas sites of interest and establish the proximity of mining to the sites. This has been completed as summarised in Figure 8.

Further aims of the Phase I work were to determine the vertical separation distances of deepest mined coal and the Bowland-Hodder shale unit, and the lateral separation distance between the IGas sites and mined coals.

A depth map of the top of the Bowland-Hodder unit is given in Andrews (2013), which is shown in Figure 9 for the area of interest. With the new mapping of the deepest mined coal and the shale resource maps for the region, it is now possible to estimate the separation distances (Figure 10).

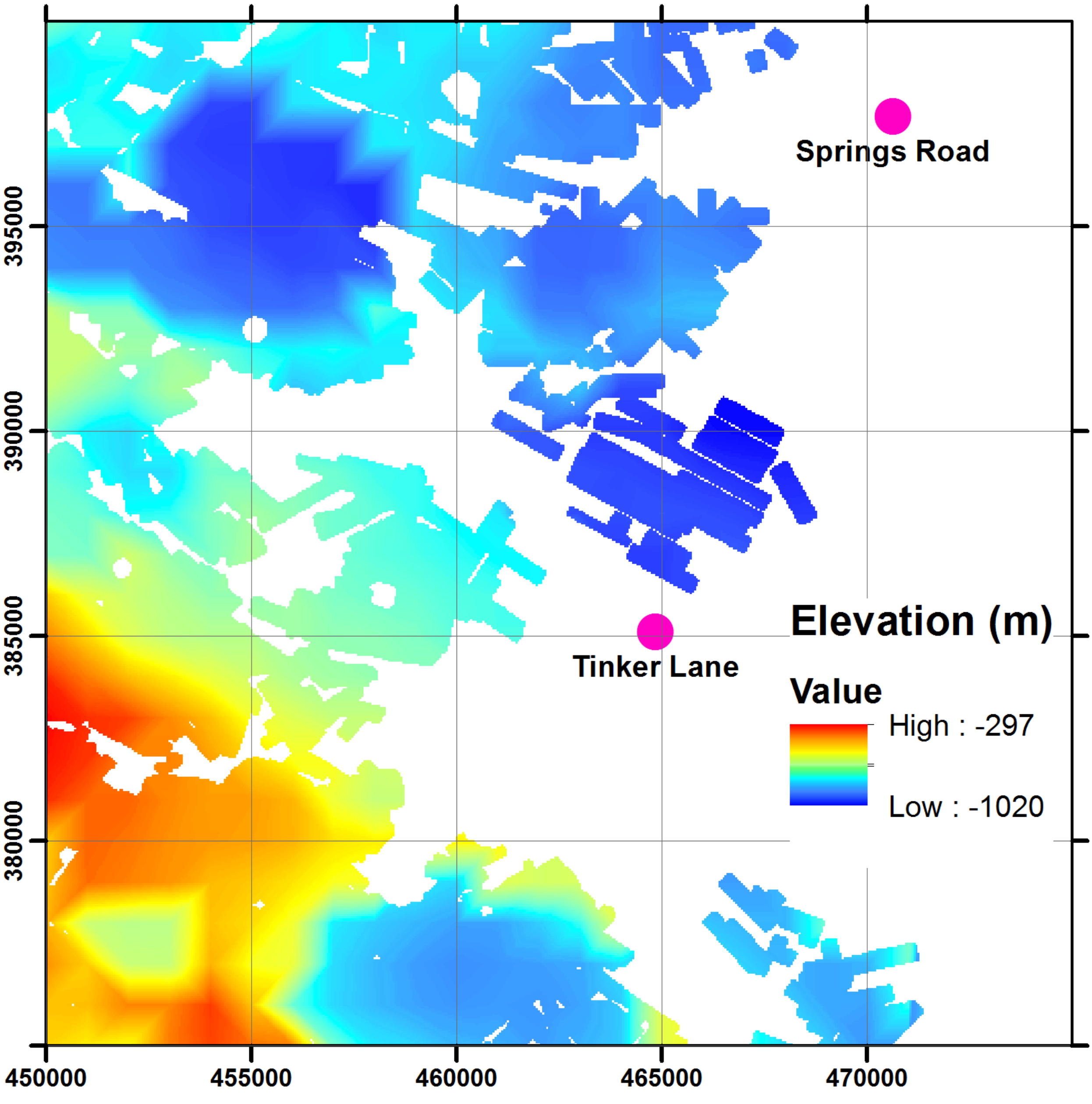

Figure 8. Map of the deepest mined coals (including shafts) in the region of the two IGas sites of interest. Depths in metres below OD and derived from CA mine plan data.

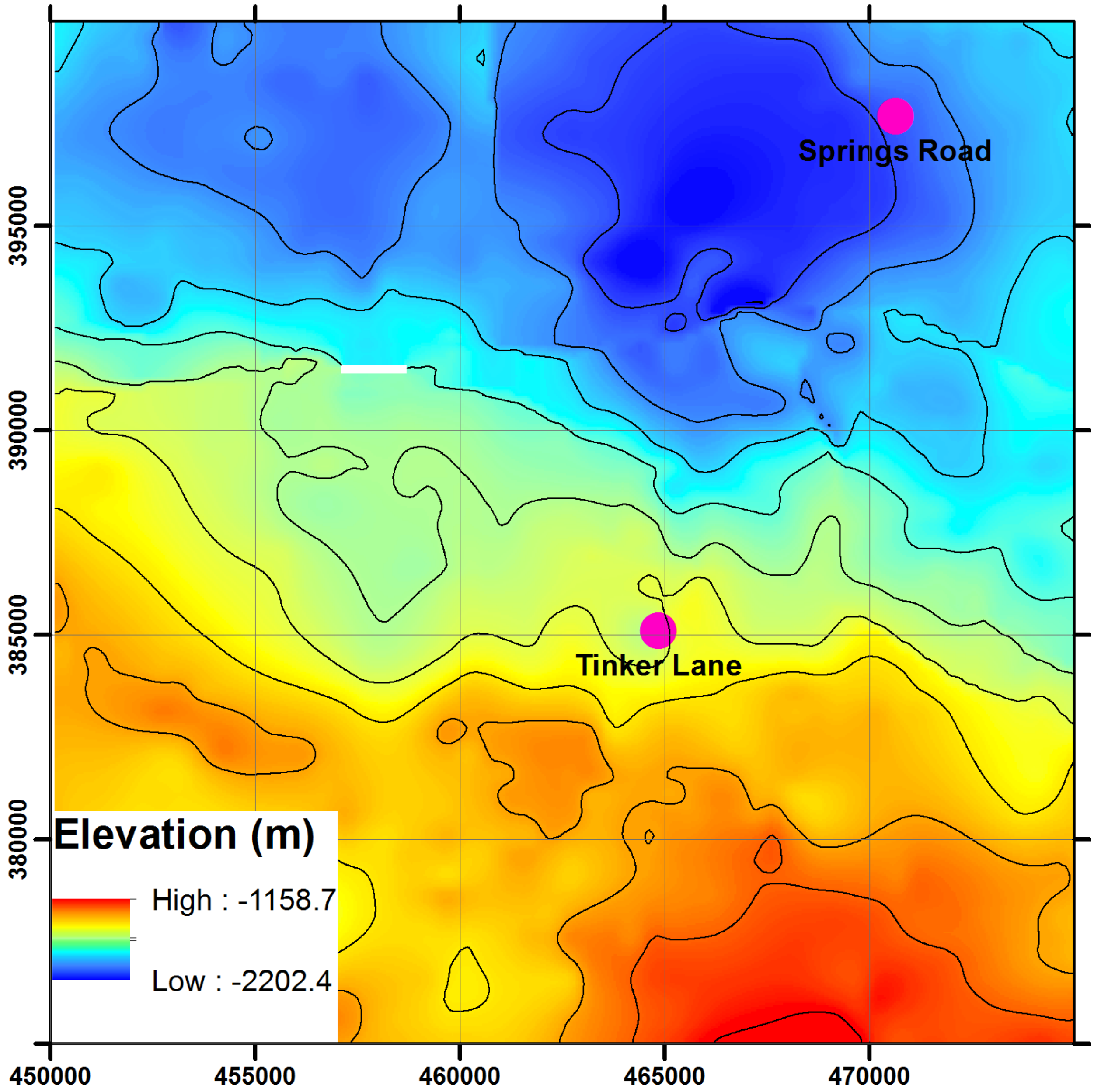

Figure 9 Map of the top of the Bowland-Hodder unit in the vicinity of the two IGas sites of interest, extracted from Andrews (2013). Elevations are in metres relative to OD and contours are at 100 m intervals. The top of the unit is seen to deepen by about a kilometre from the south to the north.

2.3.1 Vertical separation distances

The vertical separation has here been calculated by the subtraction of the gridded surface for top Bowland-Hodder shale unit (Figure 9) from the gridded base mined coal surface (Figure 8).

The new mapping demonstrates that in addition to the lateral separation (offset of mined areas and IGas sites), significant vertical separation of at least 300 m (~170 ms TWTT) exists between the deepest mined levels and the Bowland-Hodder shale unit (Figure 10). The smallest separation distances of around 300 m exist in the south of the area and they increase to the north to over 1300 m, west of the Springs Lane site.

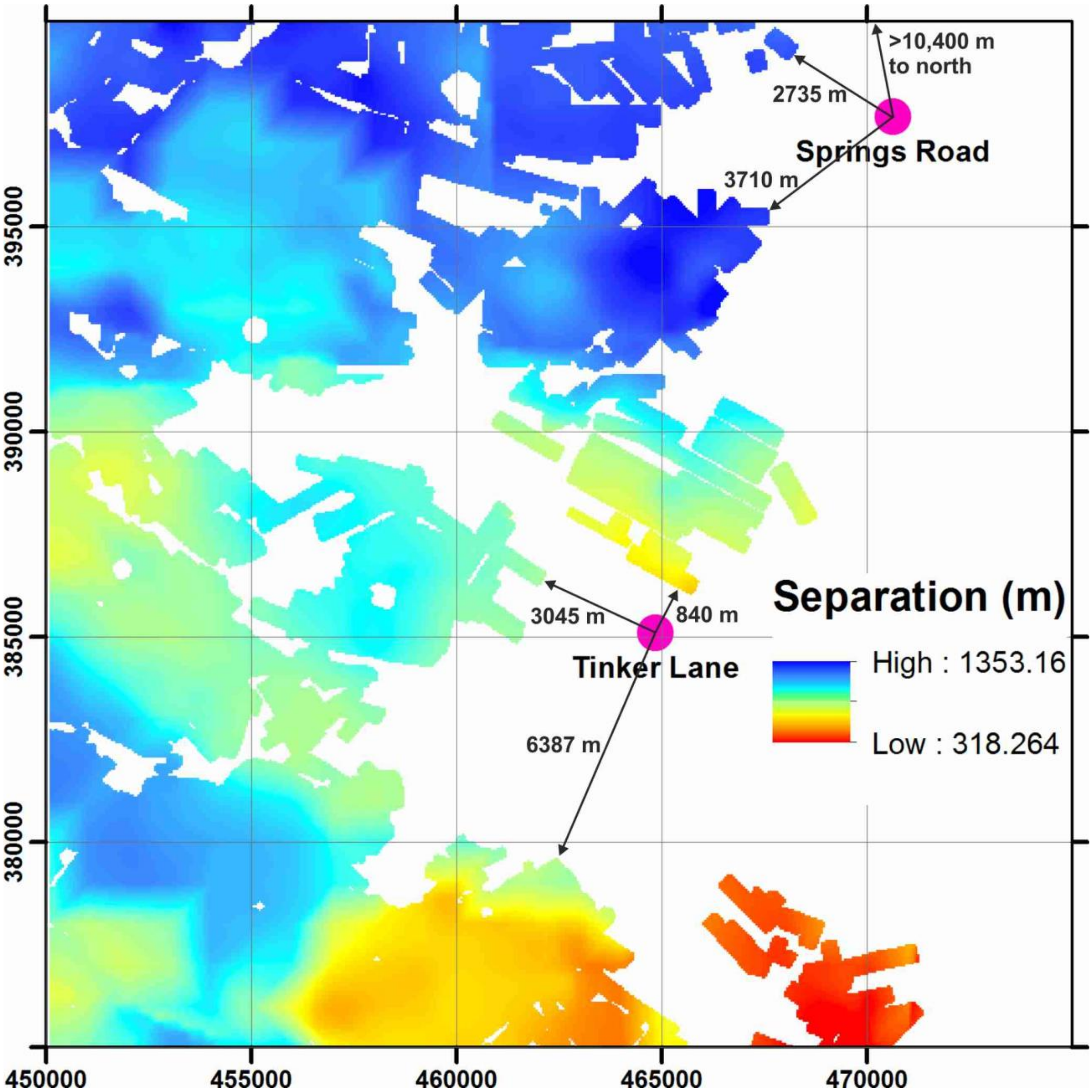

Figure 10. Map of the vertical and lateral separation distance between deepest mined coal and the Bowland-Hodder shale unit in the vicinity of the proposed IGas well sites at Tinker Lane and Spring Road. The smallest vertical separation distances exist in the south of the area (~300 m) and increase northwards (to over 1300 m), to just west of the Springs Lane site.

2.3.2 Lateral separation distances

The lateral separation distances have been calculated simply by measuring the horizontal distance from the IGas site to the edge of mined coals (Figure 10). The distances do not represent that direct from site at surface to the edge of mining in the subsurface.

As illustrated in Figure 10, the Tinker Lane site in the south has a minimum horizontal separation of around 840 m with mined coals to the north of the site. Other separations vary up to more than 6.5 kms to the south and southwest. There are no mined coals to the east and southeast of the site.

The nearest mined coals to the Springs Road site lie around 2.7 kms to the NW, but others vary between 3.7 kms and 5 kms. The closest mined coal to the north is in excess of 10.4 kms and no mined coals are known to the east or southeast of the site.

3 The seismic interpretation

A rapid, limited, seismic interpretation has been undertaken to produce a composite seismic reflection line that illustrates the general structural setting and stratigraphical relationships existing between the two IGas sites (Tinker Lane in the south and Spring Road in the north: Figure 1). The seismic interpretation was based upon non-exclusive 2D hydrocarbon exploration lines of varying vintage (1982-1987), obtained from UKOGL. It was constructed using the following 2D seismic lines and just north of the Everton #1 borehole, includes a jump-tie of circa 1 km between lines:

- RTZ84G-14 (south end)
- E87G-03
- E86D-35

---(jump tie)---

- RTZ82G-01
- RTZ82G-05 (north end)

A number of hydrocarbon exploration boreholes with time/depth data were also available and used to calibrate the seismic lines in the region of interest. Those used in this study and within 1500 m of the composite line are (Figure 1):

- Ranskill 1
- Scaftworth B2
- Everton 1
- Lound 1

Across the region, many other boreholes are available for the generation of a regional velocity curve with which to depth/time convert various data, including the maps of depth to deepest mined coal/shaft and the top and base of the Bowland-Hodder shale unit.

The seismic lines were obtained in digital format from UKOGL and loaded to a seismic workstation running the Petrel seismic interpretation software. Boreholes and their well top information close to the area of interest were loaded to the workstation to provide calibration of, and assist interpretation of, the seismic lines.

For the purposes of this study, the following seismic picks were carried on the composite line and its component lines (Figure 11 & Figure 12):

- Top Zechstein
- Base Permo-Triassic/Top Westphalian C/D
- Top Westphalian B
- Top Westphalian A
- Top Namurian
- Top Dinantian limestone (approx.)
- Base Dinantian/Top Caledonian Basement (approx.)

Also displayed as ‘picks’ are the maps of the deepest mined coal and the top and base Bowland-Hodder unit surfaces of Andrews (2013). As indicated above, in order to display as ‘picks’ in Petrel and thereby display alongside the seismic picks carried on the composite seismic line (refer Figure 11 & Figure 12), these maps were converted to time using depth-TWTT curves from local wells only – there was no curve generated from the wells across the region and penetrating these intervals. The time surfaces were then loaded to Petrel.

Two versions of the interpreted line are presented:

1. One in which the key borehole and stratigraphical data and seismic picks are included (Figure 11)
2. A simplified version in which the main geological units/intervals are shown as block filled colour, with the majority of the detail shown in Figure 11 is omitted (Figure 12)

In terms of the composite line, running generally N-S, the deepest mined coal (‘white picks’ in Figure 11 & Figure 12) is only crossed over the southern end of the line, where strata appear largely unfaulted at these levels. The top and base Bowland-Hodder unit surfaces of Andrews (2013) are laterally more extensive, relative to the composite line, and were re-interpreted around faults that were interpreted/identified during the current study.

The composite seismic line shows the general structure within the Gainsborough Trough (GT). Stratigraphic calibration is provided by the Ranskill #1, Scaftworth B2 and Everton #1 boreholes (Figure 11). The boreholes provide excellent calibration of the seismic line down to Top Namurian levels, beneath which the boreholes provide little stratigraphic control. Hence the tentative nature of the top Dinantian and Base Carboniferous picks at this stage, for which there are no deep borehole provings in the area of study, or more widely in the Gainsborough Trough (Fraser & Gawthorpe, 2003), and that are currently based on experience gained in adjacent areas.

The base Carboniferous is poorly imaged and constrained. It is currently interpreted between ~2000 and perhaps 2700 ms on the northern end of the line. This is in part based on other interpretations (e.g. Fraser & Gawthorpe, 2003; Andrews, 2013) in which it is around 2.3 to 2.5 seconds in similar areas of the basin. It could be that the base Carboniferous is somewhat shallower, being nearer some laterally continuous reflective energy at around 2300 ms on the northern end of the line. As noted above, however, there are currently no boreholes proving the base Carboniferous in the main GT depocentre. Should the base Carboniferous be shallower, then it could impact the shale volume and resource estimates.

The composite seismic line does not reach the northern basin bounding, down-to-the-south fault, which is offline to the north and also delineates the southern margin of the Askern-Spital High (Fraser & Gawthorpe, 2003). The seismic line reveals a generally northerly thickening Namurian succession overlain by a more uniform Westphalian succession. Major variations in the thickness of the Dinantian succession are evident. This thickening is associated with intra-basinal, generally down-to-the-south, Dinantian syndepositional normal faults that apparently formed smaller sub-basins and into which the sequences thicken. During the later stages of this faulting, up to 3000 m (10,000 ft) of the lower part of the Bowland-Hodder Formation is thought to have been deposited (Andrews, 2013).

Figure 11 & Figure 12 also include the base of deepest mined coal (white pick), which as alluded to above, plots around the top of the Westphalian A pick (green pick). Given the regional velocity model this is an extremely good fit, providing confidence in the process of seismic interpretation and depth/time conversion.

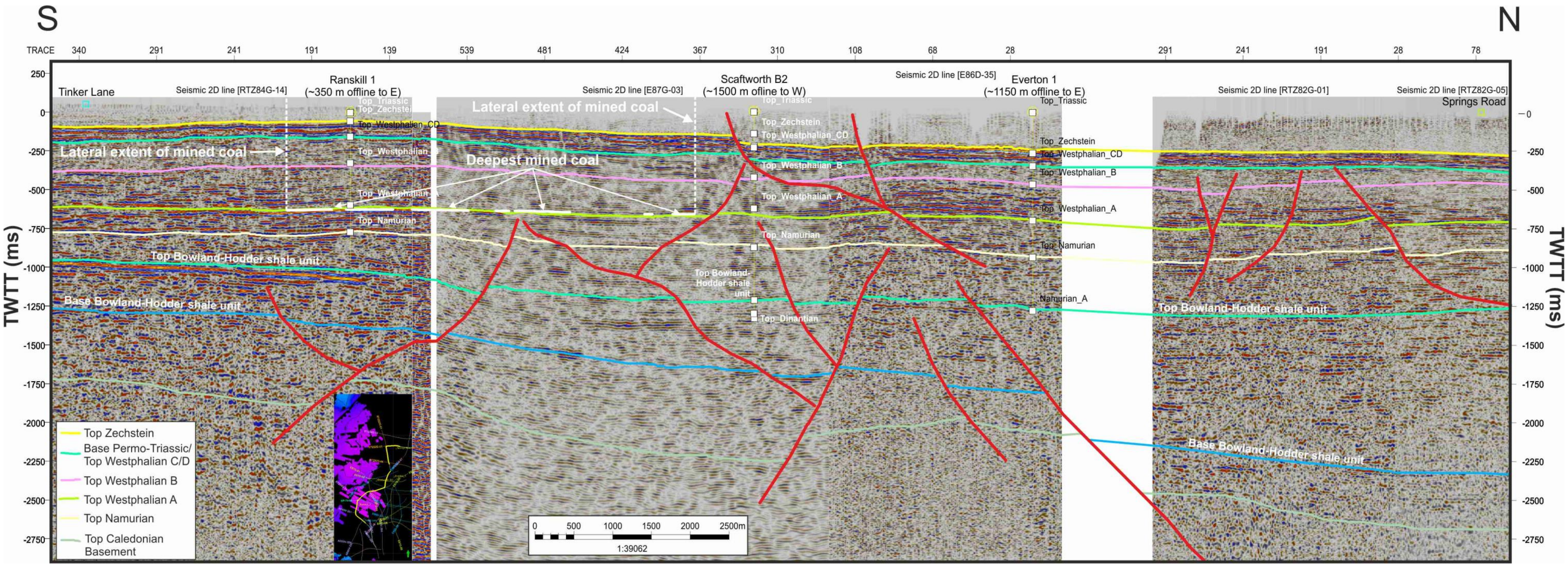

Figure 11. Interpreted composite S-N seismic line between the two proposed IGas sites (insert map shows composite line location, highlighted in yellow). Also shown are the areas of deepest worked coal (shaded blue-purple on inset map) and a projection onto the seismic line of the mine levels (white 'picks') converted from depth too time, using a regional velocity model, based on the time/depth data in the available boreholes. In general the line crosses and lies within the Gainsborough Trough, a major Carboniferous depocentre, within which up to 3000 m of Bowland-Hodder shale unit was deposited (Andrews, 2013).

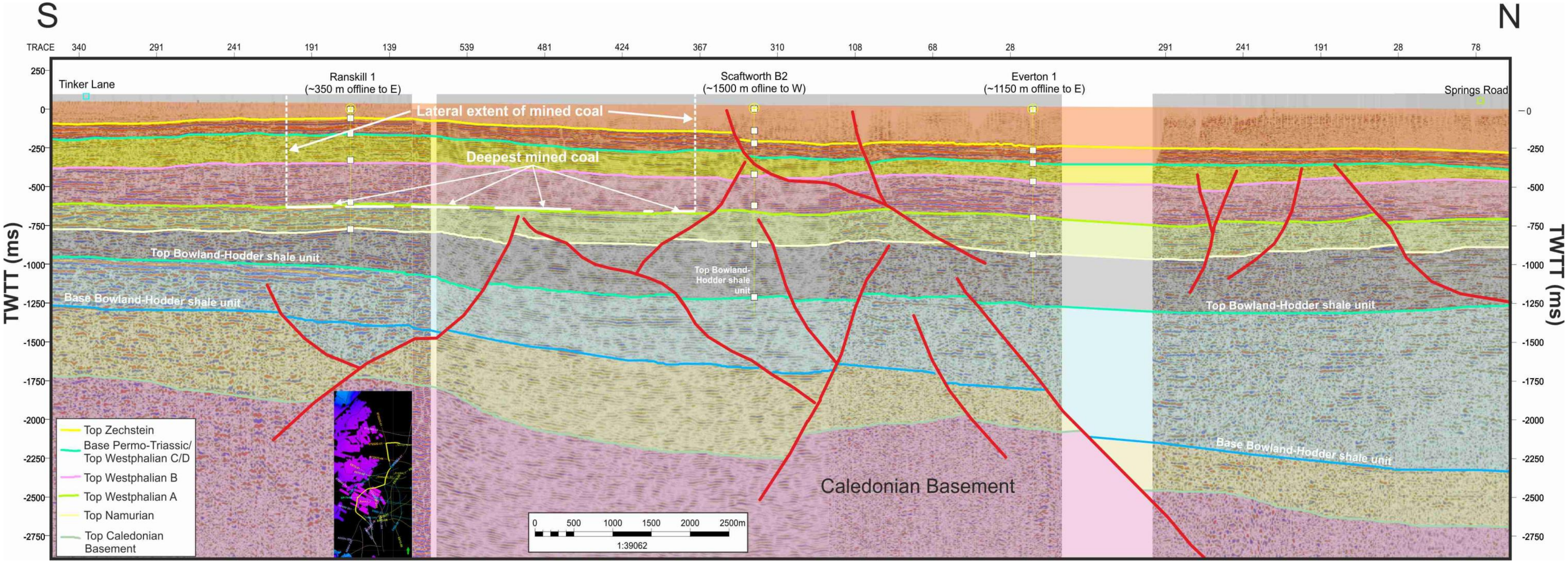

Figure 12. Simplified interpreted composite S-N seismic line between the two proposed IGas sites (insert map shows composite line location, highlighted in yellow). Also shown are the areas of deepest worked coal (shaded blue-purple on inset map) and a projection onto the seismic line of the mine levels (white 'picks') converted from depth too time, using a regional velocity model, based on the time/depth data in the available boreholes. The line shows the main geological subdivisions. In general the line crosses and lies within the Gainsborough Trough, a major Carboniferous depocentre, within which up to 3000 m of Bowland-Hodder shale unit was deposited (Andrews, 2013).

4 Conclusions and future work

Phase 1 of the work has delivered a map of the deepest mined coal across the Yorkshire-Nottinghamshire-Derbyshire Coalfield and in particular, the East Midlands area of the Nottinghamshire Coalfield. This has been derived from licensed Coal Authority data on mined coal levels and modelled in GoCAD.

From these data, an isopach map representing the interval between the top of the Bowland-Hodder shale unit and base of the deepest mined coal level (including shafts) has been calculated – the vertical separation distance. This shows the minimum vertical distance to be around 300 m in the south, with a maximum distance of over 1300 m towards the north. The main minimum lateral separations with respect to the mined coals near the two sites are seen to be ~800 m and ~2735 m for the proposed sites at Tinker Lane or Springs Road respectively.

The map of deepest mined coal has been converted to two-way-travel-time (TWTT) in order to permit displaying as if a seismic pick on 2D seismic lines across the area. In this way, display of the depth map on seismic lines alongside the seismic picks is possible, where the vertical axis is in time. It provides not only regional context to the mined-coal areas and the major structures that controlled Carboniferous and basin development and sediment distribution, but also an appreciation of the lateral and vertical offset of the mined coal levels and the top of the Bowland-Hodder shale unit. The deepest mined coal levels plot in the region of the Top Westphalian A pick, which at this stage and based on only a regional velocity model, illustrates an excellent correlation between the seismic picks for the tops of Westphalian A and B and the ages of the mined coals (late Westphalian A and early-mid Westphalian B in age).

The time-converted top Bowland-Hodder unit, given the relatively poor well control, shows close correlation with that of the near top Dinantian limestone pick. This suggests the regional model for the Bowland-Hodder unit is robust and of good accuracy.

The accuracy of time-converted base Bowland-Hodder unit is less easily assessed. At present, the base of the unit is deep. However, it may be shallower, but well data in the current study did not permit accurate determination of the base Carboniferous, nor the base mudstone unit. If shallower, then the Bowland-Hodder unit would be thinner and thus impact any shale resource calculations. Any future work (Phase II) should aim to make an assessment of the veracity of the current base Bowland-Hodder unit (and thus thickness) and interpretation of base Carboniferous a priority. This could be achieved by extending the seismic interpretation further from the area of immediate interest in Phase I, to include seismic lines that tie deep boreholes and for which time-depth data were acquired. However, it is noted that Fraser & Gawthorpe (2003) state that within the depocentre no borehole penetrations below the top Dinantian (EC6; Early to mid-Brigantian [late Dinantian]) exist. Such a study would permit an assessment and/or revision of the current volume of shale resource estimates, not only in the immediate area of interest, but also regionally.

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