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Unconventional energy resources in a crowded subsurface: Reducing uncertainty and developing a separation zone concept for resource estimation and deep 3D subsurface planning using legacy mining data

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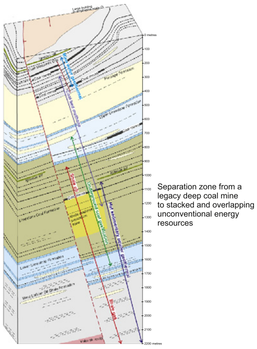
HIGHLIGHTS

- UK and Europe contain legacy coal mines above deep, stacked subsurface energy resources
- Legacy coal mine data reduces geological uncertainty in 3D geometry and faulting
- Spatial separation zone concept developed around mines limits overlapping resources
- Exemplar shale gas/oil resource estimation limited by deep mining Carboniferous, Scotland

GRAPHICAL ABSTRACT



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ABSTRACT

Over significant areas of the UK and western Europe, anthropogenic alteration of the subsurface by mining of coal has occurred beneath highly populated areas which are now considering a multiplicity of 'low carbon' unconventional energy resources including shale gas and oil, coal bed methane, geothermal energy and energy storage. To enable decision making on the 3D planning, licensing and extraction of these resources requires reduced uncertainty around complex geology and hydrogeological and geomechanical processes.

An exemplar from the Carboniferous of central Scotland, UK, illustrates how, in areas lacking hydrocarbon well production data and 3D seismic surveys, legacy coal mine plans and associated boreholes provide valuable data that can be used to reduce the uncertainty around geometry and faulting of subsurface energy resources. However, legacy coal mines also limit unconventional resource volumes since mines and associated shafts alter the stress and hydrogeochemical state of the subsurface, commonly forming pathways to the surface. To reduce the risk of subsurface connections between energy resources, an example of an adapted methodology is described for shale gas/oil resource estimation to include a vertical separation or 'stand-off' zone between the deepest mine workings, to ensure the hydraulic fracturing required for shale resource production would not intersect legacy coal mines. Whilst the size of such separation zones requires further work, developing the concept of 3D spatial separation and planning is key to utilising the crowded subsurface energy system, whilst mitigating against resource sterilisation and environmental impacts, and could play a role in positively informing public and policy debate.

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1. Introduction

During the 19th to mid-20th Century, extensive subsurface mining of Carboniferous-aged coals drove co-incident industrialisation of large areas of the UK. Although coal mining has ceased, these areas remain population centres with significant energy and infrastructure demands. The geological sequences that produced coal also contain a range of subsurface unconventional energy resources. For example, significant shale gas, shale oil, coal bed methane, underground coal gasification energy resources within the same Carboniferous succession that reaches depths of over 5 or 6 km in parts of central and northern England and in central Scotland (Jones et al., 2004; DECC, 2010a, 2010b; Andrews, 2013; Monaghan, 2014; Fig. 1). Geothermal energy resources and opportunities for energy storage are also being considered within that same rock volume (Campbell et al., 2010; Gillespie et al., 2013; Younger, 2016b). In these areas, legacy deep coal mines occur above, and in some cases at similar burial depths, to the unconventional energy resources (Figs. 1, 2).

Conflicts can exist between the various subsurface uses. For example, for both effective resource exploitation and to mitigate against environmental impacts, exploration for unconventional oil or gas would strongly avoid hydraulic connection with aquifers (Younger, 2016a) and pathways to the ground surface. Abandoned deep coal mines form a rock volume with an anthropogenically-created aquifer of altered stress, fracture, permeability and hydrogeochemical state. Associated boreholes and shafts also provide a potential route to overlying strata and the surface (The Royal Society, 2012; Davies et al., 2014; Younger, 2016a), given that some were drilled over 100 years ago and the borehole completion and integrity is not always known. Given the spatial extent where coal mining legacy could overlie unconventional resources (Fig. 1), and the relative paucity of published literature on potential subsurface connections and separation zones between deep (100s m to kilometres) energy resources, further investigation is required.

To enable decision making on the 3D planning, licensing and extraction of unconventional resources in the deep subsurface where overlain by coal mines, this paper highlights how coal mining data can both reduce uncertainty around complex geology and limit unconventional resource estimate volumes. An exemplar from central Scotland, UK illustrates an anthropogenically-altered, mined subsurface with a multiplicity of potential unconventional energy resources. Using mine data and a case history of a shale resource volume reduced by legacy mining, the exemplar area is used illustrate the application of a vertical separation zone. From that, the concept of 3D spatial separation zones to mitigate against environmental impacts in the hydrosphere, biosphere and anthroposphere is developed. Potential positive impacts in informing public and policy debate are considered.

2. Geology of the exemplar area: Carboniferous, central Scotland

Across central Scotland, Carboniferous sedimentary and volcanic rocks forming a succession up to 5500 m thick are located within an

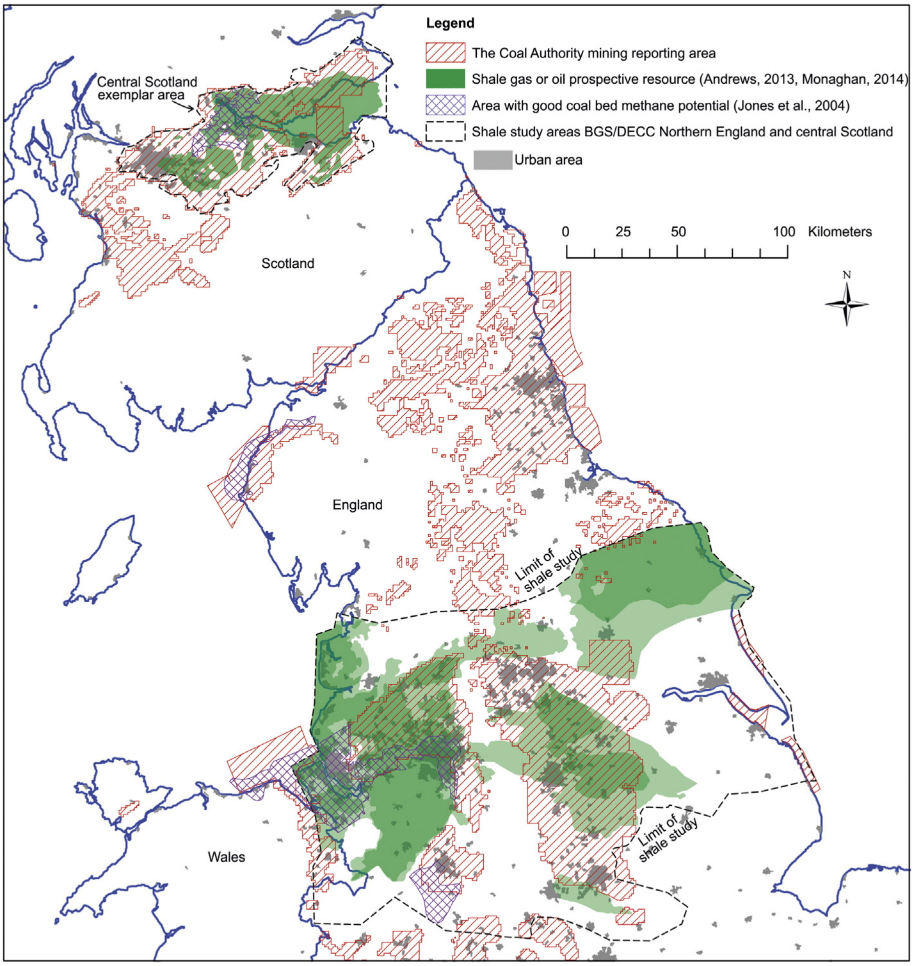

Fig. 1. Coincidence of resources across central and northern England and central Scotland UK: regional illustration of areas prospective for coal bed methane (Jones et al., 2004) and shale (Andrews, 2013; Monaghan, 2014) that are overlain by The Coal Authority 'Reporting Area' (a regional overview of the potential extent of abandoned coal mine workings in Carboniferous strata downloaded from The Coal Authority website December 2016). Shale prospective extents are limited to the study areas shown. Over many of the areas shown, there is a large spatial separation between legacy coal mining (in the top few hundred metres) and potential shale resources (at kilometres depth), but not in all areas e.g. parts of central Scotland exemplar (see below).

internally complex series of basins within the geological terrane of the Midland Valley of Scotland (Cameron and Stephenson, 1985; Browne et al., 1999; Underhill et al., 2008).

The vertically and laterally variable sedimentary succession has been divided to stratigraphic units comprising various quantities of mudstone, siltstone, sandstone, coal, oil shale, limestone and ironstone (Table 1, Browne et al., 1999). Tournaisian age parts of the Carboniferous succession are represented by fluvial sandstones, coastal plain mudstones-limestones and by various volcanic units (Table 1). In Visean times, lacustrine organic-rich mudstones and oil shales accumulated in the West Lothian area whilst mixed fluvio-deltaic sequences were deposited across eastern areas (Table 1; see also Monaghan, 2014). Namurian- and Westphalian-aged strata are characterised by cyclical lacustrine, fluvio-deltaic and marine sequences with abundant coal and organic-rich mudstones in some units (Table 1, Browne et al., 1999).

Further complexity in the Carboniferous succession results from syn-depositional volcanism and post-depositional intrusive magmatism (Cameron and Stephenson, 1985; Browne et al., 1999; Upton et al., 2004) and faulting is observed on numerous orientations and scales (Read et al., 2002; Underhill et al., 2008).

3. Subsurface energy resources, central Scotland

The Carboniferous geological succession in central Scotland contains a variety of exploited and prospective energy resources. Deep mining of coal fuelled industrial and population growth across central Scotland from the 12th century until the closure of Longannet Colliery in 2002. Mining exploited seams within the Westphalian Scottish Coal Measures Group and Namurian Passage, Upper Limestone and Limestone Coal formations (Table 1).

The oil-shale industry was initiated in central Scotland in the 1850s utilising the West Lothian Oil-Shale Formation (Hallett et al., 1985; Russell, 1990). Conventional oil and gas fields have also been exploited (Hallett et al., 1985; Underhill et al., 2008). More recently, Jones et al. (2004) mapped areas of coal bed methane and underground coal gasification prospectivity with exploratory wells subsequently drilled at Airth (DECC, 2010b) and license blocks allocated (CNR website, 2016). Coals within the Limestone Coal Formation, overlying Upper Limestone Formation and Coal Measures Group (Table 1) are considered prospective for coal bed methane and underground coal gasification.

In-place shale gas and shale oil resources were also identified in four prospective Carboniferous stratigraphic units containing organic-rich, variably mature shale at suitable depths: the Limestone Coal Formation, Lower Limestone Formation, West Lothian Oil-Shale unit and Gullane unit (Monaghan, 2014; Table 1). The mature organic-rich shales are stacked in sandstone/limestone/shale intervals up to 3000 m thick, with individual shale units varying in thickness from centimetres to 50 m and the percentage of shale in the succession varying from 0 to 85%. The lithologically variable sequence containing numerous relatively thin shales in central Scotland contrasts with some of the shale gas and shale oil plays around the world which utilise mudstone units hundreds of feet thick (e.g. Barnett, Marcellus shales: Jarvie, 2012), and with the thick Bowland-Hodder Shale of northern England (Andrews, 2013). Abandoned deep coal mine workings are locally present within the Limestone Coal Formation, tens of metres above prospective shale units within the same formation.

Abandoned coal mine workings are also being considered as mine water geothermal and heat storage resources (e.g. Campbell et al., 2010; Gillespie et al., 2013). Potential hot sedimentary aquifer geothermal resources have also been considered (Browne et al., 1987; Gillespie et al., 2013).

4. A crowded, complex subsurface

The highly populated area of central Scotland considered as an exemplar highlights the numerous potential uses of the deep subsurface as an energy source and store – an energy system (Fig. 2). Stacked within the subsurface rock volume, from hundreds of metres to kilometres depth are prospective shale, tight/hybrid oil and gas, coal bed methane, underground coal gasification, geothermal and possible heat storage resources, with locally utilised aquifers at shallower levels (Fig. 2). Whilst there is depth differentiation between the potential resources, the Carboniferous geology is such that the interbedded coals, mudstones, siltstones, sandstones and limestones form stacked and spatially overlapping resources (Fig. 2).

Faulting and igneous intrusion within the succession add complexity. One of the major uncertainties in onshore UK shale gas, coal bed methane and other unconventional resources is around the geological structure of basins at depth, including the spacing and character of faulting (e.g. The Royal Society, 2012; Andrews, 2013; Clarke et al., 2014; Monaghan, 2014). 3D seismic data is not generally available and UK legacy 2D seismic data is of variable quality for detailed study at Carboniferous shale- and coal-bearing stratal levels (e.g. Chadwick et al., 1995; Clarke et al., 2014), and it is relatively widely spaced, commonly 1–3 km line spacing, with a limited number of good quality well ties. Resultant geological uncertainty in assessments of resource volumes, fault spacing and fault linkage negatively influences environmental impact studies and public perception. For example, uncertainties in the position and spacing of faults have led to questions over induced seismicity and migration of fluids along potential hydrogeological pathways (The Royal Society, 2012; Clarke et al., 2014; Smythe, 2014). Thus criteria applied to shale resource estimations favour large stable basins without faulting (e.g. Charpentier and Cook, 2011) and knowledge of unfaulted volumes is critical in directional borehole drilling for exploration and production. Legacy mining data accurately records geometry and faulting in coal seams at depth and its utility in reducing uncertainty is described below.

In addition to the geological complexity, legacy coal mining results in an anthropogenically-modified subsurface to depths of hundreds of metres. The increase in subsurface permeability created by abandoned deep mining (either collapsed longwall, or partially collapsed ‘stoop and room’ (pillar and stall) workings) and mining infrastructure (shafts, roadways etc.) creates potential pathways for fluid (oil, gases, water) migration (Davies et al., 2014; Younger, 2016a) and changes in hydrogeochemistry (e.g. Ó Dochartaigh et al., 2015). In addition, deep mining will cause local variations in the stress state of the rock volume (NCB, 1975; Younger, 2016a). Unconventional resource exploration, whether for shale and involving hydraulic fracturing, or for coal bed methane/underground coal gasification, or for deep hot sedimentary aquifer geothermal therefore requires to avoid abandoned mine workings to avoid movement of injected fluids, oil and gas, mine waters etc.

Thus whilst the coal mining dataset can be used to reduce uncertainty in the geology, it also limits unconventional energy resource volumes. For example, legacy coal mining has necessitated the use of a vertical separation (or stand-off) zone in a shale resource estimation (discussed further below) highlighting how the extraction of one energy resource has effectively sterilised parts of another (Fig. 2). As well as being a consideration for unconventional energy resource volumes, the development of a separation zone concept may prove useful for the deep 3D subsurface planning and licensing that will be required for competing uses of the crowded subsurface. Given public and policy concerns around unconventional oil, gas and coal energy resources, the separation zone concept may help to positively influence the debate by providing assurance around integrity and isolation of anthropogenically-altered rock volumes.

5. Reducing geological uncertainty using legacy mining data

5.1. Dataset constraints

The dataset available to define the 3D geological framework in the exemplar area of central Scotland is typical of onshore UK. It includes 1970s, 1980s 2D seismic data, hydrocarbon well, stratigraphic borehole

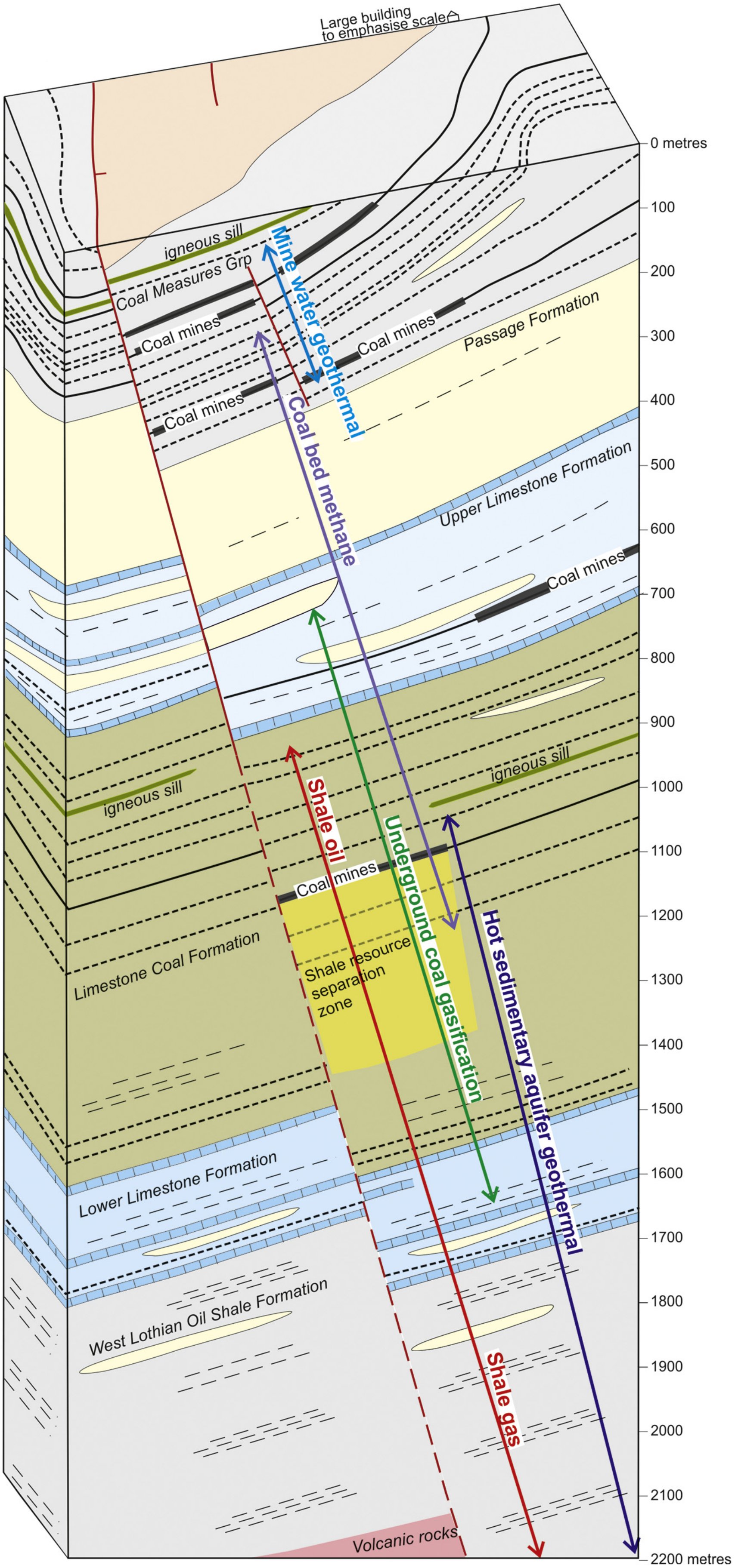
Large building to emphasise scale
igneous sill
Coal Measures Grp
Mine water geothermal
Coal mines
Coal mines
Coal mines
Passage Formation
Coal bed methane
Upper Limestone Formation
Coal mines
Underground coal gasification
igneous sill
igneous sill
Shale oil
Coal mines
Hot sedimentary aquifer geothermal
Shale resource separation zone
Limestone Coal Formation
Lower Limestone Formation
West Lothian Oil Shale Formation
Shale gas
Volcanic rocks
0 metres
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200 metres

Table 1
Summary of the Carboniferous stratigraphy of central Scotland (modified after Browne et al., 1999, Monaghan, 2014©DECC). The four prospective shale-rich intervals are colour-shaded. Thick red lines indicate the horizons modelled to define the rock volumes for each unit in the shale resource estimation. Abandoned deep coal mine workings (*) are present in the Coal Measures to Limestone Coal formations. Shale mine workings ($^{+}$) are present in the West Lothian Oil-Shale Formation.

Age	Group	West - Glasgow, Lanarkshire	West Lothian			East Lothian	East - Fife		
West-phalian	Scottish Coal Measures Group	Scottish Upper Coal Measures Formation							
		Scottish Middle Coal Measures Formation*							
		Scottish Lower Coal Measures Formation*							
Namurian	Clack - mannan Group	Passage Formation*							
		Upper Limestone Formation*		Bathgate Hills Volcanic Formation		Upper Limestone Formation.*			
		Limestone Coal Formation *				Limestone Coal Formation.*			
Visean		Lower Limestone Formation				Lower Limestone Formation.			
	Strathclyde Group	Lawmuir Formation	West Lothian Oil-Shale Formation^{+}			Aberlady Formation	Pathhead Formation	Kinghorn Volcanic Formation	West Lothian Oil-Shale unit
		Kirkwood Formation		West Lothian Oil-Shale Formation^{+}			Sandy Craig Formation		
							Pittenweem Formation		
		Clyde Plateau Volcanic Formation	Salsburgh Volcanic Formation		Gullane Formation		Anstruther Formation		Gullane unit
							Charles Hill Volcanic Member		
							Fife Ness Formation.		
					Arthur's Seat and Garleton Hills volcanic formations.				
Tour-naisian	Inverclyde Group	Clyde Sandstone Formation							
		Ballagan Formation							
		Kinnesswood Formation							

information, mine plan depth data and outcrop geology (Fig. 3). Data on bedrock hydrogeology, porosity, permeability, stress and rock strength from depths greater than a few hundred metres is limited to a small number of hydrocarbon wells and deep boreholes, and subsequent core analyses (e.g. Brereton et al., 1988; Ó Dochartaigh et al., 2011; Monaghan et al., 2012).

During the deep subsurface mining of coal, mining surveyors took detailed measurements to produce mine plans. In the UK, these plans are publically available records lodged with The Coal Authority. These legacy coal mine plans provide both the 3D geometry of coal seams and record fault information, to a level of accuracy and detail unlikely to be resolvable in all but the highest resolution 3D seismic data.

The coal mine plans show the extent of mining, position of shafts and roadways, depths of the mined coal seam (as spot heights or contours) and observed or interpreted fault planes. An ex-mine surveyor estimates that the uncertainty in the depth (Z) information on mine plans is commonly <1 m for mid-late 20th Century plans, with uncertainty in spatial extent (XY) slightly larger (W. McLean, *pers. comm.* 2016). This level of accuracy is far greater than the resolution of legacy 2D seismic data and the majority of 3D seismic data. Extensive mine plan data in central Scotland records coal seam workings to 500 m depth and a small number of collieries working in the latter half of the 20th Century record coal seam workings up to 1 km depth. Thus, used together with coal and hydrocarbon borehole datasets and seismic data, legacy mine plans can provide significant insight into subsurface geometry (3D contour maps), and character and spacing of faulting to reduce structural and volumetric uncertainty.

5.2. Reducing uncertainty in 3D geometry and faulting

Significant reductions in the uncertainty in 3D geology at depths of hundreds of metres subsurface can be achieved using surveyed mining datasets and lithostratigraphic intersections proven in legacy (often coal exploration) boreholes. In the central Scotland exemplar area, the patchy 1–10 km spacing of legacy 2D seismic data, its variable quality and the limited number of high quality well ties result in 3D geological framework models produced by the British Geological Survey incorporating additional borehole and mining datasets to reduce uncertainty. For example, to define the geometry of the base Limestone Coal Formation, Monaghan (2014) used 1803 km of 2D seismic data tied to 37 wells and also incorporated 514 borehole and extensive mine plan spot height and contour datasets to constrain a 3D digital geological model. An example is given in Fig. 4 to illustrate the detail and spatial coverage available in mine plans compared to widely spaced 2D seismic lines and sparse conventional hydrocarbon wells.

Mine plan data can be used to characterise fault spacing and geometry. Fault planes observed and measured in underground mining and noted on mine plans provide information on fault orientation, spacing and throw (Fig. 5). Faults can also be inferred between mined areas where offsets in measured depth spot heights or contours are observed. Where multiple coal seams were mined, 3D fault plane geometries can be deduced from stacked fault traces. For example, many faults in central Scotland can be mapped as planar structures to depths of a few hundred metres, with dips of 45–70° and throws of tens to hundreds of metres. Of particular significance are mined areas surveyed with *no*

Fig. 2. To-scale cartoon of depth ranges of potentially overlapping unconventional energy resources from the exemplar area in central Scotland. Carboniferous strata are shown with a vertical separation (stand-off) zone highlighted in yellow (see text for discussion and limitations) as a modification to a shale gas/oil resource assessment due to abandoned deep coal mines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

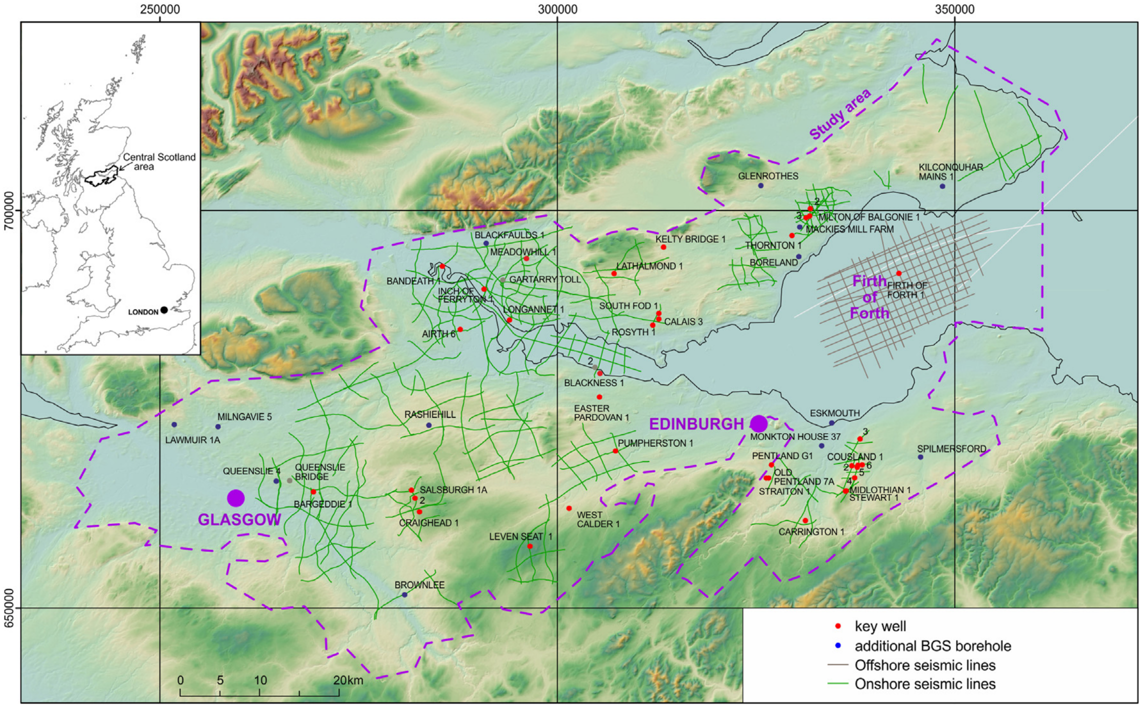

Fig. 3. Seismic and well data coverage map as utilised in a shale resource estimation (modified from Monaghan, 2014©DECC), to highlight a typical legacy seismic and deep well dataset spacing in the UK.

observed faulting for several kilometres or more, proving the extent of continuity and integrity of the rock volume within faulted Carboniferous blocks (Fig. 5). Thus whilst the exemplar area, along with other areas of the UK, may not meet the preferred 'large stable basins' criteria for shale exploration (Charpentier and Cook, 2011), mining data proves significant blocks of unfaulted geology exist and can be used to characterise the fault spacing, throw, extent etc. above an unconventional energy resource. Increasing the certainty of unfaulted rock volumes is also desirable to facilitate more predictable directional drilling, avoid potential environmental impacts and alleviate public concerns (IEA, 2012; The Royal Society, 2012).

The use of mine plan data to study the structure and geometry of the subsurface is not new (e.g. Rippon, 1984; Walsh and Watterson, 1988; Huggins et al., 1995) but integration with other datasets in 3D

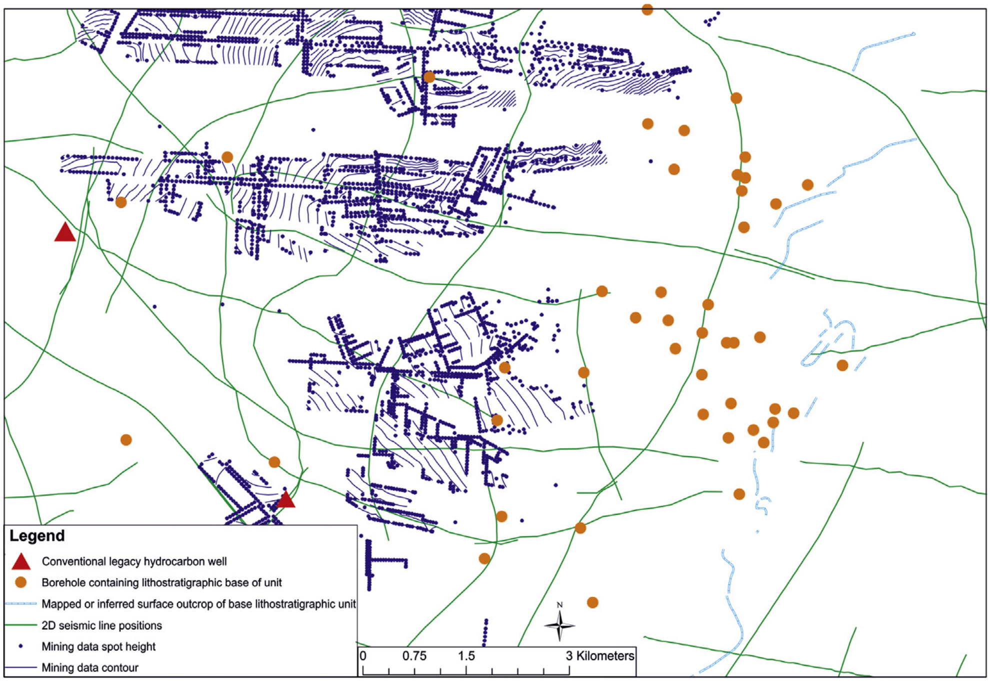

Fig. 4. The significant spatial extent of BGS-digitised mine plan data in defining subsurface 3D geology, in conjunction with seismic, borehole and well data points, using an example from the Upper Hirst Coal, Upper Limestone Formation, central Scotland.

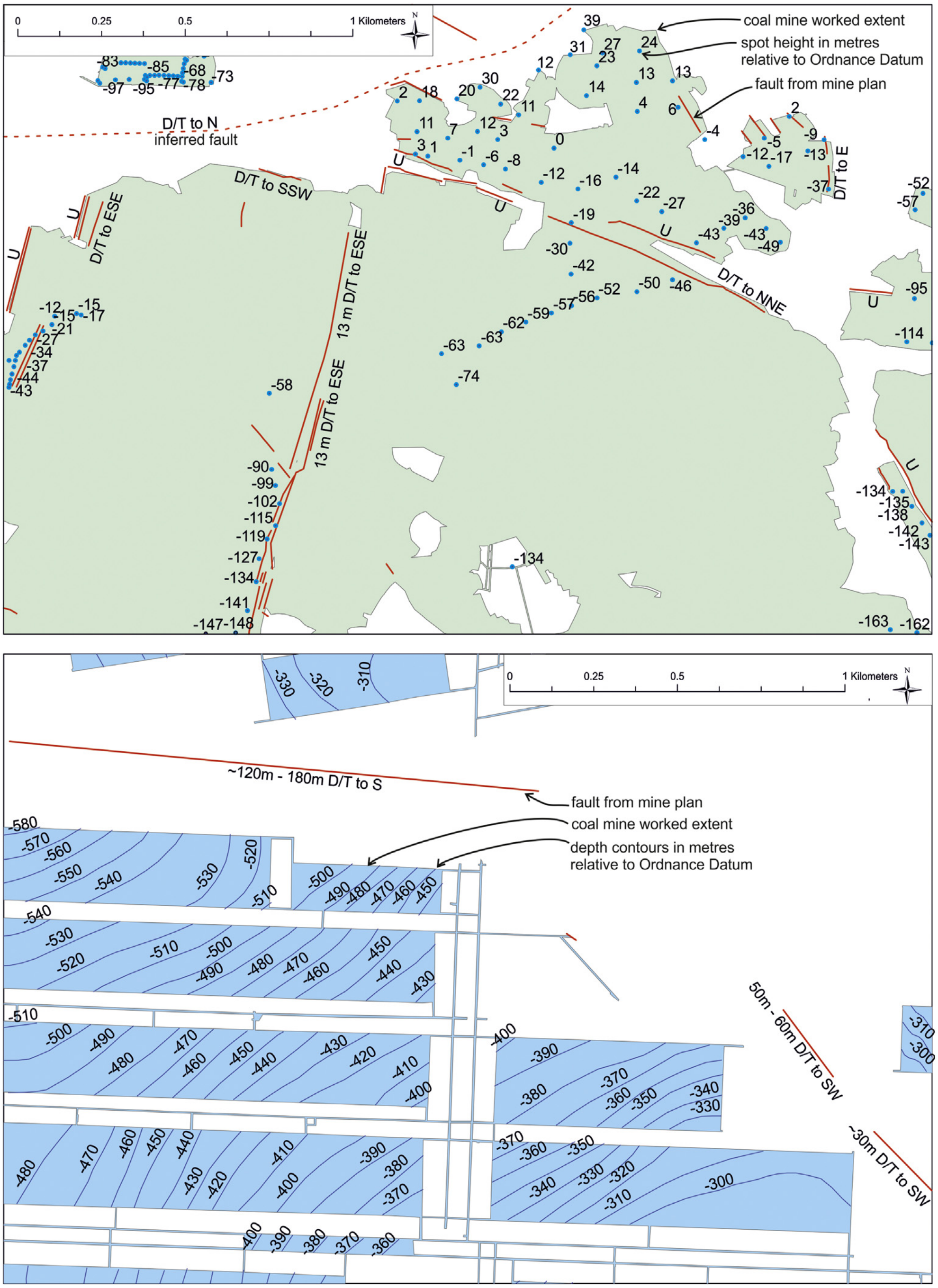

Fig. 5. Digitised BGS extracts of coal mine plans showing worked extent, spot height and contour measurements and observed and inferred faults. D/T = downthrow, U = unknown direction and size of throw. The plan above (eastern Glasgow area) illustrates several orientations of faulting, the plan below (Clackmannan area) has fewer faults of larger throw. Both plans shown at the same scale and highlight worked panels over 1 km across with no observed faults – they give a good indication of local fault orientation and spacing.

modelling software and application to a range of unconventional resources is not widely recognised, as coal mining knowledge and research has diminished with the demise of the industry.

6. Adapting unconventional resource estimation methodology in legacy mining areas

This section provides a case history of how abandoned coal mines reduced the volume included in a shale gas and oil resource estimation, as well as an adaption of that methodology for a lithologically variable succession (a ‘hybrid play’).

In the UK, shale gas/oil well production data is not available to estimate a Technically Recoverable Resource such as is possible in the USGS/USEIA “top-down” shale estimates (e.g. Charpentier and Cook, 2011; USEIA (U.S. Energy Information Administration), 2011). Instead a ‘bottom up’ approach based on the geology, organic geochemistry and maturity of the rock volume has been taken to produce a geologically-based in-place resource assessment (Andrews, 2013, Monaghan, 2014; Fig. 6). Similar ‘bottom up’ approaches to resource estimation have been taken by TNO (2009) and

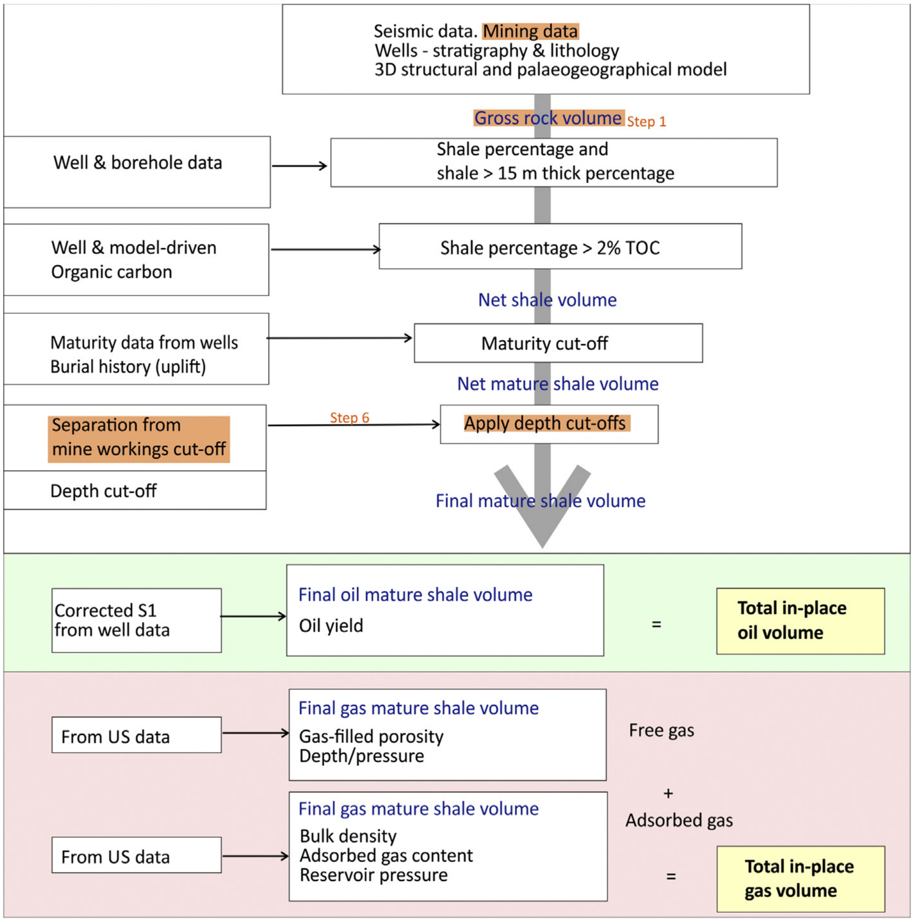

Fig. 6. Summary of methodology for an adapted 'bottom-up', geologically based, in-place shale gas and shale oil resource assessment applicable to a lithologically variable succession in a legacy mining area. Steps involving mining data highlighted orange.
Modified from Andrews (2013), Monaghan (2014)©DECC.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (2012, 2016) and some similar geological criteria on total organic carbon, depth etc. have been applied in the 'risked oil and natural gas in-place' and 'unproved technically recoverable oil and natural gas resource' estimates of the world shale resources by USEIA (2013).

The adapted methodology for the shale resource estimation follows a number of steps (Fig. 6).

1. 3D digital geological depth models were used to define gross rock volumes for the stratigraphic units of interest. Legacy mining, seismic and borehole data were used to constrain the 3D geology and faulting.
2. To incorporate lithological variability, for each prospective unit, maps of the percentage of shale, and percentage of shale over 15 m thick, were gridded. The maps were based on measured values from wells, boreholes and interpolations guided by palaeogeographic reconstructions. Igneous rocks were included in the non-shale intervals.
3. Using sample analysis data, maps were also interpolated of shale with Total Organic Carbon (TOC) >2%, a criteria required for shale gas plays (TNO, 2009; Charpentier and Cook, 2011; Gilman and Robinson, 2011)
4. The gross rock volume was reduced to an organic rich, shale rock volume by multiplying by percentage shale and TOC > 2% (for input as P10), or percentage shale >15 m thick and TOC > 2% (for input as P95).
5. These volumes were truncated upwards by a depth cut-off of 805 m related to likely pressure/flow rates, and by oil and gas maturity–depth surfaces interpolated from well sample maturity measurements.
6. Due to the abandoned deep coal mines in relative proximity to the shale resource, the volume was truncated by an additional mining-related depth cut-off, created by including a vertical separation zone from mine workings deeper than 500 m (Section 6.1).
7. Net mature, organic rich shale volumes were then converted to gas- and oil-in-place figures and a Monte Carlo simulation was used to determine a range of P10–P50–P90 values. Critical data for UK Carboniferous shales (e.g. recovery factory, gas filled porosity etc.) is not publically available resulting in the range of in-place resource estimation values (Andrews, 2013; Monaghan, 2014).

Within this methodology, mining data assists in reducing uncertainty in initial gross rock volumes (Step 1) and application of the mining-related vertical separation zone (Step 6) limits the mature, organic-rich shale volume input to the gas- and oil-in-place calculation (Step 7).

6.1. Mining separation zone

In the central Scotland exemplar, abandoned coal mines are widespread across the areas underlain by strata with shale resource potential (Fig. 1). However, the majority of the abandoned coal mines are at depths <500 m, well above the prospective resource that is defined by an upwards cut off at 805 m relating to pressure and flow rate. However, in some spatially restricted areas, the Limestone Coal Formation prospective shale units are within tens of metres of a limited number of abandoned mines >500 m depth (see Monaghan, 2014 Fig. 63). Thus

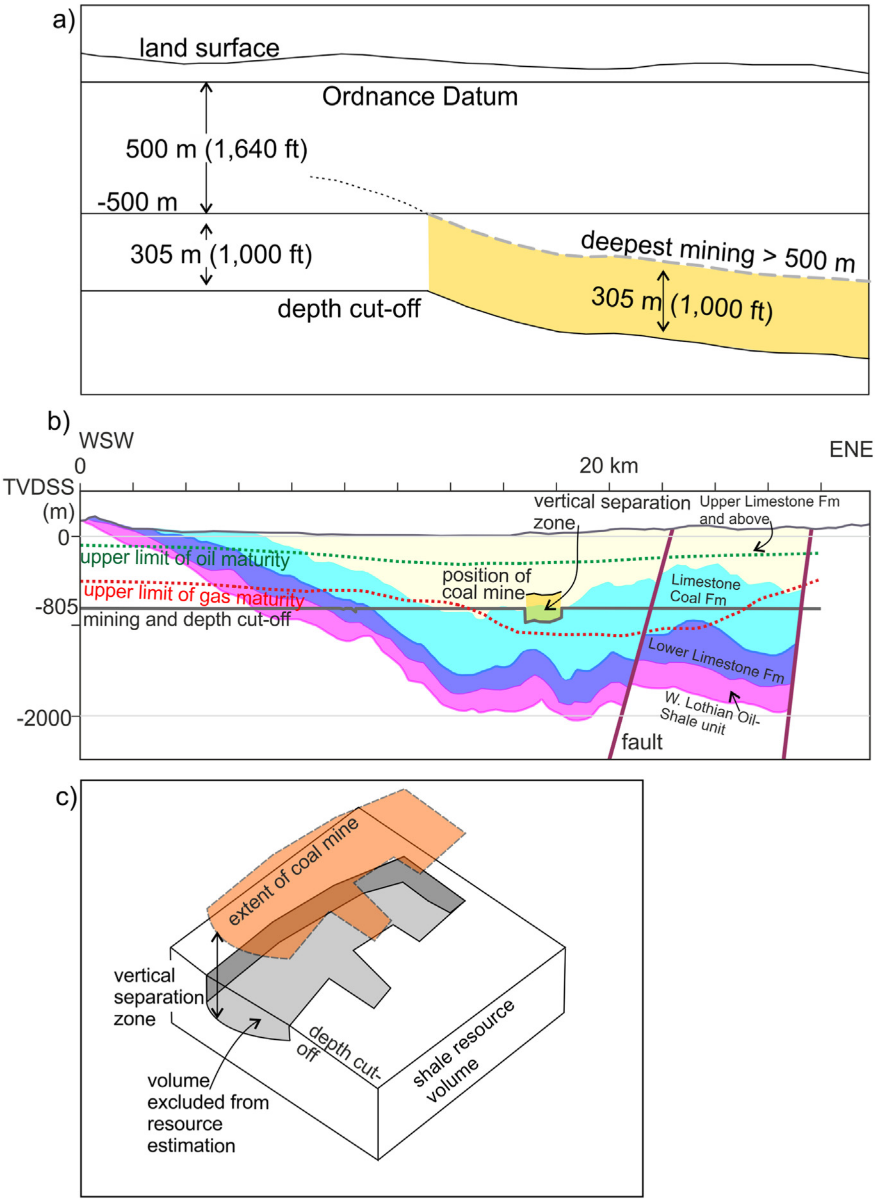

Fig. 7. a) Sketch showing the 805 m depth cut-off applied in the central Scotland shale oil/gas resource estimation, modified to include a vertical separation zone of 305 m from any deep mine workings present below 500 m depth (in yellow) b) Cross-section illustrating a coal mine vertical separation zone (in yellow) and cut-off as output from the 3D geological model in the Clackmannan area. Note the modelled surfaces appear irregular and with considerable relief due to the high vertical exaggeration of the section and because smaller faults have been excluded from the model. TVDSS = true vertical depth subsea, modified after Monaghan (2014©DECC) c) Cartoon to illustrate a volume excluded from a resource estimation as a result of applying a vertical separation zone to the resource volume. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for shale resource estimation, a mining-related vertical separation (or 'stand-off') zone is incorporated, in addition to the depth cut-off related to pressure/likely flow rate (Fig. 7). The vertical separation zone is applied over the spatial extent of mine workings >500 m depth, resulting in a rock volume within the 3D geological model being excluded from the resource estimation (Fig. 7).

The thickness of the vertical separation zone would ideally be based on evidence of the height of stimulated hydraulic fractures observed in central Scotland on rocks of similar type and with similar faulting patterns, or failing that on geomechanical studies using central Scotland rock properties, stress fields and existing fault patterns. There is no central Scotland specific data available at the current time. Baptie et al. (2016) discuss the limited data on seismicity, stress fields and rock strength data in greater detail.

In the USA (Kentucky, Pennsylvania and West Virginia), the hydraulic fracturing of the Marcellus shale is undertaken beneath active coal mines. However, the vertical separation distance is large, approximately 2200 m and hydraulic fracturing of the shale is not covered by specific coal-mine related regulation. In the USA, regulations are in place to ensure special casing/plugging of wells through coal-bearing intervals, for coal pillars to be left around oil/gas wells, well plans to be available to coal operators and extra documentation for when mining is within 300 ft. (90 m) of a well (e.g. Coal and Gas Resources Coordination Act implemented as Pennsylvania code http://www.pacode.com/secure/data/025/chapter78/chap78toc.html).

Published plots of simulated fracture heights on various shales in the USA show maximum fracture heights of around 500 m, with the majority being much smaller than that (Fisher and Warpinksi, 2011). A summary of simulated fracture heights worldwide gave a probability of 1% for a vertical extent >350 m (Davies et al., 2012), though the approach was purely statistical and blind to local geology (Davies et al., 2013).

For the central Scotland shale resource estimation, a 305 m (1000 ft) vertical separation zone below abandoned coal mines deeper than 500 m was excluded from the shale in-place resource estimation, otherwise a minimum depth cut-off of 805 m below Ordnance Datum was used (Fig. 7). This mining-related vertical separation distance should not be used to guide exploration, well testing or regulation; specific local geomechanical and fracture growth height studies are required to give a more robust figure.

In this exemplar, the separation zone was vertical, related to the expected vertical propagation direction of simulated fractures required for shale gas and oil exploration. Developing the concept more widely for a multiplicity of energy resources would involve a 3D separation zone (i.e. in any direction) in which vertical and horizontal components would vary in size dependent on subsurface conditions.

For example, utilising knowledge from previous deep mining, Younger (2016a) considers the 305 m vertical separation zone used in the shale resource exemplar a conservative figure based on a 105 m statutory stand-off distance (in any direction) in longwall coal mines (mine to aquifer or seabed), where the extraction of coal has ‘far greater stratal disruption and induced seismicity than shale gas fracking could ever produce’, and an example is given of no evidence of hydraulic connection between mined areas that are 105 m apart. The example given by Younger (2016a) further highlights the use of legacy mining data and knowledge gained on the geomechanical and hydrogeological properties of Carboniferous successions.

The spatial extent of mine workings >500 m depth across the exemplar area, and the thickness of the vertical separation zone are relatively small compared to the shale resource extent and thickness. The impact of the vertical mining separation zone on resource volumes is therefore not critical at the regional scale of study, though it is of great importance in demonstrating due consideration to an anthropogenically-altered subsurface. However, the impact of a separation zone on resource volumes at local scale, and on other energy resources facing different constraints could be considerable.

7. Discussion: Unconventional resources in a crowded subsurface

Whilst the legacy of abandoned mine workings can reduce uncertainty in geology, hydrogeology, geomechanics etc., this anthropogenic alteration of the subsurface illustrates challenges in effective exploitation and mitigation of environmental impact of other deeper and adjacent unconventional energy resources. For example, the high permeability pathways created from the deep to shallow subsurface by mine workings and shafts.

Using an exemplar of a shale resource estimation from central Scotland, the exclusion of a vertical separation (or stand-off) zone between abandoned deep coal mines and the prospective resource has highlighted how the extraction of one energy resource has sterilised parts of another. In the exemplar area, in common with others across the UK and parts of Europe, the geological character of the Carboniferous is such that a range of energy resources from shale to coal bed methane to geothermal are prospective at overlapping depths from hundreds of metres to kilometres subsurface (Fig. 2).

In Europe, a range of unconventional resources are documented in similar coal and shale-bearing Carboniferous successions, some of which contain deep abandoned coal mines. For example the Lorraine basin in France (Collon et al., 2015 mine water geothermal; USEIA 2013 shale); the Rhine-Westphalia basin in Germany (USEIA, 2013; BGR, 2016; shale), Carboniferous strata of The Netherlands/Belgium (USEIA 2013 shale; coal bed methane Limburg area) and Poland (USEIA 2013, shale, coal bed methane). The methodology and concepts described for the exemplar area therefore appear to have much wider use.

In such areas, approaches require to be developed for 3D planning and licensing of the deep subsurface. These should include improved geological and hydrogeological datasets to study environmental impacts in an anthropogenically altered rock volume. Competing demands and subsurface planning have, thus far, been considered at shallower levels beneath cities (e.g. Van der Meulen et al., 2016), in the context of energy storage (Bauer et al., 2013; Gaelle Bader et al., 2016) or between one or two resources (e.g. Ferguson, 2013; Bentham et al., 2014). Van Campenhout et al. (2016) recognise the need to view the deep and shallow subsurface as a system, however an understanding of competing demands, processes and environmental impacts of legacy mining *and* future unconventional energy resources appears to be in its infancy. Developing a 3D separation zone concept between legacy mining and energy resources could form a key part of future subsurface planning and licensing.

The exploitation of the deep subsurface is strongly controlled by public and political considerations, for example at the time of writing the Scottish Government has placed a moratorium on unconventional oil and gas consents (shale, coal bed methane; Scottish Government, 2015a) and does not support underground coal gasification (Scottish Government, 2016), whereas geothermal energy is a major ambition (Scottish Government, 2015b). In contrast, in England the UK Government is supporting shale gas exploration (e.g. Gov.uk website, 2016). Further development of the concept of, and data behind, 3D spatial separation zones and planning could positively inform the public and policy debate on utilising the crowded subsurface energy resources by summarising technical data on the geomechanical and hydrogeological integrity and isolation of rock volumes in a simple way.

8. Conclusions

The UK onshore, in common with similar strata in The Netherlands, Belgium, France, Germany and Poland, contains a multiplicity of overlapping prospective unconventional energy resources in deeply buried Carboniferous successions, including shale gas/oil, coal bed methane, underground coal gasification, mine water and hot sedimentary aquifer geothermal and energy storage. Key aspects for evaluating the resources (e.g. geometry, faults, and fluid and geomechanical processes) are commonly poorly constrained by widely spaced legacy 2D seismic and well datasets. This leads to uncertainty in the viability of exploitation, and concerns over environmental impact.

Previous deep subsurface mining of coal has provided a legacy of accurate, surveyed mine plans, lithological borehole data (this paper) and understanding of hydrogeological and geomechanical processes (see Younger, 2016a) above and adjacent to the unconventional energy resources. This legacy of anthropogenic activity of the subsurface provides measured data to reduce uncertainty and could be greater utilised for site specific study. For example, mine plans define 3D geometry of the rock strata and faults at hundreds of metres depth in the subsurface. An important outcome is to prove *unfaulted* subsurface volumes in areas considered structurally complex, and to do so using mine plans considered to be of sub-metre scale accuracy in Z (depth), far greater than the resolution of seismic data.

To negate environmental impacts to the hydrosphere, biosphere and anthroposphere, as well as for effective exploitation, unconventional energy resources (excepting mine water geothermal) require to avoid hydrogeological and geomechanical connection with legacy mine workings. An exemplar of a shale resource estimation from central Scotland illustrates the concept, adapting methodology in a legacy mining area to remove a vertical separation (or stand-off) zone relating to potential hydraulic fracture heights, from the prospective rock volume. Further study is required to better determine the size of 3D separation zones, however the impact of the extraction of one resource in reducing the volume and sterilising parts of another is clear. Given the crowded nature of the multiple subsurface energy resources in the exemplar area and across other parts of the UK and western Europe, the need for development of the 3D separation zone concept to deep geological 3D subsurface planning and licensing is evident.

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