"Paucity of legacy oil and gas subsurface data onshore United Kingdom: implications for the expansion of low carbon subsurface activities and technologies"

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Running title: Legacy subsurface data onshore UK

Abstract

The decarbonisation of energy systems to achieve net zero carbon emissions will likely see the rapid development of carbon capture and storage, energy storage in the subsurface and geothermal energy projects. Subsurface data such as seismic reflection surveys and borehole data are vital for geoscientists and engineers to carry out comprehensive assessments of both the opportunities and risks for these developments. Here, for the first time, legacy subsurface data from onshore oil and gas exploration in the UK is collated and analysed. We provide a description of the spatial coverage and a chronology of the acquisition of key seismic reflection and borehole data, as well as examine data resolution and limitations. We discuss the implications of spatial variability in subsurface datasets and the associated subsurface uncertainty. This variability is vitally important to understanding the suitability of data for decision making. We examine societal aspects of data uncertainty and discuss that when the same data are used to communicate subsurface uncertainty and risk, the source of the data should also be considered, especially where data is not easily publicly accessible. Understanding the provenance of data is vitally important for future geoenergy activities and public confidence in subsurface activities.

Keywords: data, geoenergy, onshore geology, subsurface, uncertainty, geostatistics, public perception

Achieving a transition to net zero carbon emissions from energy systems is one of the most pressing challenges facing society globally (Rogelj et al. 2015). The UK government has set a legally binding target to reduce greenhouse gas emissions to net zero by 2050 (see Climate Change Act 2008), which to achieve will require decarbonising both industrial and residential energy systems (e.g. Broad et al. 2020; Cooper and Hammond 2018). There will likely be a need for subsurface activities, whether as part of industrial clusters and the development of carbon capture and storage (CCS) (e.g.Alcalde et al. 2019) or as part of decentralised energy systems and the use of geothermal energy (Lloyd 2018). The exploration and production of shale gas has raised concerns not only about the compatibility with low carbon energy systems and mitigating climate change (Partridge et al. 2017) but also the ability to predict the subsurface as a result of induced seismicity (Bommer et al. 2015). A fundamental question regarding the use of the subsurface for future decarbonisation pathways is whether there is enough suitable data to assess the potential contribution and impact of subsurface activities and their role in a net zero future.

Data are fundamental to understanding the risk and uncertainties associated with subsurface activities (e.g. Baker et al. 1999; Bles et al. 2019; Ross 2004). Subsurface data are used by geoscientists, environmental scientists and engineers to carry out comprehensive assessments of the resource or storage potential as well assessing the risks from the activities. Informed decisions come from the analysis, interpretations and modelling of such data. Characterising subsurface uncertainties is a vital part of risk management, covering operational safety, environmental and economic risks, as well as being key to characterising any resource potential. Society is increasingly concerned with the environmental risks and impacts of subsurface activities (van Os et al. 2016) which can have a direct impact on communities, for example as the result of induced seismicity (van der Voort and Vanclay 2015), subsidence (Franks et al. 2010), environmental pollution (O'Rourke and Connolly 2003), health (Holdren et al. 2000) and rapid changes to community life (Schafft et al. 2013). These local impacts also have broader consequences for both the public and the industries involved, for example protests or project delays (Bradshaw and Waite 2017; Short and Szolucha 2019). As a result of the increased scrutiny with which subsurface activities have come under, the need for effective communication is becoming increasingly vital to ensuring that geoscientific know-how reaches all those involved and impacted (Stewart and Gill 2017; van der Bles et al. 2019). This comes at a time where the UK’s (and the world’s) ambition to decarbonise energy systems could, despite the predicted shift from fossil fuels to new, lower carbon energy sources, require subsurface activities at significant industrial scale (e.g. Stephenson et al. 2019). This study is the first synthesis of the legacy oil and gas subsurface datasets from onshore UK, with the purpose of providing an unbiased view of the implications for future geoenergy activities using examples for geothermal and unconventional hydrocarbons.

In communicating subsurface risks, experts often discuss the degrees of uncertainty inherent in subsurface characterisation, however this is often without considering the target audience. Importantly, it has been shown that when experts avoid (or deny) discussing the uncertainties as part of public communication that it can drive distrust in science and organisations (e.g. Frewer et al. 2003; Sjöberg 1998). One suggested mechanism to improve risk communication is to focus on ‘what is being done to reduce the uncertainty’ (Frewer et al. 2002). Nascent activities, such as the recent introduction of hydraulic fracturing for shale gas in the UK, may as a result of their relative immature deployment, be associated with greater uncertainty, particularly regarding the extent of for example resources or potentially negative effects. What may have been an acceptable level of uncertainty and risk in the past, is no longer socially perceived as acceptable and, as argued by Beck et al. (1993), that disasters (or the highest impact events) shape perceptions of risk. The introduction of new subsurface activities, such as hydraulic fracturing and the development of CCS, may, due to their immature development be initially associated with greater uncertainty, particularly regarding how far their potentially negative effects extend within the subsurface (Krause et al. 2014). To describe uncertainty requires a recognition that the knowledge is limited, that “known unknowns” are identified, and acknowledging that there may also be “unknown unknowns” (Pérez-Díaz et al. 2020). Quantifying uncertainty makes it possible to analyse how interpretations might differ from reality (Pérez-Díaz et al. 2020). In this context it is useful to define data. Ackoff (1989) defines data as symbols that represent properties of objects, events and their environment, and are the products of observation. The Data, Information, Knowledge, Wisdom (DIKW) model which Ackoff (1989) described can be applied to subsurface data and information (Figure 1). It is worth noting that the differentiation between data and information is somewhat subjective in many areas of geosciences, specifically with respect to geophysical or remote sensing data, where processing of the data is required to enable a geological interpretation or analysis. **Table 1** provides a summary of typical subsurface data, information and knowledge sources. The accuracy of any subsurface interpretation or analysis is dependent on the quantity and quality of data available, but equally important is the public perception and trust in the evidence (Wallquist et al. 2012), as opposed to the uncertainty. There now exists a need to consider, not only the data required for businesses and regulators to make decisions on resources and safety, but also the public perceptions and trust in these data and whether the data is sufficient to describe the likelihood of an activity impacting local communities and society.

This study considers the onshore UK and describes the characteristics of legacy oil and gas subsurface datasets. These datasets typically investigate the deep subsurface, which in UK legislation is defined as any land at a depth of at least 300 metres below surface level (The Infrastructure Act, 2015). This study provides the first synthesis of these datasets and includes examples of why data resolution and quality are also an important consideration for future geoenergy activities and public confidence in subsurface activities.

Subsurface UK data

The geology of the onshore UK contains a geological record all the way back to the Archean, and includes a history of subduction zones, volcanic arcs, continental rifts and mountain belts (Woodcock and Strachan 2012). While extensive geological mapping of the UK dates back to the 19th century and is summarised in the now famous map by William Smith (Smith 1815), it was not until 1918 that the first deep oil and gas well was drilled, Hardstoft-1 in Derbyshire, to a depth of ~950m (Morton 2014). In the period preceding the Second World War (1939), there were a number of early seismic reflection experiments by the then Anglo-Iranian Oil Company (Jones 1937). However, it was not until after the war and the 1950s that geophysical data acquisition began in earnest for oil, gas and coal exploration. Since these early investigations, seismic reflection surveys have become the primary subsurface geophysical method employed for oil and gas exploration. Onshore UK both the acquisition of seismic reflection data, and the drilling of deep boreholes continued, with the late 1980s being the peak of onshore seismic data acquisition (see section Seismic Reflection for details). Much of the current understanding of the subsurface onshore the UK comes the data that has been acquired by the oil and gas industry. While undoubtedly this data has advanced our understanding of the geology in the UK, there has been little consideration in the literature of the implications of the source of this data for public trust and perceptions of risk. This study focuses on the coverage of both seismic reflection surveys and boreholes, as well as the characteristics of the data. The data included in this study are those held by the UK Onshore Geophysics Library (UKOGL), the British Geological Survey (BGS), and the Oil and Gas Authority (OGA), the sources of which are listed in **Table 1**. Detailed description of the data can be found in subsequent sections, but as an overview, there are ~76 136km of 2D seismic reflection data, ~2400km^2 of 3D seismic reflection data and 2242 oil and gas exploration boreholes. While the publicly available OGA borehole dataset contains records for 2242 wells (not including wells completed in 2018 and 2019), the UKOGL borehole records also include deep wells from other activities such as coal mining. There is no single consolidated record of all onshore boreholes, therefore the present analysis has used records from the BGS, OGA and UKOGL to provide a comprehensive view. Throughout this study the term "borehole" is used to refer to both shallow and deep wells or wells where total vertical depth (TVD) is not specified. For the BGS Geothermal Catalogue, the data had to be digitised into a tabulated format from the scanned PDF file format available directly through NERC. The location of data is specified either to 10 m or 100 m. In addition, there is no unique common well identifier that allows the data in the catalogue to be matched spatially with the BGS Borehole Records.

Where comparisons have been made to the offshore areas of the UK Continental Shelf, the data used was the "Surveys as Consented 2D", which is available from the OGA National Data Repository. For the comparisons made with data from the Netherlands, the data is from NLOG, which is manged by the Geological Survey of the Netherlands on behalf of the Ministry of Economic Affairs and Climate.

Methodology

This study describes the spatial distribution and characteristics of data available from the BGS, OGA and UKOGL **(Table 2)**. It used primarily geological and geophysical data collected for oil and gas exploration and production. Geological parameters and concepts are often not directly observed or measured, but interpreted from these data (Pérez-Díaz et al. 2020), In this context, this study considered data to be measurements in wells, and post-stack seismic reflection data **(see Table 1)**.

Spatial Statistics

Using geostatistical techniques (quadrant analysis, point density, average nearest neighbour, and global Moran's I), the extent and distribution of geospatial subsurface data have been quantified. The results of this analysis have then been assessed in terms of the possible impact on subsequent interpretation and analysis. All spatial statistics were computed in ArcMap 10.6.1. The quadrant analysis point density and total line length was computed for a given area of 10km by 10km area (area of 100km^2). While for individual well locations point density was used, for the BGS Geothermal Catalogue, where individual wells have more than one measurement, a quadrant analysis was used. For spatial statistics, the P-value is used to assess if there is spatial pattern among the features and therefore the probability that the observed spatial pattern was random. A small P-value is indicative of a low probability that the observed spatial pattern is the result of random processes. The Z-values are standard deviations, for example for a value of 2.5 the result is 2.5 standard deviations. The study has differentiated between shallow and deep wells based on true vertical depth (TVD), a deep well being defined as one completed to a depth >300m.

These statistics have then been used to asses the distribution of the legacy data and discuss the suitability of for future use of the subsurface, specifically geothermal and unconventional hydrocarbon extraction. The coverage of both well and seismic reflection data have been analysed with respect to the domestic and non-domestic heat demand to assess the data available for geothermal resource characterisation in demand hot spots. The study has used heat demand data for the year 2009 from Taylor et al. (2014). The original data is annual heat demand provided at a 1km by 1km resolution and in units of kWh/km^2. In this study, the data data were reduced, using an aggregated mean, to a 5km by 5km resolution to simplify the boundaries of heat demand, and then converted to MWh/km^2. These data have been used to compare areas of heat demand to the distribution of subsurface data.

Quantitative Analysis of Seismic Reflection Data

Given the recent controversy surrounding the extraction of unconventional hydrocarbon resources (Williams et al. 2017), and the differing interpretations reported in both peer-reviewed literature (Anderson and Underhill 2020) and other reports published (Cuadrilla 2019), this study has carried out an analysis of the post-stack characteristics of 3D seismic reflection data from across the Craven Basin in Lancashire (Figure 2), the area where shale gas hydraulic fracturing activities were carried out between 2011 and 2019. The study describes the characteristics of the seismic data that relate to the ability to interpret geological features, for example faults, and analysed the frequency content and how this relates to the vertical and horizontal resolution of data. As part of this analysis the bandwidth and acquisition parameters have been evaluated and described for the first time. A trapezoidal Ormsby filter, was used to filter frequencies content of the data to give an indication of how reflector continuity is related to the dominant frequency of the data. The frequency content of both the original and filtered datasets was analysed using SeisLab 3.0 (Rietsch 2020).

Data Analysis

Well Data

There are 1 335 511 boreholes onshore the UK as recorded in the BGS Borehole Records, with the depth of investigation varying from just a few meters to >3000 m **(Figure 3b)**. In the BGS borehole records 334 757 boreholes have no details on depth and most of them (851 963) are to a depth <30m. A further 136 650 boreholes investigate a depth range between 30 and 500m. A histogram of the oil and gas exploration wells by depth from the UKOGL database shows that >70% penetrate less than 1000m TVD **(Figure 3b)**. There are 2885 wells deeper than 500m, which include both oil and gas exploration and production wells and other deep boreholes. The OGA dataset includes only 2242 wells. There is a difference of 643 between the UKOGL data and the OGA records which reflects that only those specifically identified as oil and gas exploration and production boreholes are included in the OGA records, while the UKOGL includes other deep boreholes. Oil and gas exploration and production boreholes account for less than 1% of all the boreholes drilled in the UK. The spatial density of the shallow boreholes between 30 and 500m onshore the UK can be seen in **Figure 4**. Despite there being in excess of 1 million boreholes, there are areas of the UK where there are no boreholes, notably west Wales and Scotland. **Figure 5** shows a series of spatial point density maps for deep boreholes using data provided by UKOGL. The deepest onshore well drilled in the UK is the Seal Sands No. 1 well, drilled to a total depth of 4169 m TVD (Johnson et al. 2011). The mean depth of a drilled oil and gas borehole is 1152m. Of these boreholes only ~151 wells, extend deeper than 2000m TVD, and just 13 deeper than 3000m. Spatially, these are not distributed equally across the onshore of the UK. Nearly all the deep wells, because of being drilled for hydrocarbon exploration and production are in either the Carboniferous Basins of Northern England and Midlands, or the Mesozoic Basins of Southern England.

For the wells in UKOGL database, nearest neighbour analysis estimates a Z-score of -82.77, indicating that the data are clustered and there is a less than 1% likelihood that this clustered pattern is random. Global Moran's I analysis, indicates that wells are clustered with respect to depth, with a Z-score of 53.57, and less than 1% likelihood that the clustering is random. A histogram of wells drilled onshore the UK by year shows that over ~70% of the onshore wells in the UK were drilled prior to 1990. Since 3D seismic reflection data acquisition onshore UK did not start until the 1990s, that means that all these wells were drilled based on 2D seismic reflection data. As would be expected there is a spatial coincidence of both boreholes and seismic reflection data. A total of 644 boreholes are co-located with 3D seismic reflection data, and 1578 wells located within 100m of a 2D seismic reflection line.

Core and downhole log data

The BGS maintain a database of over 10 000 onshore borehole samples, which comprises a range of materials including core, core samples, individual hand specimens, bulk samples, unwashed cuttings, washed and dried cuttings, plugs, powders and bulk samples, including those collected as part of onshore oil and gas exploration and production borehole drilling. The relative spatial density of these data can be seen in **Figure 6a**. This database can be searched online. The BGS hold an archive of digital geophysical downhole log data from boreholes distributed across the UK. Basic well information, such as location and spud and completion date, is also held by UKOGL, but access to digital log data is through formal release agents. There is no single record of all downhole logs onshore UK. The BGS hold a record of ~5963 wells with digital geophysical logs, which includes both oil and gas exploration wells and other boreholes including mine gas and coal bed methane wells. The spatial density of these data is shown in **Figure 6b**. In addition to the BGS records of geophysical logs, well data is available through the OGA's appointed data release agents, who hold an inventory of digital log data for onshore wells. However, the type of data available and the quality vary from well to well and the exact nature and number of wells is a commercial product.

Temperature data

The BGS Geothermal Catalogue is a published compilation of temperature and heat flow measurements from across the onshore UK. **Figure 7a** shows the location of individual wells with temperature measurements and **Figure 7b** shows the number of temperature measurements in a 10km by 10km quadrant. Average nearest neighbour analysis returns an observed mean distance of 1668m compared with an expected mean distance of 9538m. This returns a nearest neighbour ratio of 0.1879, with Z-score of -60.31 and less than 1% likelihood that this is random indicating that the data are strongly clustered. Global Moran's I analysis, indicates that location of temperature measurements are clustered with respect to depth, with a Z-score of 35.303, and less than 1% likelihood that the clustering is random. As well as spatial clustering, the measurements of temperature in the boreholes are also over a limited depth range. As described by Rollin (1995), there are ~2600 temperatures at over 1150 sites.

Of these, geothermal gradients are estimated in the dataset for ~1700 measurements. Over 90% of the temperature data are from depths less than 2000m and ~27% are from a depth shallower than 500m (**Figure 8a).** These data indicate that less than 10% of the measurements were made at depths greater than 2km. **Figure 8b** is a plot of temperature and depth. While the dominant trend is one of increasing temperature with depth, there is no simple relationship. These temperatures in the catalogue are used to estimate geothermal gradients using a modified air surface temperature. These estimates of geothermal gradient were not used in this study, as the method of determining land surface temperature is an oversimplification an not accurate without correction. There are only 116 temperature measurements from depths greater than 2000m. There is a very significant vertical sampling bias, as well as the spatial bias shown in **Figure 8a**.

An analysis of the distribution of the temperature data with respect to the domestic and non-domestic heat demand in the UK (Taylor et al. 2014) finds 141 of the measurements (~8%) are within high heat demand areas. **Table 3** lists the four largest areas with a heat demand >10 000 MWh/km^2 and the associated deep data associated with each area. **Figures 9a-d** are maps of London, Birmingham, Manchester and Glasgow with the location of temperature measurements plotted, as well as the location of deep well and 2D and 3D seismic reflection surveys over the same geographical areas. In some heat demand hot spots there are multiple temperature measurements, and in some cases, these are across multiple wells. However, there are areas of high heat demand with no temperature measurements in the database, for example the Leeds and the Greater Manchester area. The deep wells in the UKOGL dataset may have temperature data which is not currently captured in the BGS Geothermal Catalogue. Across the areas of highest heat demand identified in **Table 3** there are 79 deep wells across the Greater Manchester to Liverpool area.

Seismic reflection data coverage

The location, line length (in the case of 2D) and area (in the case of 3D) of seismic reflection data onshore UK have been analysed to determine the spatial distribution of the data. **Figure 10a** shows the location of all 2D seismic reflection lines. Onshore UK there are ~75 871km of 2D seismic reflection data which cover an area of ~100 000km^2. As with the deep wells, it is almost exclusively in either the Carboniferous Basins of Northern England and the Midlands, or the Mesozoic Basins of Southern England. The density of data varies dramatically, with the maximum coverage being 700km in a single 10km^2 quadrant and the minimum being 7km. Across the onshore sedimentary basins the greatest coverage of 2D data is located across the Wessex and East Midlands Basins **(Figure 10b)**. As shown in **Figure 10a**, over 90% of the 2D seismic reflection data onshore UK was acquired prior to 1990. The mean length of a 2D seismic line is 8.2km and the longest individual 2D seismic line is 67.4km. As a comparison, in the 10 000km^2 offshore area of the UK East Irish Sea Basin there are 72 454 km of 2D seismic reflection lines; approximately 10 times the data density in just this one offshore basin compared with the onshore.

Three-dimensional seismic reflection data onshore UK is limited to just 32 surveys **(Figure 12)** covering an area of **~**2400km^2. As a comparison, the Netherlands has a land area of ~ 41 543km^2 across which there is ~14 000km^2 of onshore 3D seismic reflection data. Onshore the UK the largest onshore 3D survey is 363km^2, which is the Lincswold02 3D survey. Using the current (as of April 2020) Petroleum and Exploration Development Licences (PEDL) outlines from the OGA, there are 12 PEDL which have complete 3D seismic coverage. Presently, 114 out of 181 of the current PEDL have no 3D seismic coverage and 19 have less than 10% coverage. **Figure 11b** is a histogram of 3D seismic reflection area acquired by year onshore UK, and with only 638km^2 acquired since 2010. Of these surveys 5 are within the prospective shale gas exploration areas identified by the BGS (INSERT REF). These prospective areas total ~20 000km, however there has only been 452km^2 of new 3D seismic acquisition in these areas, which amounts to ~2% of the total prospective areas.

When the coverage of 2D and 3D seismic reflection data is compared with the domestic and non-domestic heat demand across the UK., only ~500km of the existing 2D seismic reflection data intersect areas of domestic heat demand above 10 000 MWh/km^2 annually. There is no 3D seismic reflection data in these areas. This is <1% of the 2D seismic reflection data. **Table 3** summarises the coverage of data and the total length of 2D seismic data and the number of wells within the ten largest areas where heat demand is >10 000 MWh/km^2. As well as the limited availability of 2D seismic reflection data, there are also only a handful of deep wells and wells with temperature measurements in these areas. **Figure 9** shows the four largest areas, London, Birmingham, Manchester and Liverpool, and the coverage of deep data. These data indicate that there is notable paucity of well and seismic data for geothermal exploration in these areas.

Seismic reflection data quality

The study has looked at the quality of 3D seismic reflection data specifically within the PEDL licence where hydraulic fracturing took place at two wells between 2018 and 2019. There are 43km of 2D lines across the PEDL and a single 3D seismic reflection survey. The 3D seismic reflection data were acquired to support the exploration and exploitation of unconventional hydrocarbons in the Craven Basin. Interpretations of this 3D seismic survey have been described previously with implications for both exploitation of resources (Clarke et al. 2018) and for the evaluation of induced seismicity (Anderson and Underhill 2020). Anderson and Underhill (2020) recently described the structural setting of the area and the implications for induced seismicity, for example geological faults below seismic resolution. Here the geophysical characteristics of the 3D survey are described, focusing on the frequency content and the implications for the resolution and quality of the data. **Figure 13** shows how the frequency spectrum for the 3D data varies by depth (in two-way-time [TWT]) of investigation. To examine the impact of frequency content on the quality of the seismic reflection data , **Figure 14** shows example seismic sections of the original post-stack seismic volume (**Figure 14a**) with different high frequency cut offs applied at 90 Hz (**Figure 14b**), 60 Hz (**Figure 14c**) and 40 Hz (**Figure 14d**). The difference (original minus filtered) seismic is shown in **Figure 15**. Filtering out the high frequency component (>90 Hz) of the 3D survey (**Figure 14b**) makes almost no difference to the seismic image (**Figure 15a**), aside from some high frequency noise in the near surface section (upper most 500ms TWT) section. Filtering out the component >60Hz removes some coherent energy above 1500 ms, but below this there is very little difference (**Figure 15b**). Filtering out >40Hz component results in removing coherent energy in the interval shallower than 1500ms as well as some deeper coherent energy (**Figure 15c**). In this area, the exploration targets were at ~1000ms. While there is overall a higher frequency content at shallower depths, this does not contribute to improving the overall interpretability of the data and suggests that much of the higher frequency content could be noise rather than coherent energy. Frequency is a key parameter controlling the resolution of faults in seismic images. The maximum vertical resolution is directly related to the ability to distinguish individual reflecting surfaces (Yilmaz 2001) and in the case of the Bowland-12 survey is approximately 60 m at the target intervals. For the horizontal resolution, assuming that the Fresnel zone is reduced to a small circle by 3D migration (Brown 2011), then in the case of the Bowland-12 survey the horizontal resolution can be estimated to be ~40m. The frequency content of the data and resulting estimated resolution means it is difficult to distinguish layers below this limit. The implications of the vertical and horizontal resolution of both 2D and 3D seismic data for shale gas exploration and other geoenergy activities is explored in the discussion.

Discussion

Like in many countries, the acquisition of subsurface data onshore UK has been driven by the exploration and exploitation of natural resources. This means that the data that exist to investigate the subsurface is biased and often displays clustering, as is evidenced by this study. Pérez-Díaz et al. (2020) break down the process of transforming geoscientific data to geological knowledge into acquisition, processing, analysis, interpretation and modelling. The findings presented here show that quantification of sampling bias, data clustering and underlying limitations are vital to understand prior to analysis, interpretation and modelling of the data.

Subsurface Mapping and Geoenergy

The ability to create accurate models of the subsurface relies on data being representative of the area of interest. Data acquisition in oil and gas exploration is location biased, and often clustered, because it is acquired to test a geological scenario that may have multiple objectives. This clustering is having been demonstrated through the use of spatial statistics. Onshore oil and gas exploration wells exhibit significant clustering, as do the temperature data that are frequently acquired in these wells. Of the total onshore area of the UK, i.e. ~243 000km², the 76 136km of 2D seismic data covers an area of ~109 900km^2. This means that just under half of the total onshore area of the UK is covered by a subsurface image. As noted previously, when compared with the offshore of the UK, where in many respects seismic acquisition is easier, there is a relative paucity of both 2D and 3D seismic reflection data.

3D seismic reflection data cover a total of 2400km^2 of the onshore UK. The limited extent of any single 3D seismic survey onshore the UK limits the ability to map or extend our geological knowledge and understanding. The largest onshore survey is 363km^2 (Lincswold-02) and is approximately 30km by 12km. Similarly, the limited extent to which surveys are adjacent to one another and form a patchwork from which larger areas can be mapped is in the same location where the Lincwold-02 is adjacent to and overlaps with the Saltfleetby-99 survey and together cover ~380km^2. Despite the UK Government encouraging and overseeing shale gas exploration and the and numerous companies embarking on shale gas exploration programmes (see Selley 2012) there has been only 638km^2 of 3D seismic reflection data have been acquired across ~20 000km the prospective areas since 2010. Overall, the paucity of 3D seismic data onshore the UK limits the ability to interpret geological structure and trends beyond a handful of areas. Despite the critical role that 3D seismic reflection data have in exploration and exploitation, and their importance in future geoenergy activities such as CCS, there is a limit to their resolution and therefore the features that can be resolved to characterise the full complexity and heterogeneity of the subsurface. For future geoenergy projects, a consideration could be that operators should report the parameters and resolution of their seismic reflection surveys ahead of consents being given, for example to hydraulically fracture.

As is now well documented, induced seismicity felt by the local population has been associated with both shale gas sites in the UK where hydraulic fracturing has been carried out (Clarke et al. 2014; Clarke et al. 2019). At both Preese Hall (Clarke et al. 2014) and Preston New Road (Clarke et al. 2019), the focus of studies has largely been the monitoring and prediction of seismicity using passive seismic techniques (e.g. Clarke et al. 2019). However, the observations and interpretations of the geology prior to the hydraulic fracturing and the suitability of 2D and 3D seismic reflection data to make confident interpretations has received limited consideration. The analysis presented on frequency content and resolution of the Bowland-12 3D survey indicate that the ability to interpret structural discontinuities, such as faults, which could be reactivated during hydraulic fracturing is fundamentally limited by the extent and quality of the data. In the case of the Preese Hall-1 well, the geological and geophysical interpretations for the hydraulic fracture plan were based on 2D seismic data (Green et al. 2012). If there is even moderate structural complexity then the migration process in a vertical plane may be inadequate to capture this (Brown 2011). The limitations for geological interpretation are compounded by the sparsity and spacing of the 2D seismic reflection data. The use of 3D seismic reflection data reduces the uncertainty in pre-drill characterisations and predictions (Brown 2011), including the presence and geometry of faults. By acquiring 3D seismic reflection data it may have been possible to improve the structural interpretation of faulting within the basin, as also suggested by Green et al. (2012). At both Preston New Road wells (PNR-1 and PNR-2) the hydraulic fracture planning did utilise 3D seismic reflection data. It has been described previously (Clarke et al. 2019) that the reactivated fault which resulted in the induced seismicity was not imaged using the Bowland-12 3D seismic reflection survey. The analysis of the post-stack seismic data here suggests that ahead of any planned drilling or hydraulic fracturing it would have been possible to report that the data would not be suitable for interpreting faults with either vertical (throw) or horizontal (heave) displacements below the 40m and 60m estimated resolutions respectively. In addition, it is possible that the resolution of the data is lower than estimated from the seismic frequency because the analysis presented indicated that the higher frequencies in the Bowland-12 3D data do not contribute to the overall interpretability of the data **(Figure 15a-c)**. The interpretation of a fault with a vertical offset of less than 50m would be highly uncertain. The overall interpretability of the 3D seismic reflection data for structural interpretations is limited by the vertical and horizontal resolution of the data.

For geothermal energy this study highlights that in areas of high heat demand there is limited existing subsurface data **(see Table 3)**. Both well and seismic reflection data show significant clustering, and the well data also have a sampling bias with respect to depth. The ability to predict subsurface properties, such as temperature, relies on calibrating models against existing data. If the existing data are clustered, and there is a significant sampling bias then making predictions, based on models, away from data rich areas inevitably comes with an increased uncertainty. As discussed for interpretation uncertainties by Bond (2015), the way in which these uncertainties are communicated in geosciences is important from a social and economic perspective because the public are increasingly concerned with the decision-making processes and the risks and uncertainties.

The subsurface will likely be required to deliver a low carbon energy transition in the UK, for example the deployment of CCS, energy storage (methane and hydrogen), for the continued, but sustainable extraction of natural resources (Stephenson et al. 2019) and likely vital for long term disposal of radioactive waste. However, our ability to sustainably exploit the subsurface relies on our ability to predict and model it accurately. Given the vintage of much of the existing seismic reflection data, a consideration of future geoenergy projects should be whether existing data are suitable or whether a step change in onshore seismic data quality (and coverage) will be required to both fully understand the opportunity and to demonstrate that activities will have a low impact on communities and the environment. The variability in the extent and quality of existing data across the UK means that decision makers should include an assessment on the suitability of data from the project inception phase.

Governance and Regulatory Challenges

In the UK the governance and regulation of deep subsurface activities involves different decision makers and regulatory bodies, including the Oil and Gas Authority, the Environment Agency and The Health and Safety Executive. Hawkins (2015) highlighted that in the case of hydraulic fracturing the existing conventional oil and gas regulation failed to translate into adequate controls for the shale gas industry. The transition from the dominant use of the deep subsurface in the UK being for fossil fuel production in the offshore areas, to a more complex and multi-faceted system, including onshore, potentially raises questions on the suitability of existing governance and regulation structures in managing activities. An example could be the move to localised energy systems for the use of geothermal energy (Lloyd 2018). As highlighted by this study, both the coverage and quality of existing subsurface data vary considerably across UK regions and communities. Consideration to governance, regulation and guidelines should be addressed ahead of expansion of these nascent subsurface activities and could consider if there should be guidance on the minimum data requirements ahead of activities which perturb the subsurface so operators of activities can better plan mitigation measures for the potential impact on communities and the environment. Given, as discussed earlier, that subsurface data have inherent resolution limitations, and that hydraulic fracturing by its very nature perturbs the subsurface, it could be argued that there should be a minimum requirement for data resolution ahead of such activities. At present there are no minimum standards or expectations for the data which decisions must be based on.

The exploration and production of unconventional hydrocarbons which use hydraulic fracturing methods have brought into sharp focus the challenges in confidently predicting the subsurface. There is typically a larger uncertainty in subsurface interpretations using 2D seismic reflection data compared with 3D seismic reflection data, with reduced uncertainty a function of both improved areal coverage and the benefits of 3D migration (Bacon et al. 2007). The Consolidated Onshore Guidance (Oil and Gas Authority 2018) specifies that “a map and seismic lines showing faults near the well and along the well path” should be included but makes no specific reference to demonstrating the suitability of the underlying data on which those interpretations are made. There is no requirement for the operators to demonstrate that the seismic refection data are specifically suitable for the activity that is being planned. The required information relates to primarily to interpretations (or knowledge).

How industry and society utilise the deep subsurface is likely to change as a result of the need to decarbonise energy systems. This change undoubtedly will bring about new regulations and guidance. The status quo of adopting previous practice from the oil and gas exploration and production is unlikely to be a justifiable position and new frameworks should consider the inherent uncertainty and possible impacts of deep subsurface activities.

Communities and Science Communication

Risks associated with subsurface development are a major public issue for UK citizens, especially since 2011 when hydraulic fracturing led to seismic activity at Preese Hall (Clarke et al. 2014). Moreover, strong public opposition to hydraulic fracturing and subsurface development appear to be linked to the uncertainty associated with seismic activity, even though few UK residents have actual first-hand experiences with high hazard seismic events (Cotton 2015; Szolucha 2018). Nevertheless, not all UK regions and communities are equally exposed to subsurface development. That is, there are significant regional and community variations in subsurface development as well as uncertainty surrounding the risks that can be modelled using the data in this analysis. This unequal distribution of subsurface risk is also compounded by various interpretations of risk. Social science research suggests that variations in perceptions of risk are explained by geography, culture, socioeconomic status, ethnicity, race and gender (Flynn et al. 1994). As just one example of the importance of context, consider the case of hydraulic fracturing in Oklahoma (USA), a state highly dependent on oil and gas development. The perceived risks associated human induced seismicity among Oklahoma residents are less of a concern than perceived risks associated with pollution, especially to water and poisoning of livestock (Campbell et al. 2020). Thus, when subsurface data is mapped out across the UK it demonstrates the potential for enormous variation in interpretation of risk according to the spatial location of wells as well as the constellation of community and demographic combinations that may together shape risk perceptions (e.g. Kropp 2018). This distribution of perception of risk has yet to explored in the UK using subsurface data, though ecosystem services suggests there are good reasons to undertake such an analysis in the future.

There is an increasing public demand for high quality information that is accurate, consistent, complete, timely and representative (e.g. Wang and Strong 1996). This analysis suggests that seismic reflection and borehole data represent an information source that can be used to contribute to information quality and aid in the communication of subsurface risk. However, simply reporting information, even high-quality information, is probably not enough. In particular, social science research suggests that credible information sources are highly important in conveying actual risk (Renn and Levine 1991). Thus, where data are uncertain or complex the public is likely rely on experts to help them make sense of subsurface risks that may be reflected in those data. As a result, trust in the experts and institutions is likely to have an important impact on general perceptions about risks associated with subsurface development.

The interpretation of these data open up an important opportunity for geoscientists to help engage UK citizens about the levels of uncertainty and subsurface risks associated with energy development (e.g. Buchanan et al. 2014). However, with opportunities also come challenges. That is, while this study is one of the first to map the onshore UK subsurface, much of the underlying data are produced by industry. Thus, information presented by geoscientists will be constantly evaluated within the context of industry trust (Seeger et al. 2018; Wachinger et al. 2013; Wray et al. 2008). The challenge, then, is to convey meaningful information about uncertainly and risk when data generated may be viewed as suspicious, especially when it is not publicly accessible. Therefore, one of the biggest obstacles in conveying accurate perceptions of risk to UK residents may rest in the fact that much subsurface data are generated by industry (Wachinger et al. 2013). Such challenges, however, are not usual in risk analysis as researchers find that stakeholders are often perceived to communicate risk through the selective use of data that advances their own interests (Leiss 1995). Future social science research might test public perceptions about trust in different types of subsurface data. That is, are some types of subsurface data likely to be trusted more by the public? If so, why? Which types of data could be best used to communicate the nature of subsurface risks? What organisations are best placed to communicate data about subsurface risks? Why? These are just a few of the issues that geoscientists may confront when attempting to map the landscape of subsurface risk.

Conclusions

Despite over a century of subsurface data collection onshore UK, this is the first synthesis of the key datasets that can be used to interpret the geology of the deep subsurface. The study highlights that there is a paucity of both well and seismic data across the onshore UK. All subsurface interpretations, be it for well-established activities such as conventional oil and gas exploration and production, or new activities as part of the energy transition, rely on these geophysical or geological data. These interpretations and models are fundamentally limited by the inhomogeneous datasets and the resolution of them. Onshore oil and gas production in the UK currently accounts for <1% of the total production from the UK (OGA, 2020) and the limited scale of resources, when compared to the offshore, that has restricted further data collection, with companies prioritising the offshore areas of the UK Continental Shelf. The lack of extensive and high-quality data could be a fundamental limitation on the expansion of nascent low carbon subsurface activities and technologies. The attention with which the public are now putting on all new energy activities will require geoscientists to clearly articulate the limitations of currently available datasets, and these limitations should highlight areas where new data collection is needed, both to improve coverage, and to improve resolution. The ability to understand and quantify uncertainties in a subsurface description is key to effectively reducing safety, environmental, health and economic risk. Gaining new knowledge through data acquisition cannot be guaranteed to de-risk a subsurface outcome, however, the new knowledge can be vital in the decision-making process.

The analysis and statistical measures shown here for the onshore UK subsurface datasets can be used to determine priority areas for future data collection. But the analysis does not address what is enough data for a given activity. There needs to be a concerted effort across geosciences and social sciences to understand what defines an acceptable level of uncertainty, financial risk, and environmental risk. This study raises the question as to whether for subsurface activities where there could be a substantive impact on communities or the environment, is there a need for regulators to demand minimum data standards as part of the planning process? There is more than ever a social dimension to subsurface uncertainty. Never has the spotlight been so focused on the ability of geoscientists to predict the subsurface.

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Data Availability

3D Seismic Data. The 3D seismic reflection presented in this study are available from the UKOGL but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly. Data are however available from the authors upon reasonable request and with permission of the UKOGL. See www.ukogl.com.

OGA Onshore 2D and 3D Seismic Data. The location of 2D and 3D seismic data onshore the UK analysed during this study is available from the Oil and Gas Authority (OGA) at https://maps.ukogl.org.uk/arcgis/rest/services/public/public_seismic_BritNatGrid/Mapserver

BGS Borehole Locations. The BGS borehole location dataset analysed during this study is available from the www.bgs.ac.uk.

UKOGL Borehole Locations. The location of the UKOGL borehole locations used in this study are available from UKOGL but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of UKOGL. See www.ukogl.com.

BGS Geothermal Catalogue. The BGS Geothermal Catalogue data analysed during this study is available from http://nora.nerc.ac.uk/id/eprint/512272/

BGS Geophysical Logs and Borehole Samples. The location of geophysical logs and borehole samples used in this study are available from the BGS but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of BGS. See www.bgs.ac.uk.

UKERC Heat Demand. The domestic and industrial heat demand data from Taylor et al., (2014) is available from https://data.ukedc.rl.ac.uk/browse/edc/efficiency/residential/Buildings/DS4DS

OGA Offshore 2D Seismic Data. The data used to compare the offshore coverage to the onshore areas is based on the Surveys as Consented 2D shape which is available from https://ndr.ogauthority.co.uk/.

NLOG Seismic. For the comparisons of 3D seismic coverage with the Netherlands, the data is from NLOG, which is manged by the Geological Survey of the Netherlands on behalf of the Ministry of Economic Affairs and Climate https://nlog.nl/en

Author Contributions

MI: conceptualization (lead), data curation (lead), formal analysis (lead), investigation (lead), methodology (lead), writing – original draft (lead), writing – review and editing (lead); **RB**: writing – original draft (supporting), writing – review and editing (supporting); **MW**: formal analysis (supporting), writing – review and editing (supporting). **PS**: validation (supporting), writing – review and editing (supporting); **RD**: conceptualization (supporting), writing – original draft (supporting), writing – review and editing (supporting);

Fig 1. Hierarchical model of data, knowledge, information and Wisdom (modified afterAckoff 1989) and how this relates to steps in geoscience workflow (taken from Pérez-Díaz et al., 2020)

Fig. 2. Simplified geological map of the UK, showing the outlines of sedimentary basins, position of volcanics at surface, and major tectonic liniments.

Fig. 3. Histograms of wells drilled onshore the UK from the UKOGL database a) by year and b) TD TVD

Fig. 4. Well density of all boreholes held by the BGS with a TD between 30 and 500 m.

Fig. 5. Map showing the density of wells from UKOGL database with total depths (TVD) of: a) >500m; b) >1km; c) >2km; d) >3km. Includes location of current PEDL.

Fig. 6. Spatial density of wells with a) geophysical logs and b) rock samples

Fig. 7. Map showing a) the location of wells with temperature measurements and b) the number of temperature measurements per $10km^2$.

Fig. 8. Histogram of a) temperature measurements by depth and b) temperature vs depth plot.

Fig. 9. Subsurface data coverage, showing the location of both 2D seismic data and the deep wells from UKOGL in relation to heat demand across a) London, b) Birmingham, c) Manchester and d) Liverpool.

Fig. 10. a) 2D seismic data across the UK and b) the number of linekm of 2D seismic per $10km^2$

Fig. 11. Histograms of a) length of 2D seismic lines acquired onshore the UK by year, and b) area of 3D seismic surveys acquired onshore the UK by year

Fig. 12. Map showing highlighting the location of Bowland-12 3D survey, and the location of all other 3D seismic reflection surveys onshore the UK.

Fig. 13. a) A simple comparison of the frequency content of the Bowland-12 3D seismic reflection survey for different time intervals. The frequency content decreases with depth.

Fig. 14. Comparison of seismic sections adjacent to the Preston New Road 2 well. a) unfiltered; b) low pass filter cut at 90Hz; c) low pass filter cut at 60 Hz and d) a low pass filter cut at 40 Hz. The section is orientated E-W (XL 1234).

Fig. 15. Difference between the original seismic data and a) low pass filter cut at 90Hz; b) low pass filter cut at 60 Hz and c) low pass filter cut at 40 Hz. The section is orientated E-W (XL 1234).

Table 1. Typical data types and their classification based on the Ackoff (1989) hierarchical model

<table>
<tr><th>Data</th><th>Information</th><th>Knowledge</th></tr>
<tr><td>Well depth</td><td></td><td></td></tr>
<tr><td>Well locations</td><td></td><td></td></tr>
<tr><td>Samples (from wells)</td><td></td><td></td></tr>
<tr><td colspan="2">Geophysical logs (wells)</td><td></td></tr>
<tr><td>Temperature (from wells)</td><td></td><td></td></tr>
<tr><td>Fluid sample (from wells)</td><td></td><td></td></tr>
<tr><td></td><td>Geothermal gradient</td><td></td></tr>
<tr><td>Raw seismic field data</td><td></td><td></td></tr>
<tr><td colspan="2">Processed seismic reflection data</td><td></td></tr>
<tr><td></td><td colspan="2">Seismic horizons</td></tr>
<tr><td></td><td></td><td>Fault geometry</td></tr>
</table>

Table 2. Data sources used in the quantitative analysis of available data onshore the UK

Data type	Collection	Source	Format	N=
2D seismic	Onshore 2D seismic locations	OGA	Lines	9283
3D seismic	Onshore 3D seismic locations	OGA	Polygons	32
Wells	UKOGL: deep wells locations	UKOGL	Points	4156
Wells	Onshore well locations	OGA	Points	2242
Wells	All boreholes locations	BGS	Points	1,335,511
Wells	Temperature measurements	BGS	Points	1712
Borehole Samples	Samples from boreholes	BGS	Database	10 427
Geophysical logs	Geophysical logs by well	BGS	Database	5963 (digital) 6454 (paper)

Table 3. Data coverage for 10 largest areas of annual domestic heat demand above 10 000 MWh/km2. Both extent of 2D seismic reflection data and number of deep wells are quantified within these areas. See Figure 9 for map view of London, Birmingham, Manchester and Liverpool.

City/Town	**Area of City/Town (km^2)**	**2D seismic reflection data (km)**	**Deep wells (>300m TVD)**
London	1295	0	14
Birmingham	492	0	7
Manchester	370	139	5
Liverpool	182	27	5
Glasgow	133	0	0
Newcastle upon Tyne	121	0	1
Leeds	81	0	0
Nottingham	81	20	3
Bristol	80	0	1

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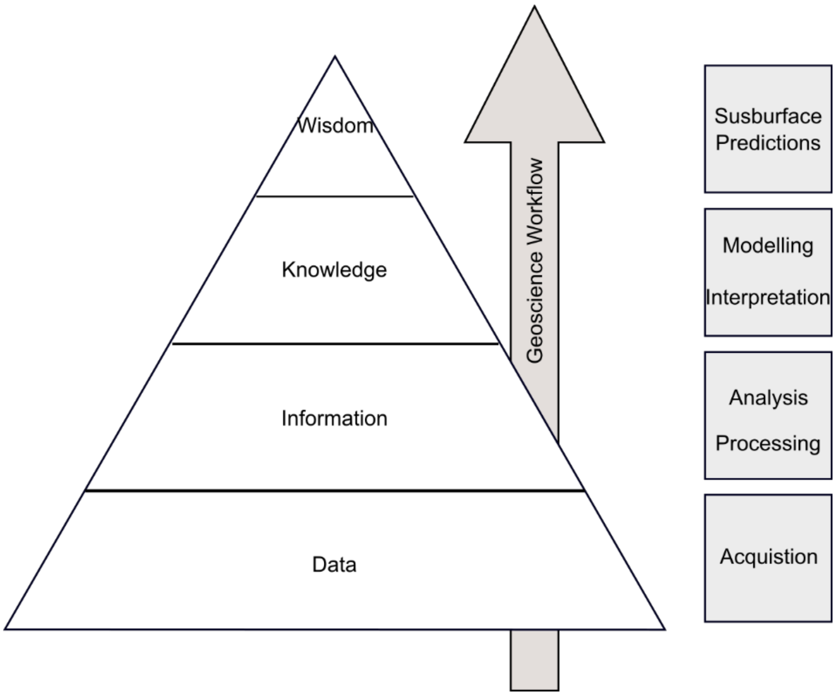
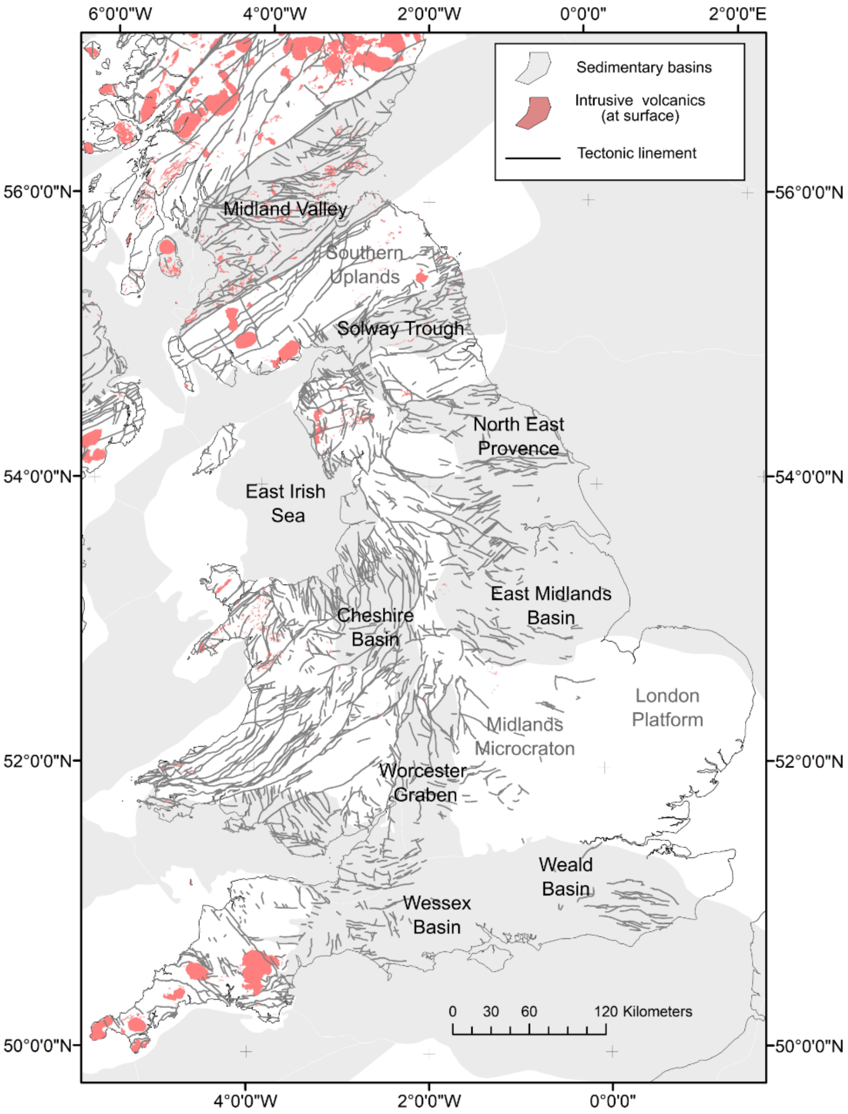
FIGURE 1.


Wisdom
Knowledge
Information
Data
Geoscience Workflow
Susburface Predictions
Modelling
Interpretation
Analysis
Processing
Acquistion

865 **FIGURE 2.**



866

867

FIGURE 3.

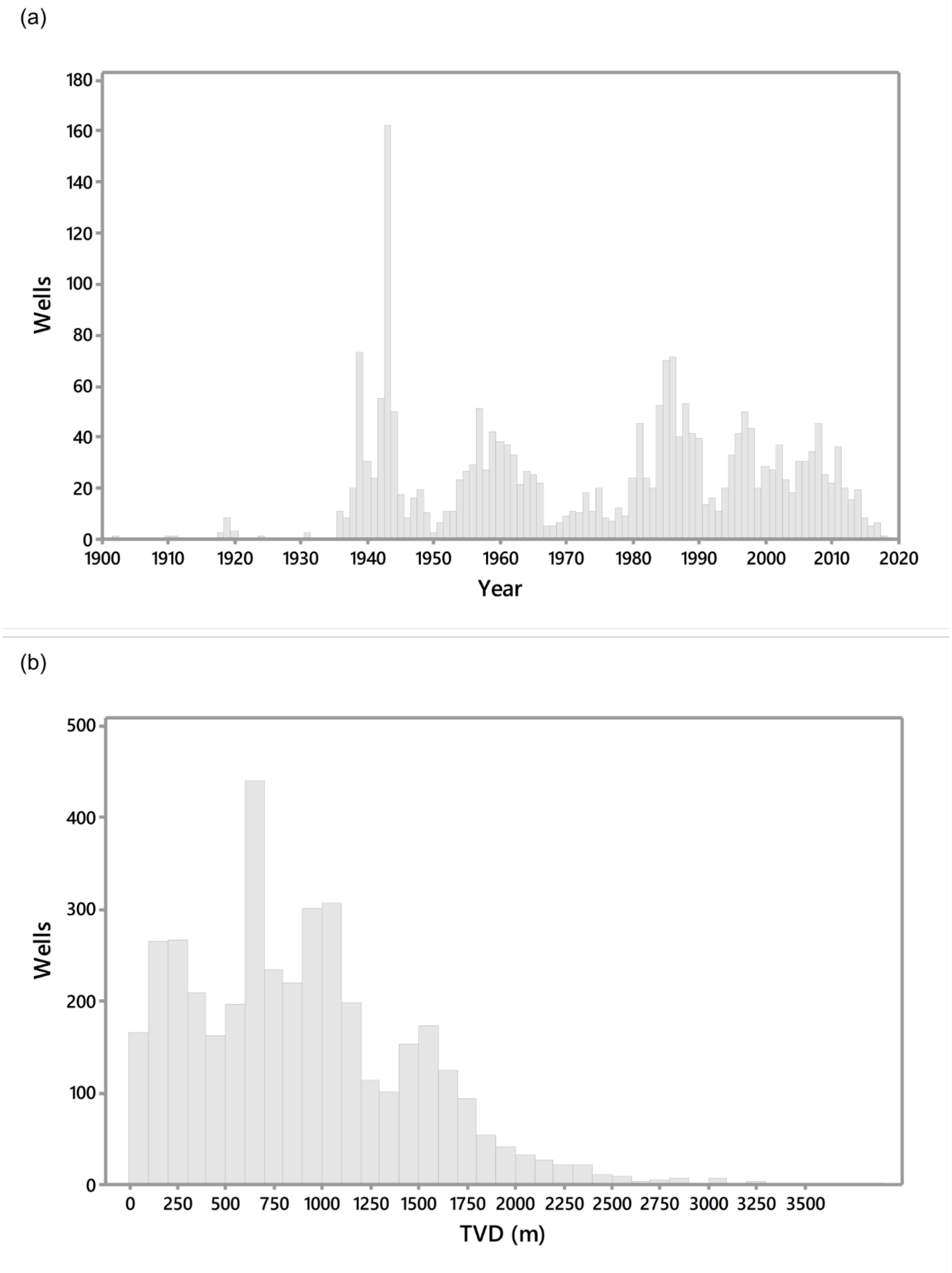

(a)
Wells
180
160
140
120
100
80
60
40
20
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
(b)
Wells
500
400
300
200
100
0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
TVD (m)

FIGURE 4.

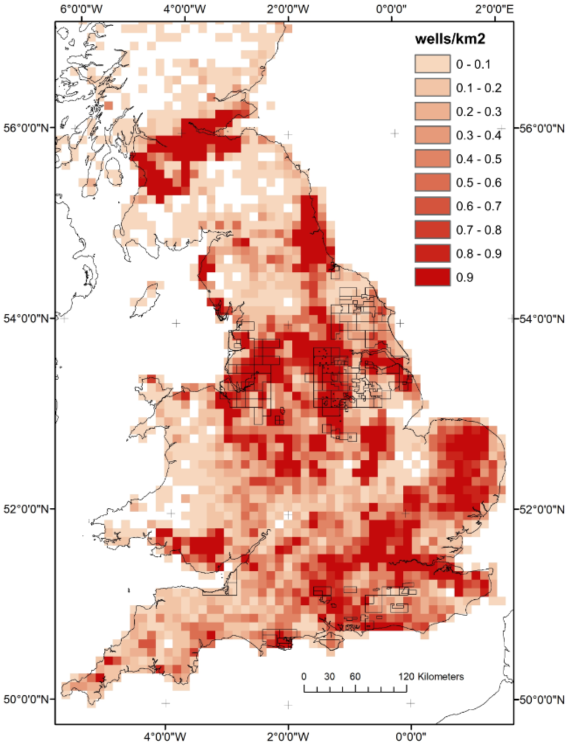

6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
wells/km2
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9
0 30 60 120 Kilometers

FIGURE 5.

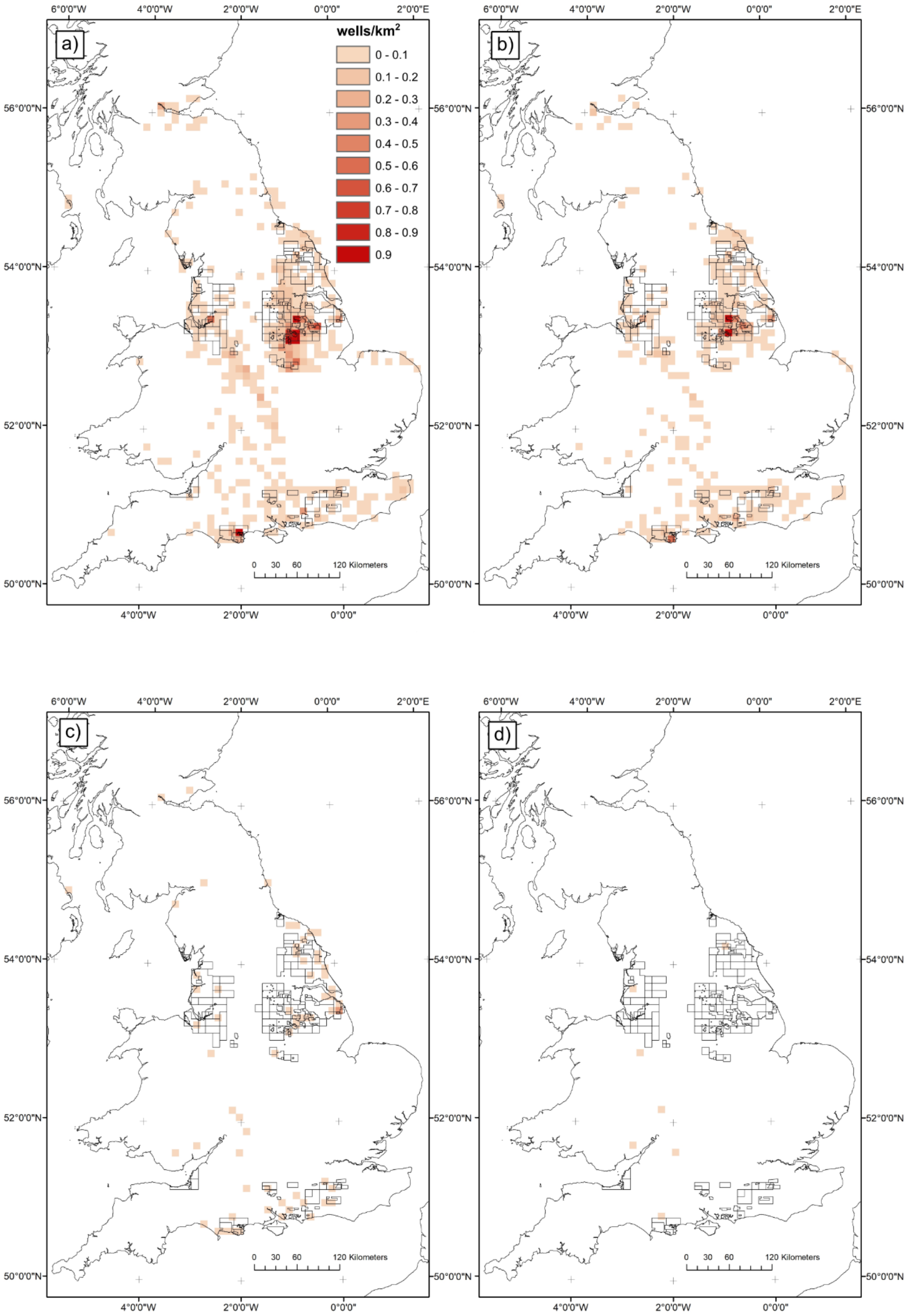

a)
b)
c)
d)
wells/km^2
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9
6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
0 30 60 120 Kilometers

FIGURE 6.

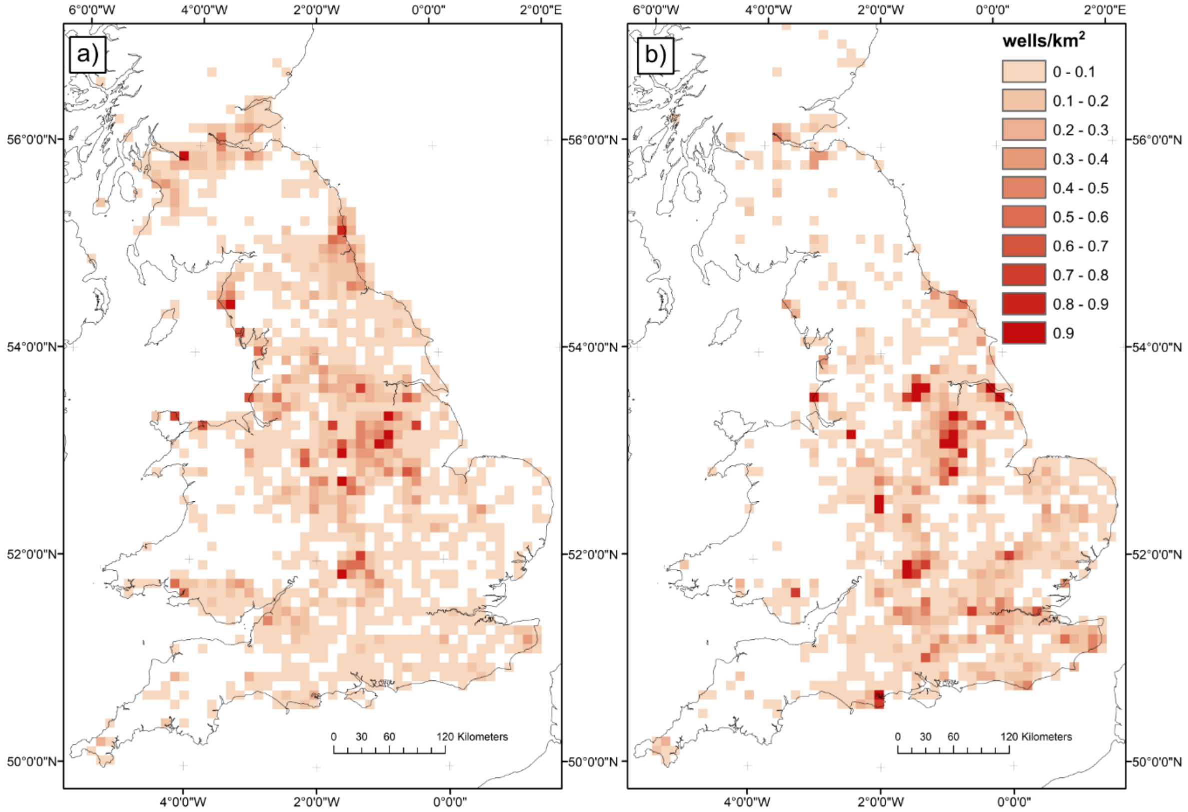

a)
b)
6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
0 30 60 120 Kilometers
wells/km^2
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9

FIGURE 7.

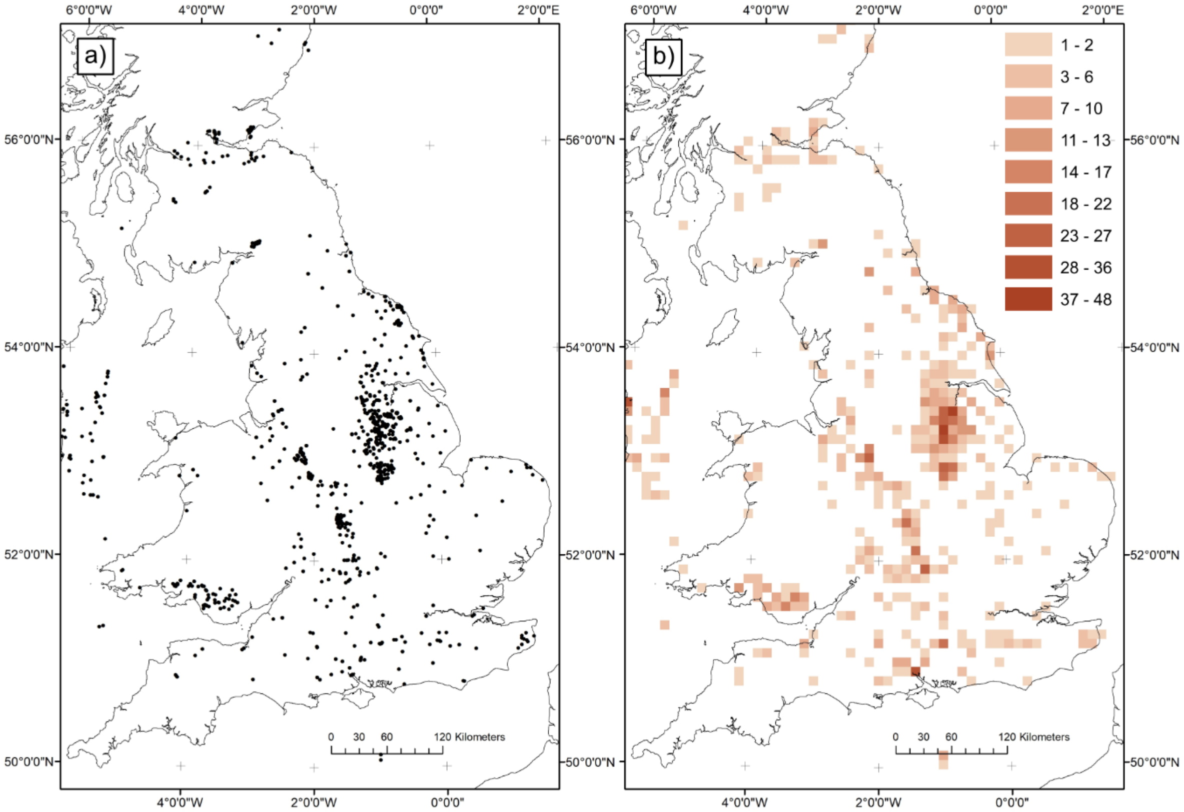

a)
b)
6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
0 30 60 120 Kilometers
1 - 2
3 - 6
7 - 10
11 - 13
14 - 17
18 - 22
23 - 27
28 - 36
37 - 48

FIGURE 8.

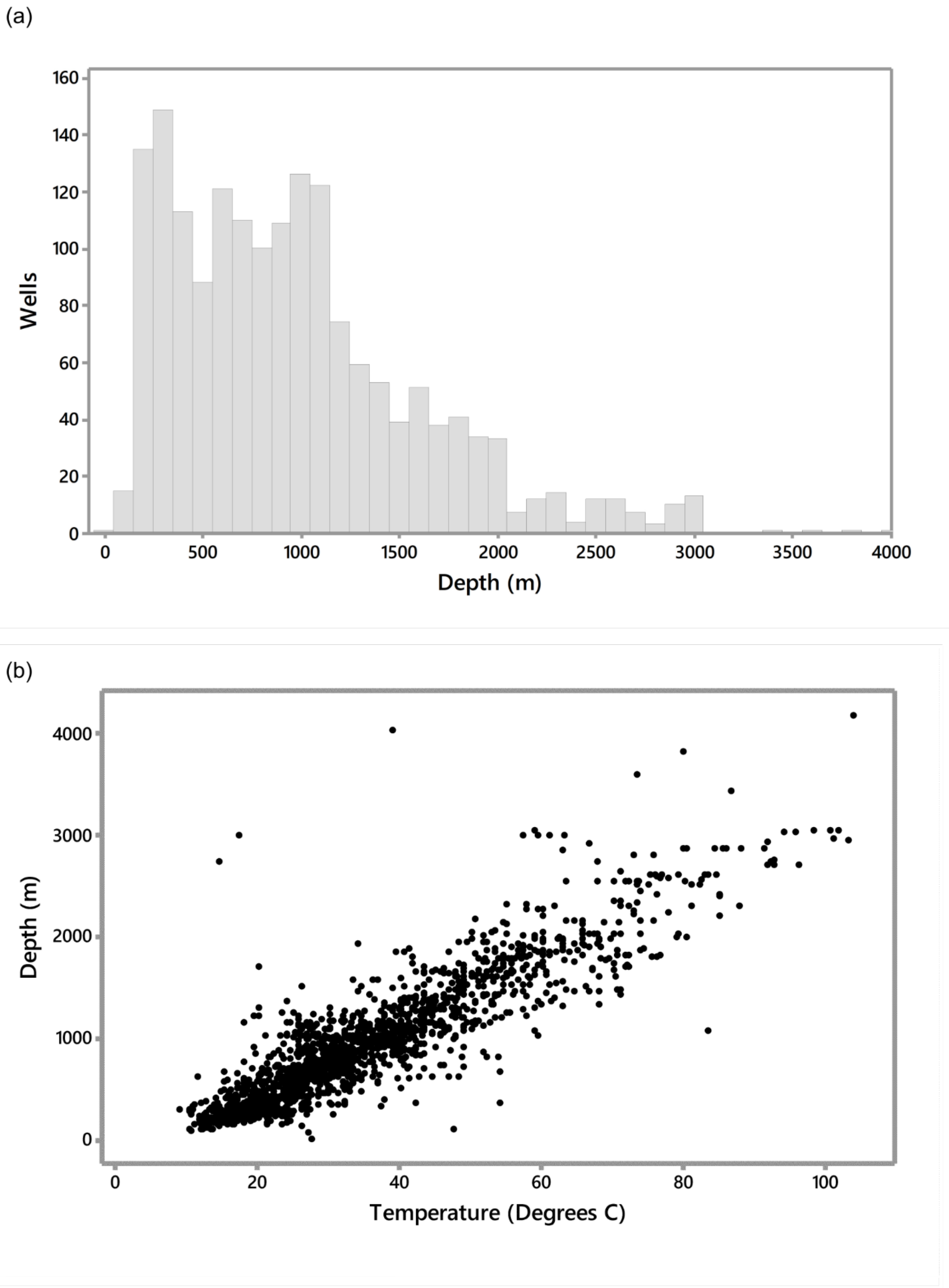

(a)
Wells
160
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
4000
Depth (m)
(b)
Depth (m)
4000
3000
2000
1000
0
0
20
40
60
80
100
Temperature (Degrees C)

FIGURE 9.

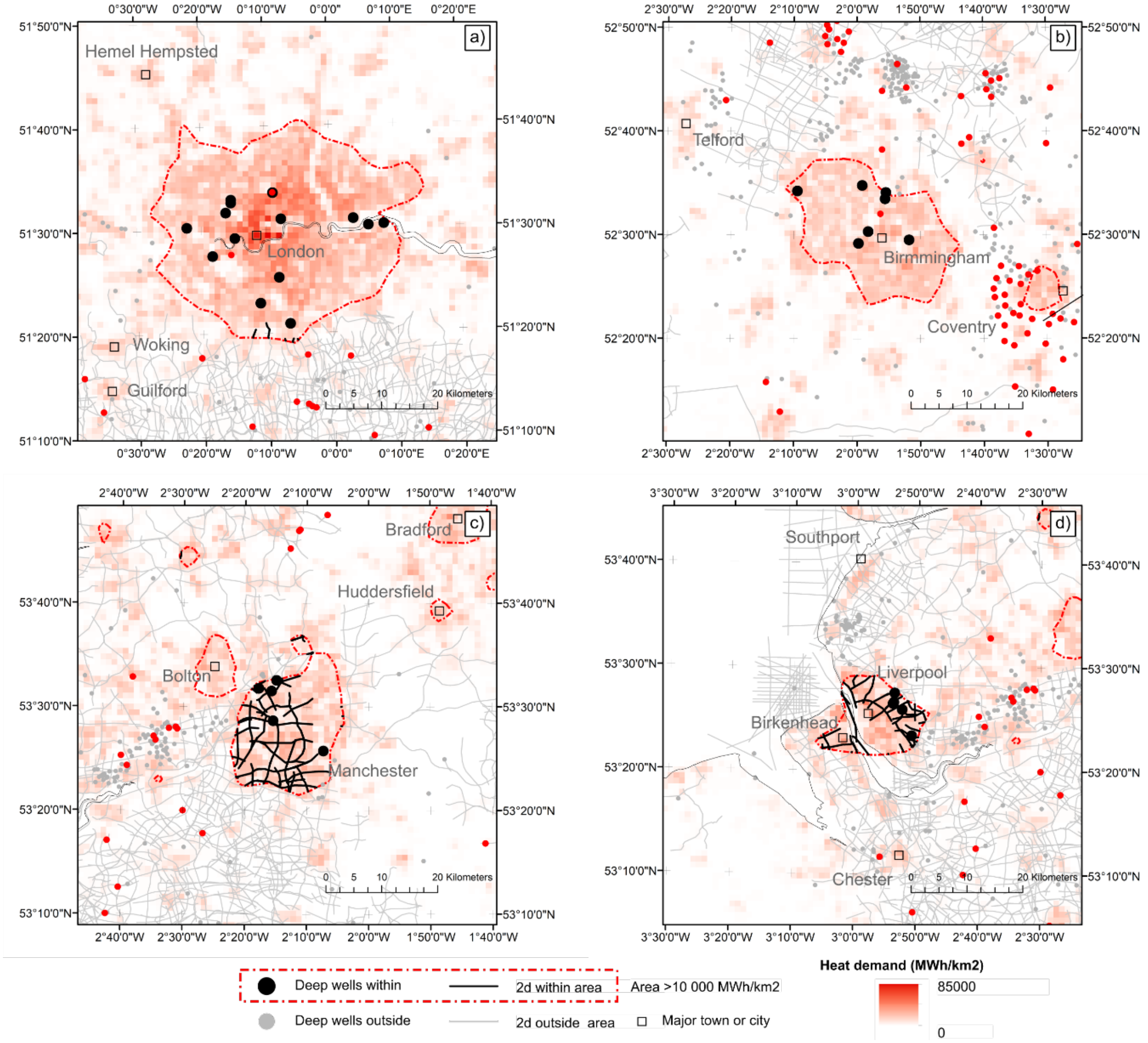

a)
Hemel Hempsted
London
Woking
Guilford
0 5 10 20 Kilometers
0°30'0"W 0°20'0"W 0°10'0"W 0°0'0" 0°10'0"E 0°20'0"E
51°50'0"N 51°40'0"N 51°30'0"N 51°20'0"N 51°10'0"N
b)
Telford
Birmingham
Coventry
0 5 10 20 Kilometers
2°30'0"W 2°20'0"W 2°10'0"W 2°0'0"W 1°50'0"W 1°40'0"W 1°30'0"W
52°50'0"N 52°40'0"N 52°30'0"N 52°20'0"N
c)
Bradford
Huddersfield
Bolton
Manchester
0 5 10 20 Kilometers
2°40'0"W 2°30'0"W 2°20'0"W 2°10'0"W 2°0'0"W 1°50'0"W 1°40'0"W
53°40'0"N 53°30'0"N 53°20'0"N 53°10'0"N
d)
Southport
Liverpool
Birkenhead
Chester
0 5 10 20 Kilometers
3°30'0"W 3°20'0"W 3°10'0"W 3°0'0"W 2°50'0"W 2°40'0"W 2°30'0"W
53°40'0"N 53°30'0"N 53°20'0"N 53°10'0"N
Deep wells within
2d within area
Area >10 000 MWh/km2
Deep wells outside
2d outside area
Major town or city
Heat demand (MWh/km2)
85000
0

FIGURE 10.

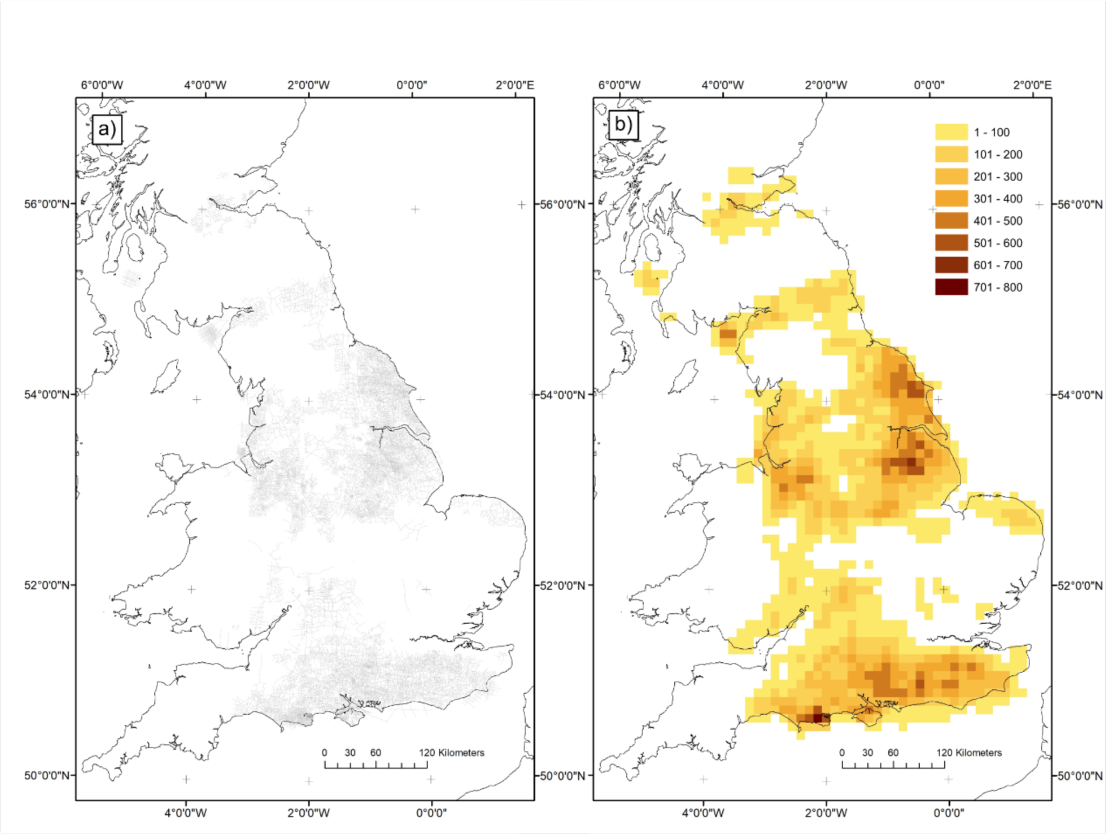

a)
b)
6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
1 - 100
101 - 200
201 - 300
301 - 400
401 - 500
501 - 600
601 - 700
701 - 800
0 30 60 120 Kilometers

FIGURE 11.

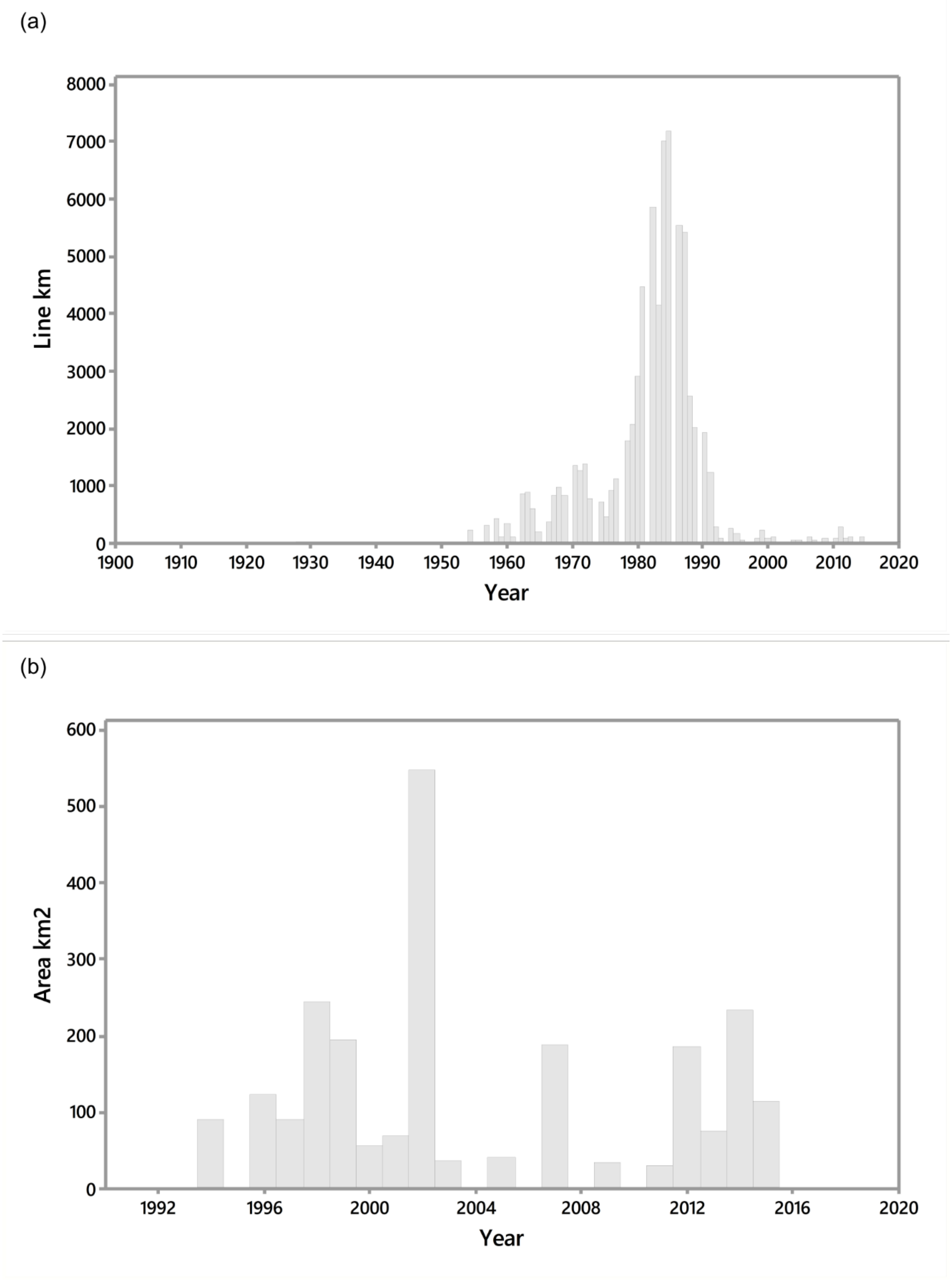
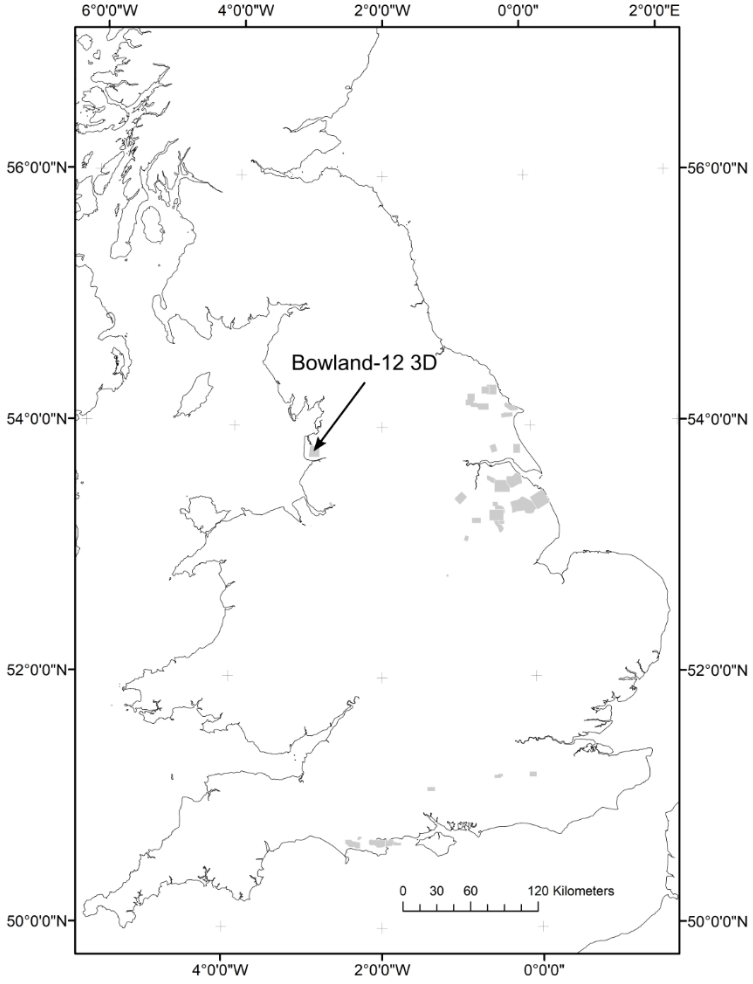
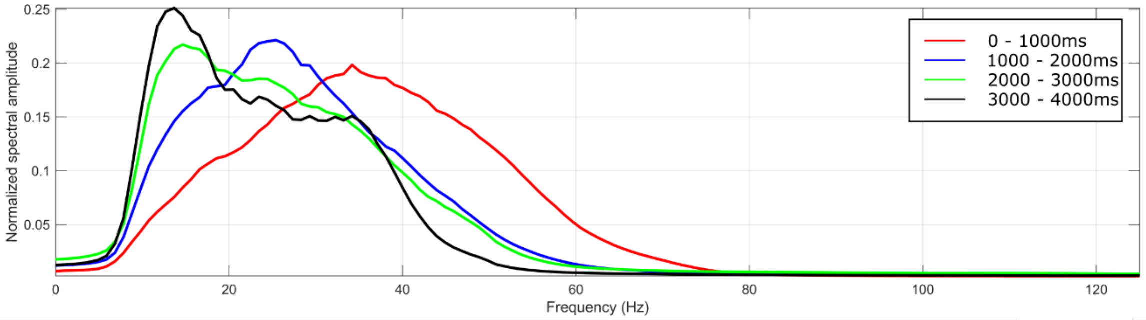

(a)
8000
7000
6000
5000
4000
3000
2000
1000
0
Line km
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
(b)
600
500
400
300
200
100
0
Area km2
1992
1996
2000
2004
2008
2012
2016
2020
Year

FIGURE 12.


6°0'0"W
4°0'0"W
2°0'0"W
0°0'0"
2°0'0"E
56°0'0"N
54°0'0"N
52°0'0"N
50°0'0"N
Bowland-12 3D
0 30 60 120 Kilometers

899 **FIGURE 13.**



900

901

FIGURE 14.

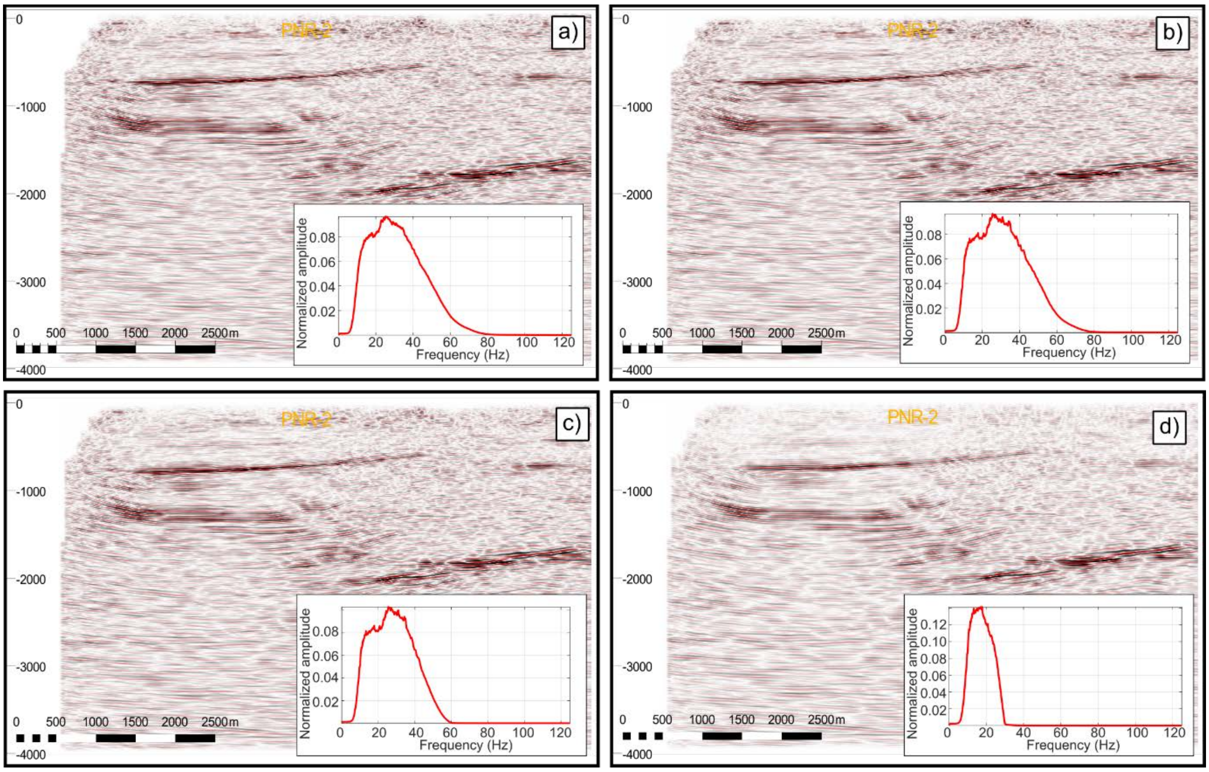

a)
b)
c)
d)
PNR-2
0
-1000
-2000
-3000
-4000
0 500 1000 1500 2000 2500 m
Normalized amplitude
0.02
0.04
0.06
0.08
0.10
0.12
Frequency (Hz)
0 20 40 60 80 100 120

FIGURE 15.