Institution: University of Oxford

Unit of Assessment: UoA7 (Earth Systems and Environmental Sciences)

Title of case study: UoA7-4: Seismological techniques for improved location of seismic events aids in identifying potential underground nuclear explosions

1. Summary of the impact

The Comprehensive nuclear Test Ban Treaty (CTBT) is the leading tool for minimizing the high-magnitude threats posed by nuclear weapons to the environment and to world peace. A major impediment to monitoring compliance with the CTBT is the difficulty of distinguishing natural earthquakes from man-made explosions: the seismic discrimination problem. Seismological research at Oxford University into fundamentals of theoretical and computational seismology led to the development of new methods and algorithms that are now integrated into discrimination for CTBT monitoring. The resulting impact has been a major upgrade in the UK's capability in seismic discrimination, and a significant contribution to global capabilities in this area.

2. Underpinning research

A major thrust of Oxford seismological research is to image the Earth's interior in three dimensions; a research field known as global seismic tomography. Spatial variations in the wave speeds in the earth act as a distorting lens when one seeks to image seismic earthquakes and explosions. Armed with better knowledge of wave speed variations in the Earth's interior, it is possible to obtain a better image of seismic events.

Key developments in understanding the nature of the earth's interior have come from large-scale measurement campaigns which provide seismological data required to construct and improve earth models (e.g. Trampert and Woodhouse, 1996 [1]). Theoretical and computational methods, pursued by Woodhouse and collaborators, built three-dimensional models of earth structure (e.g. Ritsema et al. 2011 [2]) from unprecedentedly large and diverse observational datasets (e.g. Trampert and Woodhouse, 2001 [3])

In a related line of research, new methods and algorithms were developed at the University of Oxford to assess the influence of earth structure on received seismic waveforms, with reference to the nature of the source and its location. For example, this work assessed the influence of the source on received seismic waves given variable earth models (Ferreira and Woodhouse 2006 [5]), including those produced by Woodhouse and colleagues. It also assessed the role of upper-mantle attenuation on received wave amplitudes, with particular reference to the nature of the seismic source (e.g. Selby and Woodhouse 2002 [4]). This latter work was developed further by scientists at AWE Blacknest to assess the geographical variation of Ms magnitudes (e.g. Selby et al, 2003. Empirical path and station corrections for surface-wave magnitude, Ms, using a global network. Geophys. J. Int., 155, 379-390). Coupled to the improved earth models developed by Woodhouse and collaborators, this work identified novel approaches that could be used to more accurately locate the source of the events generating seismic waves.

Source characterization, location, and depth determination are of high utility in the seismic discrimination problem. Determining with confidence that the depth of an event is greater than 10 km may be used to rule out an anthropogenic source. Similarly, the geographical location, and good understanding of location uncertainties, can help to define the region to be investigated during an on-site inspection to support the CTBT. Understanding the effect of three-dimensional earth structure on the propagation of seismic waves can improve the capability to estimate source mechanisms and discriminate between natural and man-made seismic sources.

3. References to the research

The three asterisked outputs best indicate the quality of the underpinning research.

1. * Trampert, J., Woodhouse, J.H., 1996. High resolution global phase velocity distributions.

Geophysical Research Letters 23, 21-24.
Presents a new large set of dispersion measurements and uses them to constrain earth structure.

2. Ritsema J, Deuss A, van Heijst, H. J. and J. H. Woodhouse, S40RTS: a degree-40 shear velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime, and normal-mode splitting function measurements, Geophys. J. Int., 184, 1223-1236, doi: 10.1111/j.1365-246X.2010.04884.x , 2011.
3. Trampert, J. and J. H. Woodhouse, Assessment of global phase velocity models, Geophys. J. Int., 144, 165-174, 2001.
4. Selby, N.D., Woodhouse, J.H., 2002. The Q structure of the upper mantle: Constraints from Rayleigh wave amplitudes. Journal of Geophysical Research B: Solid Earth 107, ESE 5-1 - ESE 5-12.
5. * Ferreira, A.M.G., Woodhouse, J.H., 2006. Long-period seismic source inversions using global tomographic models. Geophysical Journal International 166, 1178-1192.
Assesses the influence of source on received seismic waves given variable earth models.
6. *Fox, B.D., Selby, N.D., and Woodhouse, J.H, 2012. Shallow seismic source parameter determination using intermediate-period surface wave amplitude spectra. Geophys. J. Int., 191, 601-615.
Uses surface waves recorded by a global network to estimate the depth and source mechanisms of an event, confirming that the event was an earthquake.

4. Details of the impact

The research described in Section 2 has its impact through the operation of AWE Blacknest, which has for over 50 years been a leading centre in the world for research into techniques of detecting underground nuclear explosions and is now responsible, under a contract from the Ministry of Defence, for meeting the UK's requirement to determine whether seismic events are violations of the Comprehensive nuclear Test Ban Treaty (CTBT).

An essential element of the CTBT regime is that any violation should be detectable. The examination of seismic waves is one of the principal methods by which this detection can be achieved. A major component of detection is the ability to distinguish reliably between seismic waves generated by naturally occurring earthquakes and those from man-made explosions – the seismic discrimination problem. A closely related operation is "event-screening", the process whereby those seismic events that can be confidently identified as earthquakes are discounted as potential violations of the Treaty.

The forensic seismology involved in seismic discrimination is a continually evolving field. As more, and higher-quality data become available, scientists seek to lower the threshold at which detection of tests can be achieved. A fundamental part of this evolution is to discover new discrimination techniques, key among which are the determination of depth and geographical location of the events.

The potential for applying Woodhouse's fundamental research to improvement of source location, thereby enhancing event screening, was recognized by Oxford University (Woodhouse) and AWE Blacknest scientists in the early 2000s. To quote the Team Leader of Forensic Seismology at AWE Blacknest:

"John conducted fundamental work in the late 1990s and early 2000s to improve observational databases and 3-D models of earth structure. Resulting earth models enable more accurate interpretation of seismic waveforms and, through a number of novel algorithms developed in Woodhouse's research group, have considerable relevance for the accurate characterisation, depth determination and location of seismic events" [7]

AWE Blacknest subsequently sponsored focused research at Oxford University in the period 2003-2010, to modify the algorithms developed by Woodhouse's group for specific use in the CTBT context. This work involved a graduate studentship sponsored by AWE (Heyburn) and a NERC studentship with AWE CASE support (Fox). Both students were supervised by Woodhouse and worked closely with him. Heyburn subsequently joined AWE Blacknest as a Junior Scientist and continues to use the algorithms developed at Oxford University in event screening as part of AWE's work in support of the CTBT. Fox also worked for some years at AWE following completion of his Ph.D. He presented his joint Oxford-AWE work at several international conferences and, together with Woodhouse, recently published the key findings of his portion of the collaborative Oxford-AWE research on identification of source location [6].

This collaborative work between the University of Oxford and AWE built on the fundamental work of Woodhouse to achieve significant advances, including:

1) A technique based on intermediate seismic surface waves to investigate the focal mechanism and depth of shallow earthquakes [6]. This work compares observed and theoretical amplitude spectra using state-of-the-art methods and models for the calculation of theoretical seismograms.
2) An algorithm for constraining depth using body-wave data. The method uses advanced signal processing techniques to detect correlated signals as a tool for identifying depth phases and thereby constraining the depth of a seismic event.
3) Studies of measurement and model uncertainties in seismic travel times. The resulting method is in regular use at Blacknest for assessing event location.

Blacknest routinely makes use of the methods developed from this research and has done so throughout the REF period (2008-13), including the adoption of new techniques developed from the collaborative work in 2008-2009. These methods are used for the analysis of specific events, and to further understanding the background seismicity in areas of interest for CBTB monitoring. A particular example was the use of research derived from the University of Oxford to constrain uncertainties in the locations of the North Korean explosion of 2009. Further research at Blacknest continues to build on such University of Oxford research.

Quoting: *"…techniques developed from John's fundamental research, have been extensively used by AWE Blacknest. They were used, for instance, to assess the location of the 2009 Korean nuclear test and the uncertainty on that location. These techniques help us to fulfil our UK obligation within the CTBT – a key role of AWE Blacknest."* [7]

The primary beneficiaries of this work are those involved in identification of explosions which may contravene the CTBT. In the UK, this has specific relevance to AWE Blacknest who are tasked by the MoD to fulfil national obligations for such event screening. Given AWE Blacknest's international leadership in the field, this work also has wider significance for the CTBT internationally. The full benefits of the CTBT are to world security and the limiting of radionuclide contamination of the environment.

5. Sources to corroborate the impact

7. A letter from a Senior Scientist at AWE-Blacknest confirms the importance of Woodhouse's fundamental work; the AWE sponsorship of research to apply these findings to the CTBT, and the continued use by AWE, during the period 2008-2013, of algorithms based on University of Oxford research for source location as part of their CTBT remit.