

OBSERVATIONS ON SEISMICITY IN SOUTH-WEST ENGLAND AND THE NORTH DARTMOOR GEOCHEMICAL ANOMALY

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Seismic data obtained from the British Geological Survey suggest that earthquake activity across Britain, from Cornwall to the North Sea and northwards to Scotland, is linked. Whether over short distances or regionally over hundreds of kilometres, one seismic event appears to trigger a following earthquake. Only after a large event, such as the 3.8 magnitude Penzance earthquake of 10 November 1996, does this sequence appear to be broken. Seismicity is likely to relate to NW to SE compressive stresses across Great Britain. The continuous pattern of seismic events over time would be consistent with the gradual long-term plate tectonic movement of north-west Europe. Within Devon a geochemical anomaly is apparent over the NW to SE Sticklepath Fault system and close to the northern margin of the Dartmoor granite. A high soil gas helium anomaly and deep soil solution potassium showed a correspondence to the 1996 Penzance earthquake. In addition, high deep soil solution magnesium corresponded to the 3.6 ML Bristol Channel earthquake off Hartland on 31 May 2001. Other peaks in potassium and magnesium correspond with months when there was seismic activity. This suggests that there is a north Dartmoor geochemical anomaly providing a measure of the stress within the crust, as well as the stress responsible for earthquakes over large areas of South-West England.

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INTRODUCTION

Earthquake activity from around the world has occasionally been associated with enhanced radon emissions, and sometimes with changes in the concentration of ions in groundwater, as shown by the two following examples.

Using radon alpha tracks, Hirotsuka *et al.* (1988) recorded radon anomalies before the Japanese 6.8 magnitude Nagano Prefecture earthquake on 14 September 1984. There was a gradual increase in radon counts three months before the quake and a remarkable increase two weeks before the shock. Yasuoka *et al.* (2005) recorded stable radon activity of 20 Bq l⁻¹ in a 17-m deep well from the end of 1993. From October 1994 activity increased to 60 Bq l⁻¹ in November 1994, and 1995 radon activity was anomalous 7 to 10 days before a 7.2 magnitude earthquake on 17 January. Radon activity returned to pre-October 1994 levels after the earthquake.

In South-West England, soil gas surveying using the methods described in Duddridge *et al.* (1991) was carried out from 1996 to 1997 by the University of Exeter. This was part of the EU-funded Seismic Hazard Zonation project (Ciotoli *et al.*, 1998). The aim was to establish background soil gas values for helium, radon and carbon dioxide, and the relationship to meteorological variables, such as barometric pressure (Duddridge and Grainger, 1998). However, instead of background soil gas values, the work revealed soil gas anomalies at the time of the November 1996 Penzance and Okehampton earthquakes. Over a number of weeks before the seismic events, peak soil gas values rose significantly above background levels. After the earthquakes soil gas values returned to background levels.

The present paper reviews the 1996-97 soil gas anomalies, and presents additional information on earthquake patterns. The links between seismicity and geochemical anomalies in South-West England and elsewhere are also considered.

BRITISH ISLES EARTHQUAKE ACTIVITY, THE NORTH SEA AND NETHERLANDS

Earthquake data from the start of instrumentation in 1980 up to 2012 was obtained from the British Geological Survey (BGS) Global Seismology Unit in Edinburgh. This consists of 9,174 events that include onshore earthquakes from the British Isles, the English Channel, Channel Islands, and the North Sea as far as Norway and Denmark.

Analysis by number of events is unreliable, as the density of seismometer recording stations can vary and they are not available for offshore areas. This paper therefore also uses relative energy values based on a modified empirical formula of $(10^{\text{magnitude}})^{1.5}$ first derived by Charles Richter and best explained by the U.S. Geological Survey (2014). This gives an energy increase of times 31.6 for every whole number step in magnitude and is a more straightforward way of comparing the magnitude data. Offshore areas may still be under represented by minor earthquakes, but not sufficiently to obscure overall results dominated by higher magnitude earthquakes.

The BGS earthquake data may be divided into two geographical areas of approximately equal size and relative energy. For the area covering the North Sea (Central North Sea,

Skagerrak and Norwegian coast), the total number of earthquakes is 2,023. This is excluding the Roermond earthquake of 1992 in the Netherlands, which is better considered with other Netherlands data. For the remaining area of the British Isles, inclusive of Ireland and the English Channel, there are 7,150 earthquake records. For these 33 years, the North Sea accounts for 50.2% of the seismic energy (288×10^6 energy units) and the remainder of the British Isles to the west accounts for 49.8% of the seismic energy (290×10^6 energy units). This appears to show that over a number of years the released seismic energy balances out between different geographical areas. In terms of earthquake numbers, a peak period of activity was seen in the North Sea from 1985 to 1990 and for a further four years to 1994 for the rest of the British Isles (Figure 1).

Figure 2 plots the separated North Sea and remaining British Isles seismic data between 1980 and 2012 in terms of relative energy released. Three peaks stand out within the British Isles data and are due largely to three earthquake events. Firstly, on 19 July 1984 the 5.4 ML Lley Peninsula quake accounted for 96.5% of the seismic energy in that year, and further Lley Peninsula shocks for another 3.2%. This was balanced four years later by a 5.4 ML earthquake in the northern North Sea on 8 August 1988, which accounted for 98.3% of the seismic energy in the North Sea area in that year. Thirdly, in Shropshire on 2 April 1990 the 5.1 ML Bishops Castle earthquake near the Welsh border accounted for 99.3% of the 1990 seismic energy released across the British Isles and helped balance other episodes of North Sea activity within the period from 1982.

From the mid-1990s seismic activity was clearly much reduced, with fewer events and less released energy, until more recent activity which included the 5.2 ML Market Rasen earthquake on 27 February 2008. Only the period from 2000 to

2002 shows any other significant events. In this period seismicity increased in 2001 and again in 2002 to include the 4.6 ML Dudley event. The year 2001 included the 3.6 ML earthquake off Hartland in Devon on 31 May, and a few days later a series of earthquakes at Constantine in Cornwall.

Within the period from 2000 to 2003, 45.9% of the total seismic energy represented by the subdivided BGS data came from the North Sea and 54.1% from the remaining British Isles and offshore areas. Within the latter, 61.4% of the energy was from the 4.7 ML Dudley earthquake of 22 September 2002, 30.8% from a 4.5 ML earthquake in north-west France on 30 September 2002 and a long series of 117 quakes in the Greater Manchester area from 19 October 2002. The Manchester series accounts for 6.8% of the 2002 seismic energy.

The large-scale pattern of earthquakes in the period from 1980 to 2012 shows that larger events in the North Sea are generally balanced by earthquakes elsewhere in the British Isles. These can occur anywhere across the British Isles from the South-West of England to the North Sea and within a period of two to four years.

Further to the east in continental Europe seismic data from the Dutch Meteorological Institute (Het Koninklijk Nederlands Meteorologisch Instituut (KNMI)) show a variable pattern similar to that of the North Sea and a significant positive correlation of the per annum total energy values, based on the ranked Spearman test (R value of 0.562 above the critical value of 0.3624). The Netherlands seismic data have been added to Figure 2 as a logarithmic plot. In the Netherlands, the most significant event between 1980 and 2012 was the 5.8 ML Roermond earthquake of 13 April 1992. It would appear to mark the end of enhanced seismic activity across the British Isles, the North Sea and the Netherlands that is evident for most of the 1980s. This quake produced 55 subsequent shocks in the Roermond area and seismic activity continued frequently for the rest of 1992 and beyond.

BRITISH ISLES EARTHQUAKES BETWEEN 1993 AND 2012

This paper concentrates further on earthquakes from 1993 when most geochemical data are available. Onshore and offshore earthquake epicentres from 1993 to mid 2013 are shown in Figure 3. This map reveals that the west side of Britain has more seismic events than the east side. Over the 20.5 year period most seismic energy was actually released within a SW to NE zone running from the Midlands to Lincolnshire and orthogonal to the main NW to SE compressive stress across Great Britain. Earthquakes within the ellipse shown on Figure 3 account for around 85% of the seismic energy released (within the map area depicted) between 1993 and mid 2013. Of this, the 4.7 ML Dudley earthquake of 22 September 2002 and the 5.2 ML Market Rasen earthquake of 27 February 2008 contributed 11% and 65% of the energy, respectively. Using seismic tomography, Bott and Bott (2004) also identified the SW to NE belt of earthquakes from Cornwall to Lincolnshire that included Wales and the West Midlands, plus a south to north zone from Cornwall to the West Highlands of Scotland. They considered that uplift and seismicity of mainland Britain was related to hot and low-density uppermost mantle beneath.

The SW to NE and S to N directions are those followed more often by sequences of earthquakes, whether on the scale of minutes, days or weeks. South-West seismicity is closely linked to that across the whole of the British Isles, including the North Sea. Overall patterns of seismicity appear to be releasing and evening out stress across the whole British Isles, with events often progressing in several steps eastward before returning to the west side of Britain. Figure 4 further illustrates, for a 6 month period in 1993, how the South-West of England is linked to seismicity across the whole British Isles. Although complex, a pattern of eastward progression can be discerned from the colour coding. This indicates the possibility that geochemical

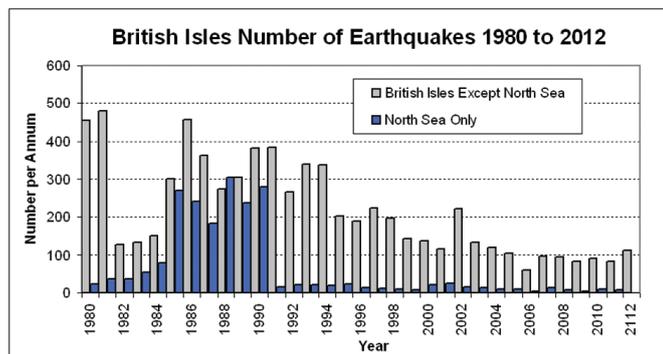


Figure 1. Variation of British Isles earthquake activity from 1980 to 2012 by number of events.

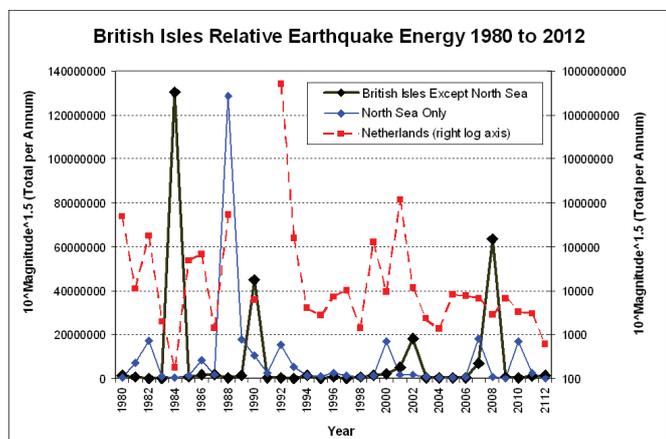


Figure 2. Variation of relative earthquake energy over time. Calculated from magnitude data that have been subdivided between the North Sea and remaining data. Dutch data are also included for comparison.

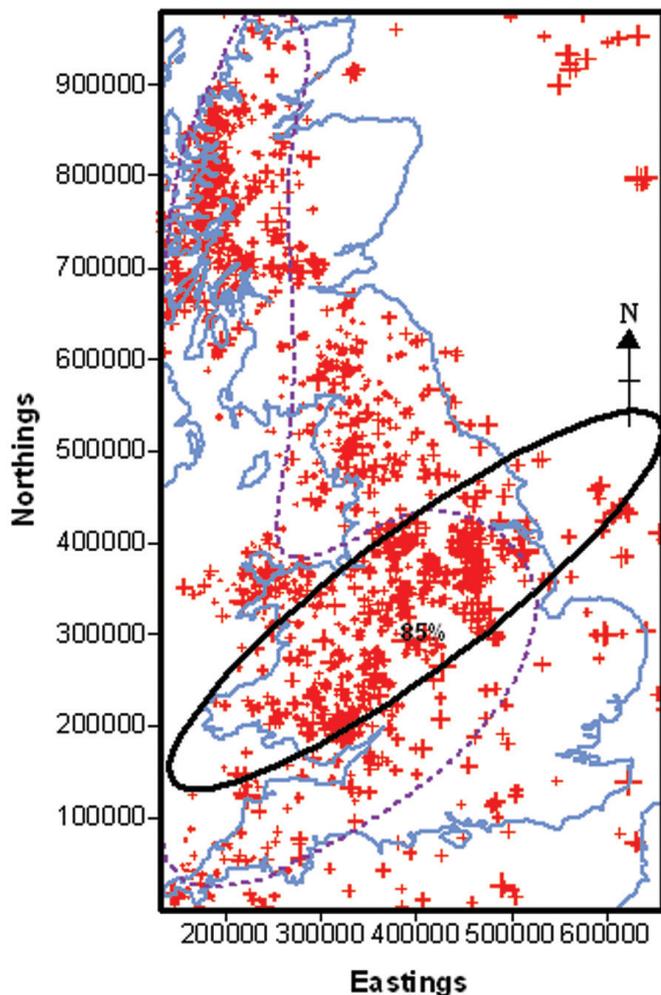


Figure 3. Earthquake epicentres between 1993 and mid 2013. Plus symbols are proportional to magnitude to help illustrate the geographical density of occurrence. The ellipse is drawn to enclose earthquakes that account for 85% of the seismic energy released relative to the rectangular map area. The purple dashed line identifies the anomalous mantle zone of Bott and Bott (2004) and determined by S-wave seismic tomography.

changes in radon or groundwater, that are suspected to relate to seismicity, may be a response to both local and more distant activity.

GEOCHEMICAL ANOMALIES AND EARTHQUAKES IN CORNWALL AND ELSEWHERE

Duddridge and Grainger (1998) reported anomalous soil gas helium, radon and carbon dioxide peaks in South-West England that coincided with two November 1996 earthquakes near Penzance and Okehampton. Soil gas monitoring was carried out every two weeks, and the association with seismicity was clearer than any possible meteorological effect. Figures 5 and 6 are adapted from the data used in Duddridge and Grainger (1998), but additionally show 29 earthquakes from August 1996 to December 1997 (Table 1). These include all the earthquakes recorded by BGS for the period, although only to the west of a line through Portsmouth, Basingstoke and Wallingford (National Grid Easting 461113) and south of a line through South Wales: Fishguard and Llandovery, then Ledbury and King's Sutton (National Grid Northing 34138).

During 1996-97 soil gas was monitored by the author at Aysh near Throwleigh, on northern Dartmoor. The 1.5 ML Okehampton earthquake (near Wembworthy) of 26 November 1996 was preceded by a clear helium anomaly (Figure 5). Soil

gas helium rose over a 6-week period from 145 ppb ΔHe (difference above normal air value of 5,220 ppb He) to 570 ppb ΔHe the day before the earthquake. Delta He concentrations never reached such high values again during a further year of fortnightly soil gas monitoring to December 1997. At the nearby agricultural research institute at North Wyke, the Environmental Change Network (ECN) monitors deep soil solution ions (Sykes and Lane, 1996). The site is on the north side of Dartmoor and about 9 km north of the 1996-97 Aysh soil gas monitoring site. Monthly averaged potassium was uniquely high in November 1996 at 62.99 mg l⁻¹. This was significantly above background values of less than 1.00 mg l⁻¹ (Figure 7).

Both the Aysh and North Wyke monitoring sites are located in close proximity to the Sticklepath Fault system. This fault may be acting as a conduit for fluid movements that vary their concentration during times of stress. Between Aysh and North Wyke permeability might be enhanced by the geometry of the fault at this location. The dextral off-set and south-west dip of the fault plane must place greater amounts of low density granite on the hanging wall side compared to denser Carboniferous rocks on the north-east foot wall side. Edmonds *et al.* (1968) report a density value of around 2.5 g cm⁻³ for the granite and 2.68 g cm⁻³ for denser Carboniferous rocks.

Soil gas monitoring by the author at Tremough near Penryn in Cornwall recorded a Rn-222 anomaly of 182 Bq l⁻¹ the day after the Penzance earthquakes of 10 November 1996. This was 4.7 times the average radon activity for the whole 17-month monitoring period (Figure 6). As the peak was monitored the day after the earthquake, it is not known whether it had been higher just before the seismic event (Duddridge and Grainger, 1998).

The linked pattern of earthquakes across the British Isles, as previously considered, suggests that over time stresses are transferred over large distances (Figure 4). It is therefore possible, although not provable, that the 3.8 ML Penzance earthquake of 10 November 1996 was in part responsible for the geochemical anomalies seen at Aysh. This is a distance of 142 km and could mean that other earthquakes might be detectable by soil gas geochemistry at Aysh and North Wyke.

The soil gas monitoring at Tremough and also nearby at High Cross was started just after the Constantine earthquake of 23 August 1996 (Duddridge and Grainger, 1998). Soil gases that may have built up prior to the Penzance earthquake may have been dispersed by this preceding seismicity. In contrast, Aysh on north Dartmoor demonstrated a slow build up of helium (Figure 5) and also carbon dioxide. This anomaly is most likely associated with the Penzance earthquake and large regional stresses acting up against the Sticklepath Fault system. After the Penzance earthquake, stress was reduced and helium increased at a much slower rate until the 1.5 ML Okehampton earthquake (actually located east of the Sticklepath Fault and near Wembworthy) dispersed the soil gas anomaly.

In the three months following the November 1996 Okehampton earthquake no seismicity was recorded in the South-West or South Wales, but it continued in North Wales, Northern England and in Scotland. The Scottish activity included a long series of events around Musselburgh. At Aysh, the levels of soil gas helium, radon and carbon dioxide were consistently low, as was deep soil solution potassium at North Wyke. This could suggest that fluids had dispersed from deep sources and a large section of the earth's crust had been de-stressed between south-west Cornwall and the Sticklepath Fault system. Earthquakes only returned to South-West England in March 1997 and this was marked by the start of increasing helium (Figure 5), carbon dioxide, radon and deep soil solution potassium (Figure 7) at the Aysh and North Wyke monitoring sites. Figures 5 and 6 also show earthquakes located from Gloucester to Jersey and Carterton in Oxfordshire. None appears in this area in the months after the Penzance earthquake. Therefore the area of de-stressed crust may have extended to areas north and east of the Sticklepath Fault system.

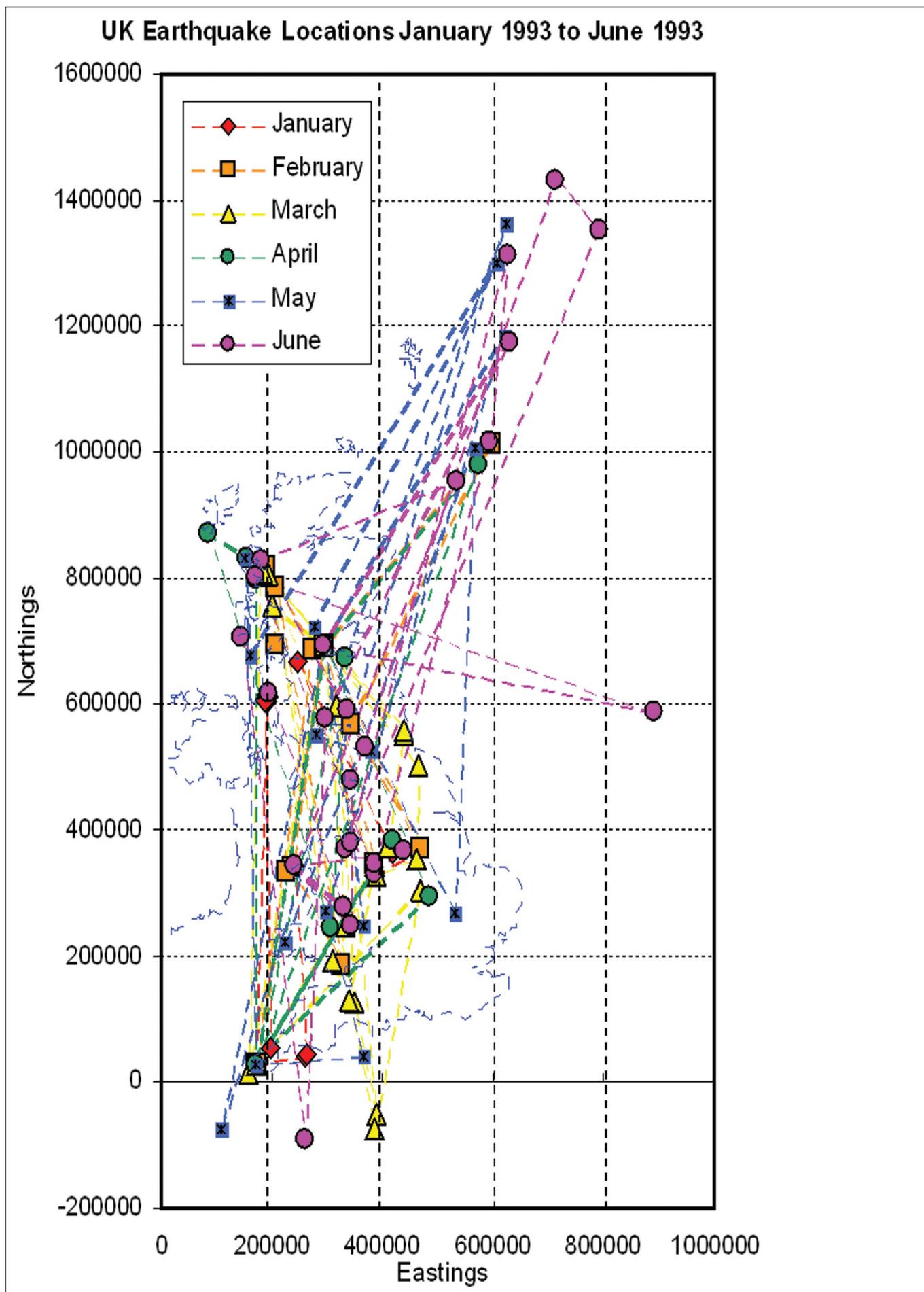


Figure 4. Earthquake sequences illustrating the links between those in South-West England, the rest of Great Britain and the North Sea.

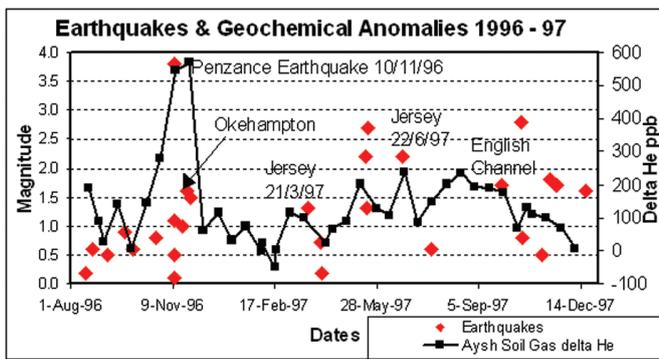


Figure 5. Soil gas delta helium variation from the North Dartmoor geochemical anomaly and earthquake magnitudes across the wider south west and South Wales.

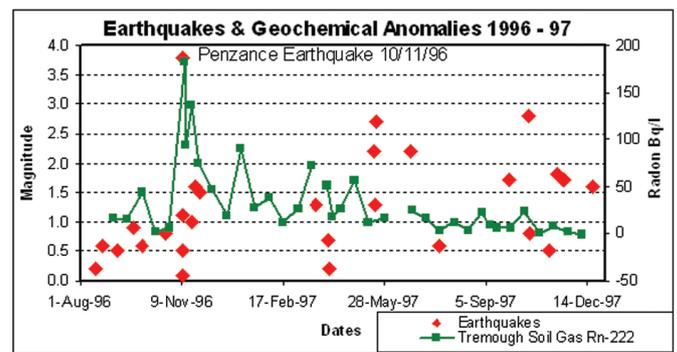


Figure 6. Soil gas radon variation from the Tremough soil gas monitoring site near Penryn, Cornwall and earthquake magnitudes across the wider south west and South Wales.

Date	Latitude	Longitude	Easting	Northing	Depth	ML	Location
16/08/1996	48.985	-1.854	410717	-101623	9.1	0.2	Jersey, Channel Islands
23/08/1996	50.109	-5.182	172498	28099	7.3	0.6	Constantine, Cornwall
06/09/1996	51.755	-3.290	310982	207127	6.7	0.5	Merthyr Tydfil, Mid Glam
22/09/1996	49.769	-5.781	127753	-7651	8.7	0.9	SW Lands End, Cornwall
01/10/1996	50.466	-4.756	204447	66569	12.7	0.6	Bodmin, Cornwall
24/10/1996	49.373	-2.354	374289	-58510	5.9	0.8	Jersey, Channel Islands
10/11/1996	50.000	-5.577	143719	17241	8.3	3.8	Penzance, Cornwall
10/11/1996	50.005	-5.585	143176	17902	11.8	1.1	Penzance, Cornwall
10/11/1996	50.008	-5.583	143335	18228	9.9	0.5	Penzance, Cornwall
10/11/1996	50.018	-5.577	143772	19265	8.8	0.1	Penzance, Cornwall
18/11/1996	51.766	-3.838	273166	209095	5.5	1.0	Glanaman, Dyfed
23/11/1996	48.989	-4.263	234462	-98788	15.9	1.6	English Channel
26/11/1996	50.877	-3.935	263880	110423	5.8	1.5	Okehampton, Devon
21/03/1997	49.185	-2.020	398579	-79435	7.0	1.3	Jersey, Channel Islands
02/04/1997	51.821	-3.590	290403	214842	16.7	0.7	Glyn Neath, W. Glamorgan
04/04/1997	50.102	-5.456	152913	28191	1.6	0.2	Mount's Bay, Cornwall
17/05/1997	51.900	-2.294	379794	222450	15.4	2.2	Gloucester,
18/05/1997	49.185	-2.021	398469	-79468	7.0	1.3	Jersey, Channel Islands
19/05/1997	51.759	-1.640	424809	206812	6.2	2.7	Carterton, Oxfordshire
22/06/1997	49.252	-2.278	379771	-71917	10.9	2.2	Jersey, Channel Islands
20/07/1997	48.878	-2.145	389369	-113517	20.8	0.6	Jersey, Channel Islands
28/09/1997	49.028	-3.914	260065	-95066	9.5	1.7	English Channel
16/10/1997	50.390	-3.730	277023	55989	10.4	2.8	Dartmouth, Devon
18/10/1997	51.859	-2.713	350889	218057	14.7	0.8	Monmouth, Gwent
06/11/1997	50.230	-5.397	157776	42313	0.5	0.5	St Ives Bay, Cornwall
14/11/1997	51.627	-3.034	328455	192556	4.3	1.8	Newport, Gwent
19/11/1997	51.699	-4.243	244994	202405	20.1	1.7	Burry Port, Dyfed
21/11/1997	51.320	-2.588	359028	158075	13.5	1.7	Bristol, Avon
19/12/1997	51.914	-4.576	222863	227157	4.3	1.6	Near Carmarthen, Dyfed

Table 1. Earthquake data from British Geological Survey records for the United Kingdom and used in Figures 5, 6 and 7. Depth in km.

EARTHQUAKES IN JERSEY AND NORTH WYKE POTASSIUM ANOMALIES

A 1.3 ML earthquake in Jersey on 21 March 1997 (Table 1 and Figure 5) followed a Norwegian Sea earthquake three days earlier, and was the first South-West event after the Okehampton quake of 26 November 1996. Three earthquakes occurred on the 17, 18 and 19 May 1997 and coincided with the rising deep soil solution potassium levels at North Wyke (Figure 7). They also coincide with a moderate rise to 200 ppb Δ He soil gas at Aysh (Figure 5). The 2.2 ML Jersey earthquake

of 22 June 1997 coincided with a peak in the fortnightly soil gas monitoring on the 23 June 1997. Soil gas Δ He reached 240 ppb and carbon dioxide 5.26%. June 1997 also marked the month of the second deep soil solution potassium anomaly of 9.06 mg l⁻¹ at North Wyke.

Figure 8 presents a comparison of the monthly Jersey earthquake energy with ECN deep soil solution potassium data from September 1994 to 2012 at North Wyke. This shows 12 clear incidents where a rise in potassium, often over several months, shows a close correspondence to a month of one or more earthquakes. As in the case of high soil gas helium

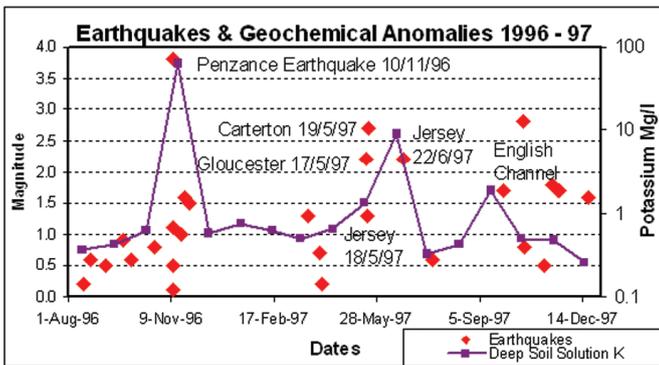


Figure 7. Average monthly deep soil solution potassium variation from the ECN site at North Wyke compared to earthquake magnitudes 1996-97. Monthly potassium data displayed at the middle of the month.

associated with the Okehampton/Penzance earthquakes, potassium also decreased after the period of seismicity.

Figure 9 shows a logarithmic plot for 28 of the 30 Jersey earthquakes occurring from September 1994 to 2012 against the North Wyke deep soil solution potassium concentrations. Two are omitted as they occurred at times of no recorded potassium data. Events in South Wales, in the Bristol Channel and on the north-easterly side of the Sticklepath Fault are not included. The 1996 3.8 ML Penzance earthquake is included and a number of English Channel events, such as the 1.7 ML earthquake of 28 September 1997, are shown. The plot shows that earthquake energy has a positive association with increasing deep soil solution potassium at North Wyke, and indicates an apparent potential to forecast earthquake energy from potassium concentration. Potassium appears to be recording the stress over large distances of the crust despite Jersey earthquakes being over 200 km from North Wyke. However, they are within 3 degrees of the SE strike of the Sticklepath Fault. These stresses are likely to have been

transmitted through the crust beneath the Mesozoic cover of the English Channel and close to the area of the Start-Cotentin ridge. Figure 10 shows the position of the earthquake epicentres coinciding with potassium peaks from the North Wyke deep soil solution data.

BRISTOL CHANNEL EARTHQUAKES AND GEOCHEMICAL DATA FROM NORTH WYKE

At North Wyke, the Environmental Change Network has recorded not only potassium, but also magnesium in deep soil solution over a number of years. Figure 11 shows deep soil solution magnesium in relation to the total monthly earthquake energy from a wide geographical area taking in the English Channel, South Wales and east into Oxfordshire. Earthquake data east of around longitude -1° and north of latitude 52° are excluded. The most easterly earthquake included is a 2.2 ML event at Wallingford, Oxfordshire on 8 January 1994. The most northerly earthquake included is the 1.1 ML event at Talgarth, Powys on 7 June 2003.

There is some correspondence in peaks of magnesium and monthly earthquake energy values. The May 2001 Mg peak at 4.96 mg l^{-1} is the highest level seen in the whole 20-year period from 1993 to 2012, and coincides with the third highest monthly relative seismic energy level. The 3.6 ML Hartland earthquake occurred on 31 May 2001 and the slow build up from background levels, starting from a low of 0.90 mg l^{-1} in October 2000, and the sudden drop to 1.21 mg l^{-1} in June 2001 is what might be expected of an earthquake related geochemical anomaly.

The year 2001 was one of enhanced seismicity around the British Isles (Figure 2) and it is likely this was significant for North Wyke which lies on the NW-SE Sticklepath Fault system. May 2001 started a sequence which saw a 4.2 ML quake in the Ekofisk region of the North Sea, a 2.6 ML quake in the southern North Sea, a 1.2 ML quake in South Wales, and these were followed by a series of quakes in south-west Scotland before seismicity occurred again in the North Sea on 15 May. After a 16-day gap seismicity moved briefly south-west via Rotherham

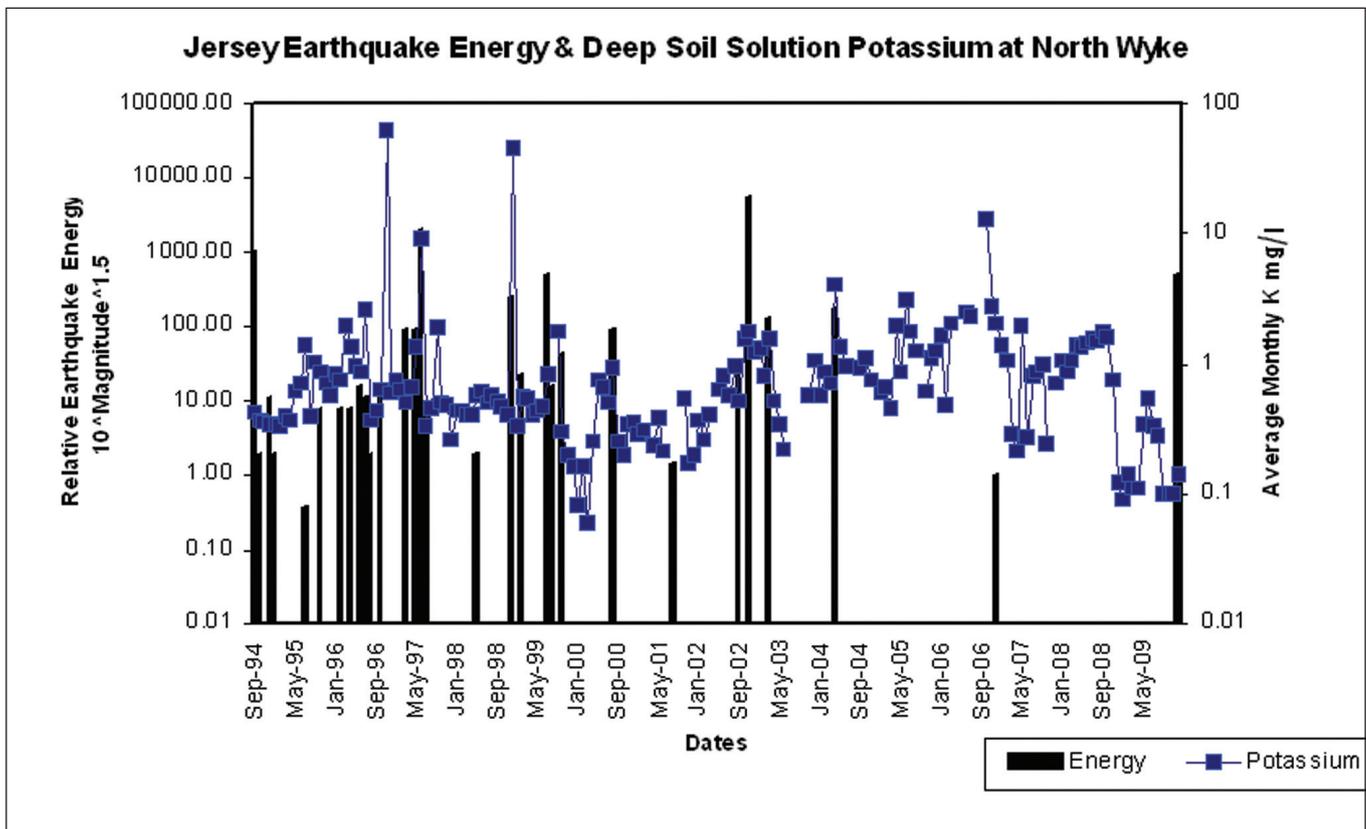


Figure 8. Relative energy of 28 Jersey earthquakes plotted against average monthly deep soil solution potassium peaks from North Wyke.

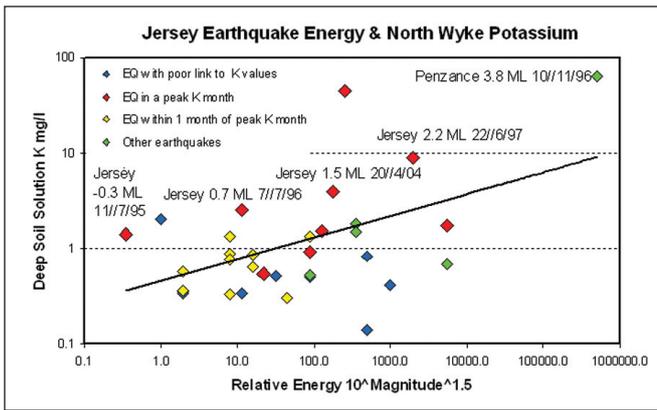


Figure 9. Relative energy of individual Jersey earthquakes plotted against North Wyke deep soil solution potassium values. The Penzance earthquake and an English Channel earthquake are also shown. The four Jersey earthquakes and the Penzance earthquake correspond to an overall trend where deep soil solution potassium increases with earthquake energy. This is an indicator of stress across the region.

(1.6 ML) and the 3.6 ML Hartland earthquake before moving back to the North Sea (3.7 ML). The close linking of these earthquakes is suggested from the close timing: 18:19 hours at Rotherham, 23:42 hours at Hartland and 06:18 hours in the North Sea. For the next 16 days activity was concentrated at Constantine and the North Sea with one intermediate event occurring at Bristol (1.2 ML) on 5 June 2001. From 20 June to the end of August 2001 seismicity switched to various north-south sequences between Wales and Scotland.

Some months were characterised by a potassium anomaly rather than a magnesium response. For example, November 1996, at the time of the Penzance earthquake, was the highest month for energy (Figure 11), but had no peak in magnesium concentrations. Some peaks, such as one of 2.65 mg l⁻¹ for Mg

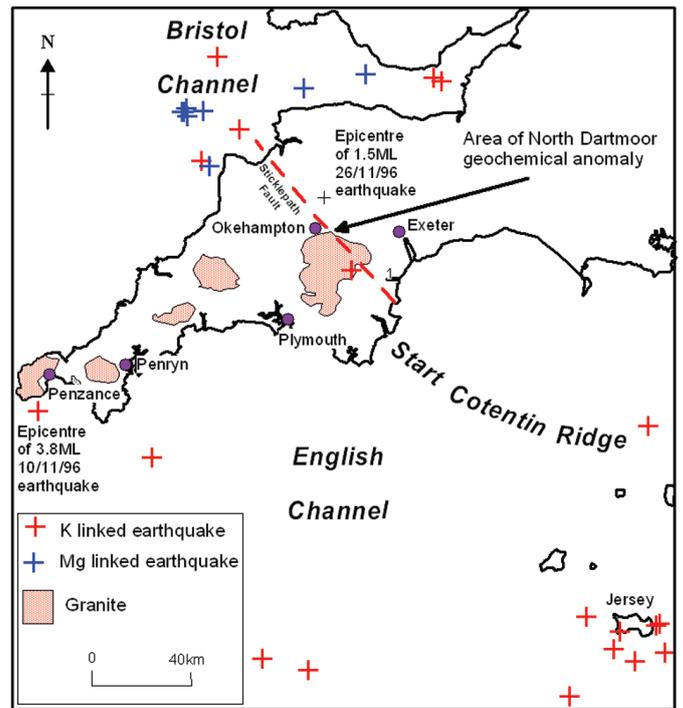


Figure 10. Map showing the epicentres of earthquakes most clearly associated with peaks in deep soil solution potassium or magnesium from the north Dartmoor geochemical anomaly at North Wyke.

in December 1993, coincide with quite distant South Wales and Hampshire earthquakes, in this case at Bargoed, Abergavenny, Southampton and Pontycymer on the 15, 24, 26 and 31 December, with magnitudes of 1.3, 1.3, 1.2 and 1.9, respectively. Other events such as a 1.8 ML earthquake at St. Clears on 30 October 1998, are unlikely to have been detected at North Wyke.

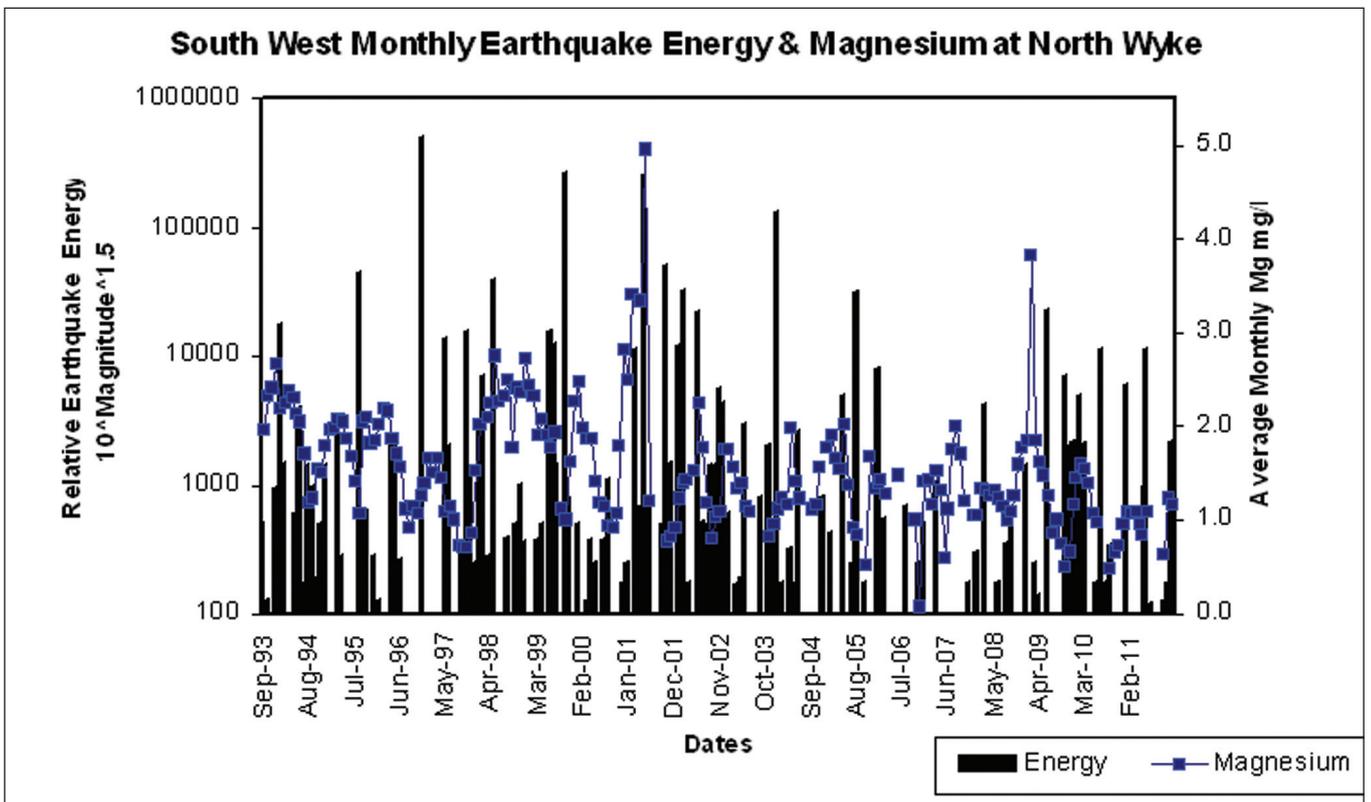


Figure 11. Relative energy of 1993 to 2012 earthquakes, west of longitude -1° and south of latitude 52°, plotted against deep soil solution magnesium from North Wyke.

Given that the May 2001 Hartland earthquake coincided with a distinctive magnesium peak, other Bristol Channel events were also examined regarding magnesium levels. Earthquake information and Mg geochemistry are summarised in Table 2. It was found that of 18 Bristol Channel earthquakes, there were three where geochemical data had not been recorded for the relevant months. Eight earthquakes, including the May 2001 Hartland event, were linked by month to Mg peaks, and five to potassium peaks at North Wyke. Two events corresponded to months of both low Mg and K, but follow 5 and 6 months after the large 4.96 mg l⁻¹ Mg peak linked to the May 2001 'off Hartland' earthquake. It is likely that the geochemistry was in a recovery phase from this event.

Magnesium and potassium peaks rarely coincide, and at least in the case of the Bristol Channel, four potassium peaks relate to shallower earthquakes of around 6 to 11 km depth (Figure 12). These earthquakes must result from stress at this depth, and at a level which is stressing a point where the Dartmoor Granite is intersected by the Sticklepath fault system and reaches the surface near North Wyke. It is assumed that the potassium enrichment is related to potassium minerals within the granite or the metamorphic aureole. A number of the Bristol Channel earthquakes are aligned together from east to west, suggesting a possible link with Variscan thrust faulting. In contrast, the Mg anomalies associated with Bristol Channel earthquakes occur over a wide range of depths down to 30 km, and are clustered

Month	Mg Rise	Mg Peak	End of Mg Peak	Relative Energy	Earthquake	Comments
December 1993 & January 2004	3 months or longer from 1.26	2.65	Drops to 1.19 over 8 months to August 1994	November - 6 December - 949 January - 17,958 February - 1,507	1/1/1994 - 2.8 ML in Bristol Channel 88.3% of January seismic energy	
October 1994	On shoulder of larger peak	1.54	Drops to 1.5 in November & then continues rise	September - zero October = 126 November - zero	14/10/1994 - 1.2 ML Bristol Channel, Lundy Island	K peak, declining, other earthquakes SW of Plymouth & Jersey
July 1995		No peak		September - 1,000 October - 191 November - 501 December - 1,435	5/7/1995 - 0.6 ML Barnstaple Bay, 95.7% of July seismic energy	K peak of 1.4
October 1995	Rapid rise over 2 months from 1.07	2.1	Drops to 1.81 over 1 month to November 1995.	September - zero October - 614 November - zero December - 276	14/10/1995 - 1.6 ML Bristol Channel, 40.9% of October seismic energy	
May 1998	Rising for 7 months from 0.71 to first peak	2.75	Drops to 1.78 over 4 months, up to 2.72 in December, down to 1.0 by October 1999.	February - 7,052 March - 283 April - zero May - 39,923 June - 4	31/5/1998 - 2.6 & 1.7 ML Bristol Channel, almost 100% of May seismic energy (Atlantic Ocean 3.0 ML of 14 May excluded)	Minor Jersey quake of 0.2 ML on 18 May
August 2000		No peak	At 0.94	August - 1,000	11/8/2000 - 2.0 ML Bristol Channel, 91% of May seismic energy.	High K, June - 0.66, July - 0.5, August - 0.93, September - 0.25
May 2001	Rising for 8 months from 0.90	4.96	Drops to 0.77 over 5 months to October 2001.	April - 708 May - 251,252 June - 708	31/5/2001 - 3.6 ML off Hartland, almost 100% of May seismic energy	
October 2001		No Peak	At 0.77	October - 50,972	8/10/2001 - 1.5 ML off Hartland, only 0.3% of October seismic energy, remainder at Bargoed	K peak of 0.53 drops to 0.17 in November, no proceeding data
November 2001		No Peak	At 0.81	November - 1,495	1/11/2001 - 1.1 ML off Hartland, only 3% of October seismic energy	Other earthquakes in the Lizard. Bristol & the Scilly Isles
August 2002		No peak	At 1.18	August - 502	23/8/2002 - 1.6 ML off Hartland, 50% of October seismic energy, rest at Abergavenny	K peak, July - 0.56, August - 0.96, September - 0.51
September 2003		No Mg data July to October		July - 3.98 August - 15.85 September - 94.72 October - zero	2/9/2003 - 1.2 ML Lynton, 7.7% of energy 16/9/2003 - 0.8 ML Bristol Channel off Lundy, 1.9% of energy	No K data. August conductivity 158 µS/cm (above background), 1.9 ML Drybrook on 19 September, 86.5% of energy.
April 2004 & May 2004	Rising for 5 months from 0.82	1.98	Drops to 1.15 over 6 months to October 2004.	March - 20.0 April - 67.4 May - 31.6 June - 246.7	20/4/2004 - 1.5 ML Jersey, 53.9% of April seismic energy 3/5/2004 - 1.5 ML Bristol Channel (5km off Barry)	K peak in March - 0.7, April - 3.96, May - 1.34, June - 0.94
May 2005	Rising for 7 months from 1.15	2.02	Drops to 0.53 over 5 months to October 2005	April - zero May - 4,970 June - 16 July - 251	30/5/2005 - 1.7 ML Lundy Island, 7.1% of May seismic energy & 0.2% offshore Jersey	97.9% of May 2005 seismic energy from 5 earthquakes at Llandeilo
November 2006		No Peak	At 0.07	August - 708 September - zero October - zero November - 251 December - 502	30/11/2006 - 1.6 ML Bristol Channel, 100% of November seismic energy	5 months of missing Mg data, K anomaly of 12.67 in October & 2.79 in November
November 2007		No Peak and no data	Drops to 1.05 in December & January 2008.	November - 178	24/11/2007 - 1.5 ML off Hartland, 100% of November seismic energy	No K data available
February 2010	Rise over 4 months from 0.5	1.58	Drops slightly to 1.55 in March & then to 0.47 in September 2010	December - 228.8 January - zero February - 432.8 March - 183.6	4/2/2010 - 2.2 ML Bristol Channel, 39.5% of February seismic energy	Other earthquakes in Carmarthenshire, Lyme Regis & Chippenham, 1.4 ML South Molton on 1 March, English Channel on 23 February.
June 2011 & July 2011	Rise over 1 month from 0.84 to 1.10	No data	No data until October when at 0.64		15/7/2011 - 1.0 ML Barnstaple Bay	1.2 ML Dartmouth on 2 June & 2.7 ML Newton Abbot on 23 June, 98.4% of June energy.

Table 2. Summary data relating to Bristol Channel earthquakes and deep soil solution magnesium anomalies from North Wyke. Mg and K values in mg l⁻¹.

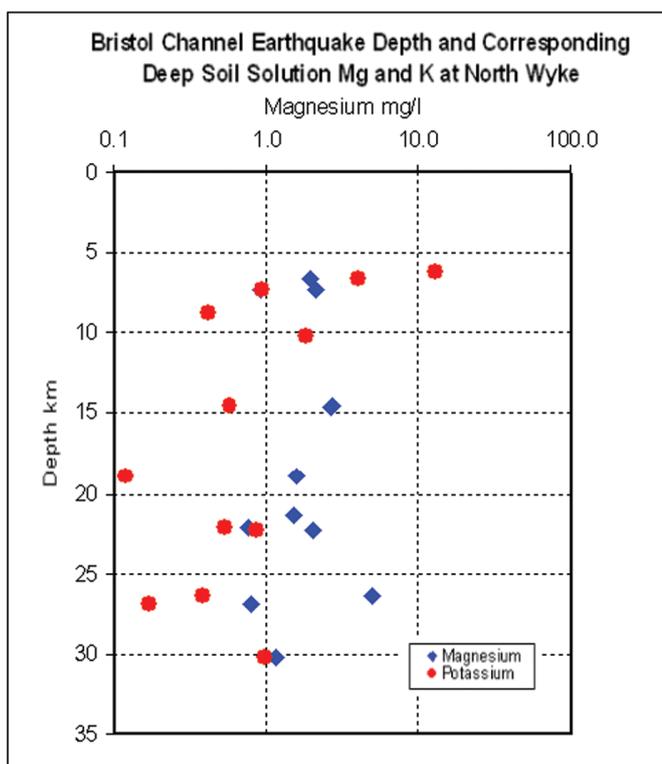


Figure 12. Relationship of North Wyke deep soil solution magnesium and potassium anomalies with Bristol Channel earthquake depth. Shallower earthquakes are more likely to be associated with potassium anomalies and deeper events with magnesium anomalies.

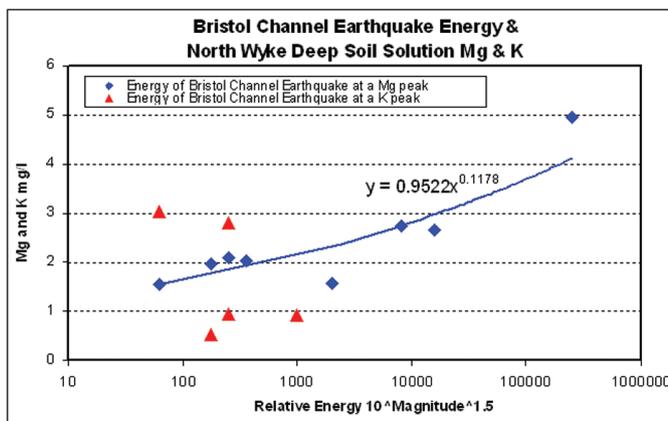


Figure 13. Relative energy of individual Bristol Channel earthquakes plotted against North Wyke monthly average deep soil solution magnesium and potassium for peak months.

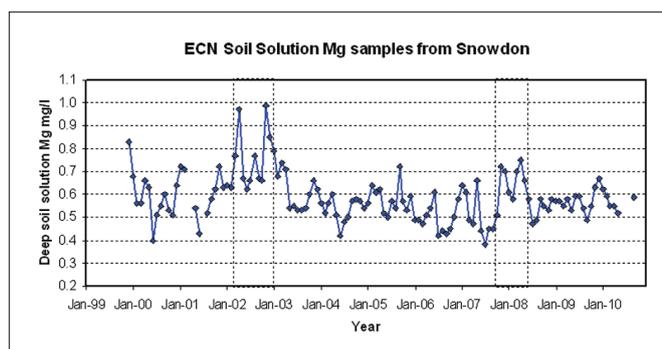


Figure 14. Average monthly variation in soil solution magnesium from the ECN Snowdon site.

on the alignment of the Sticklepath Fault system. The magnesium indicates an origin deeper than the granite, in the lower crust or upper mantle. The magnesium anomalies also show an association with increasing earthquake energy (Figure 13). The linear correlation coefficient for the Mg values with earthquake energy of the individual events is 0.800.

OTHER GEOCHEMICAL RESPONSES TO STRESS PRIOR TO AN EARTHQUAKE

In the three weeks before the 4.7 ML Dudley earthquake of 22 September 2002 there were various sequences of seismic events affecting the west coast of Scotland, the North Sea, English Midlands and South Wales. The last of these was a 2.1 ML quake at Glyn-Neath in West Glamorgan on 18 September, which occurred 4 days 18 hours before the Dudley event. Two further earthquakes of 2.7 ML and 1.2 ML followed at Dudley over the next two days. Post-Dudley events occurred in Jersey, northern France, and Ashburton in Devon (2.1 ML on 7 October 2002), as well as in the North Sea and Scotland.

It was later reported by the University of Northampton that their radon air monitoring equipment detected the Dudley earthquake as a precursor event. Two detectors 2.25 km apart in Northampton displayed “simultaneous in-phase short-term (6-9 hour) radon anomalies” prior to the main Dudley earthquake (Crockett *et al.*, 2006). As in the case of the South-West England examples, detection was a long distance from the earthquake, in this case around 90 km. Stress transmission is likely to have been through the Palaeozoic basement rocks of the London-Brabant Massif.

The ECN deep soil solution records between December 1999 and April 2010 in Snowdonia show most Mg values occurring within the range 0.50-0.60 mg l⁻¹ and averaging 0.58 mg l⁻¹ (Figure 14). Two peaks clearly rise above this background level to 0.97 and 0.99 mg l⁻¹ of Mg in April 2002 and November 2002. It seems possible that these relate to the higher seismicity across the British Isles in this year (Figure 2). This period encompasses the 4.6 ML Dudley earthquake of 22 September 2002 and a long sequence of 116 recorded earthquakes at Manchester from 21 October to 19 November 2002. Maximum magnitude for the Manchester seismicity was 3.9 ML. Slightly higher values of Mg from November 2007 to April 2008 would be consistent with higher British Isles earthquake activity in 2008. This period included the 5.2 ML 27 February 2008 earthquake in Market Rasen, Lincolnshire.

CONCLUSIONS

Earthquakes across Great Britain, the English Channel and North Sea appear to be linked to a fairly regular dissipation of seismic stress, both geographically and over time. This stress is most likely to relate to sea floor spreading from the Mid-Atlantic Ridge and NW-SE compressive forces within the European continental crust, of which Great Britain is a part. This is reflected in a general easterly advance of earthquakes, before activity jumps back to a more westerly point, whether on a regional or local scale. The 10 November 1996 3.8 ML Penzance earthquake ended such a sequence of activity.

In previous work, the author linked a radon anomaly measured at Tremough near Penryn, Cornwall to the Penzance earthquake. A helium and carbon dioxide anomaly from the same period on the north side of Dartmoor, measured over the Sticklepath Fault, may now be re-interpreted as being linked to the Penzance earthquake. Further, exceptionally high potassium, measured from deep soil solution by the Environmental Change Network on the north side of Dartmoor corresponds to the month of the Penzance earthquake. Their measurement of high deep-soil solution magnesium corresponds to the 3.6 ML Hartland earthquake (Bristol Channel) of 31 May 2001. Density contrasts from the larger areas of granite on the south-west side of the Sticklepath Fault

may help enhance the fault permeability to fluid movements.

Other earthquakes can be linked by month to peaks in the ECN potassium and magnesium data, suggesting that regional stress levels are being detected by the north Dartmoor geochemical anomaly. The relative energy of Bristol Channel earthquakes show a link to the concentration of magnesium recorded at the peak value. Potassium anomalies show an association with the earthquake energy of events in Jersey and elsewhere. A three month cessation of south-west seismicity following the Penzance earthquake (5 months cessation in Cornwall), together with low soil gas helium and low deep soil solution potassium, suggest there was a major stress release in one large event rather than a series of smaller regular earthquakes.

It is concluded that geochemical anomalies from north Dartmoor provide information on the tectonic stress within the earth's crust, and over a large area of South-West England. It suggests a potential approach for forecasting the approximate magnitude of a possible earthquake, but not whether it would actually occur. The anomalies also indicate the periods when the risk of occurrence is increasing and decreasing. Helium, radon and deep soil solution potassium had the potential to forecast the risk of a moderately high magnitude earthquake at the end of 1996 in the region, but not the actual location. Consideration should be given to extended geochemical monitoring in the north Dartmoor area, so as to continually assess seismic risk in the Bristol Channel, and also to test the validity of these observations as a method of crustal stress monitoring.

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