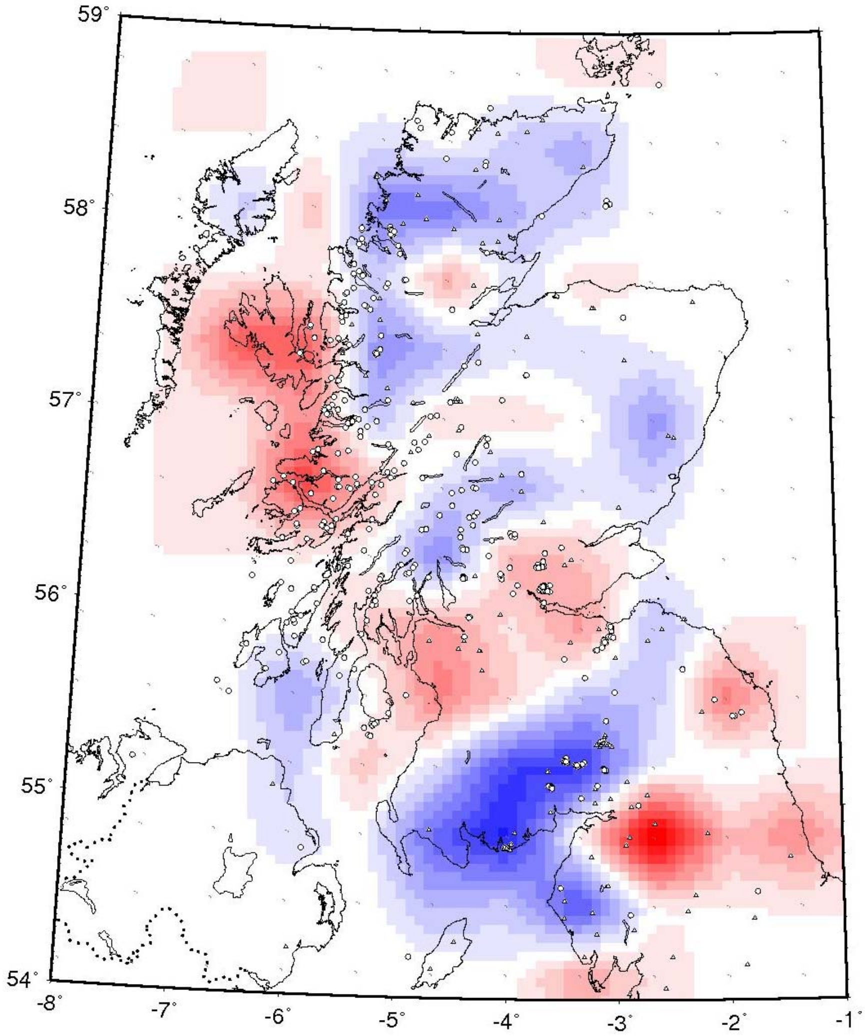
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2009/2010

BGS Seismic Monitoring and Information Service

Twenty-first Annual Report



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT OR/10/???

UK Earthquake Monitoring 2009/2010

B. Baptie (editor)

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Front cover

Depth slice at 4.5 km through 3-D P-velocity model for Scotland obtained from local earthquake tomography.

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Summary

The British Geological Survey (BGS) operates a network of seismometers throughout the UK in order to acquire seismic data on a long-term basis. The aims of the Seismic Monitoring and Information Service are to develop and maintain a national database of seismic activity in the UK for use in seismic hazard assessment, and to provide near-immediate responses to the occurrence, or reported occurrence, of significant events. The project is supported by a group of organisations under the chairmanship of the Department of Communities and Local Government (DCLG) with major financial input from the Natural Environment Research Council (NERC).

In the 21st year of the project, seven new broadband seismograph stations were established, giving a total of thirty broadband stations. Real-time data from all broadband stations and nearly all other short period stations are being transferred directly to Edinburgh for near real-time detection and location of seismic events as well as archival and storage of continuous data. Four of the broadband stations were installed as part of site-specific monitoring project around Oldbury-on-Severn. We have purchased a further five broadband sensors and high dynamic range digitisers as well as five strong motion accelerometers.

All significant events were reported rapidly to the Customer Group through seismic alerts sent by e-mail. The alerts were also published on the Internet (http://www.earthquakes.bgs.ac.uk). Monthly seismic bulletins were issued six weeks in arrears and compiled in a finalized annual bulletin (Galloway, 2010). In all reporting areas, scheduled targets have been met or surpassed.

Ten papers have been published in peer-reviewed journals. Twenty-two presentations were made at international conferences. Three BGS internal reports were prepared along with five confidential reports. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

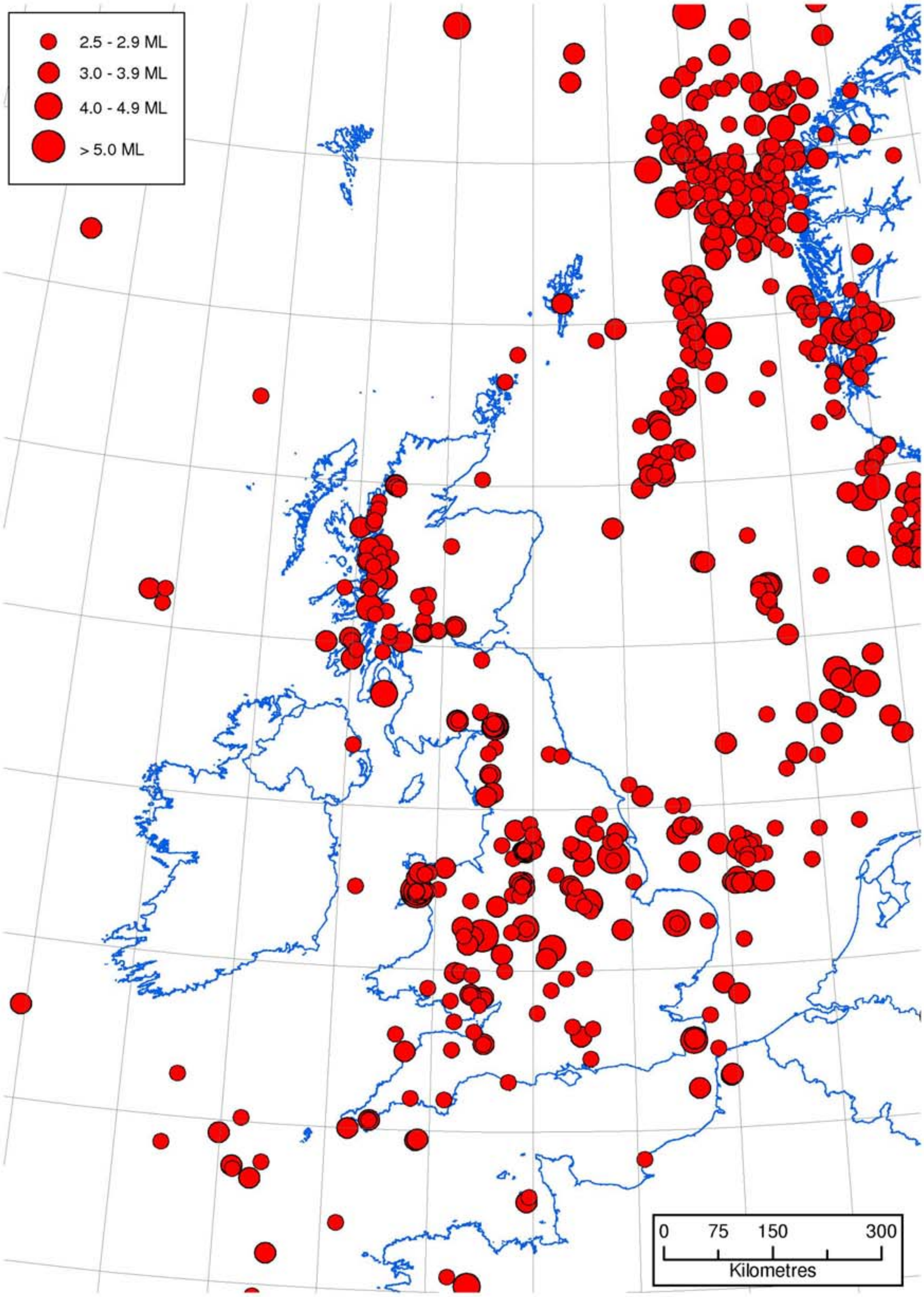
Introduction

The BGS Seismic Monitoring and Information Service has developed as a result of the commitment of a group of organisations with an interest in the seismic hazard of the UK and the immediate effects of felt or damaging vibrations on people and structures. The supporters of the project, drawn from industry and central and local government are referred to as the Customer Group.

Almost every week, seismic events are reported to be felt somewhere in the UK. A number of these prove to be sonic booms or are spurious, but a large proportion are natural or mining-induced earthquakes often felt at intensities which cause concern and, occasionally, some damage. The Information Service aims to rapidly identify these various sources and causes of seismic events, which are felt or heard.

In an average year, about 100 earthquakes are detected and located by BGS with around 15% being felt by people. Historically, the largest known British earthquake occurred on the Dogger Bank in 1931, with a magnitude of 6.1 M_L. Fortunately, it was 60 miles offshore but it was still powerful enough to cause minor damage to buildings on the east coast of England. The most damaging UK earthquake known in the last 400 years was in the Colchester area (1884) with the modest magnitude of 4.6 M_L. Some 1200 buildings needed repairs and, in the worst cases, walls, chimneys and roofs collapsed.

Long term earthquake monitoring is required to refine our understanding of the level of seismic hazard in the UK. Although seismic hazard and risk are low by world standards they are by no means negligible, particularly with respect to potentially hazardous installations and sensitive structures. The monitoring results help in assessment of the level of precautionary measures which should be taken to prevent damage and disruption to new buildings, constructions and installations which otherwise could prove hazardous to the population. For nuclear sites, seismic monitoring provides objective information to verify the nature of seismic events or to confirm false alarms, which might result from locally generated instrument triggers.



Epicentres of earthquakes with magnitudes 2.5 ML or greater, for the period 1979 to December 2009

Introduction

Monitoring Network

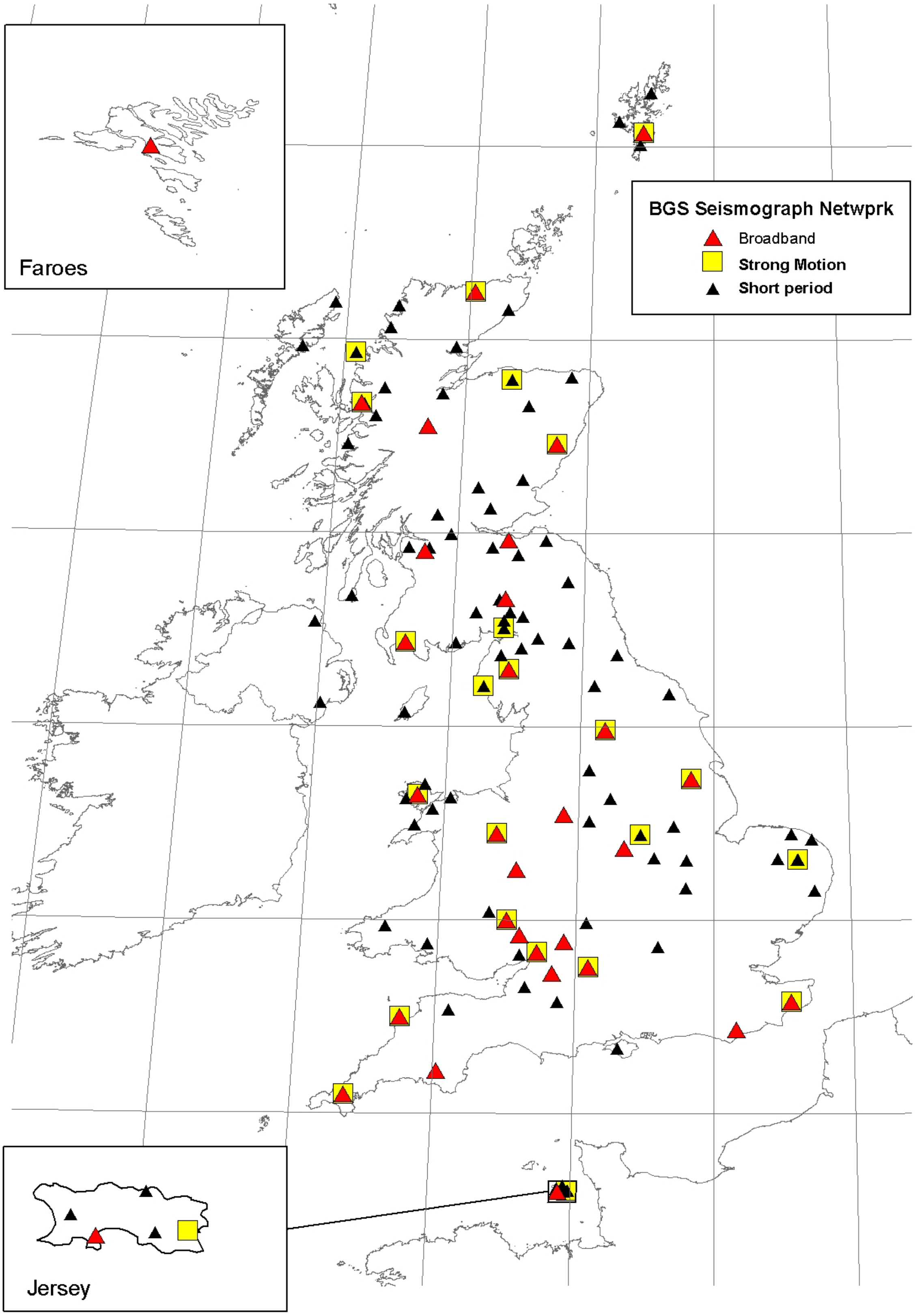
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late nineties, the number of stations reached its peak of 146 stations, with an average spacing of 70 km. We are now in the process of a major upgrade, with the installation of broadband seismometers that will provide high quality data for both monitoring and scientific research.

In the late 1960s BGS installed a network of eight seismograph stations centred on Edinburgh, with data transmitted to the recording site in Edinburgh by radio, over distances of up to 100 km. Data were recorded on a slow running FM magnetic tape system. Over the next thirty years the network grew in size, both in response to specific events, such as the Lleyn Peninsula earthquake in 1984, and as a result of specific initiatives, such as monitoring North Sea seismicity, reaching a peak of 146 stations by the late nineties.

The network was divided into a number of sub-networks, each consisting of up to ten 'outstation' seismometers radio-linked to a central site, where the continuous data are recorded digitally. Each sub-network was accessed several times each day using Internet or dial-up modems to transfer any automatically detected event to the BGS offices in Edinburgh. Once transferred, the events were analysed to provide a rapid response for location and magnitude.

However, scientific objectives, such as accurately measuring the attenuation of seismic waves, or accurate determination of source parameters, were restricted by both the limited bandwidth and dynamic range of the seismic data acquisition. The extremely wide dynamic range of natural seismic signals means that instrumentation capable of recording small local micro-earthquakes will not remain on scale for larger signals.

This year we have continued with our plans to upgrade the BGS seismograph network. Over the next few years we intend to develop a network of 40-50 broadband seismograph stations across the UK with near real-time data transfer to Edinburgh. These stations will provide high quality data with a larger dynamic range and over a wider frequency band for many years to come. So far, we have installed thirty broadband sensors at stations across the UK along with twenty-one strong motion accelerometers with high dynamic range recording.



BGS seismograph stations, March 2010

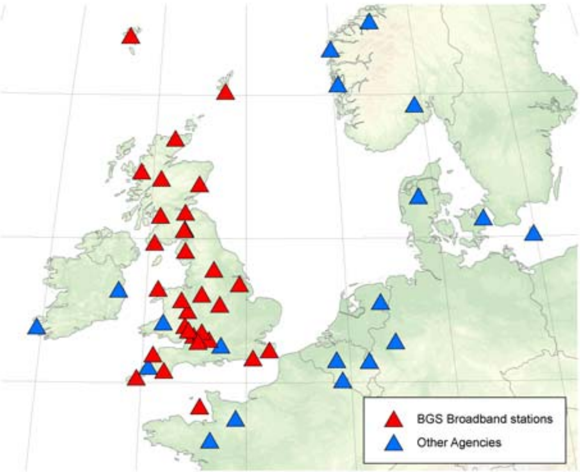
Achievements

Network Development

Broadband sensors with 24-bit acquisition are being deployed to improve the scientific value of the data and improve the services provided to customers. We continue to improve our near real-time data processing capability including the detection and location of significant seismic events in the UK and offshore area.

In the last year seven new broadband stations were installed at: Market Rasen (Lincoln), Herstmonceux (Sussex), Glendoe (Highland), Oldbury, Bath, Monmouth and Stroud. Continuous data from all these stations except Glendoe are transmitted in real-time to Edinburgh, where they are used for analysis and archived. This takes the total number of broadband stations operated by BGS to thirty.

Work is almost complete on new broadband stations at Comrie (Perthshire) and Teesdale. In addition, we have carried out site surveys for a new broadband station in Norfolk.



Broadband stations in northern Europe contributing to our near real-time detection and location capability.

Five new broadband seismometers, along with high dynamic range data acquisition, were purchased during the year 2009-2010. These will be deployed either at existing or new stations as part of our network development programme. We also purchased five strong motion accelerometers that will remain on-scale up to 0.5g. These will be deployed alongside broadband instruments at a number of stations.

We also maintain a pool of seismometers that can be rapidly deployed for studying aftershock sequences, earthquake swarms and specific studies. These instruments were deployed to capture aftershocks following the recent earthquakes at Folkestone and Market Rasen. In the case of Market Rasen, four instruments were deployed within 48 hours of the mainshock, and successfully recorded a number of aftershocks in the following months.

We have increased the flow of real-time data from seismic stations operated by European partner agencies into our near real-time processing. These include data from Belgium, Denmark, France, Ireland, the Netherlands and Norway. The use of these data greatly improves our detection capability in offshore areas.

We are continuing to use *EarthWorm* software (developed by the US Geological Survey and contributed to by BGS) as a central part of our seismic data acquisition and processing. *EarthWorm* consists of a set of modules that perform tasks, such as data acquisition, phase picking, archival etc.

Continuous data from all our broadband stations are now online within the BGS storage area network. The completeness of these data can be easily checked to gain an accurate picture of network performance. In general, we find that the data from most broadband stations are over 92% complete. Data losses result from failure of outstation hardware, communications problems, or failure of central data processing. The data acquisition is able to recover from short breaks in communications links to outstations by re-requesting missing packets of data from local data buffers, but failure of outstation hardware requires intervention by local operators or maintenance visits.

Testing broadband sensors in the seismic vault at the Royal Observatory Edinburgh.

Information Dissemination

It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 28 UK events within the reporting period, two of which were of a suspected sonic origin and one was for an explosion, and for 36 global earthquakes. Notifications for all local earthquakes were issued to Customer Group members within two hours of a member of the 24-hour on-call team being notified. The alerts include earthquake parameters, reports from members of the public, damage and background information. In addition, two enquiries were received from Nuclear Power Stations after alarms triggered; Heysham2 on 3 September 2009 and Hartlepool on 17 September 2009. In each case a response was given within 15 minutes.

An up-to-date catalogue of recent events continues to be available on the Seismology web pages. This is updated whenever a new event is located. Our automatic macroseismic processing system remains a key part of our response to felt events and is used to produce macroseismic maps for the Seismology web pages that are updated in near real-time as data is contributed. This was used to collate and process macroseismic data following the Ulverston earthquake on 28 April 2009.

Data from the returned questionnaires are grouped by location into 5x5 km squares using postcodes and an intensity value is assigned to each square, given at least five responses are received from any square. Where fewer responses are received (especially the case in sparsely populated areas) the intensity is either given as “felt” or “not felt” (which is also defined as intensity 1). These data are processed automatically to produce the macroseismic maps for the Seismology web pages.

Preliminary monthly bulletins of seismic information were produced and distributed to the Customer Group within six weeks of the end of each month. The project aim is to publish on CD, the revised annual Bulletin of British Earthquakes within six months of the end of a calendar year. For 2009, it was issued in July 2010.

Achievements

Collaboration and Data Exchange

Data from the seismograph network are freely available for academic use and we have continued to collaborate with researchers at academic institutes within the UK throughout the past year, as well as exchange data with European and world agencies.

A PhD student at Edinburgh University, funded partially by BGS, has used ambient seismic noise recorded on broadband stations across the UK to derive the first surface wave group velocity maps of the UK using only ambient seismic noise. A BGS CASE student at the University of Cambridge is using recordings of distant earthquakes to image upper mantle structure under the UK and investigate causes of regional uplift of the British Isles.

BGS is collaborating on a novel research project led by the School of Environmental Sciences at the University of Ulster and Concern Worldwide, to investigate how science informs both local and international humanitarian organisations who are engaged in earthquake and tsunami preparedness activities in Padang, a coastal city of nearly one million people in West Sumatra. A large earthquake on the segment of the Sumatran subduction zone west of Padang is imminent. This earthquake will generate strong ground shaking in Padang and has the potential to generate a large tsunami. The study has identified numerous obstacles to the take-up and application of scientific knowledge. These obstacles fall into two main groups: problems around communication, and cultural differences between the humanitarian and scientific communities.

The European Mediterranean Seismological Centre (EMSC), BGS and others have continued to collaborate on development of online macroseismic surveys, now within the framework of an European Seismological Commission (ESC) working group in Internet Seismology. BGS are working with INGV, Milan, and others on the NA4 module of the NERIES project. BGS are working with ETHZ, NORSAR, INGV and others on the SHARE project (seismic hazard harmonisation in Europe).

BGS data is exchanged regularly with European and world agencies to help improve source parameters for earthquakes outside the UK. Phase data for global and regional earthquakes are distributed to the (EMSC) to assist with relocation of regional earthquakes and rapid determination of source parameters for destructive earthquakes. BGS data for 48 events were supplied to the EMSC. *EarlyBird* automatic alerts are also sent to the EMSC. Phase data for global earthquakes are sent to the National Earthquake Information Centre (NEIC) at the USGS. Phase data are also made available to the International Seismological Centre, an agency providing definitive information on earthquake hypocentres. Data from the BGS broadband stations are transmitted to both ORFEUS, the regional data centre for broadband data, and IRIS (Incorporated Research in Seismology), the leading global data centre, in near real-time.

Achievements

Public Understanding of Science

An important part of the BGS mission is to disseminate information to the community and promote the public understanding of science. Our "School Seismology" project has aimed to support the teaching of seismology in schools and stimulate interest in Earth Science.

The UK School Seismology Project (UKSSP) continues to grow and create new partnerships. The aim of the project is to develop specific resources for teaching and learning seismology in UK schools, including an inexpensive seismometer that is robust enough to be used in schools, but still sensitive enough to record earthquakes from the other side of the world. These provide teachers and students with the excitement of being able to record their own real scientific data and help students conduct investigations using their own data.

The School Seismology Project was launched in Scotland with an event at Dynamic Earth Edinburgh attended by 150 guests and opened by Keith Brown MSP, the Minister for Schools and Skills. The event entertained an audience of children, teachers, directors of science centres, academics, government and industry leaders and was featured in both local and national media. Generous support from the Scottish Oil Club helped fund the launch.

In 2009-2010 the BGS ran six training workshops in Scotland that were attended by 124 teachers. Two of these workshops were funded by RCUK. The other four workshops were run in partnership with the Universities of Aberdeen, Edinburgh, Glasgow and Highlands and Islands, who each matched funding from the Scottish Oil Club and the Petroleum Exploration Society of Great Britain. All of the teachers attending these workshops were provided with free seismometers.

The British Geological Survey worked with colleagues in the USA and Ireland to merge their data bases of school seismology data. From October 2009 visitors to the BGS School Seismology website (http://www.bgs.ac.uk/ssp) could see data uploaded by schools in the USA to the IRIS site (http://www.iris.edu/hq/sis) and vice versa. For schools in the UK this also means that the upload process has become much easier and quicker.

BGS have advised the Earth Science Education Unit (ESEU) on the development of a CPD course to teach A – level physics with an Earth Science context. Similarly in Scotland, BGS has helped SSERC develop a Higher Physics exemplar on earthquakes.

The BGS Open Day attracted 923 visitors with many of them visiting the interactive earthquake display. A further 132 school pupils from 7 different schools visited during the following Schools Week.

The seismology web site continues to be widely accessed, with over 696,000 visitors logged in the year (over 10 million hits). Significant peaks (over 10,000 more than the monthly average) were observed following the Ulverston earthquake (April 2009), the Haiti earthquake (January 2010) and the Chile earthquake (February 2010).

BGS remains a principal point of contact for the public and the media for information on earthquakes and seismicity, both in the UK and overseas. During 2009-2010, 688 enquiries were answered. These were logged using a new enquiries tracking database. Some 146 of these were from the media, many of which led to TV and radio interviews, particularly after the Haiti and Chile earthquakes.

Seismic Activity

The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletin for 2009, published and distributed in July 2010 (Galloway, 2010).

There were 86 local earthquakes located by the monitoring network during the year, with 26 having magnitudes of 2.0 M_L or greater, and six having magnitudes of 3.0 M_L or greater. Eleven events with a magnitude of 2.0 M_L or greater were reported felt, together with a further six smaller ones, bringing the total to seventeen felt earthquakes in 2009.

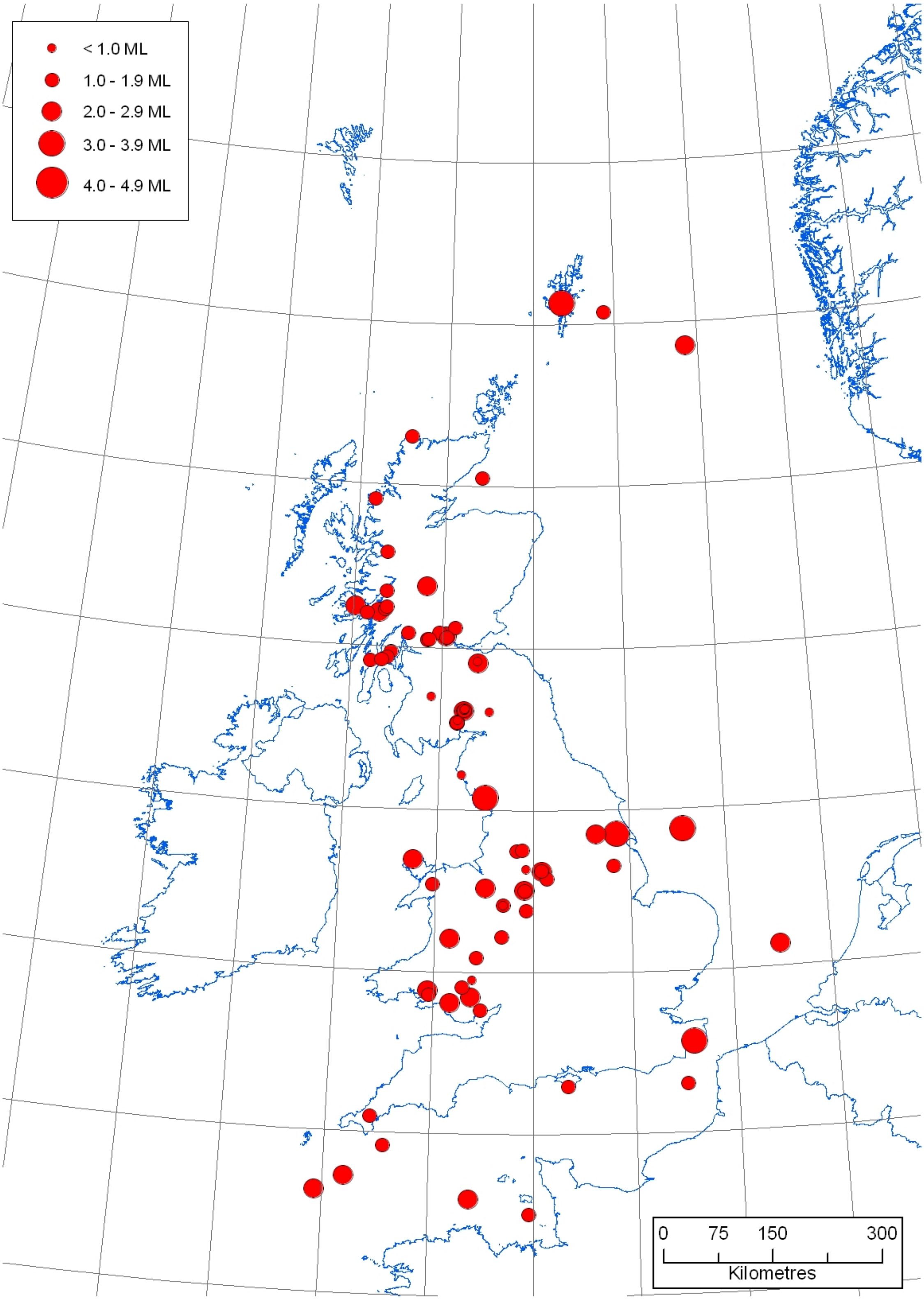
A magnitude 3.5 M_L earthquake occurred near Ulverston, Cumbria at 10:22 on 28 April. Over 800 of the people who completed our online survey felt the earthquake. The earthquake was felt as far away as Newcastle (135 km north east) and Leeds (100 km southeast). The results show that the maximum intensity experienced was 5 EMS, which was observed over an area extending approximately 25 km to the northeast and 35 km to the south of the epicentre. There were no reports of damage to property.

On 11 April, an earthquake with a magnitude of 3.0 ML occurred near Goxhill, North Lincolnshire, approximately 10 km southeast of the centre of Hull. It was felt by several residents in the surrounding areas. This earthquake was around 2,000 times smaller in terms of energy release than the magnitude 5.2 ML earthquake that struck nearby at Market Rasen on 27 February 2008.

A magnitude 2.9 M_L earthquake occurred in the Maesteg, Bridgend region of South Wales on 5 June. Macroseismic data suggest an intensity of 4 EMS. Historically, several larger earthquakes, with magnitudes ranging from 4.9 to 5.2 M_L, have been known to occur in the area, the last and largest of these being a magnitude 5.2 M_L earthquake that occurred in 1906 close to Port Talbot and also known as the Swansea earthquake. This was one of the most damaging earthquakes in Britain throughout the whole of the 20th century.

The largest offshore earthquakes occurred in the southern North Sea region, approximately 100 km east of Hull on 15 September with a magnitude of 3.3 M_L. A further four events occurred in the North Sea and adjacent waters during the year, with magnitudes ranging between 1.7 and 3.0 M_L.

The UK monitoring network also detects large earthquakes from around the world, depending on the event size and epicentral distance. Recordings of such earthquakes can be used to provide valuable information on the properties of the crust and upper mantle under the UK, which, in turn, helps to improve location capabilities for local earthquakes. During the period April 2009 to March 2010, a total of 526 teleseismic earthquakes were detected and analysed



Epicentres of all UK earthquakes detected in 2009.

Seismic Activity

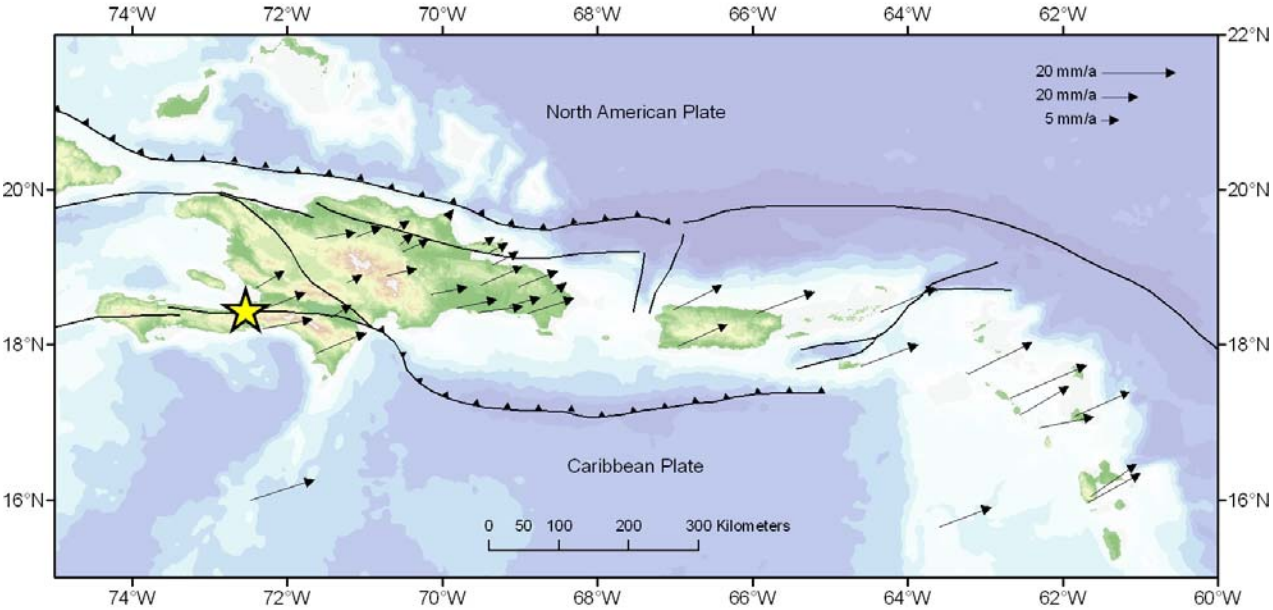
The Haiti Earthquake 12 January 2010

The magnitude 7.0 earthquake that struck Haiti on January 12, 2010 was one of the most deadly earthquakes in recent years. Over 220,000 people were killed, 300,000 injured and 1.3 million displaced. Almost 100,000 houses were destroyed and over 180,000 were damaged. The earthquake has highlighted the need for better construction practices in areas with a history of devastating earthquakes.

The January 12, 2010, Haiti earthquake occurred in the boundary region separating the Caribbean plate and the North America plate. This plate boundary is dominated by left-lateral strike slip motion and compression, and accommodates about 20 mm/y slip, with the Caribbean plate moving eastward with respect to the North America plate.

Haiti occupies the western part of the island of Hispaniola, one of the Greater Antilles islands, situated between Puerto Rico and Cuba. At the longitude of the January 12 earthquake, motion between the Caribbean and North American plates is partitioned between two major east-west trending, strike-slip fault systems: the Septentrional fault system in northern Haiti; and the Enriquillo-Plantain Garden fault zone (EPGFZ) in southern Haiti.

The location and focal mechanism of the 12 January earthquake are consistent with the event occurring on the EPGFZ. This left-lateral fault zone runs roughly east-west along the southern peninsula of Haiti, continuing offshore to Jamaica in the west. fault system accommodates about 8 mm/y, nearly half the overall motion between the Caribbean plate and North America plate.



GPS vectors (Manaker *et al*, 2008) show the motion of the Caribbean plate relative to a fixed North America. Black lines show major fault systems in the region. The epicentre of the 12 January earthquake is shown by the yellow start.

The Enriquillo-Plantain Garden fault system has not produced a major earthquake in recent decades. The EPGFZ is the likely source of historical large earthquakes in 1701, 1751, 1770 and 1860, though none of these has been confirmed in the field as associated with this fault.

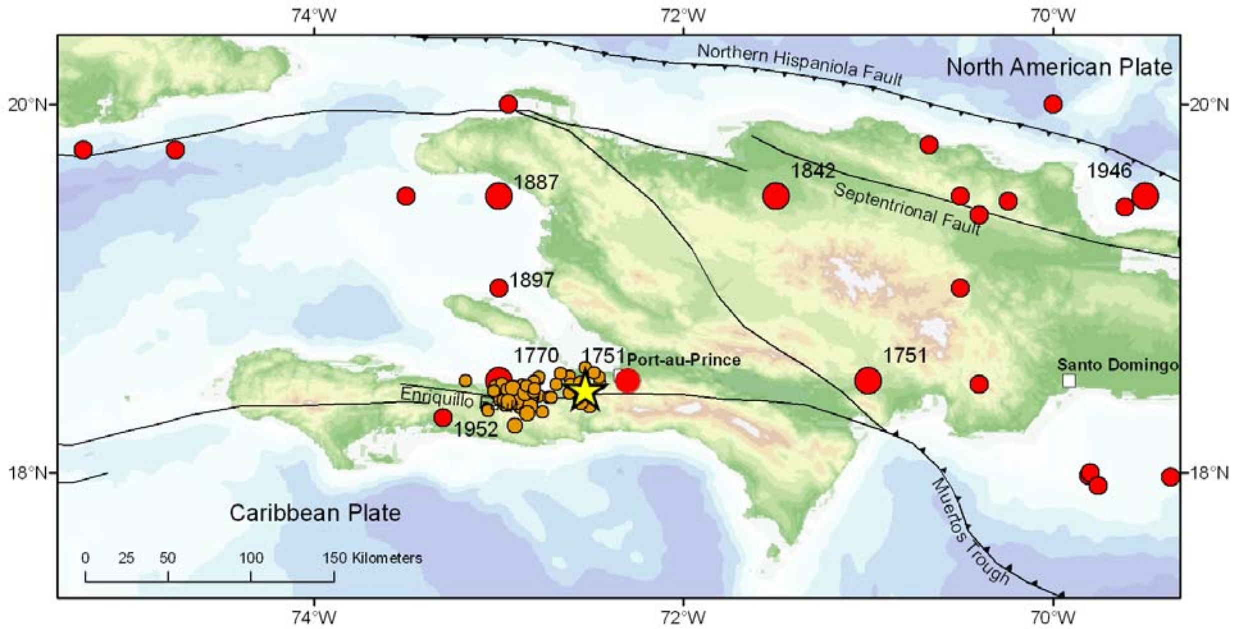
Several BGS scientists participated in the analysis of high resolution satellite and aerial photos to assess damage and provide vital information for the relief effort such as where to target emergency food and medical supplies, prioritise repairs to infrastructure to allow aid to reach where it's most needed, and to plan reconstruction and recovery.

This analysis used the Virtual Disaster Viewer (VDV), an interactive tool developed by ImageCat and supported by an international consortium of earthquake experts from Europe and the USA, including the UK-based Earthquake Engineering Field Investigation Team (EEFIT). The VDV promotes the sharing and dissemination of satellite- and field-based damage data assessments for non-profit applications and research.

Example of aerial photograph from the VDV used for phase 2 damage assessment.

Hundreds of earthquake scientists and engineers worked with the VDV to access high-resolution 'before and after' satellite and aerial photos of the disaster zone. These specialists were part of the newly created Global Earth Observation Catastrophe Assessment Network (GEO-CAN).

In phase 1, analysts used satellite imagery to identify collapsed and heavily damaged buildings in the Port-au-Prince region for targeting relief and assessing the scale of the disaster. In phase 2, aerial photographs were used to determine the footprint of collapsed and heavily damaged buildings to aid the resourcing of reconstruction for the World Bank.



Historical seismicity of Hispaniola (red circles) along with mainshock (yellow star) and aftershocks (orange circles) from the 12 January earthquake.

Scientific Objectives

Revising the local magnitude (M_L) scale for the UK

BGS currently determines M_L using the scale developed for southern California by Hutton and Boore (1987). It is perhaps reasonable to expect that this may not be appropriate for the UK and could lead to biases in our determination of M_L. As a result, a new UK-specific M_L scale has been developed, in collaboration with the University of Bergen.

Local magnitude, ML, is defined by Richter (1935, 1958) as

$$M_L = \log A - \log A_0 + S \qquad (1)$$

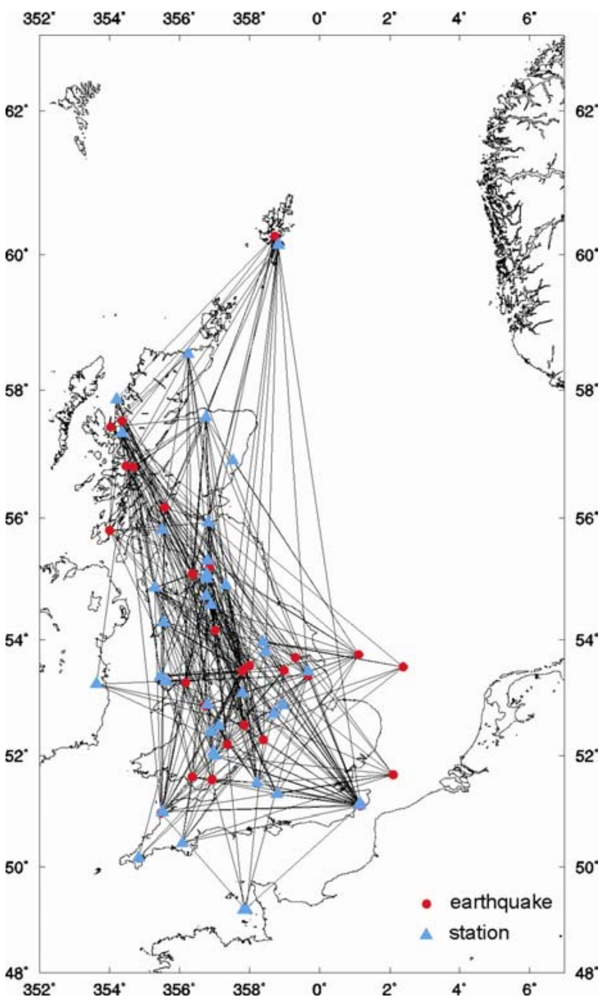
where A is the observed maximum amplitude of the horizontal seismogram, A_0 is used to correct for the decay of amplitude with distance, and S is a station correction. The distance correction can be expressed as

$$-\log A_0 = a \log(r/100) + b(r-100) + 3.0 \qquad (2)$$

where a and b are distance-dependent factors related to geometrical spreading and amplitude attenuation respectively. According to Richter's original definition, an event of 3 M_L gives a displacement of 1 mm at a distance of 100 km on a Wood Anderson seismograph.

Our dataset consists of 690 observations from 33 earthquakes recorded at 45 three-component stations since 2000. This gives relatively good coverage for the UK region. Horizontal waveforms were corrected for instrument response and convolved with the Wood-Anderson seismograph response.

We used an inversion scheme to determine the best-fitting distance and station correction and source terms (a, b and S). A single correction is determined for each station and and we constrained

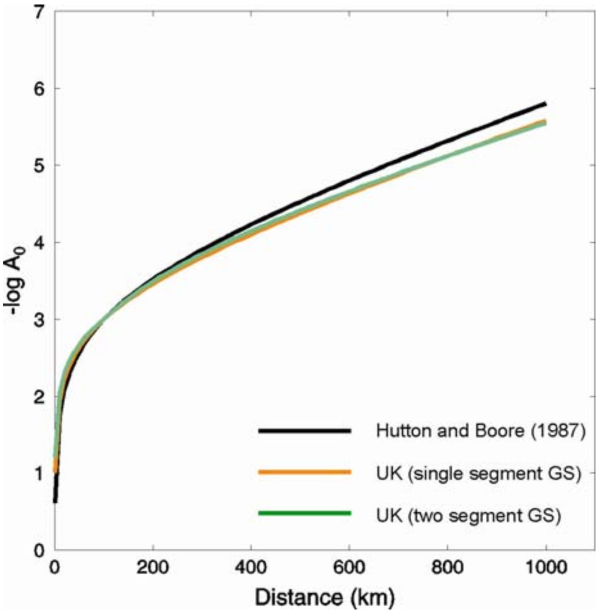


Earthquake (red circles) and stations (blue triangles) used in the inversion.

the average of these to be zero in the inversion. We also experimented with two geometrical spreading models: a single segment model assuming a constant rate of decay with distance; and, in order to model the effect of the transition from body wave (spherical) to surface wave (cylindrical) spreading. This transition is assumed to occur at 100 km.

The results are shown in Table 1. Models 1, 2, 4 and 5 assume a single segment geometrical spreading model (where *a1* denotes the geometrical spreading parameter, i.e. *a*) and model 3 is a two segment model (*a1* to 100 km and *a2* beyond). σ is a measure of the misfit between the model and the observations.

We find that the distance correction for the UK using a single segment model (models 1 and 2) is comparable to that for southern California (Hutton and Boore, 1987). *a* is slightly smaller for the UK while *b* is very similar. Any improvement in the quality of the fit to the data appears to be due to the inclusion of the station corrections. The similarity between the distance corrections determined in models 1 and 3 and the distance correction for southern California is illustrated in the figure.



Distance corrections A0 calculated for the UK using single segment (orange line) and two segment (green line) geometrical spreading corrections, along with the the distance correction for southern California.

These results are consistent with earlier work by Booth (2007) who used a reduction in variance technique to investigate the M_L distance correction in the UK and the L_g-wave quality factor model determined by Sargeant and Ottemoller (2009).

Model	a_1	a_2	b	σ
1 without station corrections (UK)	0.957		0.00193	0.2662
2 with station corrections (UK)	0.904		0.00186	0.2221
3 with station corrections (UK)	0.822	1.102	0.00161	0.2205
4 without station corrections (southern California)	1.1		0.00189	0.2724
5 with station corrections (southern California)	1.1		0.00189	0.2231

Table 1. Results of the inversion

Scientific Objectives

Local Earthquake Tomography

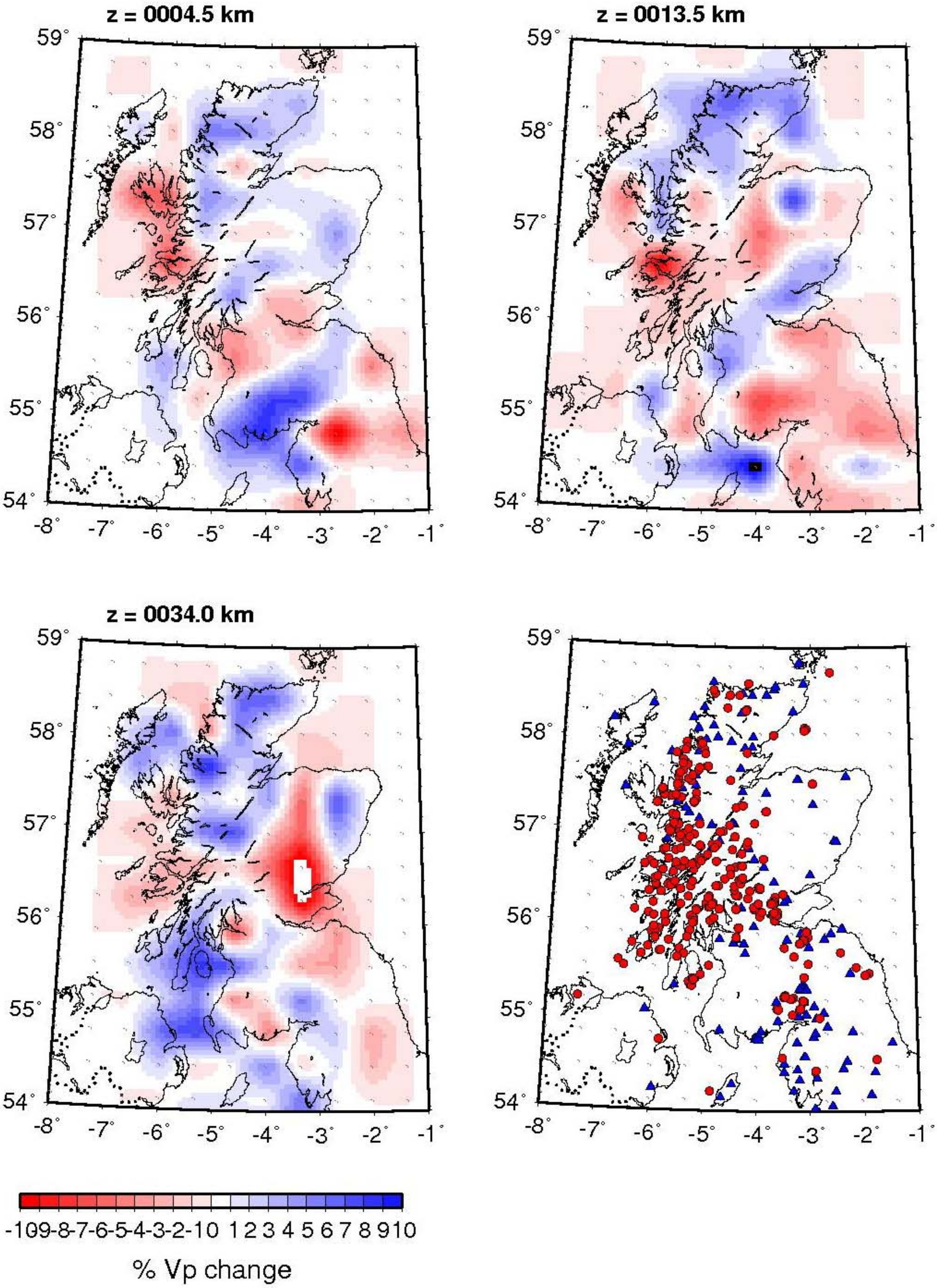
Most of the published information on seismic velocity structure in Scotland has been obtained from large-scale seismic refraction and wide-angle reflection experiments. We are using local earthquakes recorded at seismograph stations in Scotland to construct a 3-D model of seismic velocity in the Earth's crust.

The study used over 400 well-located earthquakes and combined data from the BGS catalogue with data from the RUSH II experiment (Ascenio *et al*, 2003), a temporary deployment of 21 broadband sensors across the North of Scotland between 2001 and 2003. The use of the RUSH data allowed 95 previously undetected earthquakes and quarry blasts for this period to be added to the BGS database and dozens of existing earthquake locations for this period were refined, using data from the RUSH stations.

Tomography results can critically depend on the initial model used for the inversion (Ellsworth *et al*, 1991). We used the method of Kissling *et* al (1994) to determine a best-fitting 1-D velocity model by joint inversion of hypocentres, velocity and station delay that minimises the mean RMS residuals for all events. Velocity information from refraction and reflection lines and other studies are often used to help constrain the initial starting model. Here, we used the LOWNET 1-D velocity model, routinely used for earthquake location in Scotland and derived from the LISP-B seismic refraction profile Bamford *et al*. (1978).

Seismic travel times were inverted simultaneously for P-wave velocity and hypocentre parameters using the SIMULPS code (Thurber 1983; Evans et al. 1994) on a series of grids. Station delays were also calculated to compensate for near-surface heterogeneity and also to reduce artefacts in areas of low resolution. The preliminary models shown here have a relatively coarse node spacing of 40 km. Resolution estimates indicate the model is most reliable at mid-crustal depths beneath central Scotland.

The resulting depths slices through the 3-D *P*-wave velocity model show a number of interesting features. At shallow depths (4.5 km) there is a clear low velocity anomaly in central Scotland that corresponds to the Midland Valley, with high velocity anomalies to the north and south that correspond to the Southern Uplands and the Highlands. There is also a high velocity anomaly in the far northwest that corresponds to the Lewisian terrane. Interestingly, there also appears to be a low velocity anomaly associated with the Inner Hebrides. At mid-crust depth, the high velocity anomaly in the northwest is also apparent, though north of the Highland Boundary fault velocities are lowest than the minimum 1-D model. In the lower crust, velocities are higher that the 1-D model north of the Great Glen.



Coarse 3-D tomographic model of Vp shown as a percentage change relative to the initial 1-D model. Blue and red colours show higher and lower velocities, respectively. Horizontal depth slices through the model are shown at (a) 4.5 km, (b) 13.5 km and (c) 34 km. The final hypocentres are shown in (d) as red circles, with stations used in the inversion (blue triangles).

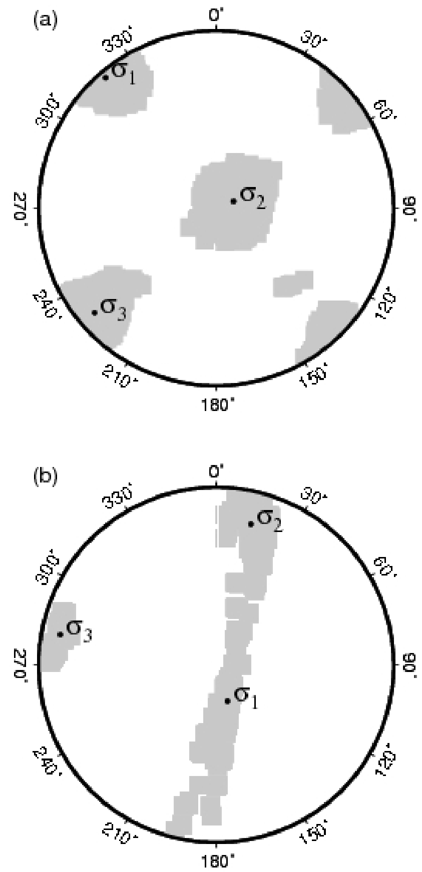
Scientific Objectives

Seismogenesis and State of Stress in the UK

A paper published in Tectonophysics highlights differences between earthquake focal mechanisms in England and Wales and those in Scotland. These results suggest subtle differences in the state of stress in the Earth's crust that may be related to present day deformation.

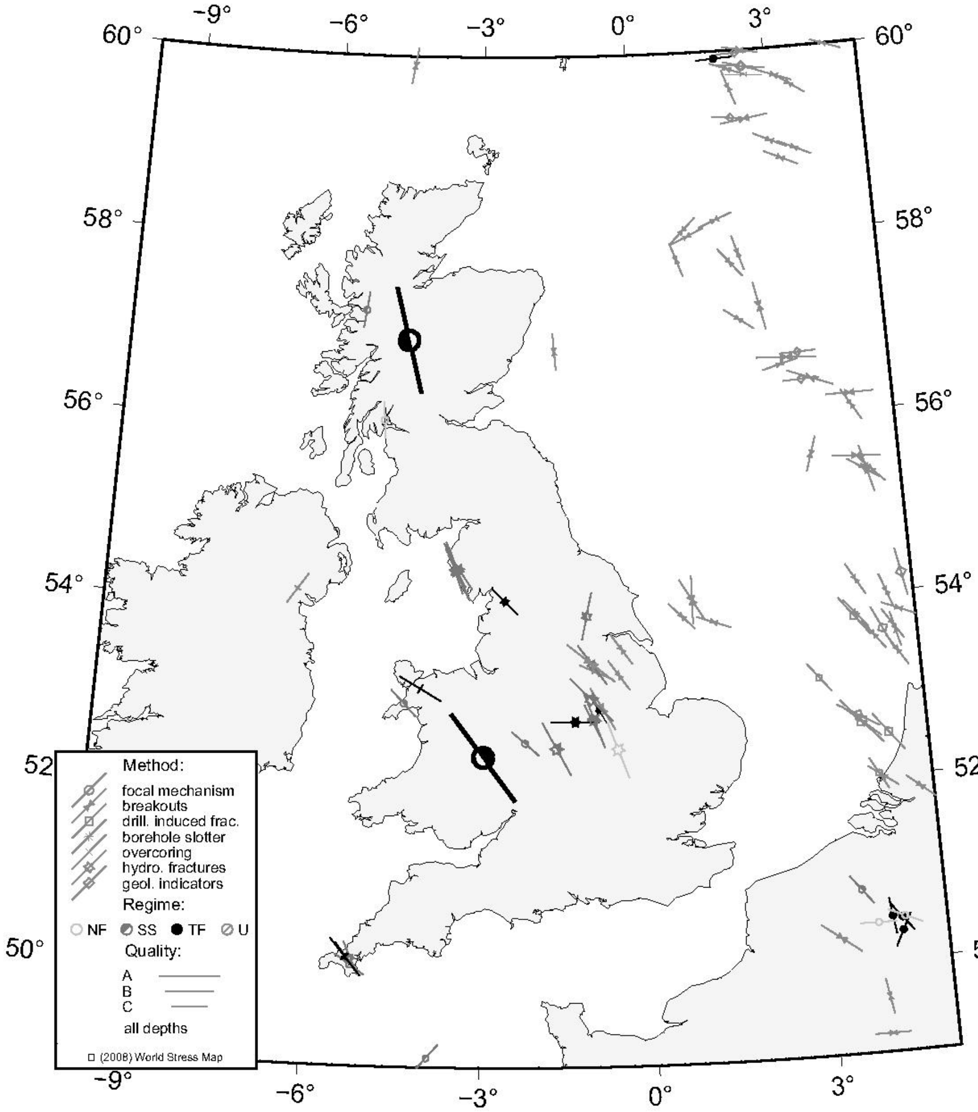
Baptie (2010) presents a compilation of focal mechanisms for earthquakes with magnitudes greater than 3.0 M_L in the British Isles that can be used to help constrain our understanding of the driving forces of earthquake activity. The fault plane solutions consist of both previously published mechanisms for significant British earthquakes, and new solutions calculated from regional and local data for more recent and smaller earthquakes that were previously unpublished. Focal mechanisms for earthquakes in the UK are dominantly strike-slip with northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. In many cases there is also an oblique component to the slip. P and T axes from individual solutions are relatively well constrained in azimuth, though less so in dip, with P-axes orientation for most events clustering between north and north-west, indicating sub-horizontal compression. However, some spatial variation in P- and T-axes orientation is also apparent, with near north/northeast compression and east-west extension in northwest Scotland, changing to northwest-southeast compression in England and Wales.

A best-fitting stress tensor is estimated using a linear inversion method (Michael, 1987) for two different subsets of the data.



Best fitting stress tensors obtained for: (a) for England and Wales only; (b) for northwest Scotland only. The 95% confidence intervals are indicated by the shaded areas.

Confidence regions are determined using a bootstrap technique. The results from the two different datasets suggest that there is a significant difference in the stress state between northwest Scotland and England and Wales. Calculated σ_1 directions for England and Wales are northwest-southeast, consistent both with existing stress data and expected stresses from first order plate motions. By contrast, the inversion results for northwest Scotland show near east-west extension with possible σ_1 and σ_2 directions lying in a north south band, and that the magnitudes of σ_1 and σ_2 are similar. The relative magnitude of the principal stresses determined for England and Wales suggests that the intermediate stress σ_2 is close to the average value of σ_1 and σ_3. The clear difference in the stress inversion results between northwest Scotland and England and Wales suggests that the principal stress directions expected from first order plate motions have been modified in Scotland by local stress conditions due to glacio-isostatic adjustment.



Stress data for the British Isles from the World Stress Map 2008 release (Heidbach *et al*, 2008). Different stress indicators and tectonic regimes are indicated by the symbols shown in the legend: NF=normal faulting; TF=thrust faulting; SS=strike-slip; and U=unknown. Line length is proportional to WSM data quality (A,B,C). The large bold symbols show the s_H orientations determined for Scotland and England.

Scientific Objectives

Ambient Noise Tomography

Recent research has shown that information about Earth structure between a pair of seismic stations can be extracted from cross-correlation of continuous background noise recorded at each station. This approach has been applied by Nicholson *et al* (2010) to produce the first surface wave group velocity maps of the Scottish Highlands using only ambient seismic noise.

Conventional 3D seismological models of the Earth are generally obtained from recordings of waves that have travelled to a given receiver from a single, known, energy source, for example an earthquake. However, seismic waves propagate inside the Earth all the time, created by sources such as wind, ocean water movement, human-related activity and small-scale rock fracturing. Such waves are commonly regarded as “noise” by seismologists, however, these waves also reflect, refract and diffract from exactly the same heterogeneities as do waves from single active sources.

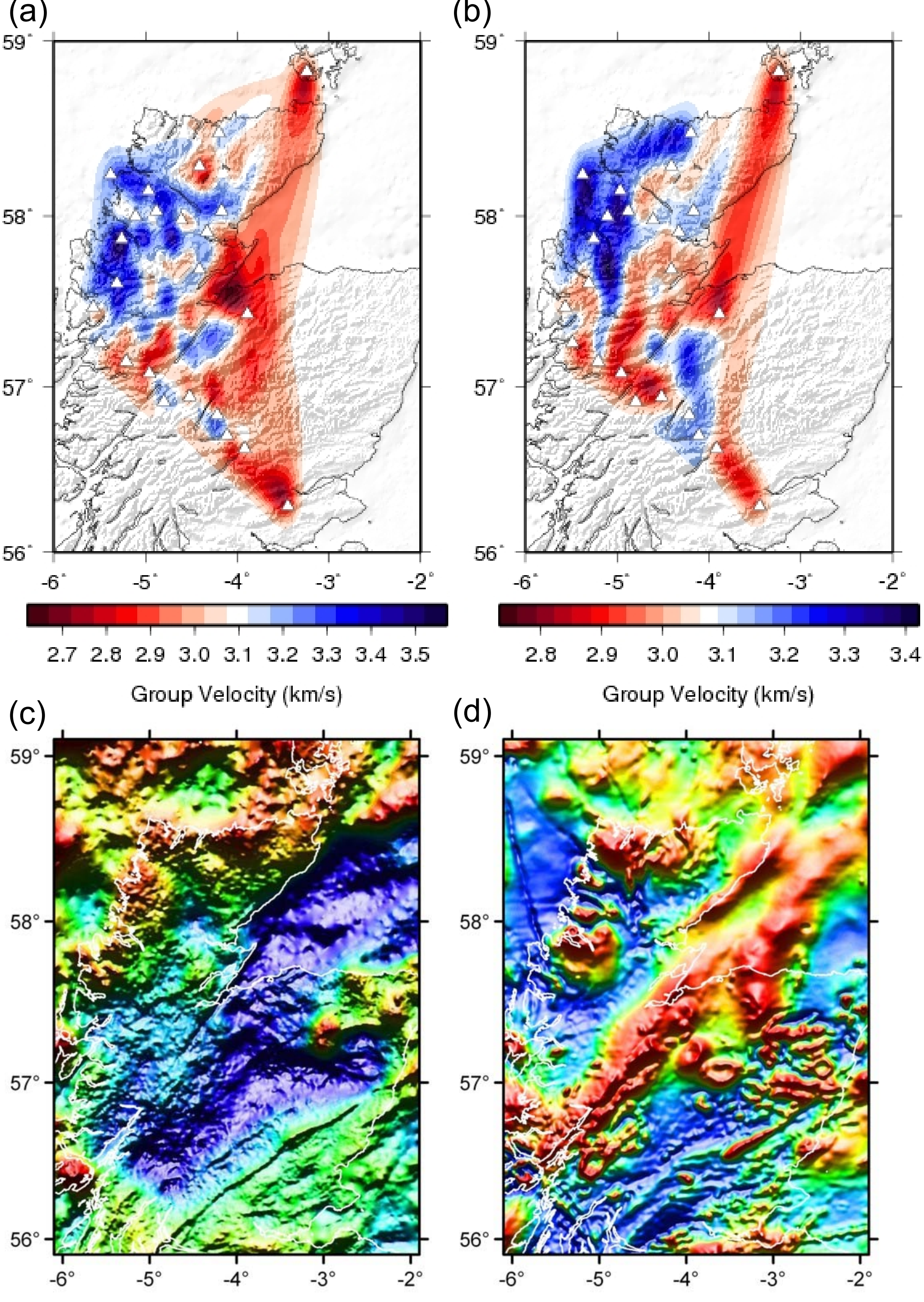
Recent advances in theory (e.g. Wapenaar, 2004) have shown that the cross correlation of the random wavefield between two seismic stations can provide an estimate of the Green’s function between the stations. This has been confirmed using seismic data (Shapiro and Campillo, 2004). Nicholson *et al* (2010) have used data from broadband stations across Scotland to construct surface wave Green’s Functions, which are then used to produce maps of the variation in surface wave velocities at different periods.

Rayleigh waves with periods of 5 and 12 seconds are sensitive to velocity variations in the crust to depths of approximately 8km and 15 km, respectively. A number of interesting geological features can be identified on each map.

On the 5-second map (a) a low velocity anomaly in the Moray Firth basin extends toward the south west and northwards along the north east coast. This feature agrees well with a strong positive anomaly on the aeromagnetic map (d), and may be attributed to the Devonian sedimentary rocks of the north east coast.

Fast velocity anomalies in the very northwest are coincident with the Lewisian rocks of the Hebridean terrane and can also be associated with gravity and magnetic anomalies. Immediately to the south east, a low velocity anomaly is co-located with the Lairg gravity low (Leslie et al., 2010), located on the gravity map (c) at approximately (-4.5°E, 58.0°N).

The 12 second map (b) also highlights low velocity anomalies again coincident with the Midland Valley and the Moray Firth basin. The low velocity region observed north of the Great Glen at 5 seconds can be seen to extend further northwards into the Northern Highlands terrane. The high velocity anomaly ascribed to the Lewisian complex in the far northwest at 5 seconds is also present at 12 seconds.



Rayleigh wave group velocity maps of the Scottish Highlands from cross-correlations of ambient seismic noise between RUSH-II stations (white triangles) for (a) 5 seconds and (b) 12 seconds. (c) Shaded relief gravity anomaly map. Red colours indicate positive anomalies and blue colours indicate negative anomalies. (d) Shaded relief aeromagnetic anomaly map. Red colours indicate positive anomalies and blue colours indicate negative anomalies. Reproduced from Nicholson *et al* (2010)

Scientific Objectives

The UK Historical Earthquake Database

Intensity observations for a large collection of British earthquakes are now available online. Users can interactively search and explore these data to examine the felt effects of any earthquake in the database. This may be a useful resource for creating realistic scenario earthquakes for future planning purposes.

Over the past few years researchers at BGS have worked closely with European partners on the international European-funded project NERIES. One part of this was the creation of a distributed archive of macroseismic observations of historical earthquakes in Europe. A second objective was the creation of a homogenous earthquake catalogue based on the distributed archive.

The project has three important aims. Firstly, to make the large collection of intensity observations for UK earthquakes collected by BGS over the last forty years, publically available for the first time. This is a scientific resource of national significance for researchers.

Secondly, it is anticipated that this resource will also be of considerable interest to the public, who will be able to investigate the UK's seismological history freely.

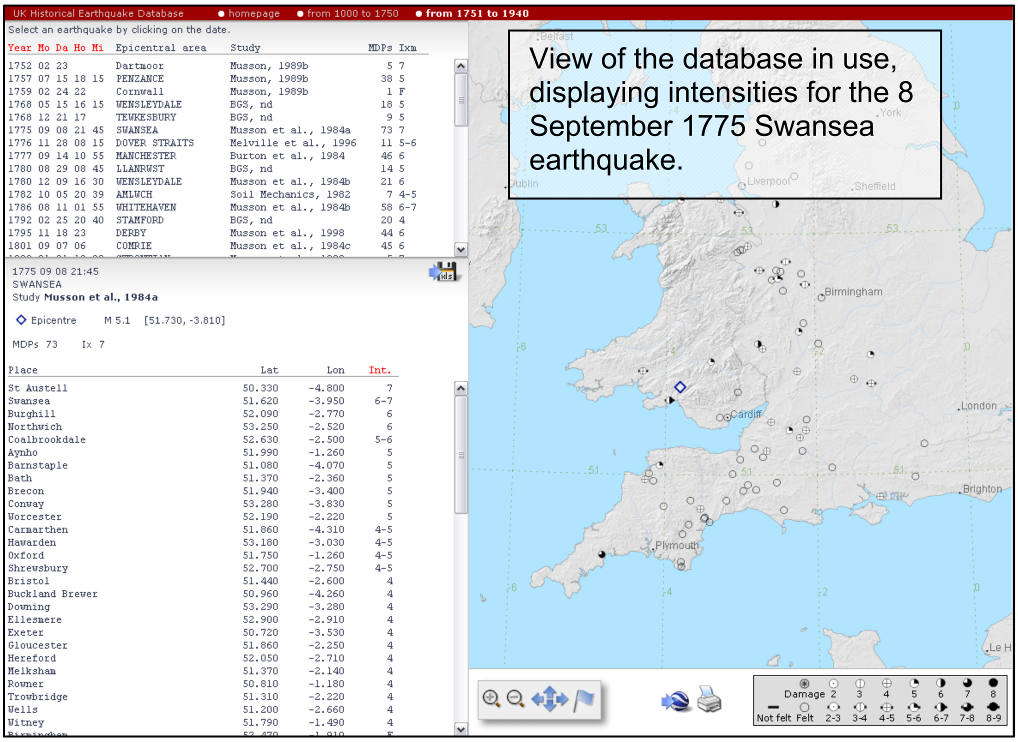
Thirdly, this resource is likely to be of value to planners and civil defence workers, as it can be used to create credible scenario events that can be matched against present-day building stock.

Intensity data point (IDP) files have been processed for earthquakes in the UK matching the time-magnitude criteria for different periods as defined in the project. This data set is now made available to the public through the seismology website. We expect that the available data will gradually be expanded to include all UK earthquakes for which there are IDP files.

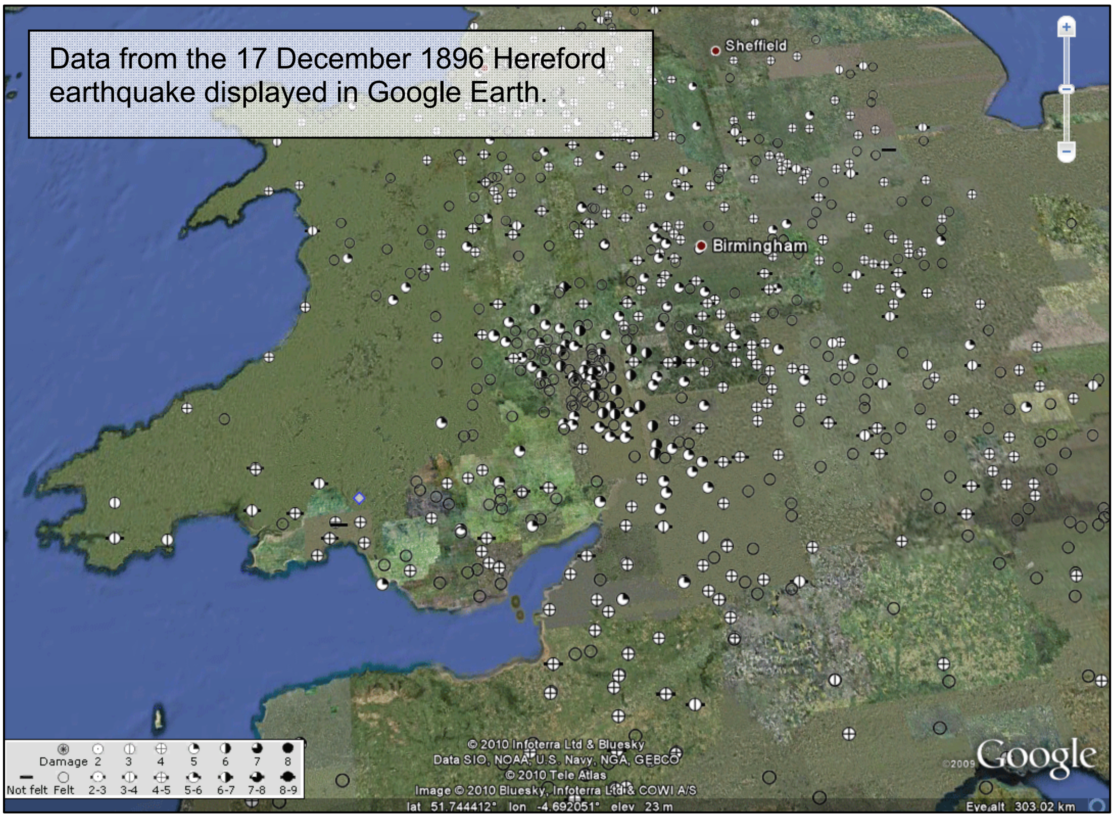
Interactive software, developed largely by Mario Locati at INGV Milan, provides a very easy to use interface with which to explore the data. The screen is divided into three main panels. Top left is the catalogue view, where one can scroll down the list of earthquakes (arranged by date) and see their parameters. Clicking on an event in this panel opens the other two displays.

The lower left panel shows a listing of the IDPs for the selected earthquake, giving the names of the places where it was reported, the co-ordinates of the places (latitude and longitude) and the assigned intensity. It is possible to copy and paste the entire file from this panel, should the user wish to export the data for further analysis, or the file can be downloaded with just one click.

The right-hand panel is the map view. This shows an intensity map of the earthquake, using the symbolic representation of intensity as a series of increasingly filled-in circles (developed in the 1960s). This map can be zoomed and panned using a familiar GIS-like interface, and points can be identified by clicking on them. Furthermore, if the user has Google Earth installed, the entire file can be imported into Google Earth by one mouse click, and the data then viewed together with satellite imagery, and using the powerful Google Earth viewing capabilities.



View of the database in use, displaying intensities for the 8 September 1775 Swansea earthquake.

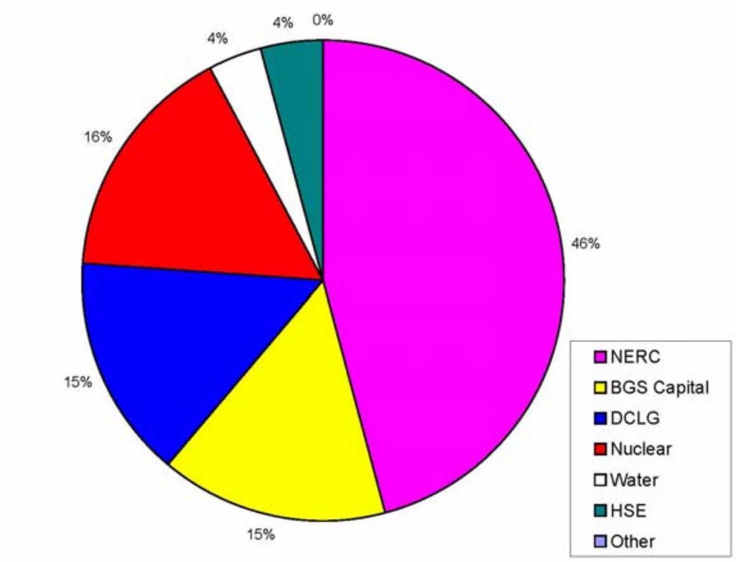


Data from the 17 December 1896 Hereford earthquake displayed in Google Earth.

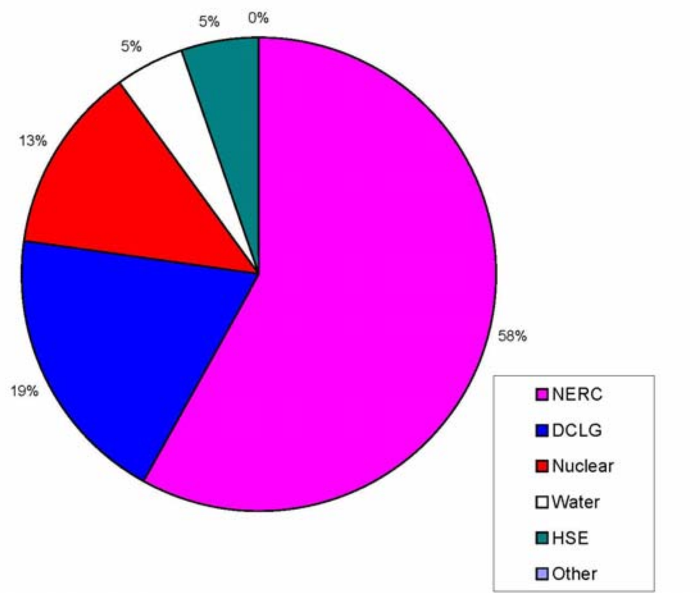
Funding and Expenditure

In 2009-2010 the project received a total of £601k from NERC. This was matched by a total contribution of £440k from the customer group drawn from industry, regulatory bodies and central and local government. In addition, we received a further £200k in BGS capital funds as part of a five year spending plan to upgrade the seismic monitoring network and improve data quality of science. This money was spent on the purchase of new instrumentation and improvements in station and network infrastructure.

Funding Received 2009-2010



Funding Expected 2010-2011



The projected income for 2010-2011 remains approximately the same, with NERC providing £602k. The five years of capital funding for network improvements has come to an end. However, this program of network development has contributed to significant efficiencies in network operations and maintenance. Over the next few years, we are confident that we can provide an effective monitoring service that responds to customer requirements.

Acknowledgements

This work would not be possible without the continued support of the Customer Group. Station operators and landowners throughout the UK have made an important contribution and the BGS technical and analysis staff have been at the sharp end of the operation. The work is supported by the Natural Environment Research Council and this report is published with the approval of the Director of the British Geological Survey (NERC).

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Appendix 1 The Project Team

BGS Seismic Monitoring and Information Service	
Brian Baptie	Project Leader
Research	
Roger Musson	Seismic Hazard
Alice Walker	UK & Regional Seismicity
Susanne Sargeant	Seismic Hazard
David Booth	Crustal Structure
Richard Luckett	Seismic Data Processing
Outreach	
Aoife O'Mongain	Media and Communications
Analysis Team	
Glenn Ford	Seismic Analyst
Davie Galloway	Seismic Analyst
Julian Bukits	Seismic Analyst
Technical Operations	
John Laughlin	Senior Electronics
Andy Blythe	Field Engineer
Heiko Buxel	Field Engineer
Tony Swan	Field Engineer
Computing Support	
Dave Scott	Software Engineer
Consultant	
David Kerridge	Theme Leader

Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2009. Earthquake Monitoring 2008/2009, BGS Seismic Monitoring and Information Service, nineteenth Annual Report, BGS Internal Report OR/09/072.

Galloway, D. A., 2009. Bulletin of British earthquakes 2008, BGS Report OR/09/060.

Musson, R.M.W., 2009. MEEP 2.0 User Guide, British Geological Survey Open-file Report, OR/09/045.

In addition, three confidential reports were prepared and bulletins of seismic activity were produced monthly, up to six weeks in arrears for the Customer Group.

External Publications

Baptie, B., 2010. Seismogenesis and state of stress in the UK, *Tectonophysics*, **482**, 150-159.

Baptie, B.J., 2010. Lava dome collapse detected using passive seismic interferometry. *Geophys. Res. Lett.*, **37** (1), L00E10.

Booth, D. C., 2010. UK 1-D regional velocity models by analysis of variance of P-wave travel times from local earthquakes, *J. Seismol.*, **14** (2). 197-207.

Musson, R.M.W., 2009. Subduction in the Western Makran: The historian's contribution, *J. Geol. Soc.*, **166**, 387-391.

Musson, R.M.W., Sellami, S. and Brüstle, W., 2009. Preparing a seismic hazard model for Switzerland: The view from PEGASOS Expert Group 3 (EG1c), *Swiss J. Geosci.*, **102**, 107-120.

Musson, R.M.W., 2009. Ground motion and probabilistic hazard, *Bull. Earthquake Engineering*, **7**, 3, 575-590.

Musson, R.M.W., Grünthal, G. and Stucchi, M., 2010. The comparison of macroseismic intensity scales, *J. Seismol.*, **14**, 413-428.

Sargeant, S.L. and Musson, R.M.W., 2009. Rotational earthquake effects in the United Kingdom, *Bull. Seis. Soc. Am.*, **99**, 1475-1479.

Sargeant, S. and Ottemoller, L., 2009. Lg wave attenuation in Britain, *Geophys. J. Int.*, **179** (3), 1593-1606

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Appendix 3 Publication Summaries

Seismotectonics and state of stress in the British Isles

B. Baptie

Both the underlying causes and the spatial distribution of earthquake activity in the British Isles remain poorly understood. In this study, I present focal mechanisms determined for twenty-eight British earthquakes of magnitude $M_L > 3.0$ that can be used to examine the nature and coupling of some of the competing ideas on crustal stress and the driving forces for earthquake activity in the British Isles. The resulting focal mechanisms are mainly strike-slip with northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. This results in dips for the P axes that are sub-horizontal, while the T axes vary from horizontal to vertical. The P-axes orientations for most events cluster between north and northwest. The orientations of the principle stresses found by inversion of the focal mechanims data are a sub-horizontal σ_1 striking northwest-southeast, a near vertical σ_2, and σ_3 striking southwest-northeast. The relative magnitude of the principal stresses is given by the parameter, $R=(\sigma_3 – \sigma_1)/(\sigma_2 – \sigma_1) = 0.7$, suggests that $\sigma_1 >> \sigma_2 > \sigma_3$, i.e. σ_2 and σ_3, are relatively close in value, resulting in a prolate stress ellipsoid stretched along a NW-SE axis. The observed spatial variation in P-axes orientation between north and south is different from the orientation of the maximum horizontal compressive stress, S_H, expected for northwest Europe from first order plate boundary forces. This may suggest that the northwest southeast compression expected for the region is modified by flexure dependent stresses resulting from glacio-isostatic adjustment (GIA), resulting in a change to the expected σ_1 direction in northern Britain. However, to fully understand the relative magnitude of horizontal strains from ridge push and GIA we need long term geodetic data that will allow use to compare horizontal deformation rates.

Lava dome collapse detected using passive seismic interferometry.

B. J. Baptie

The collapse of the lava dome at the Soufrière Hills Volcano on Montserrat in July 2003 is the largest recorded in historical times. I use noise correlation Green's functions to measure the changes in seismic properties that resulted from this collapse. Continuous three component seismic data recorded at two pairs of stations were cross‐correlated to retrieve three‐component Green's functions along two paths that intersect the volcanic edifice before and after the dome collapse. Particle motion analysis shows that the Green's functions are dominated by Rayleigh waves and are consistent with the expected Green's tensor for a vertical point force source at one station recorded by a three‐component receiver at the other. Following the collapse, there is a clear decorrelation and phase shift in the Green's functions corresponding to a change in velocity of approximately 0.5% that can be interpreted in terms of the unloading of the lava dome.

UK 1-D regional velocity models by analysis of variance of P-wave travel times from local earthquakes.

D. C. Booth

A method is presented for deriving 1-D velocity depth models from earthquake bulletin data. The models can be used as initial models for more advanced modelling techniques such as tomographic inversion. The method is useful when there is little or no refraction and long-range reflection survey data. The bulletin travel times are subjected to an analysis of variance, where they are separated into source, distance, and receiving station terms. The distance terms describe the variation of travel time with distance, and the associated trend lines allow 1-D velocity models for the crustal layers to be determined. The velocity models provide an average crustal model for the region derived from local data. This does not include superficial layers which are necessarily poorly determined. Earthquake bulletin P-wave data from propagation paths across three different regions of the UK are employed to illustrate the use of the technique.

MEEP 2.0 User Guide

R. M. W. Musson

In the past, the assessment of parameters of historical earthquakes tended to be conducted by "expert judgement", usually following undocumented procedures. More recently, it has come to be felt that this question needs to be handled in an objective, repeatable way. Hitherto, procedures for assessing earthquake parameters from intensity datapoints have been two in number – the BOXER method, developed by Paolo Gasperini and co-workers, and the Bakun-Wentworth method. MEEP (macroseismic estimation of earthquake parameters) is a third method, based on the fitting of the well-known Kovesligethy model to a field of intensity datapoints. Unfortunately, all three models are somewhat dependent on local calibrations. The MEEP method was extensively tested in the scope of the NERIES project, under which it was developed. Differences between parameters assessed by the three methods already represent something of the epistemic uncertainty in the catalogue determination. This user guide explains the theoretical basis of the method and the practical steps in the implementation of the software.

Preparing a seismic hazard model for Switzerland: The view from PEGASOS Expert Group 3 (EG1c)

R. M. W. Musson, S Sellami and W Brüstle

The seismic hazard model used in the PEGASOS project for assessing earthquake hazard at four NPP sites was a composite of four sub-models, each produced by a team of three experts. In this paper, one of these models is described in detail by the authors. A criticism sometimes levelled at probabilistic seismic hazard studies is that the process by which seismic source zones are arrived at is obscure, subjective and inconsistent. Here, we attempt to recount the stages by which the model evolved, and the decisions made along the way. In particular, a macro-to-micro approach was used, in which three main stages can be described. The first was the characterisation of the overall kinematic model, the "big picture" of regional seismogenesis. Secondly, this was refined to a more detailed seismotectonic model. Lastly, this was used as the basis of individual sources, for which parameters can be assessed. Some basic questions had also to be answered about aspects of the approach to modelling to be used: for instance, is spatial smoothing an appropriate tool to apply? Should individual fault sources be modelled in an intraplate environment? Also, the extent to which alternative modelling decisions should be expressed in a logic tree structure has to be considered.

Ground motion and probabilistic hazard

R. M. W. Musson

It might be thought that an empirical ground motion prediction model has only to describe the variations in the input data set as accurately as possible in order to be useful, with the proviso that the data set is reasonably extensive and well-selected. If the model is to be used in probabilistic seismic hazard assessment, however, the model will probably be subject to extrapolation beyond the parameter space within which it was constructed, especially for hazard at low annual probabilities. In this case, features of the model, especially its functional form, may turn out to have unexpected and undesirable implications. The end result can be conclusions about the hazard that are clearly not in accordance with commonsense. In this study, two test cases are used to examine the application of some recent ground motion models to probabilistic hazard studies. Problems are found that suggest that, although a ground motion model may be a correct representation of its data set, the effects of the functional form applied can be such that it becomes doubtful whether the model should be used for probabilistic hazard purposes.

Some notes on regional variations in intensity attenuation

R. M. W. Musson

Compared to models for the prediction of physical measures of earthquake strong ground motion, macroseismic intensity has received relatively little attention. Classic studies of the subject have been couched in terms of studies of the decay of intensity (I) with distance from the epicentral intensity (Io), leading to the concept of "attenuation studies". Recently, the term "attenuation" has become unfashion-able in engineering seismology because what is desired is to estimate the absolute value of ground mo-tion at distance R from an event of magnitude M; not the attenuated value from some central value. Comparable models, predicting expected intensity for different magnitudes and distances, are relatively uncommon; nevertheless, they can be very useful for estimating expected effects from some future earthquake; or rapid estimates of effects of an earthquake that has just occurred; or for general studies of earthquake hazard and risk.

In the 1990s a survey of European practice was made by the ESC Working Group Macroseismology, which highlighted that many countries were still relying on models of the form Io – I = fn [R] rather than I = fn [M, R]. The author at that time attempted to compile a collection of models of the form I = fn [M, R] for different parts of the world, a work which included constructing such models for some countries from available datasets of isoseismals. Today, far more macroseismic data are available online as IDP (intensity datapoint) sets, though constructing intensity models from IDPs has some pitfalls, as shown by Baumont and Scotti (2006). The author's collection of regional relationships based on isoseismal data reveals some interesting comparisons – the models for New Zealand and Turkey, for instance, are prac-tically identical. Plotted together, the models fall strongly into two groups corresponding to intraplate and interplate areas, where, very approximately, the predicted values for an intraplate event are around two degrees higher than a corresponding interplate event.

Subduction in the Western Makran: The historian's contribution

R. M. W. Musson

The Makran subduction zone, which runs along the southeastern coast of Iran and the southern coast of Pakistan, is a major control on the seismic hazard of the region. Whereas the eastern part of this zone has been active in recent historical times, the western part has not. This could indicate a zone currently locked, or it could be that subduction is occurring aseismically or not at all. Evidence for large thrust activity rests on one event, apparently very large, in 1483. Historical research, especially taking into consideration the political situation in the region at the end of the 15th century, suggests that this 1483 event was a moderate magnitude earthquake in the vicinity of Qeshm Island that has been misassociated with a second, later, earthquake. This interpretation removes from the earthquake catalogue any evidence for major earthquake activity along the Western Makran, and adds weight to the tectonic interpretation that major seismicity has a westerly termination at the Sonne Fault. This presents an interesting example of how a piece of obscure historical information has a significant effect on resolving a question of tectonic interpretation, and with it, influences the estimation of regional seismic hazard, including tsumani hazard in the Indian Ocean.

The comparison of macroseismic intensity scales

R. M. W. Musson, G Grünthal and M Stucchi

The number of different macroseismic scales that have been used to express earthquake shaking in the course of the last 200 years is not known; it may reach three figures. The number of important scales that have been widely adopted is much smaller, perhaps about eight, not counting minor variants. Where data sets exist that are expressed in different scales, it is often necessary to establish some sort of equivalence between them, although best practice would be to reassign intensity values rather than convert them. This is particularly true because difference between workers in assigning intensity is often greater than differences between the scales themselves, particularly in cases where one scale may not be very well defined. The extent to which a scale guides the user to arrive at a correct assessment of the intensity is a measure of the quality of the scale. There are a number of reasons why one should prefer one scale to another for routine use, and some of these tend in different directions. If a scale has many tests (diagnostics) for each degree, it is more likely that the scale can be applied in any case that comes to hand, but if the diagnostics are so numerous that they include ones that do not accurately indicate any one intensity level, then the use of the scale will tend to produce false values. The purpose of this paper is chiefly to discuss in a general way the principles involved in the analysis of intensity scales. Conversions from different scales to the European Macroseismic Scale are discussed.

Rotational earthquake effects in the United Kingdom

S.L. Sargeant and R. M. W. Musson

The United Kingdom is an area of low to moderate seismicity, and damaging earthquakes are uncommon. However, even in the limited record of damage from historical British earthquakes, a number of instances can be found of rotational effects on parts of structures, primarily chimneys or the tops of spires. We have assembled all the instances we know of from the United Kingdom record and present them here with illustrations and extracts from the original reports. It is not possible to determine whether these are the effects of true rotational motion or the effects of translatory shaking. Interestingly, this problem was considered in some detail by field investigators as long ago as the 1880s.

Lg wave attenuation in Britain

S. Sargeant and L. Ottemoller

The Lg wave quality factor (QLg) in Britain has been modelled using data from the UK Seismic Network, operated by the British Geological Survey. The data set consists of 631 vertical, mostly short-period recordings of Lg waves from 64 earthquakes (2.7–4.7 ML) and 93 stations. We have inverted for both regional average QLg and tomographic images of QLg , and simultaneously a source term for each event and a site term for each station for 22 frequencies in the band 0.9–10.0 Hz. The regional average model is 266f0.53 between 1.0 and 10.0 Hz and indicates that attenuation in Britain is slightly higher than in France, and significantly higher than in eastern North America and Scandinavia. Tomographic inversions at each frequency indicate that QLg varies spatially. Broadly speaking, southeastern England, the Lake District and parts of the East Irish Sea Basin, and a small region between the Highland Boundary Fault and the Southern Uplands Fault are characterized by higher than average attenuation. Southwestern England, eastern central England and northwestern Scotland are regions of relatively low attenuation. To some extent, these regions correlate with what is known about the tectonics and structure of the crust in the UK.