The Seismicity of Wales

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Introduction

Although the UK is not thought of generally as prone to earthquakes, the country is by no means devoid of them. However, since the UK is well away from the nearest crustal plate boundary (these being the Earth's main seismic zones), British earthquakes tend to be restricted in size and sufficiently infrequent that they are soon forgotten by the general public. On average, the UK experiences an earthquake of 4.7 in magnitude (sufficient to be felt to some degree over half the country) every ten years (Musson 1994). (Note that in this text all magnitude figures quoted are local magnitude, usually abbreviated ML, and equivalent to the original "Richter Scale").

However, the distribution of seismicity in the UK is very uneven, with some areas repeatedly active throughout history and others almost aseismic. As a simplification, one could say that the western side of Great Britain tends to be more seismically active than the eastern side, though the pattern is rather more complex than that. (Ireland, incidentally, is almost completely free from earthquakes.) Wales, therefore, is somewhat more earthquake-prone than many parts of England.

The pattern of seismicity within Wales, though, is quite varied. Figure 1 shows a map of all locatable earthquakes in Wales from the BGS database, with the exception of microseismicity registering below 2 in magnitude. The database comprises the historical earthquake catalogue of Musson (1994) with amplifications and later revisions, plus the full instrumental record of earthquakes recorded by BGS since 1970. The database is, of course, increasingly incomplete for smaller magnitude events as one goes back in time.

One can see at once from Figure 1 that some parts of Wales are much more subject to earthquake activity than others. There is a small area in NW Wales that is highly seismic, and includes some of the largest British earthquakes. The rest of N Wales is only moderately active in comparison. Mid Wales is much quieter, while South Wales is again an active zone. It will be helpful to discuss each of these areas in turn; but first we should consider the sources of data for Welsh earthquake studies.

Sources and methods

Recent seismicity in Wales is well recorded by the UK national seismic monitoring network run by BGS (Baptie and Ottemöller 2004). This was started in 1970, and its initial configuration consisted of only a few stations in Central Scotland, which were only able to pick up the larger Welsh earthquakes. The network gradually expanded to its present distribution, and now any British earthquake above magnitude 2 can be located.

Instrumental data from early seismometers is available for larger Welsh earthquakes only, back to 1903, and is of poor quality, since these instruments were designed for studying large distant events and were not good at picking up small local earthquakes. Thus, before 1970, the prime source of information is macroseismic data, i.e. data on earthquake felt effects, classified by strength and represented by numerical intensity values. The scale used is the European Macroseismic Scale (Grünthal 1998), where 1 = not felt and 7 = many houses suffer some moderate damage (the highest level observed in Wales).

Since intensity decays with distance from the epicentre, a map of intensity values enables one to estimate the position of the epicentre, often with quite good accuracy. The area affected by the earthquake is a function of magnitude. As a simple approximation, the logarithm to base 10 of an earthquake's felt area (in sq km) roughly equals the magnitude; more precise equations are available, derived from modern earthquakes that have both instrumental parameters and macroseismic data available (Musson 1996).

How far back in time one can push the earthquake catalogue, complete with numerical parameters (at least date, epicentre and magnitude), is a function of the quality of the descriptive sources that allow one to reconstruct past earthquakes.

In Wales, as in the rest of the UK, the earliest sources are monastic chronicles. Standard texts such as the Annales Cambriae (Williams 1860a) and Brut y Tywysogion (Williams 1860b), as well as more minor chronicles, contain a number of references to earthquakes. Unfortunately these are generally very terse. Thus, especially for the 13th century, one can pick out the dates on which some evidently significant Welsh earthquakes occurred, but one cannot locate them reliably. Perhaps the largest was the earthquake of 20 February 1247, reputed to have damaged the cathedral of St David's. It is not safe, on the basis of damage to one building, to plot an epicentre near St David's for this event; on the evidence available the earthquake could equally well have occurred in NW Wales or a number of other places.

After the decline in the monastic practice of keeping annals, the record of Welsh earthquakes becomes very sparse until the 18th century, with a few events recorded in the 17th century and one in 1534. The latter is an interesting event; the epicentre was probably in NW Wales but the evidence is restricted to a description of the earthquake being felt in Dublin, and a short poem in Welsh, which concentrates more on the date than the effects. Generally speaking, up to the end of the 17th century, one is reliant on the chance survival of letters, diaries and memoranda.

With the coming of the newspaper, the documentation of earthquakes improves greatly (Musson 1986). Because newspapers were both published on a regular basis, and took it as their task to report newsworthy events, one can have reason to suppose that if an earthquake occurred, it would be reported on, and the data should still be available. In the Victorian and Edwardian periods the amount of descriptive data available for some widely-felt earthquakes in Wales is enormous, allowing some very detailed studies (e.g. Musson et al 1984a, 1984b, 1986). After WW1 newspapers slowly decline in their usefulness as a source, due to a journalistic evolution from dense pages of reportage in small type to a terser style using block headlines and pictures.

One can also mention the systematic collection of macroseismic data by seismologists, principally by Charles Davison between 1889 and 1926 (and increasingly sporadically towards the end of that period) and ATJ Dollar episodically between 1935 and 1965. Data collected by Dollar is particularly important for studying the Caernarfonshire earthquake of 12 December 1940, which was not well reported on by local newspapers because of the war.

Welsh seismicity by region

The different areas of Wales will now be considered in turn. Earthquakes discussed individually in the text are summarised in Table 1 (except for those occurring before 1600), and the index numbers in Table 1 allow events to be identified in Figure 1. Note that not all earthquakes in Figure 1 are located with equal accuracy, so apparent alignment of epicentres, especially within a cluster of events, may be spurious. A word about the naming of events is also in order. It is traditional practice to refer to earthquakes by a place name, as in Table 1, for ease of communication. But to call something a "Swansea earthquake" does not mean the epicentre was exactly in Swansea; only that Swansea is a well-known place in the vicinity of the epicentre. These leads to some arbitrariness in naming; the 1999 Sennybridge earthquake could just as well have been called the 1999 Brecon earthquake, and so on.

NW Wales

The area around Caernarfon is one of the most concentrated spots of seismic activity in the UK. The only reason that much more damage has not been reported here over the years is that the larger earthquakes tend to be providentially deep in focus (> 15 km).

The three largest events on record are the earthquakes of 7 October 1690, 9 November 1852 and 19 July 1984. The last of these had an instrumental magnitude of 5.4, making it the largest onshore British earthquake known. It caused damage to chimneys as far away as Liverpool (in fact, it damaged more chimneys in Liverpool than in the epicentral area). The other two events were only slightly, if at all, smaller.

One can probably add to these three the July 1534 earthquake (though any attempt at parameters for this earthquake can only be tentative) and possibly the 20 February 1247 event. This suggests a remarkably regular pattern of large earthquakes about every 150 years, perhaps with a missing earthquake c. 1400 – but such patterns can be deceptive and this should be regarded as speculation.

Amongst events less than 5 ML, the earthquakes of 19 June 1903 (4.9 ML) and 12 December 1940 (4.7 ML) are noteworthy. The latter was the last British earthquake to cause fatalities, killing two (Musson 2003).

The geological explanation for this concentration is obscure, as is usually the case in the UK. Davison (1904, 1924) explains the seismicity as due to what we would now call the Lleyn-Menai Straits Fault System (LMSFS), which runs NE-SW and does seem to align with the earthquake epicentres. What Davison didn't realise is that the coincidence of epicentres and surface fault trace is meaningless when the hypocentres are 10-15 km deep and the fault is dipping NW. The earthquakes occurred, therefore, not on the LMSFS but within the footwall block. The focal mechanism for the 1984 event showed strike-slip movement on a vertical fault trending either E-W or N-S (Turbitt et al 1985). Given the prevailing stress regime of compression from the NW (Whittaker et al 1989), vertical faults trending either N-S or E-W are those most likely to be reactivated for strike-slip movement. Blenkinsop et al (1986) suggest a N-S orientation is more likely for NW Wales.

One possibility is that this tight cluster of high seismicity may be a result of stress concentrations induced around the edges of the Snowdonian Massif, but this is speculation. Certainly the earthquakes of the last two centuries can be located with confidence in this quite narrow area. The 1940 earthquake, though it seems most likely to have had an epicentre on the SW side of Snowdonia, was followed the next year by a sequence of small earthquakes on the NE side (Musson 1989). If these were aftershocks, possibly the mainshock was also on this side; the intensity data distribution is not conclusive.

Earlier events are more indeterminate; what is known of the 1690 earthquake is consistent with an epicentre in the same area, though Melville (1983) locates it in Cheshire.

N Wales

East of Afon Conwy, the seismicity is much less, and is more or less confined to an area around Bala and Corwen. The largest event is possibly the 18 March 1613 earthquake, but this event is not well documented and the magnitude is approximate (as is the epicentre). Better documented is the 11 April 1888 Corwen earthquake (3.8 ML). The 23 January 1974 Bala earthquake has attracted some notoriety; it occurred during a meteor shower, and was variously taken for a crashed aircraft, meteorite impact or UFO(!).

Blenkinsop et al (1986) argue that alignment of epicentres along the north end of the Bala Fault, the Glyn Ceiriog Fault and in Cardigan Bay suggests that the Bala Fault may be active. Such a "join the dots" approach is dangerous. On the one hand, alignments easily occur by chance: examining randomly-generated synthetic earthquake catalogues makes it clear how true this is. On the other hand, alignments can be completely illusory when earthquakes are poorly located, and many of the epicentral positions in the seismicity map used by Blenkinsop et al (1986) look unreliable.

Mid Wales

The Mid Wales area is, of the four defined here, the lowest in terms of seismic activity. There are three small areas where earthquakes have been observed, and the rest is a blank. In the northwest, a few small earthquakes have occurred in the Barmouth-Aberdovey area, possibly offshore.

In the east, four earthquakes round about 3 in magnitude have occurred in the modern period in the Newtown area; these could be considered the fringe of the much stronger seismic activity associated with the English side of the Welsh border, in Herefordshire and Shropshire. Blenkinsop et al (1986) state that one of these events, on 15 April 1984, occurred on a mapped vertical fault in the Felindre basin, which is certainly the only Welsh earthquake for which the claim has been made that it can be attributed unambiguously to a particular mapped fault.

Lastly, in the south, a few earthquakes, again all modern, have occurred near Brecon. The largest of these, on 25 October 1999, had a magnitude of 3.6.

South Wales

Much more interesting to the seismologist is South Wales. This is another area subject to some of the largest British earthquakes, with magnitudes above 5, and also some of the most damaging.

However, this would not be at all apparent if one looked only at the seismicity recorded by the BGS network since 1970. Modern data shows a number of earthquakes occurring in the Newport-Cwmbran area, and more recently towards Bargoed, but little else. From this, one would not consider SW Wales to be an area at risk, but historical data tell another story. The earliest reported event in South Wales was on 27 August 1690, with an epicentre near Carmarthen and a magnitude around 4.7. After that, the occurrence of earthquakes large by British standards becomes quite regular, particularly close to Swansea, which was affected in 1727, 1775, 1832, 1868 and 1906, with magnitudes ranging from 4.3 to 5.2. Clearly the apparent regularity of events every 45 years or so is deceptive, since no further earthquake has occurred near Swansea since 1906 except for a 3.2 ML event in 1930. Also, the date of the last big Swansea earthquake previous to 1727 is unknown but probably must have been well before the 1680s. Whether this cluster is a chance occurrence will be discussed later.

The 27 June 1906 earthquake, which, like the 1727 event, was 5.2 in magnitude, caused extensive damage, which was very copiously described in the newspapers of the time. The damage area stretched from Kidwelly to Cardiff and as far north as Merthyr Tydfil (Musson et al 1984b). In Swansea, bricks and chimneypots fell from chimneys in all parts of the town. The gas works, the gaol, the Board of Trade offices and the church of St Andrew's were some of the specific buildings that were damaged. Casualties were surprisingly few: two were injured by falling bricks, and a factory girl at Cwmavon was severely injured by a collapsing stack of tin plates. Given how much more building has taken place in the Swansea area in the period since then, the potential for damage in the future, should the 1906 earthquake repeat, must be somewhat greater.

It can be remarked in passing that the 1906 Swansea earthquake occurred at a time when the news of the great earthquake at San Francisco was still fresh in people's minds, and this is reported to have contributed to the degree of alarm experienced in Swansea when the earthquake struck.

Besides the concentration of earthquakes around Swansea, two further notable events occurred further west, near Pembroke in 1892 and near Carmarthen in 1893. The magnitudes were 5.1 and 5.0 respectively. The Carmarthen earthquake had a precedent in the 1690 event already mentioned; a smaller event was felt there in 1802 also. In recent years also, some very small events have been detected by BGS near Carmarthen (but not felt). But the 1892 Pembroke earthquake is entirely isolated in space (unless one considers the 1247 earthquake to have originated nearby), apart from the aftershocks that immediately followed it.

These two earthquakes make an interesting comparison. The two epicentres are at nearly the same latitude and only 45 km apart. One can reasonably expect that, since the two events occurred only a year apart, there should be no social differences that would affect the reporting of the two earthquakes, and thus differences in the reported felt areas must reflect real physical differences. The Pembroke earthquake was felt strongly in Cornwall and Devon to the south, and not very much to the north, while the Carmarthen earthquake was felt strongly to the north and hardly at all to the south (Musson et al 1984b). This can only reflect differences in seismic radiation pattern.

It is hard to find a convincing geological explanation for the distribution of this seismicity. The larger earthquakes do seem to cluster near the southern termini of large, SW-trending structures (Figure 2), but the hypocentres are usually in the footwall blocks (Chadwick et al 1996). From Figure 2 it appears that the Variscan Front (Thrust) divides the 1892 and 1893 epicentres; however, this structure dips southwards, so the hypocentres are both on the same side.

A curious feature about the seismicity of South Wales is that it does not seem to follow the normal magnitude frequency distribution, or Gutenberg-Richter Law, which states that

$$\text{Log } N = a + b\,M \qquad (1)$$

where N is the cumulative number of earthquakes above magnitude M, and a and b are constants, with b typically having a value close to -1. In the magnitude range 3.7 to 4.7 there are only three S Wales earthquakes in the catalogue, while from 4.8 to 5.2 ML there are six. This cannot be completely explained away by lower completeness for the lower magnitude band; it seems that something is more than normally conducive to the production of earthquakes towards the upper bound of the magnitude range observed, i.e. magnitudes around 5 ML. This needs to be taken into consideration when calculating seismic hazard in the region.

Mining-induced seismicity

In mining areas it is normal for large numbers of small earthquakes, normally not exceeding 3 ML, to be experienced. Where long-wall extraction is used, the collapse of strata behind the advancing face generates many small shocks, but even in mines where pillars and galleries are used, mining-induced seismicity still occurs. The removal of large amounts of material upsets the balance of stresses around any local faults, making them liable to be reactivated. The coalfields of South Wales have undoubtedly been prone to induced seismicity, but because the earthquakes generated are typically small, they tend not to be very well reported. Davison (1924) lists a few examples. By the time the BGS instrumental network was sufficiently expanded to be able to detect mining tremors in South Wales, mining activity had largely stopped.

A 3.0 ML event near Mold on 18 January 1768 may have been induced by coal mining (an early example).

Aftershocks

It is commonplace in seismology that any large earthquake will be followed by a declining series of smaller shocks. It was proposed by Utsu (1971) that the number of aftershocks in a sequence is linearly related to magnitude, and Knopoff and Gardner (1974) relate length of aftershock sequence to magnitude. This largely breaks down in the UK, and noticeably in Wales; some of the larger shocks experienced have long aftershock sequences while others have almost none at all. The reason is unknown; one suggestion (Turbitt pers. comm.) is that the difference may be related to stress drop.

It seems to be the case that some parts of the UK tend consistently either to produce events with aftershocks or events without. In Wales, the Caernarfonshire area is a “with-aftershock” area, and Swansea-Carmarthen is “without-aftershock” (as is the Hereford-Shropshire area across the border), though the Pembroke earthquake in 1892 had several aftershocks, three of which were over 4 ML.

The 1984 Lleyn Peninsula earthquake had a remarkably extended aftershock sequence, lasting for about seven years (Figure 3). In any correlation between length of aftershock sequence and magnitude, the 1984 sequence would be an extreme outlier. Yet from Figure 3 it is clear that there is no time within the seven years following the earthquake that one could pick on as marking the end of the sequence.

This sequence is known in detail, including microseismicity, because of the effort made by BGS to monitor the sequence with a close-in seismometer array. Without this, few of the events would have been recorded, and even fewer had the earthquake been documented only from written records. The aftershocks described for the 19 June 1903 earthquake by Davison (1904), and those for the 9 November 1852 earthquake by Musson et al (1986) are probably just the largest ones.

Seismicity rate

Estimating the magnitude-frequency rate for the whole of Wales, in the form of equation (1) could be used at least to determine average occurrence within the principality, even if the seismicity is not completely homogeneous. In practice, the tendency mentioned previously towards events around 5 in magnitude makes such statistics of limited value. From recent instrumental data one can derive Figure 4a (aftershocks are excluded), which gives a best fit of

$$\text{Log } N = 2.84 - 1.08 \text{ ML} \qquad (2)$$

In this case the single outlier above magnitude 5 is the 19 July 1984 earthquake, which happened to occur within the window of the last twenty years, but obviously has a return period longer than this, so should be discounted from the analysis. However, when one applies this equation to a longer time window, the pattern in Figure 4b emerges. Here the earthquakes since 1750 are used; it can be conjectured from knowledge of historical data sources that the catalogue should be complete above magnitude 4 for Wales for this time period. Figure 4b shows that equation (2) does indeed correctly predict the number of earthquakes above magnitude 4 for this longer period. For smaller magnitudes, the difference between the observed data points and the line of equation (2) gives the degree of catalogue incompleteness. However, at the higher magnitude end of the figure, equation (2) seriously underpredicts the number of earthquakes around magnitude 5, which seem to constitute a separate population of earthquakes.

Hazard

Since Wales is more prone to earthquakes above magnitude 5 than most of the UK, seismic hazard becomes an issue for construction, at least in the case of sensitive structures such as dams. It is instructive to start with the record of earthquake effects in Wales, which is shown in Figure 5.

This figure shows the maximum observed intensity in the historical record across Wales. It does not include effects of earthquakes before 1700 that are too poorly documented for it to be possible to estimate intensities, and it does not include intensities observed at isolated places only (thus intensity 7 EMS is not represented on the map – it would show only as a few dots). It is constructed mostly from isoseismal maps from Musson et al (1984a, 1984b, 1986), a revised version of the map in Turbitt et al (1985), and some other unpublished isoseismal maps.

It can be seen that all of Wales has experienced intensity 5 EMS at one time or another (strong shaking, small objects are toppled, a few are frightened) and a few areas have experienced 6 EMS (slight damage to chimneys and plaster, many are frightened). In fact, the pattern is controlled by only a few earthquakes. The earthquakes of 1775 and 1852 on their own would cover most of Wales at intensity 5, and the earthquakes of 1892, 1893, 1906 and 1984 would be sufficient to generate the contour for intensity 6. Nothing we know about earlier earthquakes suggests that they would be likely to change Figure 5 substantially.

By way of comparison, Figure 6 shows a probabilistic seismic hazard map for Wales. This is an extract from the UK hazard map published in Jackson (2004), Baptie and Ottemöller (2004) and Musson (2004a), redrawn to match the style of Figure 5. The figure legend shows that the intensity values are those with a return period of 475 years, which is the probability level most often encountered in building codes. It is another way of saying that these are the intensity values that have a 10% chance of being observed or exceeded in 50 years.

The differences between Figure 6 and Figure 5 are due to the fact that in a probabilistic hazard study, the intention is to portray the broader underlying seismogenic factors over and above the observed pattern of the last few hundred years, which may not be representative of longer-scale trends. The assumption made in the model is that the seismicity of South Wales and Hereford-Shropshire should be taken together as a single population of earthquakes with consistent characteristics, which may occur anywhere within a broadly uniform crustal block showing a Caledonide trend in major structures. This block, roughly triangular in shape, is bounded by the Welsh Borderland Fault System to the northwest, the Malvern Lineament to the east, and in the south, the northern edge of the E-W trending basin structures of the Bristol Channel, which provide a distinct geological contrast.

If one assumes that, in long-term considerations, seismicity can occur anywhere within this block with equal probability, rather than, as happens to be the case in the last 300 years, mostly in the south and east, then the probability of strong earthquake shaking is as shown in Figure 6. Figure 5, by contrast, shows a pattern that is partly a product of happenstance as to where earthquakes occurred in the relatively short period of historical observation.

The question can then be asked: If this block is indeed uniform with regard to its seismogenic characteristics, how likely is it that such a cluster of seismicity near Swansea could have arisen by chance? This can be tested statistically, as shown by Musson (2000a). Applying spatial statistical analysis shows that the seismicity around Swansea does not invalidate the hypothesis that earthquakes can occur with equal probability anywhere in the South Wales-Hereford-Shropshire area.

This being so, the area with the highest probability of experiencing strong shaking is the area in the middle of this active zone, rather than along the edges, which explains why the southern contour in Figure 6 is the shape it is.

As regards NW Wales, as already mentioned, the intensity 6 contour in Figure 5 is completely determined by the 19 July 1984 earthquake, and it was a characteristic of this event (a) that it occurred at the SW end of the Caernarfonshire active area, and (b) intensities tended to be higher to the SW of the epicentre than to the NE of it. Thus the northern contour in Figure 5 is pulled to the SW by the individuality of this one earthquake, compared to the equivalent contour in Figure 6, which is more likely to be representative of future seismicity.

This is a good illustration of the principles of seismic hazard analysis in handling cases where the observed historical seismicity is really too short to get a full picture of the potential for seismic activity in the future. Figure 6 is rather more robust as a guide to hazard than Figure 5.

Maximum magnitude

In constructing a hazard model, it is necessary to include a limit to the size of earthquakes that are expected to occur.

Estimating the largest possible earthquake in any intraplate area is always a difficult task. In the UK it is conspicuous that, despite a long historical record, there is no indication that any onshore earthquake has ever exceeded 5.4 ML (offshore events have gone up to 6.1 ML), which suggests that the maximum for onshore events may actually be quite low. In Wales in particular, the way in which magnitudes just above 5 seem to be characteristic, as already mentioned, leads one to speculate that this may possibly be a limit. For the study that produced Figure 6, however, a standard maximum magnitude value of 6.5 was used in the interests of conservatism.

Depth

As has been remarked already, the mid-crustal focal depth of the larger Welsh earthquakes, especially those in NW Wales, has contributed strongly to the lack of damage. The instrumentally-determined depth of the 1984 earthquake was 18 km. The 1852 earthquake, which had a similar epicentre and was felt over much the same area, caused almost no damage. Depth for historical earthquakes can often be estimated from the isoseismal spacing; the 1892 and 1893 events seem to have been quite deep (~ 20 km); the 1906 earthquake was shallower, as one might suppose from the greater amount of damage; it is estimated to have had a focal depth of 13 km (Musson 1994).

Faulting

A common question encountered from engineers concerns the possible behaviour of individual mapped faults. For the seismologist, hazard in the UK is a matter of the probability of damaging levels of ground shaking occurring. However, questions are often asked about whether some named fault is likely to rupture at surface (with the implication that structures should not be sited across the fault). In Wales, as indeed in the rest of the UK, there is no evidence that any earthquake in historical times has broken the surface, and it is extremely improbable that any earthquake will do so in the future. Given the typical focal depths of Welsh earthquakes, and the fact that even the larger recorded events have rupture dimensions of a few km at most, it becomes obvious that the probability of any earthquake rupture intersecting with the ground surface is very slim indeed.

Risk

Convention is to use the term "hazard" to describe the probability of strong ground motion at a site, and the word "risk" to describe the probability of actual loss, either in terms of damage or financial loss (e.g. from interruption to business) – or occasionally, fatalities. Risk incorporates the concept of vulnerability; if buildings are highly resistant to earthquakes the risk may be low even when the hazard is high.

While hazard is most often expressed in terms of a physical measure of ground motion, such as peak acceleration, in the previous section intensity was used, because for the UK the relation between expected intensity and distance and magnitude is well known (Musson 2004b), whereas there is a lack of sufficient recordings of strong ground motion in the UK to understand properly the equivalent relationship for physical parameters.

Intensity is a step towards quantitative risk evaluations, because the probability of damage is inherent in modern intensity scales. The higher intensity values are defined in terms of observed damage distributions, and this implies that one can estimate the probability of different types of building being damaged given a specified intensity value to be expected at some future time. If one could combine Figure 6 with the distribution of building stock in Wales one could come up with an estimate of expected damage (Musson 2000b, Musson and Henni 2001).

In reading the detailed descriptions of the effects of some historical Welsh earthquakes, one senses that traditional Welsh housing is rather good at standing up to earthquakes. Strong stone cottages built to resist winter storms have enough capacity for lateral loading as to give them some inherent earthquake resistance. Thus the vulnerability of traditional structures is probably low.

Conclusions

The following points summarise the main contents of this paper:

- Wales is one of the more seismically active parts of the UK, and the largest onshore British earthquake occurred SW of Caernarfon.
- Within Wales, seismicity is not evenly distributed, and the larger earthquakes have occurred in NW Wales and S Wales only. Any geological explanations for this distribution are speculative.
- Seismicity in S Wales shows an overbalance of earthquake with magnitudes around 5 compared to the number of smaller events, and it seems as if this may be a characteristic magnitude.
- The larger earthquakes tend to have relatively deep focus: more than 15 km.

- Occasionally intensity 7 EMS has occurred in single places, with moderate damage to buildings, but mostly the maximum intensity has been 6 EMS (slight damage) in the higher seismicity areas and 5 EMS (strong) everywhere else.
- The intensity likely to be observed or exceeded with 10% chance in 50 years is 5 EMS for most of Wales, and 6 EMS around Caernarfon-Bangor and in S Wales.
- The likelihood of earthquake fault rupture at surface anywhere in Wales is almost zero.

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Tables

#	Date	Location	Magnitude
1	18 March 1613	St Asaph	4.0
2	27 August 1690	Carmarthen	4.7
3	7 October 1690	Caernarfon	5.2
4	9 November 1852	Caernarfon	5.2
5	19 July 1727	Swansea	5.2
6	18 January 1768	Mold	3.0
7	8 September 1775	Swansea	5.1
8	30 December 1832	Swansea	4.3
9	30 October 1868	Neath	4.9
10	11 April 1888	Corwen	3.8
11	18 August 1892	Pembroke	5.1
12	2 November 1893	Carmarthen	5.0
13	19 July 1903	Caernarfon	4.9
14	27 June 1906	Swansea	5.2
15	25 August 1930	Neath	3.2
16	12 December 1940	Caernarfon	4.7
17	23 January 1974	Bala	3.5
18	15 April 1984	Felindre	3.3
19	19 July 1984	Lleyn Peninsula	5.4
20	25 October 1999	Sennybridge	3.6

Table 1

Earthquakes mentioned in the text and highlighted in Figure 1.

Figures

Figure 1

Seismicity of Wales (all locatable earthquakes > 2 ML). Events discussed in the text are shown in white, with numbers referring to Table 1.

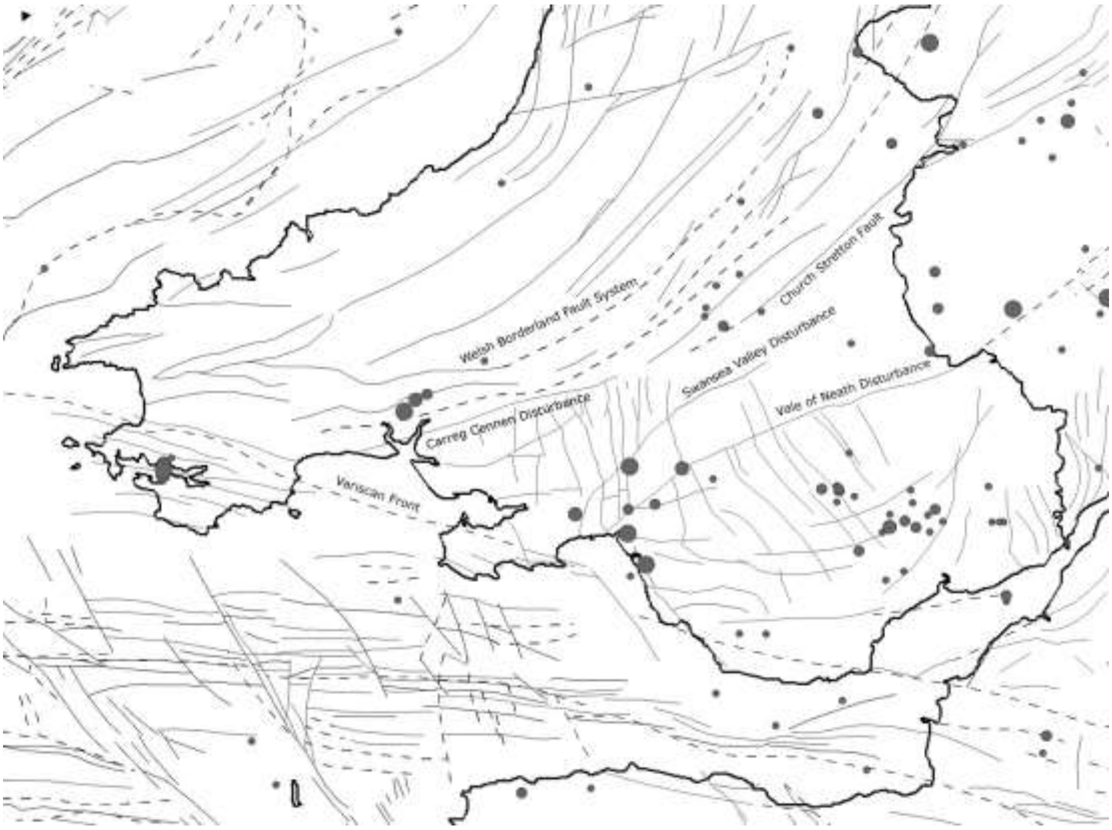

Figure 2

Seismicity in relation to faulting in South Wales. Faults are drawn from the BGS database.

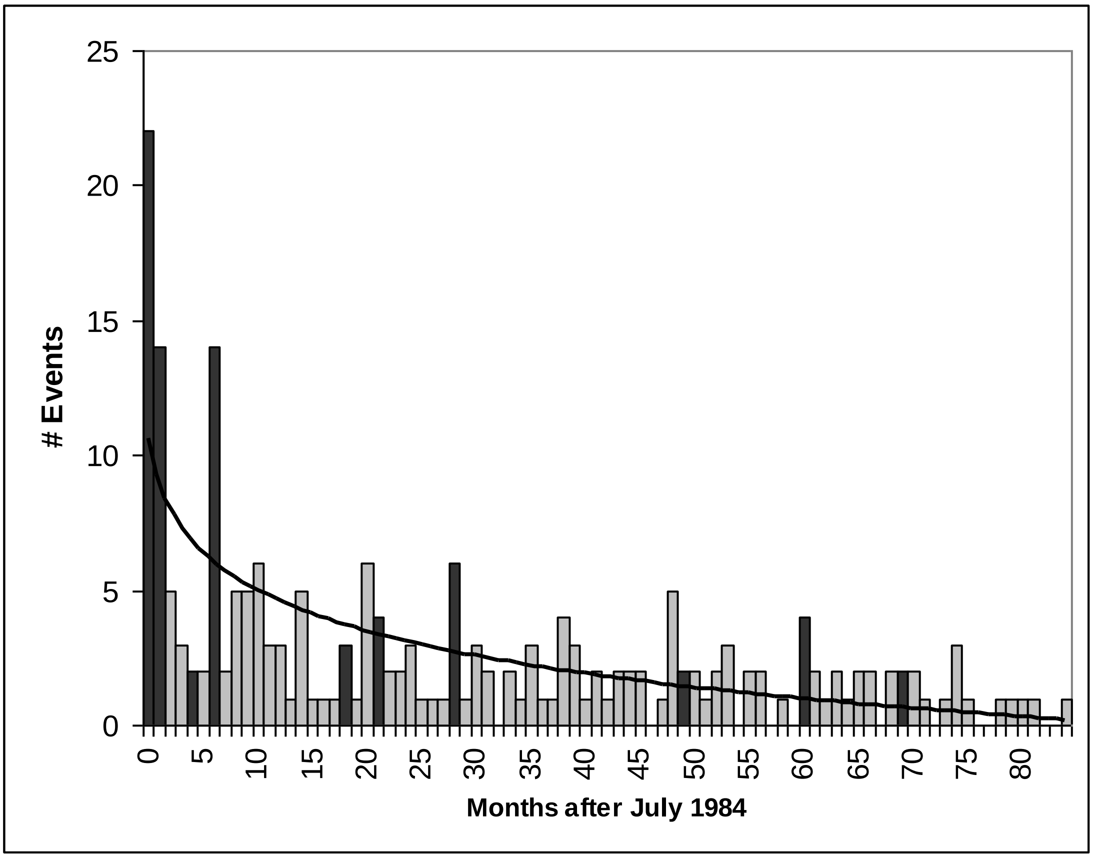

Figure 3

The 1984 Lleyn Peninsula earthquake sequence, shown as the number of detected events per month, starting with July 1984 (month zero) and showing data for the next seven years. Black bars indicate months with at least one event of 2 ML or greater. The thick black curve is the overall trend line.

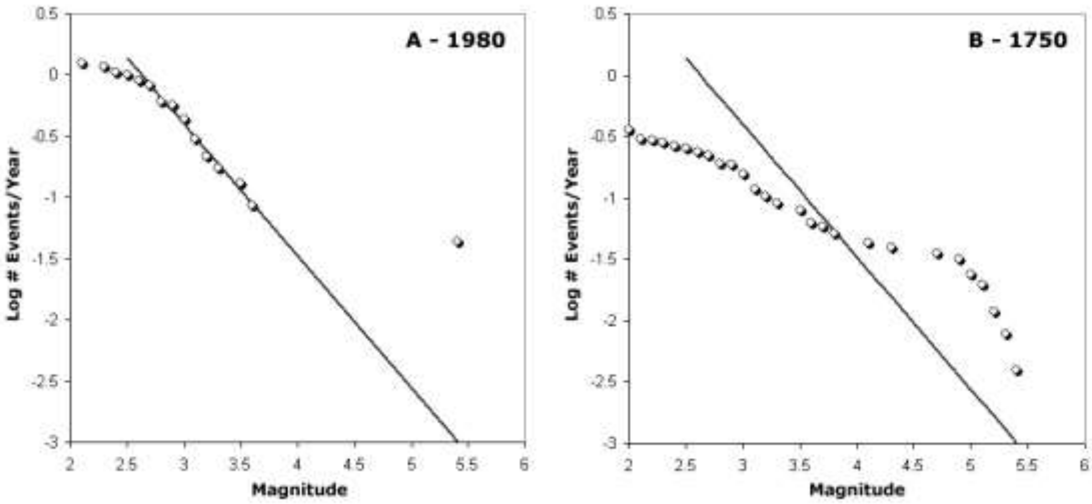

Figure 4

Magnitude-frequency plots for the whole of Wales, (a) since 1980, (b) since 1750. The best fit line for the modern data set (excluding the 1984 earthquake) has been superimposed on the historical data set; it shows that the catalogue is incomplete below magnitude 4 (confirming judgement from analysis of historical sources), but completely underpredicts the number of earthquakes around 5 in magnitude.

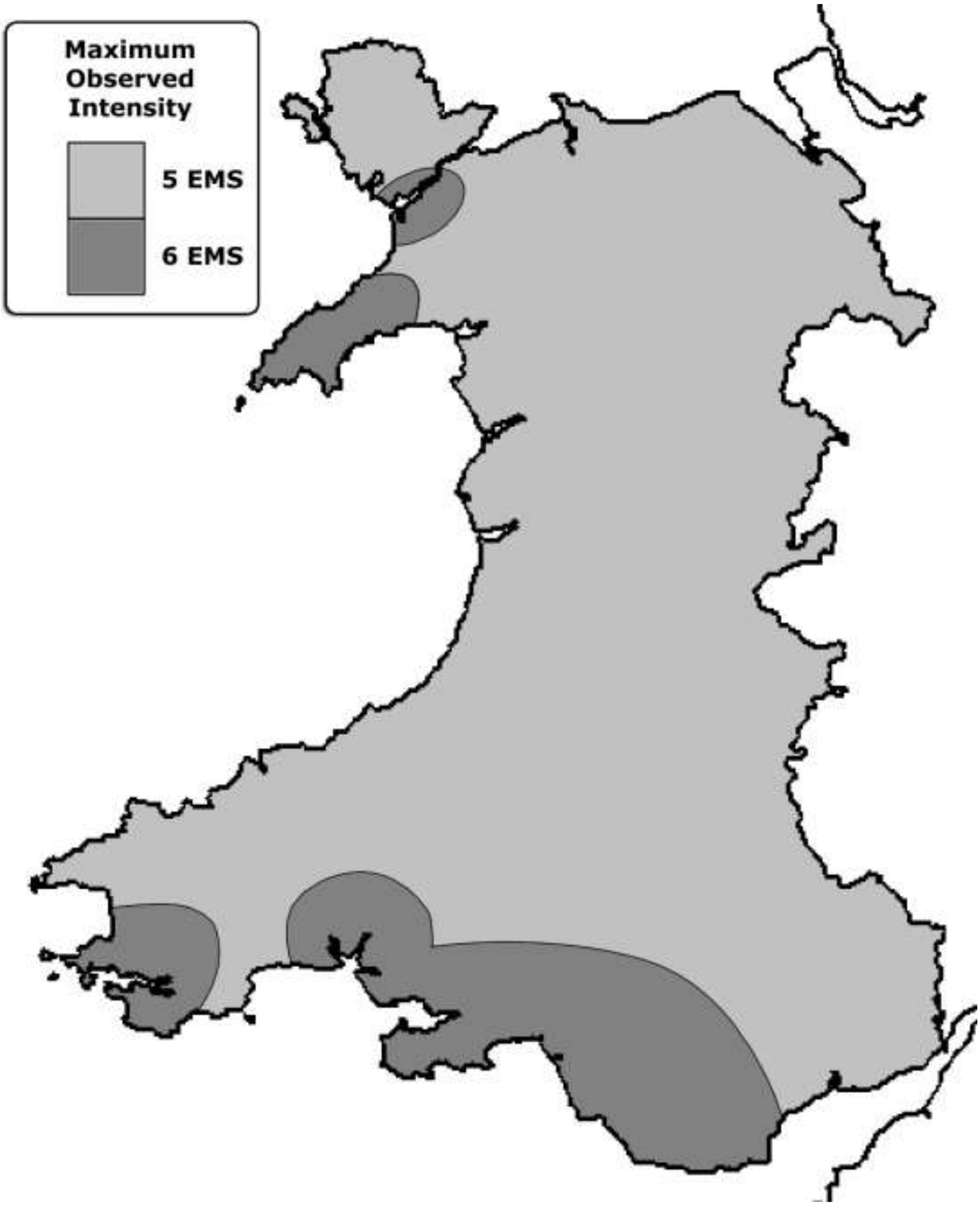

Figure 5

Maximum observed intensity in Wales. Due to lack of detail for early historical earthquake observations, the map is effectively limited to events since 1700.

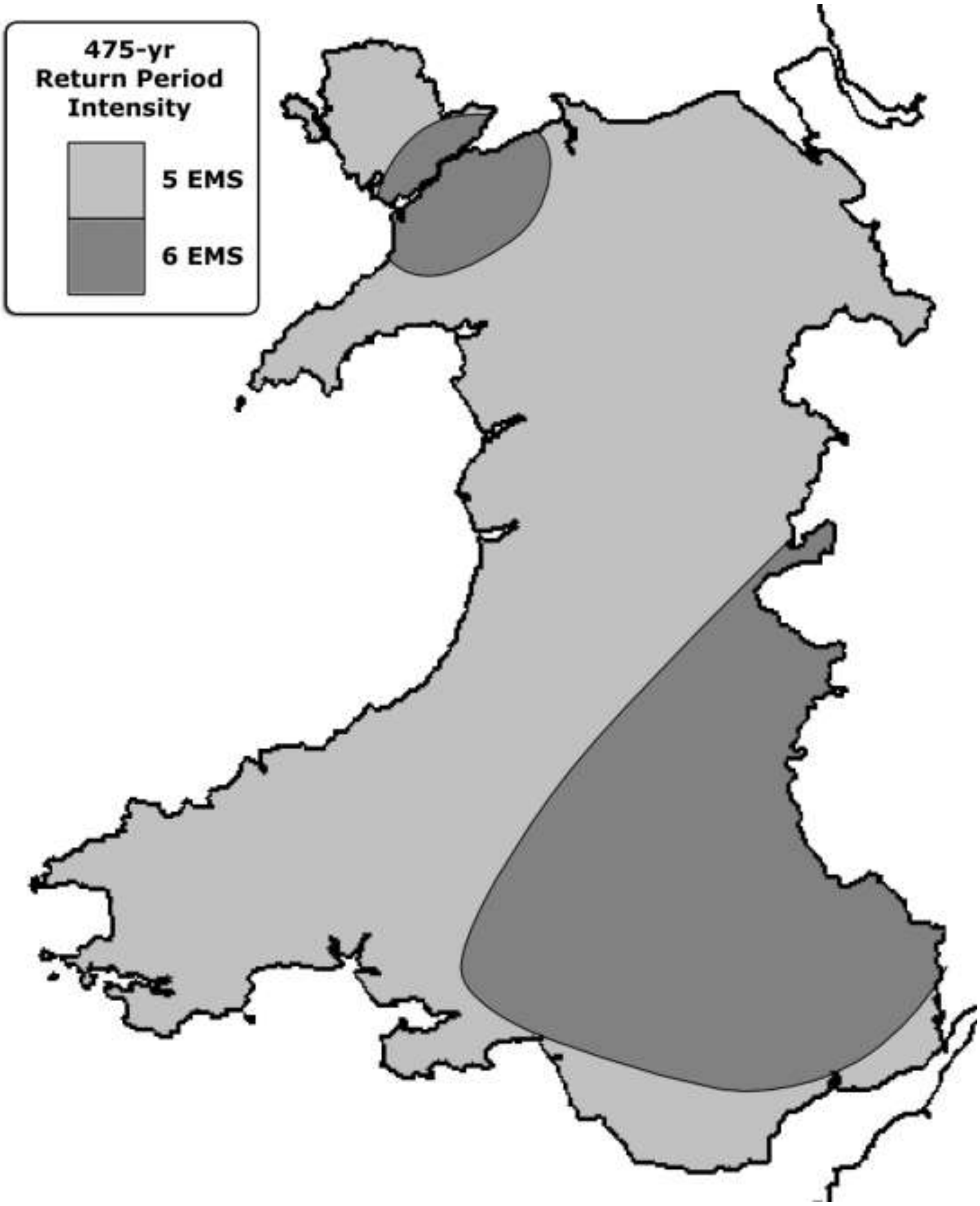

Figure 6

A hazard map for Wales, showing the intensity value with a 10% probability of occurring (or being exceeded) in 50 years (after Musson 2004a).