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Viewpoint

The importance of characterizing uncertainty in controversial geoscience applications: induced seismicity associated with hydraulic fracturing for shale gas in northwest England

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ABSTRACT

Fracking of the Preese Hall-1 well in 2011 induced microseismicity that was strong enough to be felt. This occurrence of 'nuisance' microearthquakes, unexpected at the time, was a major factor resulting in adverse public opinion against shale gas in the UK and was thus of significant political importance. Despite this, and notwithstanding the technical importance of this instance of induced seismicity for informing future shale gas projects, it has received little integrated study; contradictory results have indeed been reported in analyses that lack integration. This instance therefore provides a case study to illustrate how a small but significant multi-disciplinary geoscience dataset may be put to best use, including how best to quantify uncertainties in key parameters, which may themselves be relatively poorly quantified but whose values may significantly affect the ability to understand the occurrence of induced seismicity. The best-recorded event in this induced microearthquake sequence (at 08:12 on 2 August 2011) is thus assigned an epicentre circa British National Grid reference SD 377358, south of the Preese Hall-1 wellhead, a focal depth of ~2.5 km, and a focal mechanism with strike 030°, dip 75°, and rake −20°, this NNE-striking nodal plane being the inferred fault plane. Like other parts of Britain, this locality exhibits high differential stress, with maximum and minimum principal stresses roughly north-south and east-west. This instance indeed fits an emerging trend of the occurrence of relatively large induced earthquakes in localities with high differential stress; such an association was predicted many years ago on the basis of experimental rock mechanics data, so observational confirmation might well have been anticipated and should thus not have been unexpected. Many steep faults, striking NNE-SSW or NE-SW, mostly Carboniferous-age normal faults, are present; the stress field is favourably oriented for their left-lateral reactivation, southward leakage of fracking fluid into one such fault having presumably caused the induced seismicity. Given the pervasive presence of similarly oriented faults, future occurrences of similar induced seismicity should be planned for; they pose a significant technical challenge to any future UK shale-gas industry.

1. Introduction

The first project to apply hydraulic fracturing for the development of shale gas in the UK, utilizing the Bowland Shale Formation and other Early Carboniferous shales (Table 1), took place in the spring of 2011 from the Preese Hall-1 borehole (wellhead at British National Grid [BNG] reference SD 37525 36584) near Blackpool in northwest England (Fig. 1). The associated 'fracking' caused induced seismicity including microearthquakes with magnitude (M_L) up to 2.3 (e.g., Galloway, 2012), two of which were large enough to have been felt. Such activity, within the usually relatively aseismic continental crust of Britain, resulted in intense public concern and led to the imposition of a UK government moratorium on fracking, which lasted more than a year. Shale gas and fracking remain controversial topics in the UK; for example, in January 2015 the Scottish government imposed a second moratorium, covering development in Scotland of unconventional energy technologies including shale gas (e.g., Freeman, 2015), citing in part the uncertainties involved. Characterization of any

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Table 1
Seismic velocity model.

H (m)	V_P (m s^{-1})	V_P/V_S	V_S (m s^{-1})	ν	Stratigraphy
647	3452	1.99	1735	0.331	MMG to 207 m; SSG to 423 m; SBS to 647 m
1394	4384	1.99	2203	0.331	SBS to 1030 m; MM to 1170 m; CS to 1247 m; PLCM to 1279 m; MG to 1394 m
2065	4812	1.81	2659	0.280	MG to 1993 m; BSG to 2065 m
∞	4000	1.68	2381	0.226	BSG to 2507 m; PDL to 2576 m; HOM to 2744 m; CLL to 2773 m (not bottomed)

H is the depth of the base of each layer, V_P and V_S are the P- and S-wave velocities, and ν is Poisson's ratio, which relates to V_P/V_S in accordance with standard theory (e.g., Westaway and Younger, 2014). This seismic velocity model, used for earthquake location using the local seismograph stations (see the online supplement for details), is based on that from Clarke et al. (2014), except that layer 4 has been continued downward indefinitely rather than being superseded by a layer representing Lower Palaeozoic metamorphic basement at 2520 m. Stratigraphic information is from de Pater and Baisch (2011). Stratigraphic codes denote the following: MMG, Mercia Mudstone Group (Late Triassic); SSG, Sherwood Sandstone Group (Early Triassic); SBS, St Bees Sandstone Formation (Early Triassic); MM, Manchester Marls Formation (Late Permian); CS, Collyhurst Sandstone Formation (Early Permian), with base at the Variscan Unconformity; PLCM, Pennine Lower Coal Measures Formation (Late Carboniferous [Silesian]; Westphalian); MG, Millstone Grit Group (Late Carboniferous [Silesian]; Namurian); BSG, Bowland Shale Formation (late Early Carboniferous [Dinantian]; Viséan to Late Carboniferous [Silesian]; Namurian); PDL, Pendleside Limestone Formation (Early Carboniferous [Dinantian]; Viséan); HOM, Hodder Mudstone Formation (Early Carboniferous [Dinantian]; Viséan); and CLL, Clitheroe Limestone Formation (Early Carboniferous [Dinantian]; latest Tournaisian to earliest Viséan). These codes are searchable (at http://www.bgs.ac.uk/lexicon/lexicon.cfm) to provide additional detail.

site involves investigating a complex 3-D rock volume, which is anisotropic and heterogeneous at multiple scales, primarily on the basis of 1-D wellbores and geophysical data with limited resolution. Conceptual geological models summarizing any such characterization attempt are inherently uncertain (Bond et al., 2007a, 2012; Lindsay et al., 2013). In areas of geoscience where the 'social licence to operate' requires a high level of public confidence in geological models (e.g., onshore oil and gas; onshore carbon capture and storage; and radioactive waste disposal), it is essential to identify the sources of potential uncertainty and to try to minimize these uncertainties, while being transparent about the sources and magnitude of the uncertainties.

Injection of fluid under high pressure, during fracking, alters the state of stress around a borehole, potentially bringing adjacent pre-existing planes of weakness to the condition for failure. To characterize the nuisance arising from this cause, as a result of

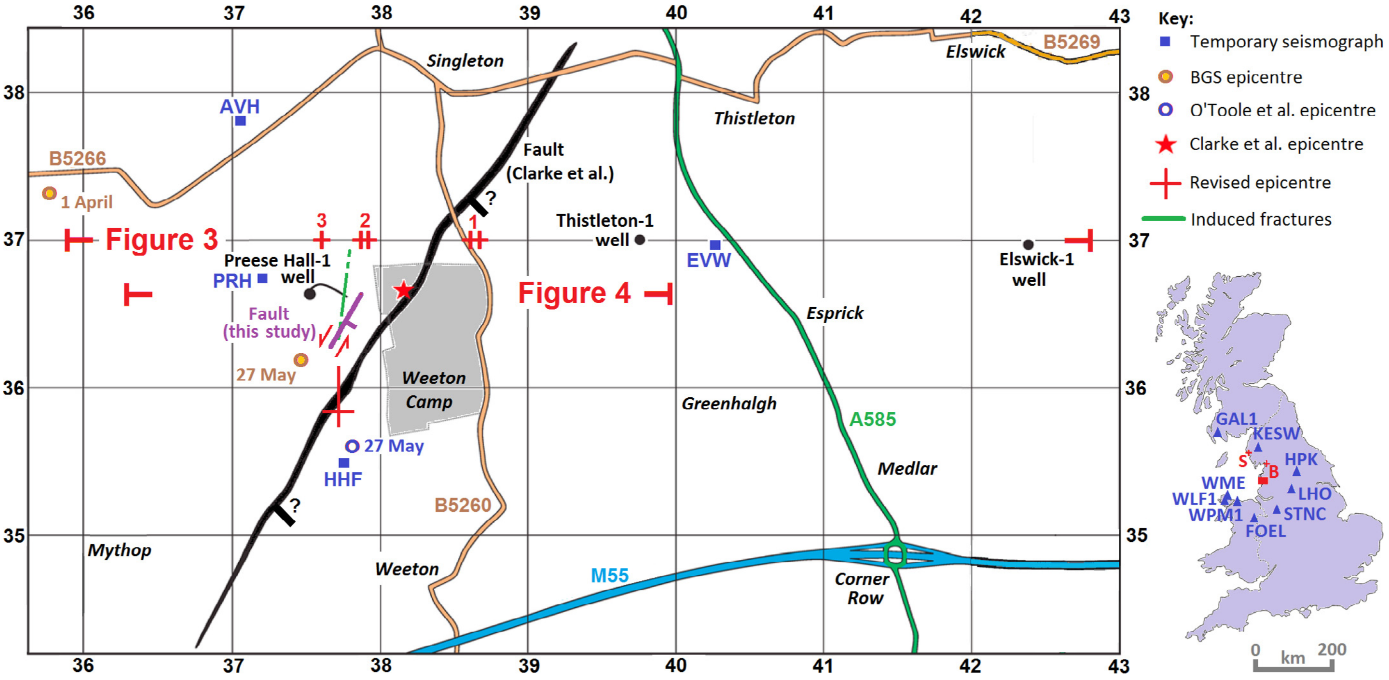

Fig. 1. Map of the Preese Hall-1 well and its surroundings, modified after Fig. 1 of Clarke et al. (2014), showing the planform of this deviated well, the temporary seismograph stations used to investigate the 2 August 2011 microearthquake, the resulting epicentral locations, and the positions of the adjacent Thistleton-1 (BGS inventory code SD33NE17; co-ordinates SD 39760 37000) and Elswick-1 (BGS inventory code SD43NW15; co-ordinates SD 42380 36965) wells and of the cross-sections in Figs. 3 and 4. The epicentral locations determined by BGS (Galloway, 2012) for the 1 April 2011 and 27 May 2011 events and by O'Toole et al. (2013) for the latter event are also shown. My revised epicentral co-ordinates for the 2 August 2011 event have been drawn with nominal error bars indicating uncertainties of 100 m, except that pointing north has been extended in recognition of the fact (evident for reasons discussed in the text) that this location is subject to significant systematic error and probably lies well north or NNW of the co-ordinates marked. Crosses labelled 1, 2 and 3 mark the points where faults 1–3 in Fig. 3 intersect the line of this seismic section at the top of the Clitheroe Limestone Formation (the dual symbols for faults 1 and 2 mark the footwall and hanging-wall cutoffs). The geometry of the seismogenic fault inferred by Clarke et al. (2014) (Fig. 4) is depicted at a depth of 2930 m; that inferred in the present study is depicted at a depth of 2740 m (Fig. 4), projected SSW for ~500 m assuming a N30°E-S30°W strike, and ornamented to indicate both the polarity of the overall fault offset and the inferred sense of coseismic slip in 2011. The induced fractures are depicted as emanating at a N7°E-S7°W azimuth (see the main text) from a notional point near the bottom of the Preese Hall-1 well. Their length depicted is ~300 m, which is appropriate for the volume of fracking fluid used if they are equidimensional (Westaway and Younger, 2014); they are shown dashed for a further ~300 m, which is plausible if their vertical growth was inhibited by variations in rock-mechanical properties, so they developed longer in the sideways direction instead (see the main text). It is suggested that the probable true location of the induced seismicity is at the intersection of this induced fracture trend with the fault line (from this study), most likely several hundred metres south or SSE of the Preese Hall-1 wellhead. Inset shows location, along with a selection of the permanent seismograph stations (none closer than ~80 km; see Galloway, 2012, for further details) that recorded the largest Preese Hall microearthquake on 1 April 2011 and the sites from which in situ stress measurements are discussed (B, Burton-in-Kendal; S, Sellafield).