EARTHQUAKES

Early British thinking on earthquakes from Shakespeare to Hooke

Roger Musson - British Geological Survey, West Mains Road, Edinburgh

Early writing in English on the subject of earthquakes suffers from a linguistic difficulty that can be traced back to the ascendancy of Latin over Greek. The Greek word "sismos" is clear, and when Aristotle writes about earthquakes, one is in no doubt that he is writing about the same phenomena that seismologists study today. In Latin, however, "terra motus" can mean a number of different things, including landslides. Writers therefore toiled to bring disparate phenomena, all considered "types of earthquake" together into any theoretical framework, and the misuse of the word "earthquake" actually did not die out until the 19th century; as late as 1839 a major landslip at Lyme Regis was reported as "an earthquake". Shakespeare, where he mentions earthquakes, was clearly familiar with Aristotle's views on the subject, demonstrating that the Aristotelean explanation (subterranean winds) must have been common knowledge not just to a playwright at the end of the 16th century, but to his audiences also.

Interest in earthquakes, and publications on the subject, tended to be linked to the occurrence of particular events. It has often been commented how the disastrous Lisbon earthquake of 1755 inspired much work on earthquake phenomena throughout Europe, but one can also look before then to the 1580 Dover Straits earthquake, the 1692 Verviers earthquake, and the two London shocks of 1750. Then as now, British media (such as existed) were headquartered in London, and an earthquake felt in London excited attention that those occurring elsewhere did not.

One important landmark was the founding of the Royal Society in 1660. The Society became a clearing house for earthquake observations, and much information on British earthquakes is to be found in the papers collected and (mostly) published by the Royal Society between 1660 and the second half of the 18th century. Such observational evidence as British earthquakes afforded did not, however, provide much basis for theoretical elucidation, and it was unclear whether earthquakes were a geological or meteorological phenomenon. Much emphasis was placed on recording the state of the atmosphere at the time of an earthquake, data that today would be regarded as useless, but at the time seemed potentially highly relevant.

Although Hooke rightly finds a place in the history of seismology because of the later importance of his work on elasticity, Hooke himself had no idea of the relevance of elasticity to earthquakes. His interest in the subject was in relation to the problem of how fossils of marine organisms came to be found at high altitudes. For Hooke, therefore, an earthquake was an explanation for large displacements of geological strata, disconnected from anything that would be considered as seismological observation today. The idea that earthquake observations were due to elastic waves travelling through rock was not proposed until the writings of John Michell in 1760.

Earthquake prediction – the Holy Grail

Ian Main - School of Geosciences, University of Edinburgh

Earthquake prediction remains one of the great 'holy grails' of science: according to Richter "a statement of the time, place and magnitude of a future earthquake, in advance, above chance, and within narrow limits" where every word counts. This kind of prediction would justify a high-level intrusive response up to a full evacuation, but has proven sadly elusive.

Most attempts at prediction involve the use of some kind of precursor – an 'anomaly' of some kind in a geophysical signal that can be related to the upcoming event, as seen consistently before catastrophic failure in laboratory experiments. All kinds of signal have been examined by amateurs and professionals alike, from behavioural psychology of animals to ground radon. Hot on the heels of the plate tectonic revolution, superpowers traded claims in the 1970's of the physical basis and statistical evidence for precursors. The 1975 evacuation of Haicheng, preceded by a series of foreshocks including a magnitude 6 event some 12 hours before the main shock, was promoted as a success for the political system as well as local officials who made the call. However, a significant number of the local population may have abandoned their homes spontaneously in the aftermath of the foreshock.

Geophysical anomalies as such are hard to define – most geophysical signals tend not to have a smooth 'background', then an anomaly, then a big event. In the 1980s no significant precursors were identified by an IASPEI commission, according to a set of reasonable criteria set out at the start of the exercise. Independently, Per Bak and others proposed the hypothesis of 'self-organised criticality' for earthquake dynamics, where the system tunes itself spontaneously to a point where deterministic forces and random fluctuations compete almost equally. Here the outcome of individual events rests on a throw of the dice as much as the physical state of the system. This hypothesis explained much of the phenomenology of earthquake population dynamics including: the size and spacing distribution of earthquakes and faults, the relatively low stress drop, the Omori law for aftershocks, and the fact that tiny stress changes can trigger aftershocks and/or induced seismicity, even far from plate boundaries. The downside is reliable and accurate prediction may not even be possible.

So what can we do? Following from lessons learned by meteorologists, contemporary earthquake forecasting research centres on actual forecasting in real time – running competing hypotheses openly in parallel and then evaluating the outcome only after sufficient data have been obtained to estimate the actual probability gain. The results so far have been rigorous but modest, with absolute hazard forecasts for damaging events of less than 1% per day, largely based on the probability of earthquake triggering or clustering. This opens up the possibility of operational forecasting, now implemented by authorities in Italy, US and New Zealand. Even at this level challenges remain, especially in estimating and communicating risk to the general population. Meanwhile, forecasts of long-term hazard for building design remains the front line of defence against future earthquakes.

Long-term slip deficit and the forecasting of slip in future earthquakes.

John McCloskey - Environmental Sciences Research Institute, University of Ulster

In the last decade a series of devastating earthquakes have between them killed more than three-quarters of a million people. None of the events were formally forecast and have been repeatedly referred to as seismological 'surprises'. Here we argue that while earthquakes within the wide swath of diffuse deformation comprising the Alpine-Himalayan belt pose a set of particularly difficult set of challenges, earthquakes which are driven by high strain-rates at plate boundaries and which have relatively short nominal recurrence times might be forecast if the data exists to perform long-term slip deficit modelling and stress reconstruction. We show that two instrumentally recorded events on the Sumatran margin in 2007 and 2010 occurred in regions of high slip deficit identified by reconstruction of slip in historical earthquakes in 1797 and 1833 under the Mentawai Islands using more than 200 years of geodetic data recorded in the stratigraphy of coral micro-atolls growing there.

In the presentation we will describe the data and a Bayesian-Monte Carlo slip reconstruction technique. The technique is based on the stochastic forward modelling of many slip distributions each using the same set of elastic Green's functions to estimate the vertical displacement at the coral locations resulting from each simulated event. Every solution, weighted by its goodness of fit to the data, is added to a stack which contains an estimate of the most likely distribution of slip in the historical earthquakes. Further, we estimate the Kullback-Liebler divergence over the fault area providing a non-arbitrary assessment of the spatial distribution of information gain, identifying regions of low- and high- model confidence.

We then model the long-term slip deficit on the megathrust assuming a zero of stress immediately after the 1652 Mentawai Islands earthquake. We use the resulting slip deficit field to compute the entire stress field including both secular loading and earthquake interaction stresses. We show that the spatial distribution of energy release in the 2007 and 2010 earthquakes correlates strongly with regions of high slip deficit accumulated over the previous 350 years and that in principle both could have been identified as areas of particularly high seismic hazard.

The following more general seismological lessons emerge from our work:

1. At least for this region of this margin, the characteristic earthquake concept entirely fails to explain the data
2. Earthquake slip tessellates the fault plane here rather than repeating.

3 The tessellation by high slip is largely constrained by the interface coupling distribution (which, of course, played no part in the slip reconstruction).

4 Homogeneous loading of a heterogeneous fault explains all the observations; no time dependence is necessary.

5 Even small amounts of nonlinearity in the rupture process would ensure that this sequence will not be repeated, calling into question many long-standing, fundamental concepts in earthquake science.

Capturing the formation of a mid-ocean ridge using broadband seismometers: dyke propagation and eruption in Iceland

Robert (Bob) White - Bullard Laboratories, Department of Earth Sciences, Cambridge University

Using a dense array of 75 modern broad-band seismometers we have captured in unprecedented detail the propagation of molten rock through a lateral dyke and its eventual eruption 48 km away from the source. Melt was injected sub-horizontally from the sub-glacial volcano Bárðarbunga beneath Vatnajökull in central Iceland at a depth of about 7 km over a two week period in late August 2014 until it erupted in an old lava field called Holuhraun just beyond the edge of the glacier. Real-time mapping of the seismicity by the Icelandic Meteorological Office using data from their regional permanent seismic array supplemented by data telemetered from stations we had deployed close to the activity enabled us to respond quickly to the onset of the magmatic intrusion. Within 24 hours a Cambridge graduate student, Thorbjörg Ágústsdóttir had deployed two stations on the Vatnajökull ice cap using a helicopter. Over the next few days she deployed a further two Cambridge stations directly above the propagating dyke using snow scooters. Fifteen additional seismometers were then deployed on Holuhraun surrounding where we guessed the eventual eruption site might be. It was a good guess and the last deployment was completed just 2 hours before the eruption started close to that position. Indeed, two of the seismometers had to be rescued shortly before they were encroached by the advancing lava in the days following the onset of the eruption. The opportunity to deploy seismometers directly above the dyke and around the dyke tip mean that the earthquake locations, and particularly their depths are unusually well constrained.

We have used a new automated location method developed at Cambridge to map in detail over 30,000 earthquakes produced during propagation of the dyke. The dyke advanced in a series of rapid bursts with intervening periods when it stalled. The excellent seismic coverage allows us to constrain the precise failure mechanisms (moment tensor solutions) that produced the seismicity. They show that the fault planes are consistently orientated parallel to the dyke, from which we infer that the seismicity is produced primarily by breaking chilled magma emplaced during an earlier injection episode. We have also mapped seismicity caused in the surrounding area by the stress changes induced by the 1 metre thick dyke intrusion. This shows that faults are failing under additional stresses of as little as 1–2 bars (100–200 kPa).

In this presentation I will show time animations of the hypocentres which map out the propagation of the underground dyke and the way the stress changes caused by the intrusion trigger seismicity in the surrounding area to distances of over 30 km. It demonstrates the power of modern instrumentation coupled with powerful parallel array computer processing to constrain igneous and tectonic processes and the nature of small microseismic events at depths where direct geological sampling is impossible. I will also show photos and movies of the eruption as it progressed. At the time of writing (4 months on), the eruption is continuing unabated with over 1 cubic kilometre of basaltic rock erupted and the caldera of the Bardabunga volcano continuing its subsidence to more than 60 metres as melt drains out from it.

INSTRUMENTS AND INSTITUTIONS

UK seismic monitoring through the decades

Chris Browitt & Alice Walker - Former Heads of the BGS UK Seismic Monitoring and Information Service, Edinburgh

From the first attempts of Victorian natural philosophers to instrumentally monitor earthquakes in Comrie, Perthshire, in the 1840s and 1870s (coining the word seismometer in the process), to John Milne's centre for his global monitoring network in Shide (Isle of Wight) in the early 1900s, and to two dozen seismic observatories that had operated at various times from then into the 1960s, the idea of a uniform monitoring network for earthquakes felt in all parts of the British Isles had not been conceived.

Following earthquakes near Bala (North Wales) and Cwmbran (South Wales), in 1974, we found that they were better located using old-fashioned macroseismic methods as the few operating seismometers were too distant. The first attempt to use modern electronics, radio communications and tape recorders for studying local seismicity had been established by Willmore and Crampin around Edinburgh several years before (LOWNET). It was, however, principally used as a test bed for studies overseas in Turkey, Iran and Papua New Guinea, and, otherwise covered only the eastern central valley of Scotland.

In 1974, we started to seek the funds to replicate LOWNET throughout the country to be centred on hubs at Universities and other hosts to which seismic data could be transmitted from up to 100km distance. The first opportunity came following a spate of strongly felt earthquakes at Stoke-on-Trent which some blamed on deep longwall coalmining. The public were concerned; there were questions asked in the House of Commons, and the Media had a field day (months, in fact). Following a successful temporary local seismic network deployment to resolve the issue, the Department of Environment (DoE) agreed to support the operation of a regional network in the Midlands. Then the Department of Energy supported networks in eastern England, Orkney and Shetland to monitor the North Sea, in order to establish the hazard for hydrocarbons exploitation. They also supported a network in SW England in support of fracking operations at an innovative Hot Dry Rock experiment to secure geothermal energy from deep within the granite. Other local networks followed, to study the higher seismicity in western Scotland, North Wales and Jersey.

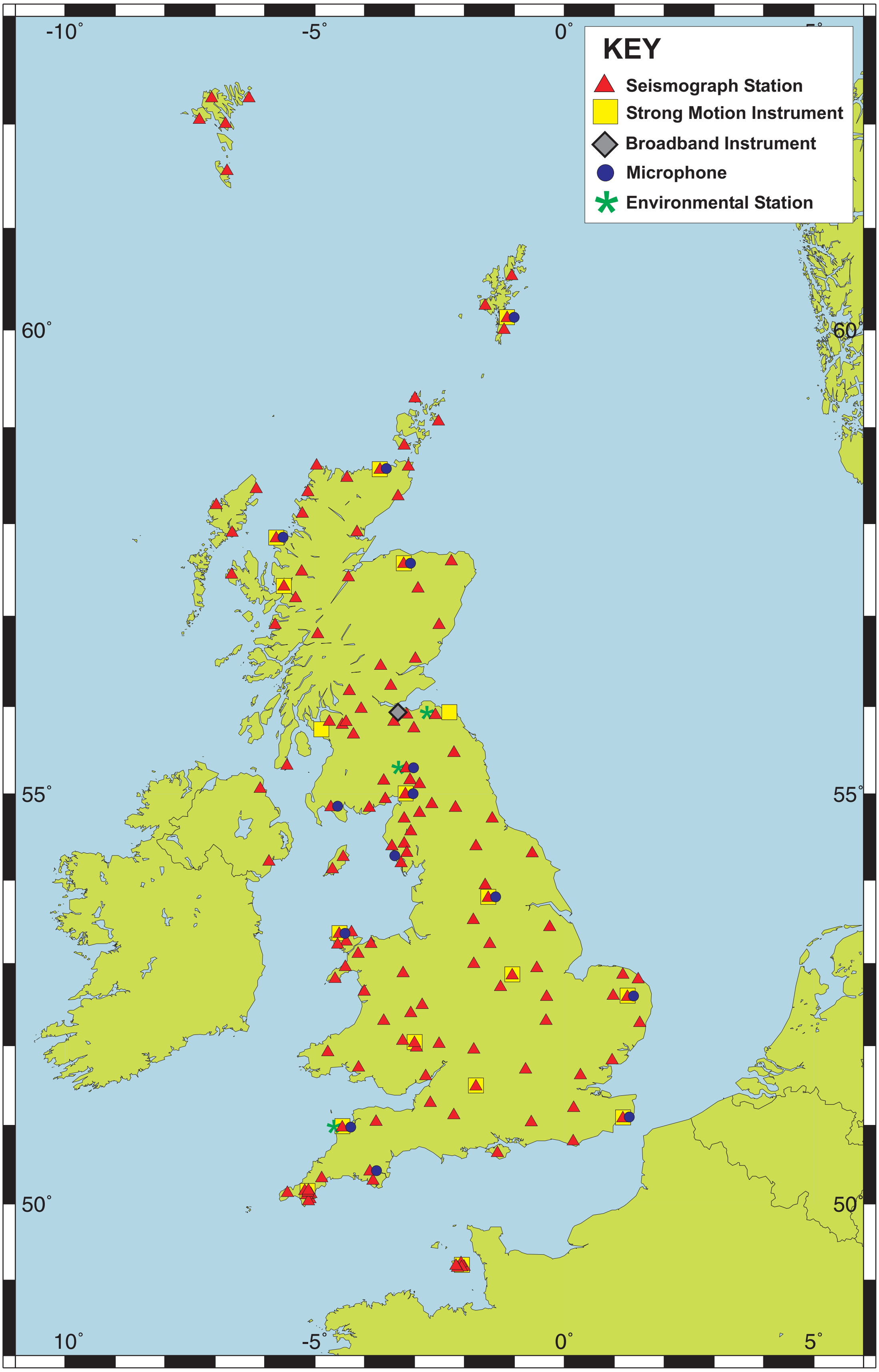
Towards the end of the 1980s, these sponsored networks were pulled together to form the UK Seismic Monitoring and Information Service with DoE and

NERC/BGS as the primary long-term sponsors. Gaps were filled as other sponsors joined in, including CEGB, the nuclear regulator, HSE (offshore oil and gas), Scottish and Southern Energy, Jersey Water, Scottish Power, Scottish Water, Magnox, Sellafield Ltd, Horizon and EDF-Energy. They formed a "Customer Group" which continues to this day. In order to extend the dynamic range of the short period seismometers and to help discriminate sonic booms, accelerometers and low frequency microphones were added to the network.

To fully surround our earthquakes with seismometers for more accurate locations, close collaboration was first established with Ireland, Norway and the Faroes, then, through two EC projects, with all of our neighbours across the North Sea, ensuring the free and rapid flow of data across borders.

Advances in technology have, once again, provided the capability to better record earthquakes over wider dynamic and frequency ranges and to rapidly transmit continuous data over the internet. From the early days of developing the UK network through tape recording at the hubs of subnetworks then, later, through dial-up, near real-time, telephone communications to seismologists in their houses in Edinburgh, another evolution is taking place. Since the early 2000s, a programme of installing broad-band stations across the UK has been conducted, and, from 2015, a large (80-station) transportable array will be deployed at various locations over the next decades in order to focus on both applied and research topics, starting with an independent monitoring of new shale gas fracking operations in Lancashire (subject to planning approval). This mirrors the BGS efforts at the Cornwall geothermal fracking site in the 1980s. It will be under the custodianship of Brian Baptie, the current Head of the BGS UK Seismic Monitoring and Information Service.

Throughout these recent decades, we recognised that despite achieving instrumental coverage of all our earthquakes of magnitude 2.5 and above (2.5ML events are usually felt), plus many smaller ones, there was still a place for the "old-fashioned" macroseismic survey, and these were extended to gather data on all of the larger felt events (now web-based). Having instrumental data to fix the epicenter, depth and magnitude, together with the macroseismics, permits the calibration of relationships between the two and, therefore, increases the accuracy of our interpretations of historical events in earlier centuries when such instrumental data was unavailable. That, in turn, contributes to a better understanding, and computation, of seismic hazard to high consequence industries, as a time base is needed that extends back well before the 1980s from when we could more uniformly cover the UK's larger events.



UK Seismic Monitoring network of 146 stations in 2003 (Walker et al., 2003)

Marine seismics: 60 years of instrument development at Cambridge

Tim Owen & Mel Mason - Bullard Laboratories, Department of Earth Sciences, Cambridge University

Marine Seismics was born around 1937, fathered by Maurice Ewing in the US but rapidly taken up by Teddy Bullard at the Department of Geodesy and Geophysics, University of Cambridge, and for the next 70 years was the major strand of the experimental work of the department. It was pivotal in developing our understanding of the structure of the oceans during the heyday of terrestrial geophysics. Cambridge was involved in developing the whole range of marine seismic techniques – ship deployed seismometers, surface sonobuoys for early refraction profiles, streamers and sources for reflection profiling, and sea bed seismometers for both deep and shallow water refraction. Almost all of the equipment needed was built in the labs, and most of it pushed the boundaries of available technology, to the extent that almost every piece of equipment was effectively a prototype, and there was never any certainty that anything would work on the day! Reading the cruise reports, it is a wonder that students and staff continued to work enthusiastically in the face of so much uncertainty and, frankly, disaster, but continue they did, thanks mainly to a constant stream of fresh, dedicated research students.

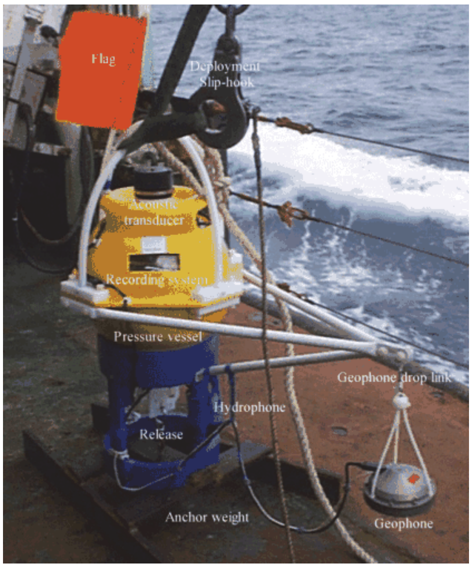
In this presentation we will describe the evolution of the experimental equipment, and its capabilities, with particular emphasis on the areas where the available technology was the limiting factor in equipment design, and the way in which the design of experiments evolved to use what was available. This evolution began when we had little idea of even the basic topographic shape of the sea floor and needed to drop a weighted line to get a single depth reading, at which point a single crustal velocity was a triumph, and finished in the era when useful data needed hundreds of thousands of data records to make any useful contribution to the science. During the period covered Universities around the world led in the field of seismic refraction and pioneered many of the techniques that were not seriously espoused by the oil exploration industry until quite recently.

Against this background, it was an immensely happy and productive environment and provided much of the experimental evidence that underwrote the major advances in our understanding of the crustal structure and the mechanics of plate tectonics. Cambridge was for many years the leading UK lab engaged in equipment building for marine geophysics, and it was Drum Matthews proud boast in the 1970s that he had never been turned down for a Royal Society or NERC grant – happy days indeed!

Early 1937 seabed geophone

Jason's Launch used for firing explosives

Tom Gaskell deploying geophone from Weather Explorer, 1939



1990s Ocean Bottom Seismometer – Minidobs

School seismology development in the UK and around the world

Paul Denton - British Geological Survey, Keyworth

Observational seismology has proven to be a powerful tool for use in schools as a means to inspire and educate students.

Amateur seismologists have been building and operating their own sensors for decades, many based on a simple horizontal pendulum designs published in the Scientific American in the 60's and 70's.

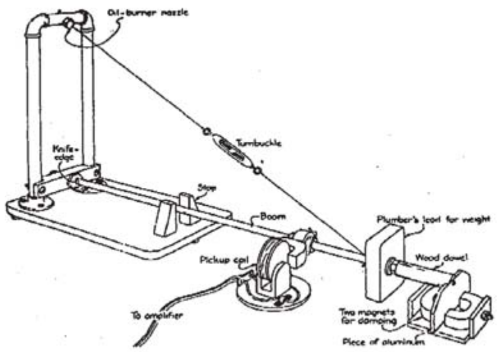
The impetus for the systematic uptake of observational seismology as an educational tool came from the academic seismology community when, in 1994, Guust Nolet proposed a network of low cost broad band seismometers to be installed in schools as a cost effective method of increasing the station density required for large scale tomography projects. This led to the development of the Princeton Earth Physics Project which set up several dozen schools in the USA with low cost Guralp broadband sensors, and the Eduseis project in Europe which led to the Sismos à l'Ecole project in France creating a network of 50 school stations using low cost broadband sensors from a variety of manufacturers.

In the USA the desire of academic seismologists for more data was accommodated by the development of the PASSCAL mobile instrument pool, however The Princeton Earth Physics Project had inspired educators about the educational possibilities of observational seismology. This led to the development of the AS-1 seismometer , a simple vertical sensor based on a Lacoste suspension system which was eventually installed in hundreds of schools across the USA together with the easy to use logging and analysis software, AmaSeis.

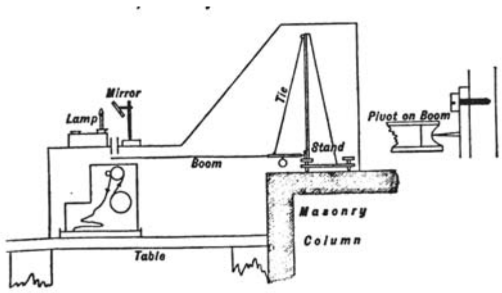
The 2004 Boxing day tsunami gave the impetus to the creation of a UK school seismology network following an inspirational article by a physics teacher and amateur seismologist Stewart Bullen, who described how he had recorded the event on a homemade sensor in his school. By 2006 a commercial version of this horizontal pendulum design was in production by MindsetsOnline. This design became the centrepiece of the UK school seismology project, initiated at the University of Leicester and taken up by the British Geological Survey, this project went on to promote the installation of over 500 such sensors in schools across the UK and around the world.

Recently the advent of ultra low cost computer systems and a "maker movement" inspiring people to make their own science kits, results in educational seismology getting simpler and more complicated at the same time. Very low cost sensors based on a very simple mass on a spring design like the

TC-1 slinky seismometer are being coupled with Arduino or Raspberry Pi dataloggers to enable anyone to build their own seismic station.

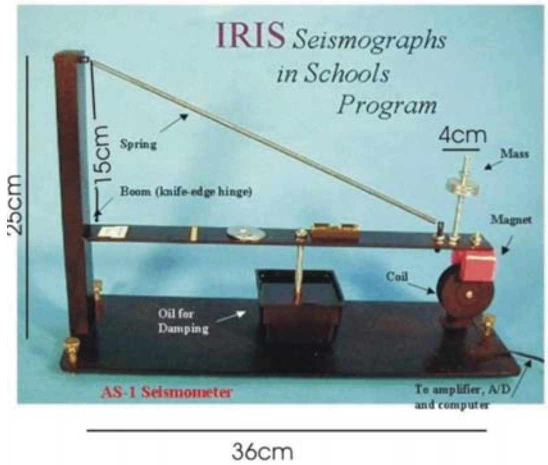


1979 amateur scientist design

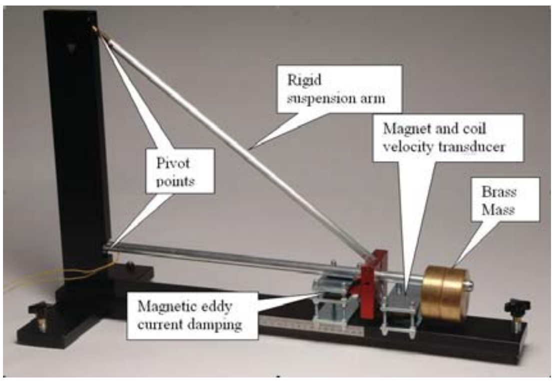


1908 Milne seismograph

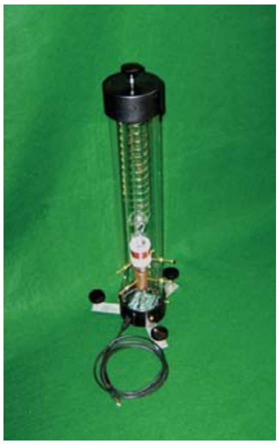
1990's Guralp "PEPP" seismometer



1990's AS-1 vertical seismometer



2006 BGS/SEP horizontal seismometer



2010 TC-1 Slinky sensor

CONTROLLED-SOURCE SEISMOLOGY AND CRUSTAL STUDIES

Explosion Seismology - thirty years evolution from Heligoland to LISPB

David Bamford – Finding Petroleum, www.findingpetroleum.com

Just like our ability to find petroleum, in which activity I have spent the last 30+ years of my life, our abilities to understand the deeper Earth have been driven by the emergence of new ways of obtaining data.

I firmly believe that "disruptive" insights occur in response to "disruptive" technologies.

If we look at another 30 years or so, from 1947 onwards, culminating in the famous LISPB experiment of the early 1970s, we can see four distinct stages of technology evolution:

1. The efforts to understand the deeper structures beneath the UK took off after WW2 with the observation of 'explosions of opportunity' such as the 1947 Heligoland blast – up to that time the largest non-nuclear explosion of all time – at earthquake stations. This approach continued for some years – for example, the work done by Brian Jacob and BGS colleagues using the Scottish LOWNET system to observe quarry blasts.
2. Certain University Departments – for example those at Birmingham, Leicester, Dublin – introduced mobile, analogue recording systems utilising Willmore seismometers, at the same time using controlled sources – such as Navy depth charges. This ushered in an era of refraction seismic experiments being where you wanted them to be, albeit with relatively few recording points. Good examples of this approach are the experiments undertaken by the University of Birmingham in the late 1960s, for example the Continental Margin Refraction Experiment of 1969.
3. The mega-step was the introduction of the Lennartz MARS 66 (analogue again) recording system, purchased in large numbers by German, Swiss, French and some British University Departments. It was this system, coupled with the disciplined approach to the fieldwork, which delivered the LISPB experiment of the early 1970s.
4. And then the Digital Era arrived! Hurrah!! For example, the Geophysikalisches Institut in Karlsruhe, Germany introduced a superb system for digitising MARS 66 data; the absolute key here was that now the whole data set – horizontal components as well as vertical - could be viewed in seismic sections, transforming interpretation away from the 'picking first arrivals' approach that had been the dominant approach heretofore.

This cumulative and ultimately "disruptive" transformation in the data acquired opened the door to new and innovative techniques for interpretation such as 2D and 3D ray tracing and full waveform elastic modelling.

My talk will illustrate some of these key technologies and the impact they had on the science of "controlled source seismology".

The KRISP and EAGLE projects: crustal structure in the East African Rift

G. Randy Keller - School of Geology and Geophysics, University of Oklahoma

The Kenya Rift International Seismic Project (KRISP) started in 1968 as a largely British effort and blossomed into a large multi-national cooperative effort that involved experiments in 1985, 1989-90, and 1994. The seismic refraction/wide-angle reflection profiles and teleseismic data produced several results that were transformative within the larger perspective of the East African rift system and for the understanding of continental rifting in general. One result was the discovery that the amount of magmatic modification of the pre-rift crust is modest rather than involving a large axial "dike" that affected the entire crustal column. Mafic underplating of the crust was observed in the Kenya topographic dome area and axial variation of crustal thickness by 50% was observed. Additionally, the crust and upper mantle anomaly associated with the Kenya dome area is deep-seated, only slightly wider than the rift valley, and surprisingly steep-sided. The seismic data agree very well with the observed north to south decrease of Bouguer gravity anomaly values. The area of thickest crust correlates with the apex of the Kenya dome where the elevation of the rift valley floor is highest. As one proceeds northward along the rift valley from the Lake Naivasha area, the physiographic expression of the rift valley widens from its minimum of about 60 km to about 180 km in the area of thinnest crust, and the elevation of the rift valley floor decreases from ~2 km to ~440 m that is the level of Lake Turkana. In addition to these observations, published seismic reflection results near Lake Turkana indicate about 35-40 km of extension across the rift while it is only 5-10 km in the region of Naivasha-Nakuru. These observations provide an internally consistent relationship between crustal thickness, amount of extension, width of the rift zone, and topographic relief.

Following KRISP, The Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE) was conducted mostly in 2002 and included a significant number of broadband instruments. A major goal was achieving a better understanding of the processes involved in continental break-up. Axial and cross-rift crustal structures in Ethiopia were similar to those in Kenya, but across the Ethiopian Plateau the thick crust is probably due to lower crustal underplating associated with extensive flood basalts. In addition, the mantle results showed that the upper mantle across the entire Ethiopian topographic dome has been modified by the presence of the Afar plume head, which is in contrast to the narrow zone of modification across the Kenya dome.

Earthquakes, explosions and North Korean nuclear tests

Anton Ziolkowski - School of Geosciences, University of Edinburgh

One of the most intriguing problems in seismology is to distinguish between natural earthquakes and man-made explosions using seismic data. It is important to be able to tell the difference in case there is an illegal breach of the Comprehensive Nuclear Test Ban Treaty when it comes into force. The problem is to work out the source mechanism from measurements made far away from the source after the seismic waves have been filtered by the Earth.

The mechanisms of earthquakes and explosions are different. It is generally assumed that earthquakes are generated by slip on a fault. The slip starts at a point and spreads over an area that first increases and then decreases to zero. The principal mechanism is shearing across the fault, creating rock fragments and fault gouge in the process. Elastic shear (S) and compressional (P) body waves are generated; surface waves are also generated.

An underground explosion generates a cavity in the rock with gas of intense temperature and pressure. The radiated stress wave loses energy due to permanent deformation of the rock immediately surrounding the cavity and decreases in intensity by this loss of energy, and by spherical divergence. At some radius from the centre of the cavity the stress decays to the elastic limit of the rock. Beyond this radius the propagation is elastic and essentially spherically-symmetric. So compressional (P) body waves are generated and, perhaps surprisingly, some shear (S) waves are also generated. It is well-known that explosions generate much less energy in surface waves than do shallow earthquakes of comparable magnitude. In fact the ratio of surface-wave magnitude M_s to body-wave magnitude m_b, is greater for earthquakes than for explosions, and this has been used for many years as a discriminant.

The announced North Korean nuclear tests of 2006, 2009 and 2013 present a problem: they fall right on the line between the earthquake and explosion populations (Figure 1). That is, they cannot be discriminated by the M_s/m_b criterion. A new approach to understanding these events is presented here. The source time functions are recovered from the data. Explosions are much more impulsive than earthquakes: this is exhibited in the source time functions.

The events of the Democratic People's Republic of Korea (DPRK, or North Korea) were very close together. The source time functions of two explosions at essentially the same location are self-similar: the amplitude and time scales are proportional to the cube-root of the energy. At a given seismometer the seismograms from the events share the same path effect, or Earth impulse response. The two seismograms and the scaling law provide three equations that can be solved for the two source time functions and the Earth impulse response. Using this idea the source time functions of the 2009 and 2013 events have been recovered using seismograms recorded at Mudanjiang (MDJ) in China. The source time function of the 2006 event was recovered by scaling. Calibrating these functions with a corresponding known explosion in granite, as shown in Figure 2, gives yields of 0.09, 1.52 and 5.65 kt, with errors of ± 34 %.

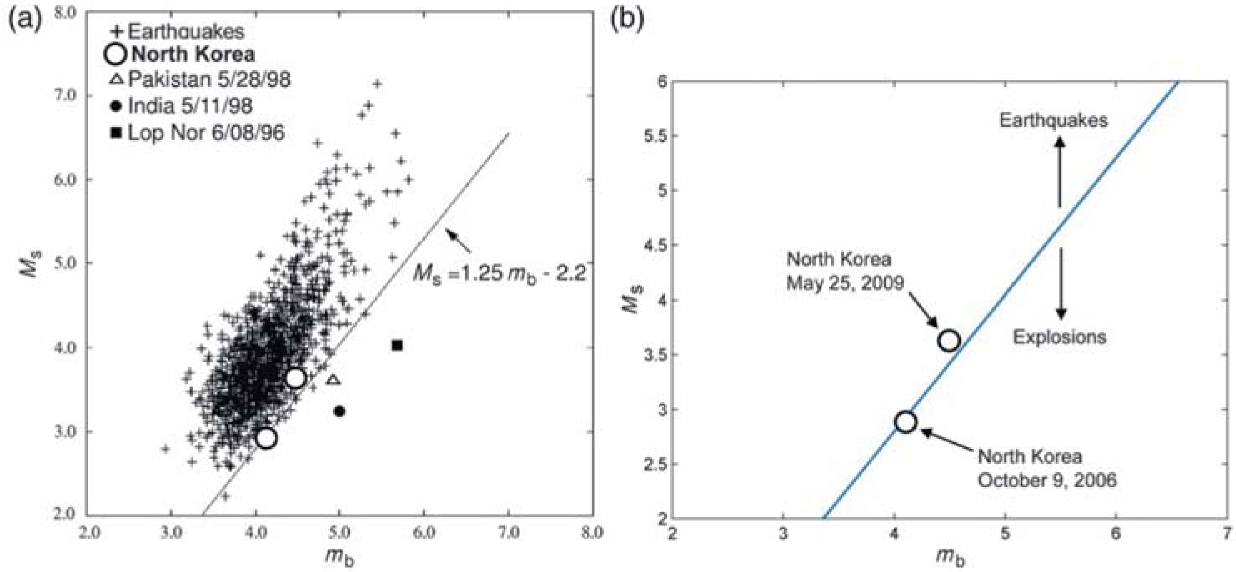


Figure 1 (a) Comparison of the M_S/m_b observations for the North Korean nuclear tests with corresponding M_S/m_b observations from other recent nuclear tests and earthquakes. (b) M_S/m_b values for the two North Korean tests with respect to the event screening line used at the IDC at the time of the tests.

(From Murphy, J.R., J.L. Stevens, B.C.Kohl and T.J. Bennett, 2013, Advanced seismic analyses of the source characteristics of the 2006 and 2009 North Korean nuclear tests: Bulletin of the Seismological Society of America, Vol. 103, No. 3, 1640-1661.)

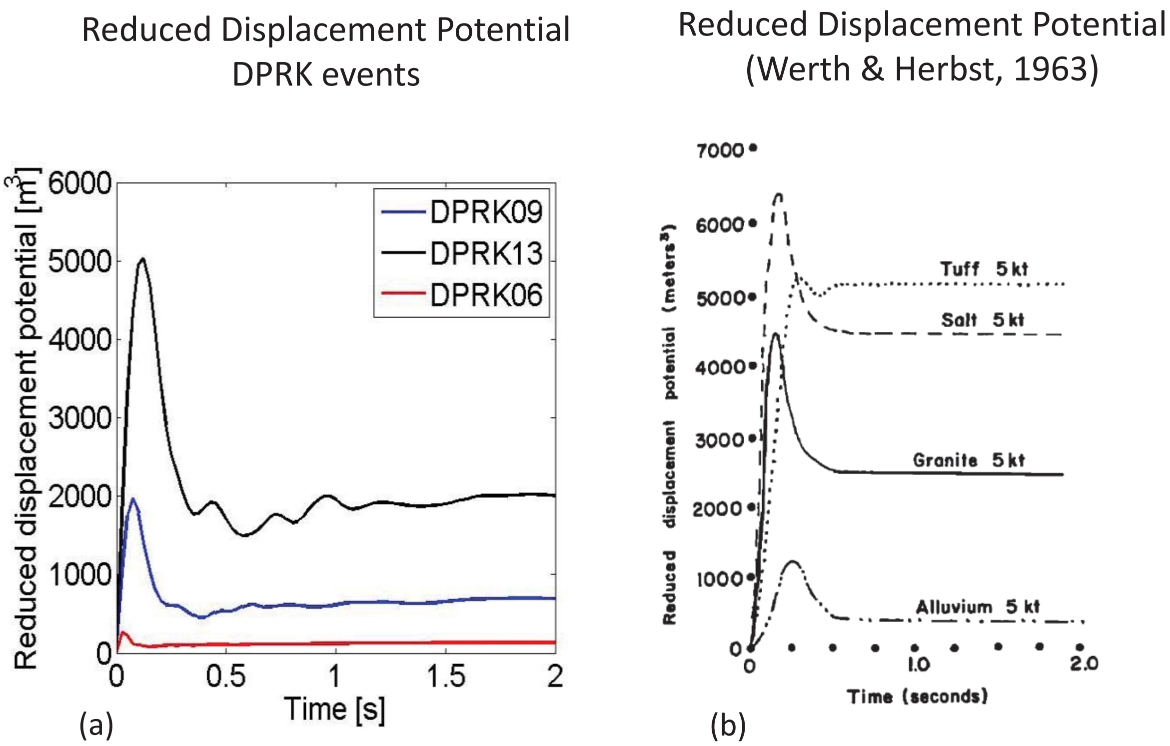


Figure 2 (a) Reduced displacement potentials of North Korean events after calibration using the granite event of (b); (b) reduced displacement potential of nuclear explosions in different rocks (From Werth, G.C. and R.F. Herbst, 1963, Comparison of amplitudes of seismic waves from nuclear explosions in four mediums: *Journal of Geophysical Research*, Vol. 68, No.5, 1463-1475.)

Reflections on BIRPS

Richard Hobbs - Department of Earth Sciences, Durham University.

In the late seventies and early eighties, the Royal Society, Natural Environment Research Council (NERC) and a group of academics led by Derek Blundell and Drum Matthews were keen to follow recent research in the United States to use seismic reflection imaging methods to map the deep structure of the Earth's crust around the UK. Plans were developed for an on-land transect to cross major tectonic structures in Scotland. In 1981 with some funds from the Institute of Geological Sciences (now BGS) and a guiding hand from the oil industry, a marine seismic profile was acquired off the north coast of Scotland – MOIST. The results were spectacular and the British Institutes Reflection Profiling Syndicate (BIRPS) was born. The NERC initially funded BIRPS for four years during which time four surveys were shot providing a network of marine profiles from the Shetland Isles in the north to the South-west approaches (partly in collaboration with the French group ECORS); and two surveys in the North Sea (mostly through collaboration with GECO). Within this flurry of activity BIRPS acquired its 'signature' profile DRUM (Fig. 1). DRUM – Deep Reflections from the Upper Mantle – ensured BIRPS success and remains an iconic reflection image of not only faults in the crust but structures in the upper mantle down to depths of nearly 100 km.

BIRPS continued work until 1998. Its outputs and future programme were reviewed every four to five years by an international visiting group. Project selection, through a mixture of directed research and then later through open submission and review, was by an over-sight committee. Day-to-day operations, which included detailed planning, contract evaluation, data acquisition, processing and initial interpretation was carried out by a Core Group headed up by Drum Matthews and from 1991 by myself. During this time BIRPS completed a ring of deep seismic profiles around the British Isles including several repeat visits to the north of Scotland where it all began. In the later years BIRPS worked increasingly on international projects. One of these not only provided some new and exciting science that is still an area of active research, but also caught the imagination of the public. The CHIXULUB project surveyed the now buried 65 Ma multi-ring crater that straddles coast of the Yucatan Peninsula in Mexico, a date that is known to dinosaur enthusiasts of all ages!

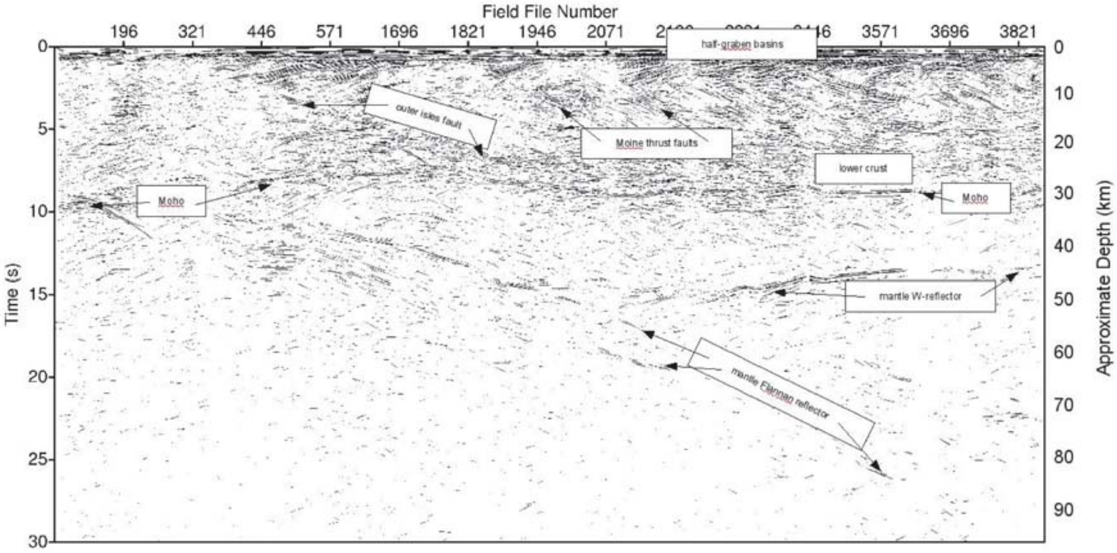


Figure 1. An enhanced seismic section of the DRUM profile acquired off the north coast of Scotland. The discovery of discrete reflectivity in the lithospheric mantle beneath the Moho was one of the major science deliverables of the BIRPS programme.

Inversion of the full seismic wavefield: high-fidelity imaging of Chicxulub, subduction zones and active volcanoes

Joanna Morgan – Department of Earth Science and Engineering, Imperial College, London

Controlled-source seismic refraction data are used to obtain models of sub-surface velocity structure. Until relatively recently, most academic studies have mainly modelled the travel-times of refracted waves, and occasionally the travel-times of reflected waves and/or variation in amplitude of the principal arrivals. Velocity models obtained using these methods, however, suffer from poor spatial resolution. It has long been realized that the full-seismic wavefield, which may take several seconds to arrive at a receiver, contains information about the fine-scale structure of the Earth through which it has travelled. Hence, inversions of the full wavefield have the potential to recover high-resolution high-fidelity velocity models, and have been a long-term goal of seismologists.

The most successful prototype full-waveform inversion (FWI) schemes were those that focused on matching the phase of the low-frequency component of the early-arriving refractions, as these arrivals are most sensitive to the intermediate-to-long-wavelength p-wave velocity structure, and inversions of phase rather than amplitude are preferable as they are less affected by inherent problems with non-uniqueness. The first FWI codes were two-dimensional and, as such, were not considered to be commercially useful. It was the development of computationally efficient and effective 3D full-waveform inversion codes over the last 5 years that has led to a change in practise in the petroleum industry. To date, 3D FWI codes have been applied mainly to industry towed-streamer (Fig. 1) and ocean-bottom- cable data, but it is straightforward to extend their use to academic datasets using ocean-bottom seismometers.

In the talk, I will present 2D FWI of streamer data across an internal ring of the Chicxulub impact crater, which will be drilled in a joint ICDP/IODP expedition in 2016, as well as 3D anisotropic FWI applied to an OBS field dataset acquired across the Endeavour oceanic spreading centre in the north eastern Pacific. The latter shows low-velocity zones beneath the oceanic ridge that are likely to correspond to magma-rich zones, and some off-axis low-velocity zones in areas of elevated seismic activity. The Endeavour study demonstrates that 3D FWI can be applied to scientific targets provided that the data coverage is adequate in three-dimensions, and that an appropriate range of offsets and azimuths are available. We anticipate that this exciting development will encourage future seismic investigations of earth science targets that would benefit from the superior resolution offered by 3D FWI, such as hazardous subduction zones and active volcanoes.

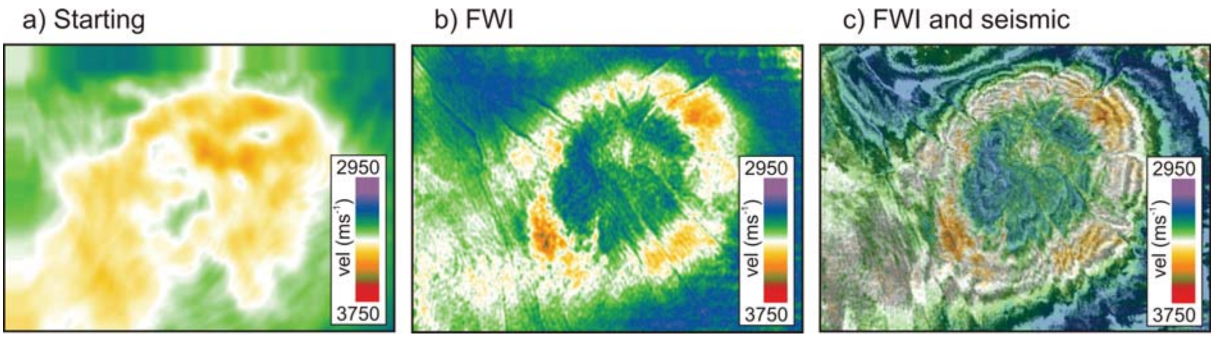


Fig. 1. Horizontal slice at 1350 m depth through the Samson dome, Barents Sea. a) Starting velocity model, b) Recovered FWI model, and c) The FWI model overlain by the migrated reflection image.

Sizing up to the energy challenge; seismology and the oil and gas industry

Patrick Bermingham - Exploration Chief Geophysicist, Shell International Exploration and Production

Seismology for oil and gas exploration evolved from the development of marine 'echo sounding' to locate enemy submarines and land 'sound ranging' to locate enemy artillery during the first world war[1]. In the 1920s, the first petroleum discoveries were made using gravity and seismic surveying methods. Seismology developed rapidly in the 1930s and, together with geology and well engineering, underpinned the development of the global oil industry which was producing around 6 million barrels of oil per day by 1938.

Seismic reflection has been the principle method for hydrocarbon exploration since the 1950s and for three decades, seismic data were acquired as 2D profiles, digitally from the 1970's[2,3], enabling oil and gas production to reach 90 million barrels of oil equivalent per day (mmboe/d) by 1980. Since then, both 3D and 4D seismic have developed, underpinning further production growth to the current level of around 150 mmboe/d.

We now face the twin challenges of growing energy demand and climate change. How is the oil and gas industry responding? Shell believes the use of cleaner burning natural gas, especially in power generation, will be vital in building a sustainable energy future. For example, from fuel production to the generation of electricity, modern gas-fired power plants emit around half the CO_2 of modern coal plants. [4]

How is seismology sizing up to these challenges? To meet the growing energy demand we need to find and produce commercial oil and gas in ever more challenging environments and more complex geology. To do this, we need to base our decisions on an accurate assessment of prospect risk and volume potential. We need to accurately assess geohazards in order to safely drill exploration and development wells and we need the ability to monitor and respond to any consequences of reservoir injection and production. These all require improvements in seismology, and simultaneously, a strong supply of capable seismologists. Improvements in acquisition include new ocean bottom sensors, increasing bandwidth and improved illumination whilst also reducing the impact on marine life. There are also improvements in seismic processing, imaging, interpretation and modelling all requiring enhancements in computer processing power.

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Reservoirs under stress: the microseismic response to fracture stimulation

Michael Kendall - School of Earth Sciences, University of Bristol

Small microseismic events, or acoustic emissions, occur both naturally and as a result of anthropogenic influences in reservoirs. Sudden stress release leads to elastic rock failure, which serves as an effective seismic source. These microearthquakes may be the result of production or hydraulic stimulation, but they may also be a consequence of natural tectonic activity. They are usually only detectable using sensitive sensors and after careful data processing. Such passive seismic monitoring has been used in mining settings for over 100 years, but its application in petroleum setting is relatively new. As such, it is a rapidly advancing field of technology, where the challenges are manifold and involve issues associated with data acquisition, processing, and interpretation. Much can be learned from methods and case studies developed for microseismic monitoring in volcanological, geothermal and mining settings, but one of the key advantages in oilfield monitoring is that a great deal is ordinarily already known about the reservoir. Comparatively good velocity models exist and production or injection information is available – the same is obviously not true for a volcano.

Clusters of microseismic events delineate faults and fracturing, highlighting reactivation or the generation of new zones of failure. Such monitoring can be done with sensor arrays deployed in boreholes or using dense arrays of sensors deployed on the surface or in shallow boreholes. Surface arrays provide better spatial coverage, whilst borehole sensors provide better sensitivity – ideally one would employ both types of monitoring arrays. Such monitoring has been very effective in helping assess the efficacy of hydraulic stimulation (i.e., frac monitoring). Longer term monitoring will no doubt provide an early warning system for detecting top seal leakage and fault reactivation in CO_2 sequestration projects, for example.

Until recently, most microseismic monitoring studies in petroleum settings have concentrated on detecting and locating events. However, considerably more information can be extracted from such data. For example, source characteristics and mechanisms provide helpful information about the stress field, especially as multi-well monitoring and surface arrays become more common. Magnitudes help quantify stress drop and focal mechanisms provide insights into the magnitude and orientation of the stress tensor. The amplitude-frequency relation, or so-called b-value, is sensitive to fluid properties and fracture network development. Furthermore, microseismic events can be used to image the surrounding media. They can help refine velocity models, study attenuation, and are ideally suited to estimating anisotropy parameters. Insights into the nature of faults, estimates of the stress tensor and velocity model refinement are all valuable inputs for reservoir simulators.

Measurements of shear-wave splitting in microseismic events provide unambiguous evidence of seismic anisotropy, which may be caused by the rock fabric and/or aligned fractures, which in turn offers insights into the state of stress in the rock. Recent work has focused on fracture compliance inversion, including both spatial and temporal variations in rock fracture networks, which can be used to track fracture development during stimulation. Furthermore, the frequency dependent nature of shear-wave splitting provides insights into fracture dimensions and fracture fluid content. Our work has shown that shear wave splitting analysis can provide a useful tool for monitoring spatial and temporal variations in fracture networks in a range of environments.

Cumulatively, our proposed processing flow for microseismic data acquired during hydraulic facture stimulation may provide a useful toolbox for assessing the efficacy of fracture stimulation in a range of settings, including tight-gas reservoirs.

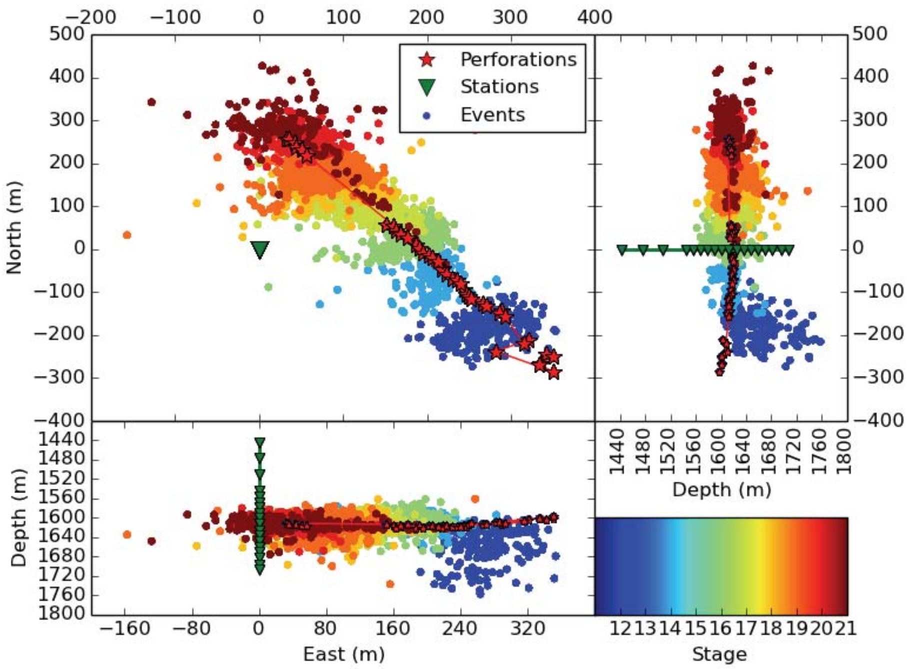

Figure: Microseismicity recorded by a downhole seismic array during hydraulic fracture stimulation in sequential stages.

PASSIVE SEISMOLOGY

Seismic tomography and the Earth's upper mantle

Stewart Fishwick - Department of Geology, University of Leicester

Knowledge of the physical state (e.g. temperature, composition, volatiles) of the uppermost mantle (e.g. the lithosphere-asthenosphere system) is critical in linking geological observations at the surface with our understanding of the Earth's dynamic interior.

Passive seismology, using observations from distant earthquakes to infer information about the structure between the source and receiver, has led to significant advances in our understanding of the lithosphere and asthenosphere. From travel time residuals, indicating regions of faster or slower material, through to the ever-developing tomographic techniques for more nuanced images of the upper mantle, seismology has frequently been used to answer geophysical and geodynamical questions. While development of methodology for tomographic studies has often been elsewhere, the application of these techniques to varied tectonic problems has been a key component of geophysical research within the UK (not least in the last fifteen years with the advent of the SEIS-UK equipment facility).

From northern Canada to Antarctica, and from Chile to New Zealand, UK seismology has been involved in the investigation of many major problems in Earth Sciences. Following an overview of some of the historical work, we use three case studies to show the developments in understanding obtained through seismological research.

Firstly, the structure of the lithospheric roots beneath the ancient Precambrian cores of the continents is discussed. In this case, tomography using data from Rayleigh Waves has been the dominant source of information. However, more recently, detailed studies using body wave tomography provide further insights into the internal architecture of these cratonic regions.

Secondly, the Carpathian-Pannonian system has been the focus of work undertaken at the University of Leeds, with the intriguing question of whether subduction processes or downwellings associated with gravitational instabilities are the driving forces of the dynamics of the region. Body wave tomography has been used to image the upper mantle structure, and the results illustrate how both extensive networks, and theoretical advancements in the tomography help answer these questions.

And, thirdly, the East African Rift system was not only a focus for significant active source seismology, but has also been a target of a long series of passive seismology experiments, led by UK institutions, with a particular emphasis in Ethiopia. Again, much of the work uses body waves to elucidate upper mantle structure – with the goal of understanding the nature of the mantle upwellings that link to the regional volcanism, and, in Afar, the incipient sea-floor spreading.

Seismic Imaging of Upper Mantle Discontinuities, Implications for the Tectonic Plate

Catherine Rychert - School of Ocean & Earth Science, University of Southampton, National Oceanography Centre

Beneath the Moho the transition zone discontinuities at 410 and 660 km depth are the major seismic discontinuities of the upper mantle. Between the Moho and the transition zone several mantle discontinuities have been proposed, including the base of the tectonic plate. However, global and continent scale stacks of long period data reveal no evidence for discontinuities at these depths (Shearer, 1991). Therefore, if discontinuities exist, they must either occur gradually in depth and/or vary significantly in depth. The base of the tectonic plate (the lithosphere-asthenosphere boundary) was typically believed to be gradual, and therefore related to the variation of a cool lithosphere to a hotter asthenosphere. Many new observations have altered this view, although better constraints on the depth and sharpness of the LAB are required to fully understand the tectonic plate globally.

Although, typically used for crustal imaging, linear, long range (>500 km), active source reflection and refraction continental experiments using large sources such as nuclear explosions, allow imaging at upper mantle depths. Discontinuities at 200 – 250 km depth have been imaged beneath the continents, often referred to as the Lehmann discontinuity and interpreted as a decrease in anisotropy with depth. Sharp discontinuities in the 80 – 125 km depth range were imaged and sometimes interpreted as the lithosphere-asthenosphere boundary. However, the lateral extent of discontinuities imaged with these methods is limited to the discrete locations where the experiments were performed.

Passive source imaging using receiver functions, in particular S-to-P phases, have increased lateral resolution, showing velocity decreases with depth at 60 – 120 km are common features in both ocean and continental regions. The phases are frequently coincident with the gradual drop in velocity from surface wave tomography, suggesting the lithosphere-asthenosphere boundary is sharp in these places. Therefore, the boundary cannot be defined by temperature alone, requiring a small amount of partial melt or hydration in the asthenosphere. However, beneath continental interiors discontinuities in this depth range must be frozen-in, since hydrations and/or melt would not be consistent with the strength, longevity, and thickness of the continental cratons. These discontinuities may offer interesting insight to continental formation.

Increased lateral resolution is provided by other passive source methods such as SS precursors that can constrain discontinuity structure beneath the oceans, where station coverage is sparse. Although sharp discontinuities are imaged beneath the oceans, results are intermittent, and interpreted both with increasing depth-age trend and also at constant depth. Better constraints on complications such as anisotropy are required to resolve apparent discrepancies. Anisotropy likely varies at the LAB, although a mechanism such as hydration or melt is also probably required for a sharp change.

Better lateral resolution of depth and sharpness of the LAB and mid-lithospheric discontinuities from a variety of methods with comparisons among tectonic environments will improve our understanding. These constraints must then be integrated with experimental results for the effects of hydration and melt on seismic velocity and viscosity, considering implications for the coupling of the plate to the asthenosphere and the formation of the continents.

Seismic anisotropy: past, current and future perspectives.

James Wookey - School of Earth Sciences, University of Bristol

Seismic anisotropy is the variation of seismic wave speed with direction. It is a key parameter that requires consideration at all scales, from proper imaging of the structure of shallow crustal hydrocarbon reservoirs to the understanding of the growth and deformation of the Earth's inner core. Anisotropy arises in the Earth from the large-scale arrangement of features (for example, crystals, fractures, inclusions, or layers) smaller than the seismic wavelength. It provides a measurable signature both for the presence and nature of these features, and the processes (such as deformation) by which they were created or aligned. Most minerals in the Earth are anisotropic at the single crystal level; understanding how these manifest in textures produced by deformation requires input from experiments or numerical simulation.

The 'classic' example of seismic anisotropy in the Earth is the alignment of the a-axes of (dry) olivine crystals in oceanic asthenosphere with the direction of plate motion. Observations of the azimuthal variation of P-wave speed inferred to be associated with this in the eastern Pacific formed a significant part of the early evidence for plate tectonics. Another unambiguous indicator of the presence of seismic anisotropy is so-called 'shear-wave splitting'. Pioneering work in the UK on shear-wave splitting by Crampin and others has led to a veritable industry of the measurement of this phenomenon, particularly in core-traversing SKS/SKKS phases. Very large datasets of SKS/SKKS splitting now exist, covering large swathes of the globe. This is not only providing new insight into upper mantle dynamics (see Figure), but provides a necessary correction to look at anisotropy in the deeper mantle. Upper mantle anisotropy is also incorporated in PREM to reconcile normal mode with body-wave data. More recent one- and three-dimensional whole Earth models also incorporate anisotropy from normal modes and surface waves, giving us a broad scale picture of deformation throughout the Earth's mantle. However, some details of these must be treated with caution — strong trade-offs exist in the inversion for anisotropic parameters. In the exploration context seismic anisotropy has been used extensively to characterise aspects of reservoirs (for example, lithologies and fractures) as well as to improve structural imaging.

Realising an improved, quantitative understanding of Earth dynamic processes from these measurements of anisotropy, however, is often a more complex problem. For example, a complete model of plate motion induced asthenosphere anisotropy would need to incorporate a geodynamic model of strain history, a petrophysical model of texture development and a realistic seismic waveform propagation model. Such integrated models are beginning to be generated in various contexts, including for the asthenosphere, subduction zones and the lowermost mantle. The eventual goal of such integrated models might be the direct inversion of seismic anisotropy for global mantle dynamics, something that would no doubt revolutionize our understanding of the dynamic Earth system.

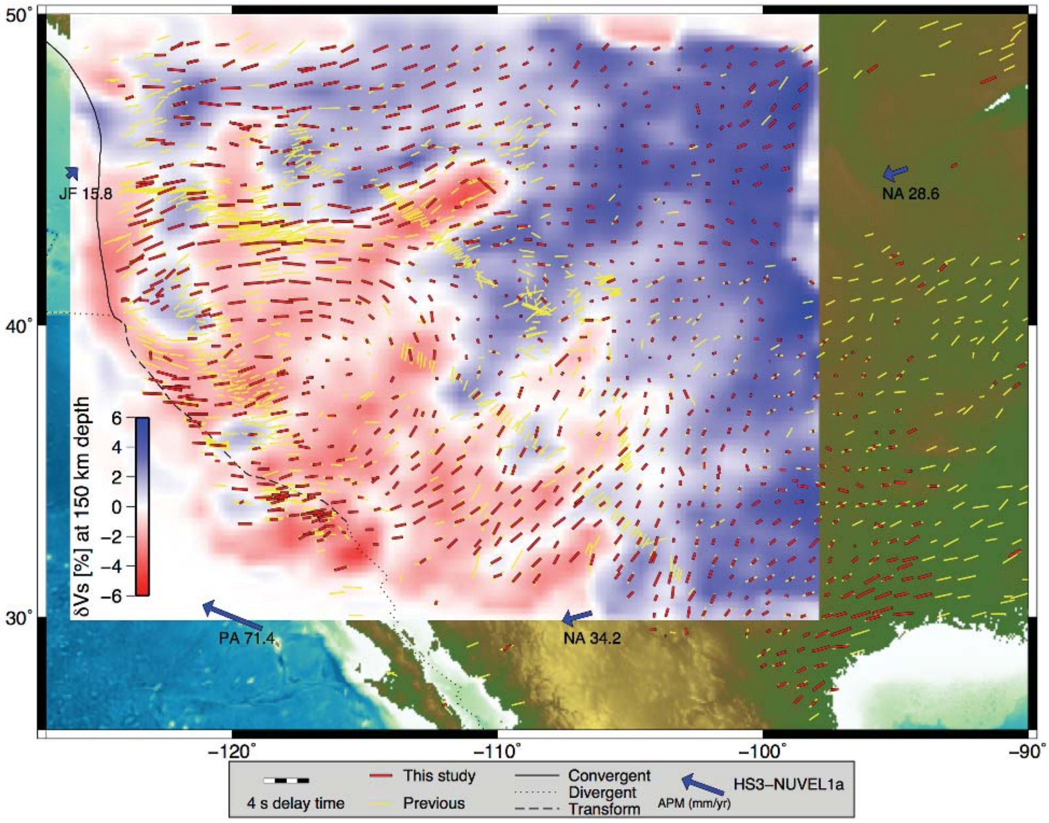

Figure: Dense measurements of SKS splitting in the Western USA (tick marks, from Walpole et al 2014; Becker et al 2012) compared to seismic shear wave speed at 150 km (colour scale, from Obrebski et al 2011). The relation between the two is evident, with the anisotropy (and by inference mantle flow) following the apparent structure.

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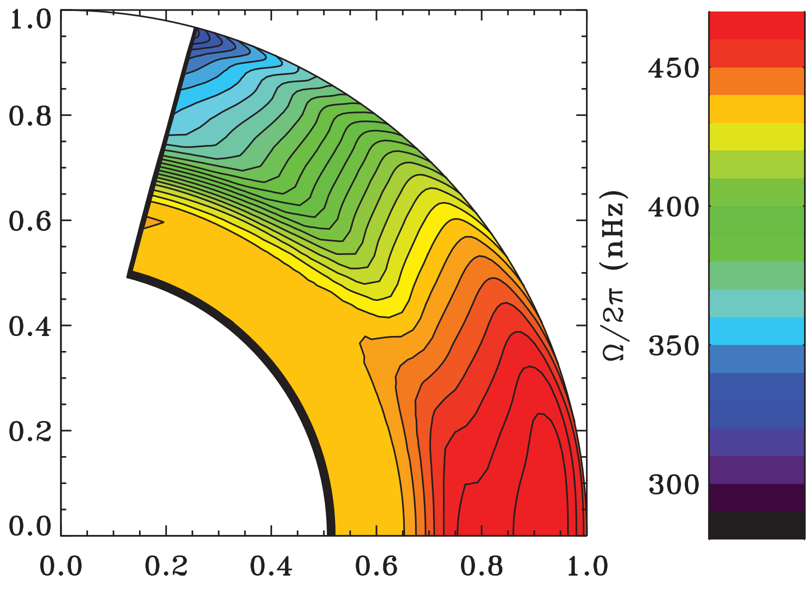
Helioseismology: revealing the Sun's internal structure and dynamics

Michael J. Thompson - National Center for Atmospheric Research, Boulder, CO USA

Helioseismology has really blossomed in the past 30 years, though its roots can be traced back to observations of oscillatory motions of the Sun's photosphere in the early 1960s and the theoretical explanation and subsequent observational confirmation of the modal nature of those oscillations in the first half of the 1970s. Particularly noteworthy have been the determination of the radial stratification and two-dimensional rotation profile over most of the solar interior. These in turn have led to inferences about the nature of energy transport in the Sun, the solar internal composition, the solar plasma's opacity to radiation, the extent of the solar convective envelope, even the robustness of the perihelion advance of Mercury as a test of General Relativity. More recent work has sought to determine the subsurface structure of sunspots and magnetically active regions, the nature of the meridional circulation inside the Sun, and how the dynamics of the solar interior vary with the solar cycle. In this talk, I shall endeavour to discuss the results in all these areas, as well as indicating briefly where the future challenges and opportunities for helioseismology lie.



Rotation profile of solar interior (units are nanoHertz) as revealed by helioseismology. Pole is at the top, the Sun's equatorial plane runs along the bottom.

Contributions to seismology by scientists from the U.K.

Walter D. Mooney - USGS, Menlo Park, California USA

Seismology was born from the desire to reduce the deadly impacts of earthquakes, and by the end of the 1800s, seismology had evolved to encompass curiosity-driven studies of the Earth's interior. Although seismology can be considered as a branch of physics, it differs from pure physics in that it is fundamentally geographically based, making it more akin to astronomy, a fact that is recognized by the inclusion of the discipline within the Royal Astronomical Society (U.K.). Given the uneven global distribution of earthquakes, it is no wonder that many of the most important U.K. contributions to seismology have been made by those who have ventured to seismically active regions such as Italy, India and Japan.

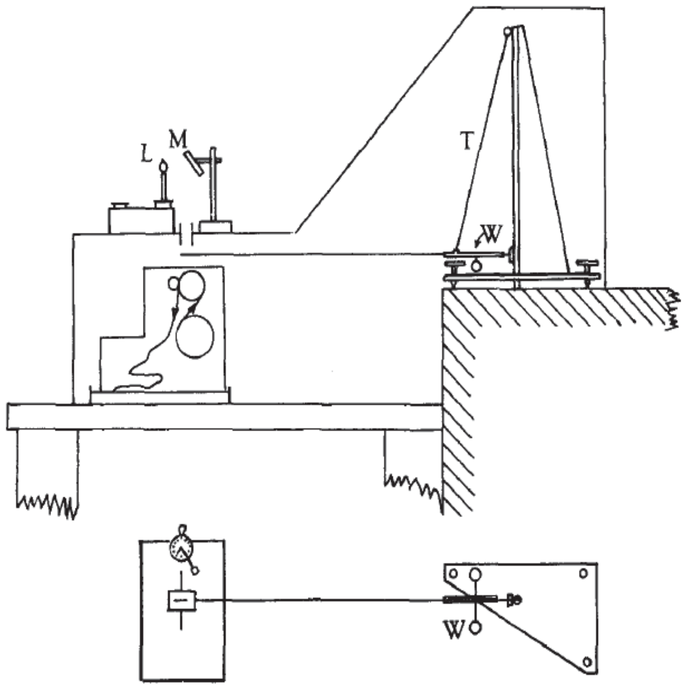


Figure 1. Milne-Gray horizontal pendulum seismograph.

<u>*Upper Diagram*</u>*, side view - Light from lamp, L, reflects from mirror, M, and passes through a pair of perpendicular slits to fall on photographic paper; the pendulum is supported by wire, T, and pivots on a hinge, W.*

<u>*Lower Diagram*</u>*, top view - showing (left) clock and narrow slit for light.*

The remarkable career of John Milne (1850-1913) is a case in point. Milne was educated as a geologist and mineralogist, with particular expertise in mining. By age 25 he had already travelled extensively, having visited Iceland, Newfoundland and Egypt, experiences that piqued his interest in geology. He arrived in Japan in 1876 to be Professor of Mining and Geology at the newly-founded Imperial College of Engineering in Tokyo. Milne was deeply impressed by damage caused by the Yokohama earthquake of 1880. He co-founded the Seismological Society of Japan a few months after that earthquake in concert with British colleagues Thomas L. Gray (1850-1908) and James Alfred Ewing (1855-1935) and several Japanese colleagues, including Ichizo Hattori, the Society's first president. Milne's interests in earthquake studies culminated in the development of the Milne-Gray horizontal pendulum seismograph that recorded ground motion with time on photographic paper (Fig. 1). However, this instrument did not include viscous damping, thereby limiting the fidelity of the ground motion that it recorded.

Milne was concerned with the mitigation of earthquake effects and was instrumental in the adoption of earthquake resistant building codes in Japan. He returned to England in 1895 and continued his seismological research, including the establishment of the first seismographic observatory in Britain on the Isle of Wight. He fostered the proliferation of seismographic stations worldwide, and much of these data were collected at Milne's observatory, making it a predecessor to the U.K. International Seismological Summary (1918-1963) and the current International Seismological Centre (1964-present).

Richard Dixon Oldham (1858-1936) was a contemporary of Milne's who shared Milne's enthusiasm for travel and seismology. Oldham moved to India in 1879 and worked for the Geological Survey of India, following in the footsteps of his father, Thomas Oldham (1816-1878), who was the director of the Geological Surveys of Ireland and India. R.D. Oldham's study of the great Assam earthquake of June 12, 1897 remains one of the most important and detailed reports on the effects of a large continental earthquake. Oldham was also the first to find seismological evidence for the Earth's core. The trail for this scientific discovery can be traced back to Sir William Gilbert (1544-1603), who argued that the Earth itself was a magnet, and hence has an iron interior (W. Gilbert, 'De Magnete', London, 1600). Nearly two centuries later, Henry Cavendish (1731-1810) conducted his masterful experiments (1797-1798) in his London home that determined the weight and average density (5.45 g/cc) of the Earth, thereby proving the existence of much high-density rock at some unknown depth beneath the lower-density (2.6 g/cc) surficial rocks. A century after Cavendish's discovery, in 1896, Emil Wiechert (1861-1928) deduced from the Earth's moment of inertia, ellipticity, and mean density that the Earth must have a dense core, inferred to be iron. R.D. Oldham, on his return from Japan to England, examined teleseismic observations compiled at Milne's observatory and deduced that delays in P-wave and S-wave arrivals were caused by lower seismic velocities within the Earth's core (Fig. 2; Oldham, 1906).

Fig. 1.

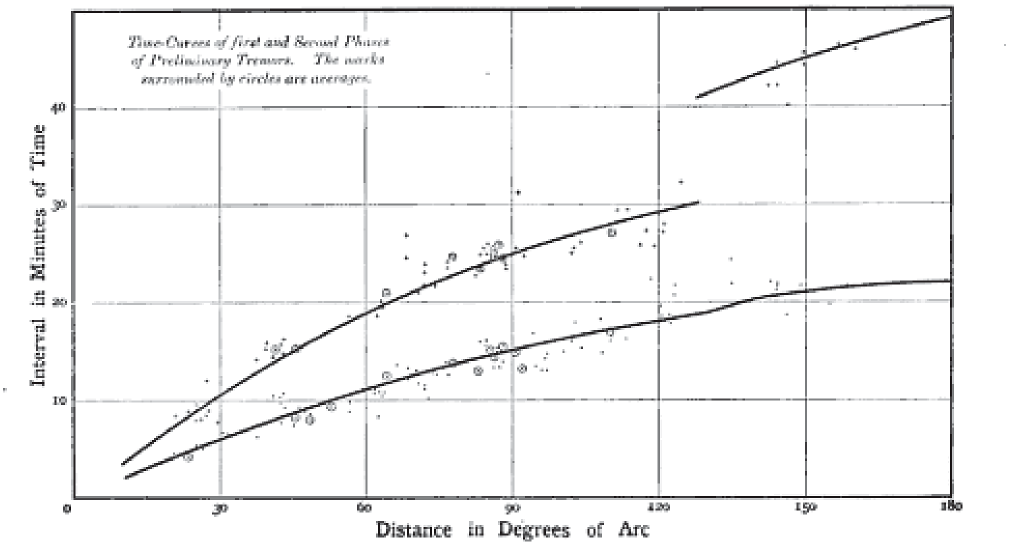


Figure 2. P- and S-wave traveltime curves published by Oldham (1906) showing a pronounced delay in the S-wave traveltime curve beyond 125 degrees of arc. Oldham correctly interpreted this delay as being due to the presence of an iron core within the Earth.

Oldham's prediction was later confirmed by Gutenberg (1889-1960), who produced core-phase traveltime curves and reported a P-wave reflection from the core-mantle boundary (Gutenberg, 1913, 1914). Harold Jeffreys (1891-1989) produced the first seismological evidence that the Earth's core was in a fluid state by demonstrating that S-waves did not traverse it (Jeffreys, 1926). The solid inner core was identified by Inge Lehmann (1888-1993) based on very clear seismic records from a Galitzen seismograph in eastern Russia (Lehmann, 1936).

Keith Edward Bullen (1906-1976) worked with Jeffreys to produce accurate global traveltime tables that were published in 1935 (with revisions in 1940). These tables, combined with the proliferation of seismographic stations in the post-World War II era, led to a fertile period for seismological research after 1945. One important application of seismology was to verify compliance with the Limited Test Ban Treaty (c.f., A. Ziolkowski, this meeting). It was also possible for seismology to confirm several of the main tenets of the plate tectonics theory that was introduced in the early 1960's. For example, Dan McKenzie (b. 1942) investigated earthquake locations and focal mechanisms to demonstrate the validity of plate tectonics in the complex Mediterranean region (McKenzie, 1972). An entirely new look at the structure of the Earth's mantle was introduced by John Woodhouse (b. 1955) and Adam Dziewonski (b. 1936) who presented a method for 3D inversion of global surface wave data (Fig. 3;

Woodhouse and Dzeiwonski, 1984). An excellent summary of additional recent seismological advances can be found in the Treatise on Geophysics (Elsevier, 2007).

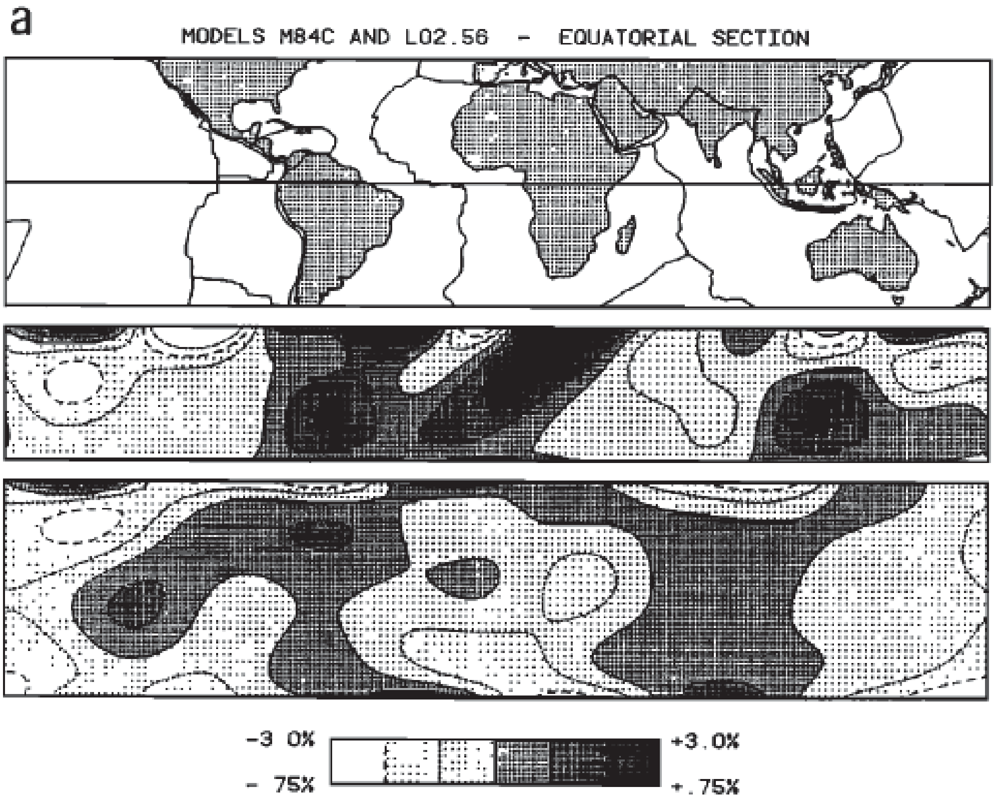


Figure 3. First 3D surface wave inversion for the seismic S-wave velocity structure of the Earth (Woodhouse and Dziewonski, 1984). Top: location of cross section; Middle: S-wave velocity variations, +/- 3% for depth 25-670 km; Bottom: S-wave velocity variations, =/- 0.75% from depth 670 to 2891 km. Positive S-wave velocities are found beneath continents and negative anomalies beneath mid-ocean spreading centers.

It is interesting to speculate as to why the contributions of U.K. seismology are larger than the U.K.'s proportion of the global population. Although my comments are primarily limited to seismology, this question may be considered as a more general one concerning the relatively conspicuous scientific contributions from the U.K. during the nineteenth and twentieth centuries, the contributions of Charles Darwin (1809-1882) being an obvious example. This disproportionate impact has undoubtedly been investigated by professional historians of science; regardless I offer my own analysis, which consists of three principle factors.

1. Learned societies, such as the Royal Society (est. 1660), provided a forum for scientific discussion and debate, as well as an outlet for the publication of scientific results. As Robert Hooke (1635-1703) wrote: “The Designe of the Royall Society being the Improvement of Naturall knowledge (by) all ways and meanes…”. The Royal Society has succeeded in fulfilling Hooke’s aspirations, initially with many contributions from gentlemen scientists who self-financed their investigations (e.g., Henry Cavendish).
2. Rational Analysis of Natural Phenomenon. The Lisbon Earthquake of 1755 is commonly credited with launching the intellectual enlightenment that rejected divine causes for natural disasters (c.f., Kant, 1724-1804). The widespread adoption of rational inquiry by scientists in the U.K. in the 1800’s was a necessary condition for progress in seismology. The Industrial Revolution instilled great proficiency in the U.K. in the design and manufacture of mechanical devices, with many inventions far exceeding the technical requirements of a seismograph. The emphasis on measurement and observation, as compared with conjecture and speculation, has long been a characteristic of science in the U.K. This attitude led Milne and others to establish a global seismic network. The benefits are clear: the theoretical contributions of seismic wave propagation of Lord Rayleigh (1842-1919) and A.E.H. Love (1863-1940) were quickly confirmed by observational seismology.
3. The tradition for travel to the far corners of the world by the citizens of the U.K. made possible scientific insights that would not have been obtained closer to home. Likewise, the existence of the Commonwealth provided opportunities for long-term employment in seismically active regions. The experiences of Thomas Oldham and R.D. Oldham in India, and John Milne in Japan are cases in point.

In conclusion, the contributions to seismology by scientists from the U.K. range from a major role in the founding of observational and theoretical seismology in the nineteenth century to significant scientific advances in more recent times. These contributions are a product of a scientific culture in the U.K. that facilitates scientific discovery.