Local Magnitude Discrepancies for Near-Event Receivers; Implications for the UK Traffic Light Scheme

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Abstract

Local seismic magnitudes provide a practical scale for quick implementation of regulation designed to manage the risk of induced seismicity, such as Traffic Light Schemes. We demonstrate that significant magnitude discrepancies occur when seismic events are recorded on nearby stations (<5km), which can be a unit higher values than those observed on more distant stations. This is due to the influence of sedimentary layers, as these shallow layers are generally lower in velocity and more attenuating than the underlying crystalline basement rocks, and require a change in the attenuation term of the M_L scale. This has a significant impact on the UK's hydraulic fracturing Traffic Light Scheme whose 'red' light is set at M_L = 0.5. As the nominal detectability of the UK network is M_L = 2, this scheme will entail the deployment of monitoring stations in close proximity to well sites. Using data collected from mining events near New Ollerton, Nottinghamshire, we illustrate the effects proximity has on travel path velocities and attenuation, then perform a damped least squares inversion to determine appropriate constants within the M_L scale. We show that the attenuation term needs to increase from 0.00183 to 0.0514, and demonstrate that this higher value is representative of a raypath within a slower, more attenuating sedimentary layer compared to the continental crust. We therefore recommend that the magnitude scale $M_L = log(A) + 1.17log(r) + 0.0514r - 3.0$ should be used when local monitoring networks are within 5km of the event epicentres.

Keywords: Earthquake monitoring, Induced seismicity, Seismic attenuation

1. Introduction

Any subsurface activity that alters the state of stress in the ground is capable of triggering seismic activity on pre-existing faults. In the United Kingdom (UK), coal mining has long been the dominant cause of these anthropogenic events (Wilson et al. 2015). However, with the coal industry in decline, concerns about induced seismicity have switched to the nascent shale gas industry.

In response to these concerns, the UK's Oil and Gas Authority has imposed a Traffic Light Scheme (TLS) to manage induced seismicity, with an "amber" warning set at a magnitude of M_L = 0.0, and a "red" light at M_L = 0.5, where injection must cease followed by a 24hr monitoring period (Department of Energy and Climate Change 2015). A local magnitude scale is used, as opposed to other scales such as the moment magnitude, as the measurement is less complicated: the local magnitude scale is empirical, directly relating the measured maximum displacement amplitude (typically associated with the S-wave arrival) and hypocentral distance to M_L. For such a scheme to maintain the confidence of both the industry, the regulators, and the general public, the local magnitude scale used to quantify event magnitudes must be robust and well constrained.

The existing UK local magnitude scale (Ottemöller & Sargeant 2013) was calibrated using larger events, most of which were recorded at considerable distance (>50km) from their epicentres. In contrast, the TLS will be administered with local networks within 5km of the epicentres of any events that may occur. In this paper we seek to highlight issues with the Local Magnitude (M_L) scale when used on shallow events located in close proximity to the receivers.

In April 2011, hydraulic fracturing operations at the Preese Hall well, near Blackpool UK, caused an M_L 2.3 earthquake (Clarke et al. 2014). This event was felt by local people causing considerable public concern, despite its relatively small magnitude. In response the British Geological Survey (BGS) installed temporary seismic stations close to the epicentre and recorded several subsequent, smaller events during further hydraulic fracturing stages.

As the first recorded instance of seismicity induced by hydraulic fracturing in the UK, these events have been the subject of much interest (e.g. O'Toole et al. 2013; Westaway 2016). One aspect of the data that was immediately apparent was the discrepancy in local magnitude. Ground motions measured using a local monitoring station located at hypocentral distances of 1.5km differed significantly in comparison to those calculated using the national UK seismic monitoring network, the nearest station of which was at a distance of approximately 80km.

Based on the existing local magnitude scale, the largest event recorded by both distant and local stations had a magnitude of M_L = 1.5 calculated on the national network, but M_L = 2.3 on a local station located at an epicentral distance of 1.5km (Figure 1). Because of this discrepancy, magnitudes of events observed on only the Preese Hall network were assigned though scaling relative to a 'master' event using the equation

$$M_{DetectEvent} = M_{MasterEvent} - log\left(\frac{A_{DetectEvent}}{A_{MasterEvent}}\right), \quad (1)$$

where A is the maximum amplitude measured on the waveform, and M is the magnitude of the master or detected event (Eisner et al. 2011).

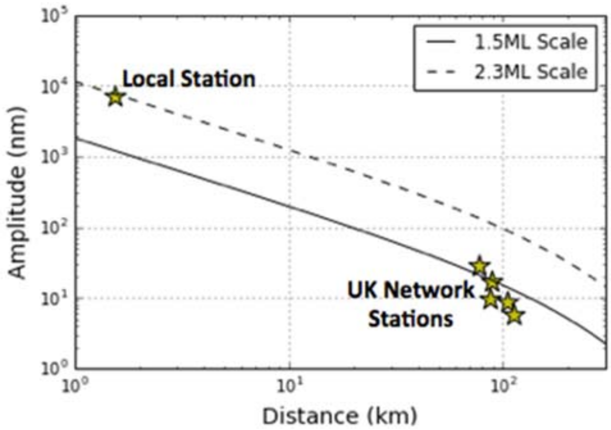

Figure 1: Measured ground displacements for the largest event at Preese Hall to be recorded by both local and distant stations (yellow stars). The expected displacement for M_L = 1.4 and M_L = 2.3 events are shown by the solid and dashed lines, respectively. These measurements show the discrepancies in ground motion between a locally installed seismic station and the more distant UK seismic network.

The BGS seismic catalogue shows several other examples of magnitude discrepancies for events in close proximity to receivers, and several studies have also identified either overestimation in magnitudes or larger than predicted amplitudes at close distances in other settings (Atkinson et al. 2014; Scognamiglio et al. 2012). A common explanation for these discrepancies is that nearby stations may be more impacted by event location errors. However, in Figure 2 we show the impact of a 0.5km location error: while nearby stations are more impacted, the resulting magnitude error is insufficient to account for the discrepancies observed at Preese Hall. Moreover, if event location errors, or local site effects, were causing magnitude errors, we would expect these discrepancies to be random in nature, leading to both under- and overestimates of event magnitudes. Instead, we tend to see only overestimation of magnitudes at close distances: a systematic error implying a methodological issue with the use of local magnitude scales.

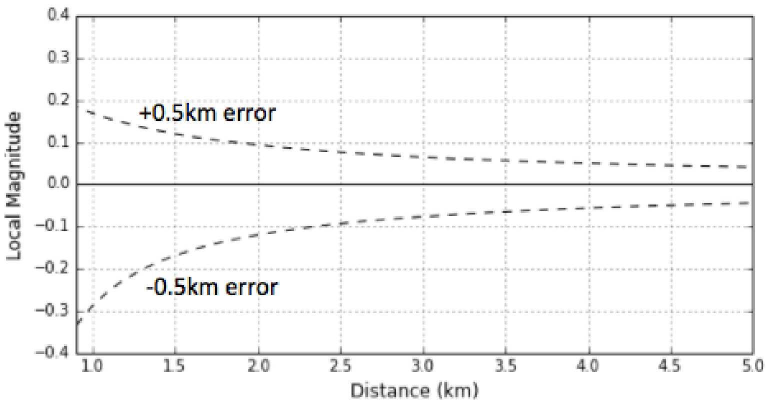

Figure 2: Impact of a introducing a positional error of 0.5km on calculated magnitudes. At a distance of 1.5km, comparable to Preese Hall, the maximum magnitude discrepancy is no more than 0.2 units.

2. Local Magnitude (M_L)

Ottemöller and Sargeant (2013) developed the most recent M_L scale for the United Kingdom, replacing the original Hutton and Boore (1987) scale which was derived for Southern California. The inversion of 1482 observations from 85 earthquakes on 50 stations, anchored to a reference distance of 100km led to the following local magnitude scale

$$M_L = log(A) + 0.95log(r) + 0.00183r - 1.76 \ , \quad (2)$$

where A is horizontal-component ground displacement amplitude filtered with Wood-Anderson response in nanometers and r is the hypocentral distance in km. As observations were taken from earthquakes recorded on the UK network, the dataset used by Ottemöller and Sargeant (2013) is dominated by events with magnitudes larger than M_L = 2.0, with epicentral distances > 50km. As a result the current UK M_L scale has not been well calibrated for small-magnitude, near-receiver events, such as those recorded at Preese Hall, or potentially at future shale gas extraction sites.

The Richter equation for M_L is defined as

$$M_L = log(A_{WA}) - log(A_0) + C \ , \quad (3)$$

where A_{WA} is zero-to-peak amplitude measured on a standard horizontal Wood-Anderson seismograph, -log(A_0) is the displacement correction term, and C is a correction term for individual stations. The displacement correction term accounts for geometrical spreading, attenuation, and calibrates the scale to Richter's original definition, while C is a constant used to correct site-effects at each station. In this equation, the displacement amplitude is given in mm, and gain corrected to a Wood-Anderson seismograph. To remove this requirement, the UK M_L scale applies the gain correction

$$log(A_{WA}) = log(A) + log\left(\frac{2080}{10^6}\right). \quad (4)$$

For a local earthquake, the S-wave amplitude A can be expressed as a function of hypocentral distance r by

$$A(r) = A_0 r^{-\beta} e^{\frac{-\pi f r}{vQ}} \ , (5)$$

where A_0 is the initial amplitude, β is the geometrical spreading, f is the frequency, v the path averaged S-wave velocity and Q the quality factor, which is inversely proportional to the anelastic attenuation. Havskov & Ottemoller (2010) show that by taking the logarithm of (5) produces

$$log\big(A(r)\big) = log(r) - 0.43\frac{-\pi f r}{vQ} + log(A_0)\ .\ (6)$$

If *f*, *v* and *Q* are assumed to be constant, the displacement correction term can be expressed in the form

$$-log(A_0) = alog(r) + br + c\ ,\ \ (7)$$

where *a*, *b* and *c* are constants representing geometrical spreading, attenuation and the base level respectively. Two different anchor points are commonly used to link the M_L scale to Richter's definition. Originally a magnitude 3.0 earthquake was defined as a 1mm displacement at 100km, and more recently a 10mm displacement at 17km has been used to adjust the scale to other regions with significantly different attenuation (Hutton & Boore 1987). Anchoring the displacement correction term to 17km results in the equation

$$-log(A_0) = alog(r/17) + b(r - 17) + 2\ .\ \ (8)$$

As the geometrical spreading does not vary significantly from 1, the greatest impact on the M_L scale will be caused by changes to the attenuation term *b*. From equations (6) and (7), this term can be represented by the equation

$$b \approx 0.43\frac{\pi f}{vQ}\ .\ \ (9)$$

When considering shallow, nearby events we would expect a greater portion of the raypath to be through shallow sediments, as opposed to the more distant events used to calibrate the UK's present M_L scale, which will have travelled predominantly through the deeper crust. We would therefore anticipate that both *Q* and *v* would be lower. Furthermore, because the path distance will be smaller, the frequency content, *f*, would likely be higher. These effects will have the combined effect of significantly increasing the attenuation constant *b*, which will have different impacts on the displacement equation (8) depending on the distance. At distances less than the anchor point, an increase in *b* will decrease the actual magnitude of the event while at greater distances the magnitude will be increased.

3. Data

To examine the impact that the proximity of receivers to seismic events has on M_L estimations, we use a series of seismic events recorded to the north of New Ollerton, Nottinghamshire, UK. The area has a history of seismic activity relating to coal mining (Bishop et al. 1993), and the locations and characteristics are consistent with coal seams worked by Thoresby Colliery, located approximately 800-900m below the surface. The seams below this area are the Parkgate and Deep Soft, and borehole records show that they are overlain by strata of sandstone, limestones and marls (IMC Group Consulting Limited 2003). Deep Soft is the most recently operational seam, and was worked from 2010 until the closure of the colliery in July 2015. The coal was extracted using the longwall mining method, where the roof is supported while a cutting machine is pulled along the width of the coal face. As the machine moves forward, the supports are advanced and the roof behind the supports is allowed to fall into the void left by the coal.

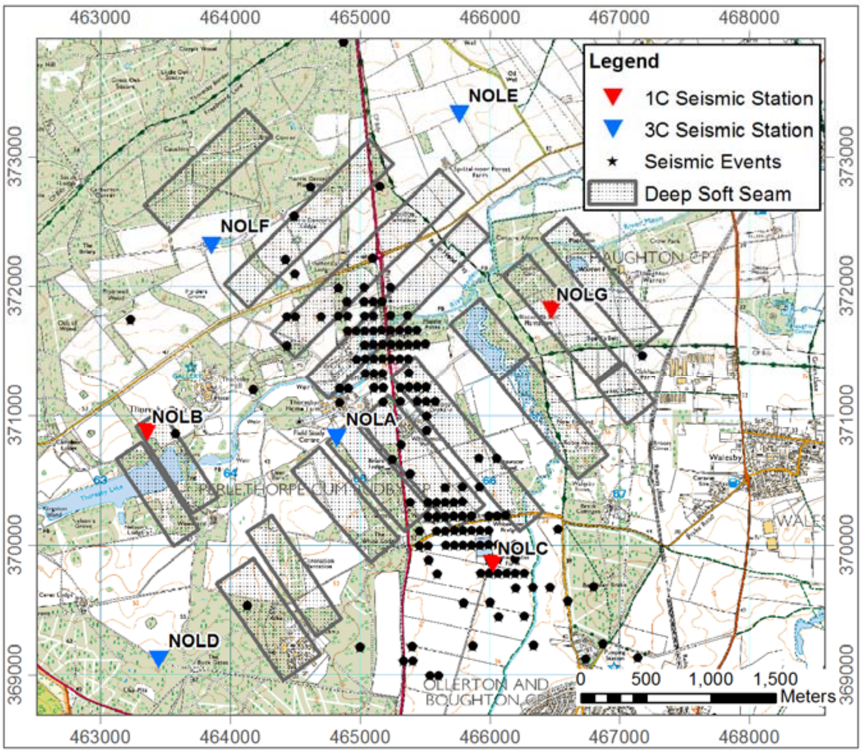

Figure 3: Location of New Ollerton Network (inverted triangles), recorded seismic events (black dots) and coal seam panels (grey rectangles).

Between 5th February 2014 and 30th October 2014 a temporary network (here called NOL) was deployed by the British Geological Survey, which comprised of four 3-component Guralp 3ESP broadband instruments (NOLA, NOLD, NOLE and NOLF) and three vertical component S13J instruments (NOLB, NOLC and NOLG) with an aperture of about 5km (Figure 3). During the deployment over 300 events were identified, which were clustered in two distinct regions, and fell within a source-receiver distance range of between 1-5km (Figure 4).

Depth (km)	V_P (km/s)	V_S (km/s)	Lithology
0-0.060	1.9	1.28	Weathered Sherwood Sandstone
0.060-0.135	2.75	1.54	Un-weathered Sherwood Sandstone
0.135-0.275	3.1	1.74	Permian
0.275-1.019	3.5	1.97	Coal Measures
1.019-2.751	5.2	2.92	Carboniferous Limestone
2.751-37.751	6.0	3.37	?Precambrian

Table 1: Seismic velocity structure for New Ollerton area, from *Bishop et al.* (1993).

Locations of seismic events were determined initially through the inversion of P- and S-wave travel time picks, and then relocated with hypoDD (Waldhauser & Ellsworth 2000) using a 1D velocity model of Bishop et al. (1993) (Table 1). Local magnitudes were initially calculated using displacement measurements made on the NOL network and the existing UK M_L scale. Of these events, those with magnitudes > 1.7M_L were also in general identifiable on the UK national seismic network after the application of a bandpass filter of 3-10Hz. When applying the same filtering to the NOL stations, the same discrepancy observed at Preese Hall – an overestimate of M_L on nearby stations – is also present in this dataset (Figure 5). This overestimate becomes larger as hypocentral distances are reduced.

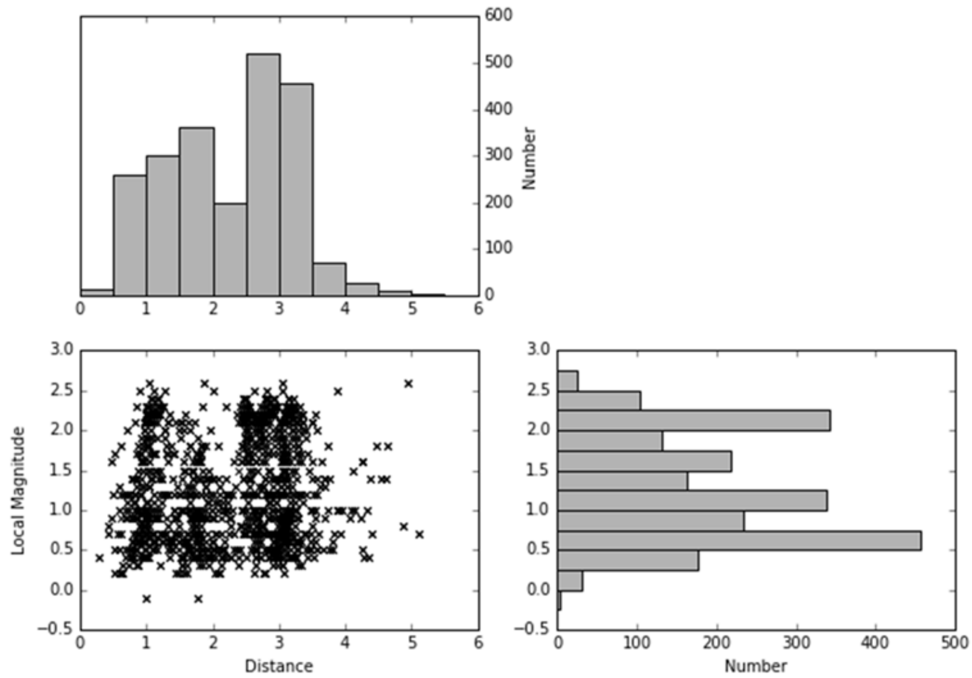

Figure 4: Distribution of hypocentral distances and local magnitudes for observations at near New Ollerton. Magnitude are computed using the NOL network and the existing UK local magnitude scale.

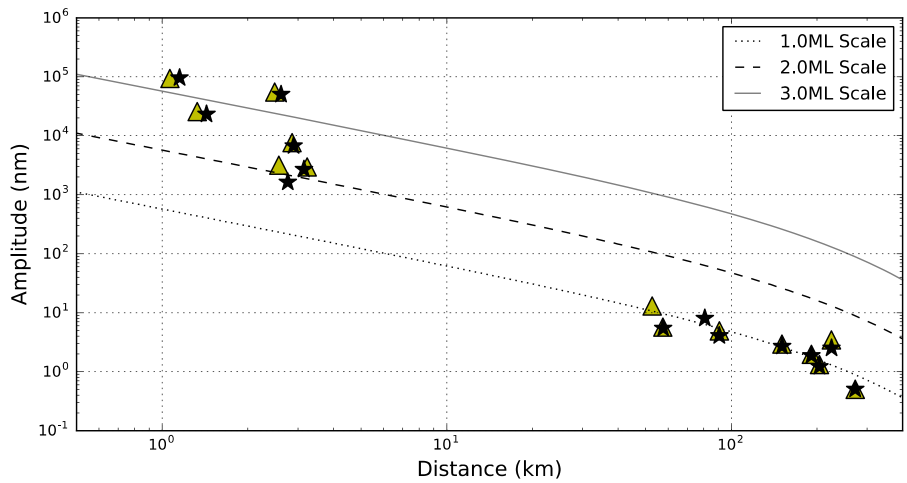

Figure 5: Displacement amplitude versus distance for two events recorded on both the NOL network (stations < 5km distance) and the UK national network (stations > 50km distance) for two events (2014/02/09 05:33 and 2014/02/12 02:35 coloured yellow and black respectively). Also plotted is the UK scale for M_L = 1, 2 and 3 (dotted, dashed and solid lines). On the distant stations, the displacements match well with the UK scale for an M_L = 1.0 event. On the nearby stations, displacements are substantially larger, and this discrepancy increases as hypocentral distance decreases.

4. Velocities and Attenuation

The velocity structure of the UK has been studied by numerous authors (e.g., Chadwick and Pharaoh 1998; Kelly et al. 2007; Davis et al. 2012), with local P-wave crustal velocity structures derived from the Lithospheric Seismic Profile in Britain (LISPB) (Kelly et al. 2007) and the Caledonian Suture Seismic Experiment (Bott et al. 1985). Booth (2010) has also determined regional 1-D velocity depth models for the northern and central regions of the UK, based on P-wave arrival from local earthquakes recorded between 1990 and 2008, which compliment the refraction survey data. Understanding of the S-wave structure comes principally from work in ambient noise Rayleigh wave tomography (Nicolson et al. 2014) and receiver functions (Davis et al. 2012; Tomlinson et al. 2006).

In general terms the velocity structure in the UK comprises a highly variable sedimentary layer (Nicolson et al. 2014), overlaying a faster continental basement, on top of a lower crust (Bott et al. 1985) which extends to the Moho mapped at depths between 25-35km (Chadwick & Pharaoh 1998). Velocities within the sedimentary layer vary significantly depending on composition (see Table 2); for example, the S-wave velocity of sandstones are typically 1.5km/s, with limestone higher at approximately 3km/s. Underlying the sedimentary layer, the continental crust is comprised of crystalline basement rocks, which typically have much higher velocities and can mark a sharp velocity discontinuity. Abercrombie (1997) has shown that anelastic attenuation, the inverse of Q, varies substantially between sedimentary and basement rocks. Within the sedimentary layer Q is typically low (e.g., <30), as demonstrated by Best et al. (2007), while in the crystalline basement rocks Q increases by at least an order of magnitude (Abercrombie 1995; Stork & Ito 2004).

At New Ollerton the sedimentary layer consists of a combination of sandstones, coal measures, grit-stones and limestones, which extend to an approximate depth of 2.75km where the continental basement is encountered (Bishop et al. 1993). The velocity model produced by Bishop et al. (1993) was derived from borehole information, which extended to the coal measures, and deep seismic refraction data used to constrain the sedimentary-continental crust boundary. Best et al. (2007) determined velocities, attenuation and densities of multiple sandstone, limestone and siltstone samples collected at depths ranging between 40-185m from Whitchester, north-east England using ultrasonic pulse-echo methods. Broadly classifying these results by lithology provides the range of velocities, attenuation and densities shown in Table 2, which are comparable to the velocities observed at New Ollerton and indicates the likely values of Q.

Lithology	V_P (m/s)	V_S (m/s)	Q_P	Q_S	$Density(kg/m^3)$
Sandstone	$3266 \pm 10 - 4807 \pm 14$	$2140 \pm 6 - 3076 \pm 9$	$13 \pm 1 - 88 \pm 32$	$10 \pm 1 - 61 \pm 10$	2491 – 2620
Limestone	$5898 \pm 18 - 6301 \pm 9$	$3066 \pm 9 - 3275 \pm 10$	$22 \pm 1 - 160 \pm 88$	$17 \pm 1 - 101 \pm 27$	2616 – 2661
Siltstone	$3372 \pm 10 - 4308 \pm 13$	$2024 \pm 6 - 2487 \pm 7$	$18 \pm 1 - 33 \pm 1$	$10 \pm 1 - 26 \pm 3$	2525 – 2637

Table 2: P and S wave velocities and Q from laboratory test, from *Best et al.* (2007).

5. Impact of Hypocentral Distance

We demonstrate the impact that the sedimentary layer has on the path effects for near-event receivers using S-wave apparent velocities and estimates of Q. S-waves are considered as their amplitudes that are primarily used to derive M_L. Because this dataset has limited observation within the range 5-20km, events recorded within the general vicinity of New Ollerton are also included, which have been sourced from the BGS catalogue.

In Figure 6 we show the apparent S-wave velocity (the epicentral distance divided by the travel time). A prominent “knee” occurs at a distance between 10-15km, with V_{app} decreasing with distance shorter distances, and stabilizing at a value of approximately 3.5km/s at greater distances. These observations are modeled using a simple two-layer case, with a shallower layer representing sedimentary layers extending to a depth of 4km with a velocity of 2km/s, and a deeper layer comprising of the continental basement with a velocity of 3.7km. Travel times (*TT*) are expressed using

$$TT = \frac{r}{v_{base}} + \frac{(2z_l - z_s)cos\theta}{v_{sed}}, \quad (10)$$

where r is the epicentral distance, z_l is the layer depth, z_s is the source depth, v_{sed} and v_{base} are the average sedimentary and crustal layer velocities respectively and θ is the take-off angle. The modeled apparent velocity (V_{app}) is therefore

$$v_{app} = \frac{r}{TT}, \quad (11)$$

and it can seen that the model provides a relatively good fit to the data (Figure 6). This model demonstrates that the increase in velocity within the first 10-15km relates to the decreasing contribution of the sedimentary layer on the raypath, with signals recorded at distances in excess of 10-15km dominated by the faster, less attenuating continental crust.

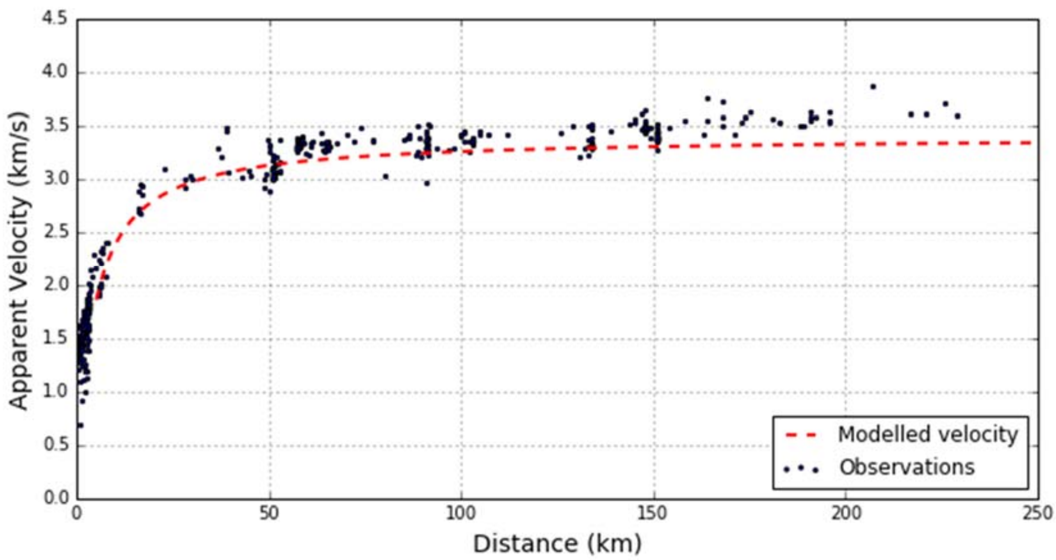

Figure 6: Apparent S-wave velocities from earthquakes within the UK. Red dashed lines represent modelled apparent velocities for the simplified 2-layer case, with shallow sedimentary layers of 2.5km/s extending to a depth of 2.75km, overlaying a continental basement with a velocity of 3.4km/s.

We calculate Q for eight events recorded on the same station (NOLF), with six 'near' events occurring at a distances of approximately 2km and depths of 0.9km and two 'far' events located at a distance of 60km and depth of 2.5km. We use spectral methods to estimate the values of Q, with displacement spectra generated using the multi-tapering technique developed by Prieto et al. (2009), and fitted with a Brune model source spectrum (following Prejean & Ellsworth 2001; Stork et al. 2014). The travel paths of near events have estimated Qs of 30, while the distant events have estimated Qs of 300.

The observations made at small epicentral distances will have significantly different attenuation effects than the distant observations used by Ottemöller and Sargeant (2013) to calibrate the UK M_L scale. Ergo a corrected scale must be developed if consistent magnitudes are to be calculated using stations deployed in close proximity to event epicentres.

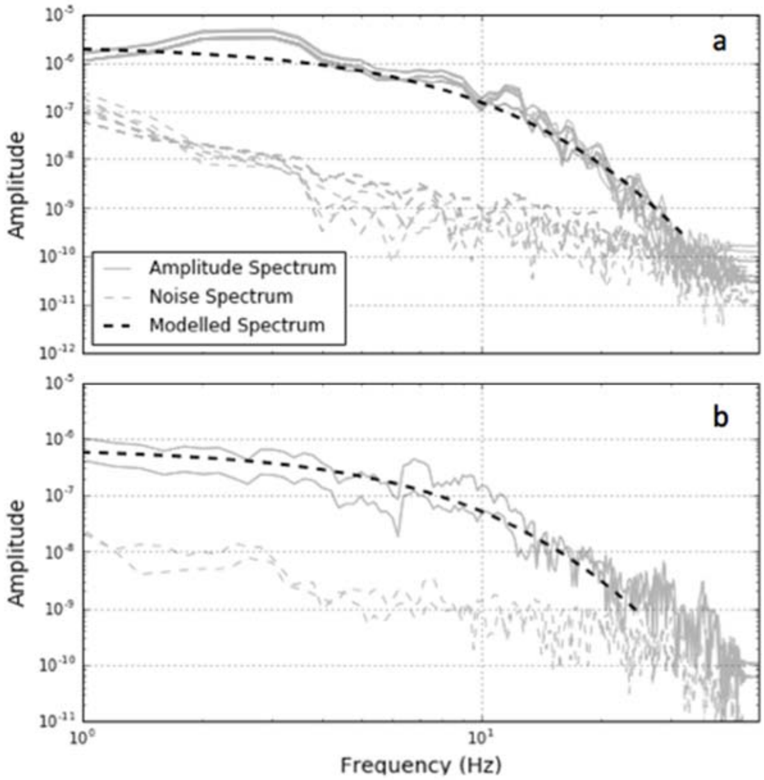

Figure 7: Source spectra for six 'near' (a) and two 'far' (b) events recorded on station NOLF. The grey curves show the observed displacement spectra, the grey dashed lines show the noise, and the black curves show the best-fit Brune model spectra. The 'near' events located at a distances of ~2km and depths of 0.9km are best-fit by Q = 30, the 'far' events at an distances of 60km and depths of 2.5km are best-fit with a Q of 300.

6. M_L Scale Recalibration for Nearby Events Based on New Ollerton

Many studies have focused on verifying the southern California M_L scale originally developed by Richter (1935), or to recalibrate it for different regions to take into account different attenuation properties (e.g. Hutton and Boore 1987; Langston et al. 1998; Keir et al. 2006; Ottemöller and Sargeant 2013; Di Bona 2016). The common approach is to invert observations using a least-squares method to determine the geometric spreading and attenuation terms, while also solving for magnitudes. Recent studies tend to anchor the displacement correction term to 17km, as it is easier to adjust the scale to other regions with significantly different attenuation (Alsaker et al. 1991). Although the events at New Ollerton are in general co-located, and could be considered as a single event, we seek to invert the observations in order to gain an indication of the appropriate scale required for near-receiver events.

We use a Levenberg-Marquardt algorithm, which is a damped least-squares method, to determine the best fitting geometrical spreading and attenuation terms at New Ollerton. Due to the limited distance range of the observations, attempts to determine these values while also treating the magnitudes as an unknown failed to converge. Furthermore, our aim was to create a scale that remained consistent with the existing UK local magnitude scale, which has been well-established for events recorded on more distant stations. Therefore we instead determined the average magnitude discrepancies observed between the NOL network and UK network, recalibrate magnitudes and use these values to constrain the inversion. We determined the geometric spreading, a, and attenuation, b, terms for observed amplitudes, A_{ijk}, magnitudes, M_{Lik}, and distances, r_{ij}, using the model

$$log(A_{ijk}) + 2 = M_{Lik} - alog\left(\frac{r_{ij}}{17}\right) - b(r_{ij} - 17) \quad (12)$$

where index i labels events, index j stations, and index k the component (north-south or east-west). Within the data there is evidence of site effects, however we choose to retain simplicity through excluding them from the inversion. This approach produces the New Ollerton (NOL) M_L scale

$$M_L = log(A) + 1.17log(r) + 0.0514r - 3.0 \quad (13)$$

which incorporates the Wood-Anderson gain correction and whose attenuation term, 0.0514, is an order of magnitude larger than the current UK scale, which is 0.00183.

We use equation (9) to establish whether the inverted values for *b* are reasonable for the two scenarios (nearby vs distant events). The value for *b* calculated by Ottemoller and Sargeant (2013) of 0.00183 can correspond to an S-wave velocity of 3.5km/s and a Q of 200. The value for *b* calculated here (0.0514) would correspond to an S-wave velocity of 2km/s and a Q of 35. These are realistic values given the expected raypaths predominantly through the deeper crust, and through the sediments respectively.

Magnitude differences for events observed on both local and regional stations are presented in Figure 8. We determine the event magnitude through taking the mean M_L derived from the UK network and calculated using the UK M_L scale, then produce differences for all available stations using the NOL and the UK M_L scales. The NOL scale successfully removes the discrepancy in the existing magnitude scale for nearby receivers, and converges with the UK scale at 17km – the point at which both scales are anchored (Figure 9). There is a lack of data in the range 5-20km, and after 17km the NOL scale rapidly diverges and introduces large magnitude discrepancies.

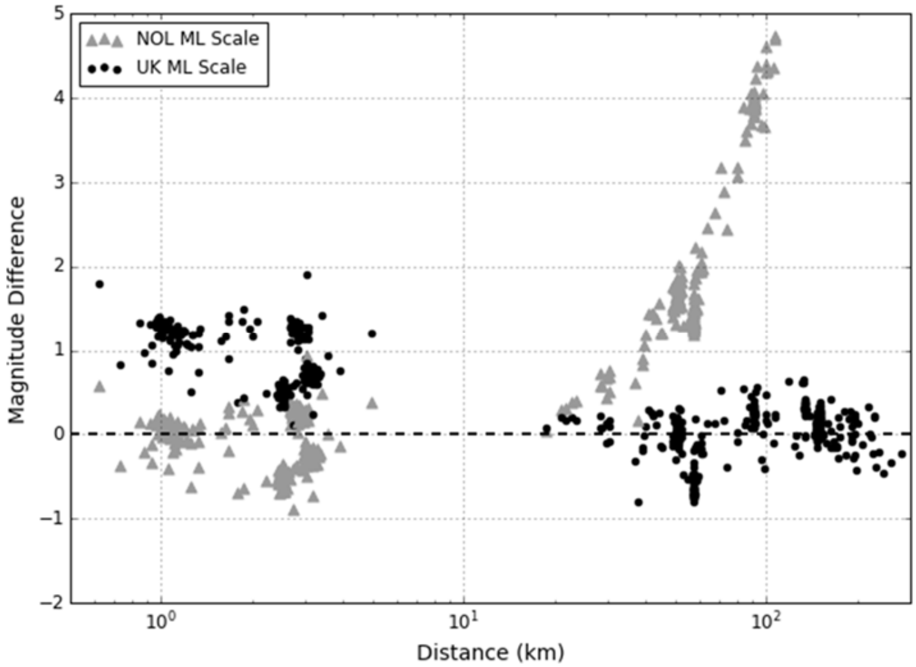

Figure 8: Magnitude differences for New Ollerton events observed on both NOL stations and the UK network. The NOL scale corrects the magnitudes at small hypocentral distances, but diverges significantly beyond the 17km anchor point.

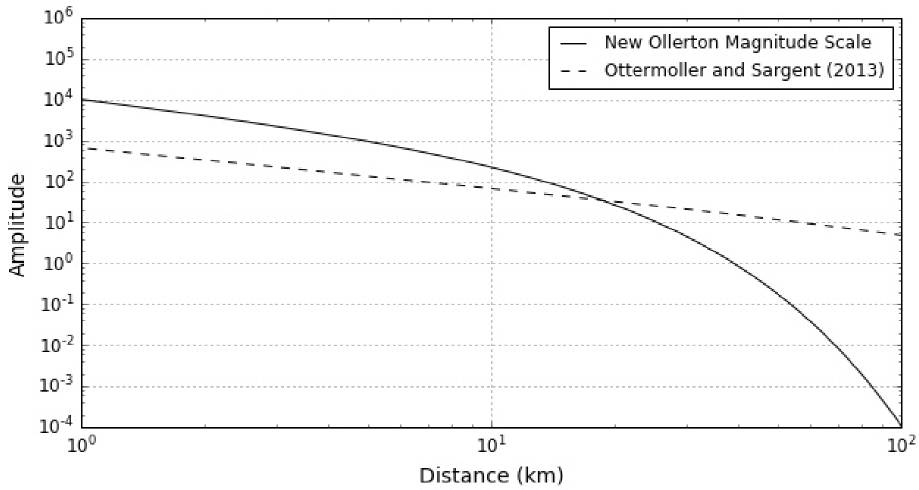

Figure 9: A comparison of the displacements anticipated for an M_L = 1.0 event, as computed by the Ottemoller and Sargeant (2013) scale (dashed line) and that evaluated in equation (13). The scales are anchored to a common amplitude at a hypocentral distance of 17km. At smaller distances, the estimated ground displacements are different by an order of magnitude.

7. Discussion

While the New Ollerton dataset can be used to understand the impact that near-receiver events have on M_L scales, the observations all occur in a single location and over a narrow distance range. We therefore consider how appropriate the NOL scale is for different UK regions, and the valid distance range of the scale.

Sedimentary layers obviously vary in composition and depth (Kelly et al. 2007; Nicolson et al. 2014), which will influence the attenuation term *b*, and the point at which the continental crust dominates the travel path. We consider the portability of the NOL scale through applying it to two Preese Hall events observed on both local stations and the UK network (Figure 10). At Preese Hall the NOL scale has significantly reduced the discrepancy between observed displacements at the nearby and distant stations (as identified in our introduction), and is now consistent with the magnitude calculated on the UK network. While in this case the NOL scale appears appropriate, if the geological composition of the shallow geology is significantly different, for example limestone dominant, the attenuation term *b* may need to be recalibrated.

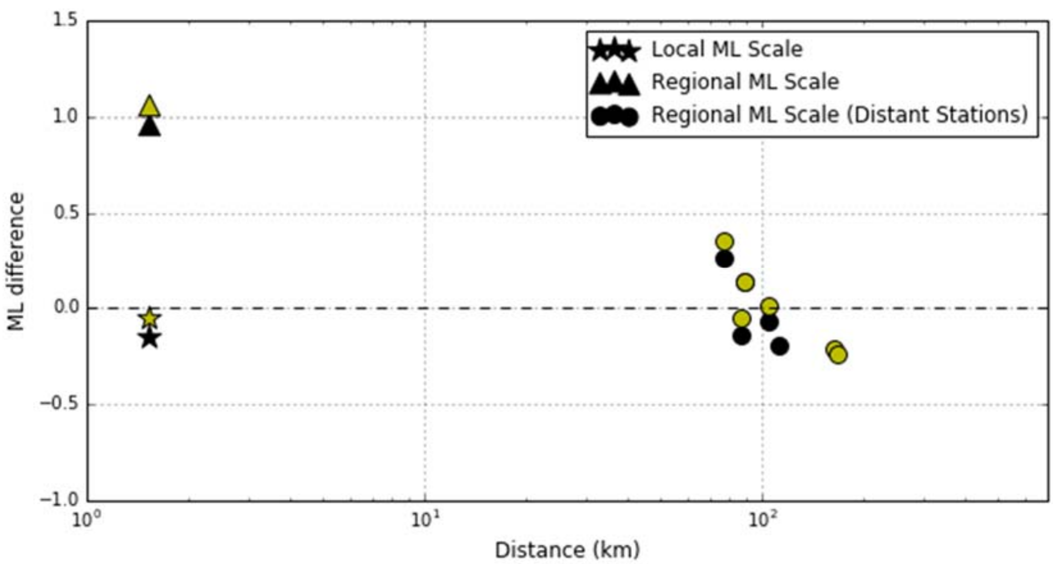

Figure 10: NOL scale (stars) applied to two Preese Hall events observed on the UK network, which significantly decreases the magnitude difference in contrast to the UK scale (triangles).

The depth of the sedimentary-continental interface will influence the cross-over point between the NOL and UK scale. The distance range 5-20km is poorly represented in the New Ollerton dataset, and over this range that the shift from a travel path dominated by the sedimentary layer to a path dominated by the continental crust occurs. There are uncertainties in the appropriateness of using a constant attenuation term over this range which cannot be addressed by this dataset, as both the apparent velocity and Q will be transitioning from sedimentary layer to continental crust values.

However, most of the UK's shale gas activities expected to take place across the north of England. Both of the sites considered here (New Ollerton and Preese Hall) fall within the limits of the Bowland Shale as defined by the BGS. The TLS will usually be administered using monitoring stations that are within 5km of the proposed wells. We therefore suggest that the updated magnitude scale developed here is more suitable for the administration of the UK's TLS than the UK standard M_L scale.

7. Conclusions

The UK's hydraulic fracturing TLS will entail the deployment of monitoring stations in close proximity to well sites. However, the existing UK local magnitude scale is based on observations of events at significant distances (>50km) from receivers, and so is poorly calibrated for events recorded on nearby stations (<5km). This discrepancy is significant because for nearby events the travel path is predominantly within the sedimentary layer, rather than the underlying basement, and so will require a different attenuation term in the M_L scale.

To address this issue, we studied the earthquakes recorded on a local monitoring network deployed to monitor coal-mining-induced seismicity at New Ollerton. Through consideration of apparent velocities, it can be observed that at distances greater than 10-15km the travel paths of recorded arrivals are predominantly through the continental crust, as S-wave velocities stabilize at a value of approximately 3.5km/s. However, at closer distances the apparent velocities reduce, implying a greater portion of the raypath is through the overlying sediments. A significant difference in Q estimates can also be seen between nearby events and distant events, with lower Q values for nearby events implying greater attenuation through the sedimentary layers.

An updated local magnitude scale has been determined for nearby events using a least-squares inversion on the New Ollerton data, and we calculate that the attenuation term in the local magnitude scale should be increased from 0.00183 to 0.0514. This change reflects the slower, more attenuating nature of sedimentary layer in comparison to the continental crust. A further indication of the suitability of this scale is provided by the fact that it also removes the ground motion discrepancies observed for the Preese Hall 2011 events at nearby stations. To ensure consistent local magnitude estimates during the future operation of the UK's TLS, the updated magnitude scale should be used when local monitoring networks are within 5km of the event epicentres.

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