

The core–mantle boundary (CMB), at a depth of roughly 2900 km, and the inner-core/outer-core boundary (ICB), at a depth of roughly 5150 km, are sites of extreme contrasts in material properties and dynamics. The juxtaposition of the Earth's slowly convecting (cm per year) and relatively cold silicate or rocky mantle, with the rapidly convecting (km per year) and relatively hot liquid-iron outer-core produces a complex thermochemical boundary layer at the base of the mantle. Similarly, the continuous growth of the boundary between the liquid outer-core and the solid inner-core, due to the inner-core's crystallization, leads to the ICB being the most dynamically active site in the solid Earth, whose properties may be melt or texture related.

Advances in observational and computational seismology in the past few years have led to new insights into the nature of the Earth's deep interior. On the observational side, the increasingly dense coverage of the Earth with global seismic networks illuminates patches of the CMB and ICB for detailed study. Simultaneously, technological development of portable seismic instrument capabilities give them sensitivities rivalling permanent observatories, thereby allowing targeted deployments (e.g. Wyssession *et al.* 1996). Unlike a single seismogram, an array can tell us the directional approach of a seismic wave (i.e. an array allows us to measure slowness) (e.g. Weber *et al.* 1996). Such analysis is analogous to the way the human eye locates light radiating from an object. Another advantage of array analysis is that stacking the data improves the signal-to-noise ratio.

Here we describe the SPICeD array (Seismic Profile of the Inner Core and D''), a temporary network designed to investigate the Earth's deep interior. D'' refers to the region a few hundred kilometres above the CMB. The name D'' is a vestige of a nomenclature (A–F) for identifying seismically distinct layers within the Earth (Gubbins 1997) that has been superseded, except in this case. Temporary stations were aligned along a nearly 2000 km transect, with permanent stations filling gaps in the profile (figure 1). A range of seismic phases can be used to image these boundaries; figure 2 shows a few of them. The SPICeD array was designed to use events from the Tonga–Fiji region, known for its prolific deep seismicity, to image the ICB. Events from the Americas and the northwest Pacific also image previously-unexplored patches of the CMB.

The experiment, funded by the UK's Natural Environment Research Council, is a collaborative effort between the University of Leeds and the University of Bristol. Considerable logistical support also came from the British Geological Survey.

SPICeD: imaging the deep Earth

Michael Kendall and George Helffrich respond to Alan Douglas's paper in the previous issue of *Astronomy & Geophysics* with a prototype three-component broadband seismic network for the UK.

There are two boundaries in the Earth's deep interior that are as significant in terms of contrast in material properties and dynamics as the lithosphere–atmosphere boundary, where we live. The natures of the core–mantle boundary and the inner-core/outer-core boundary have significant implications for the stability of the Earth's magnetic field, style of convection, moment of inertia and length of day. An array of broad-

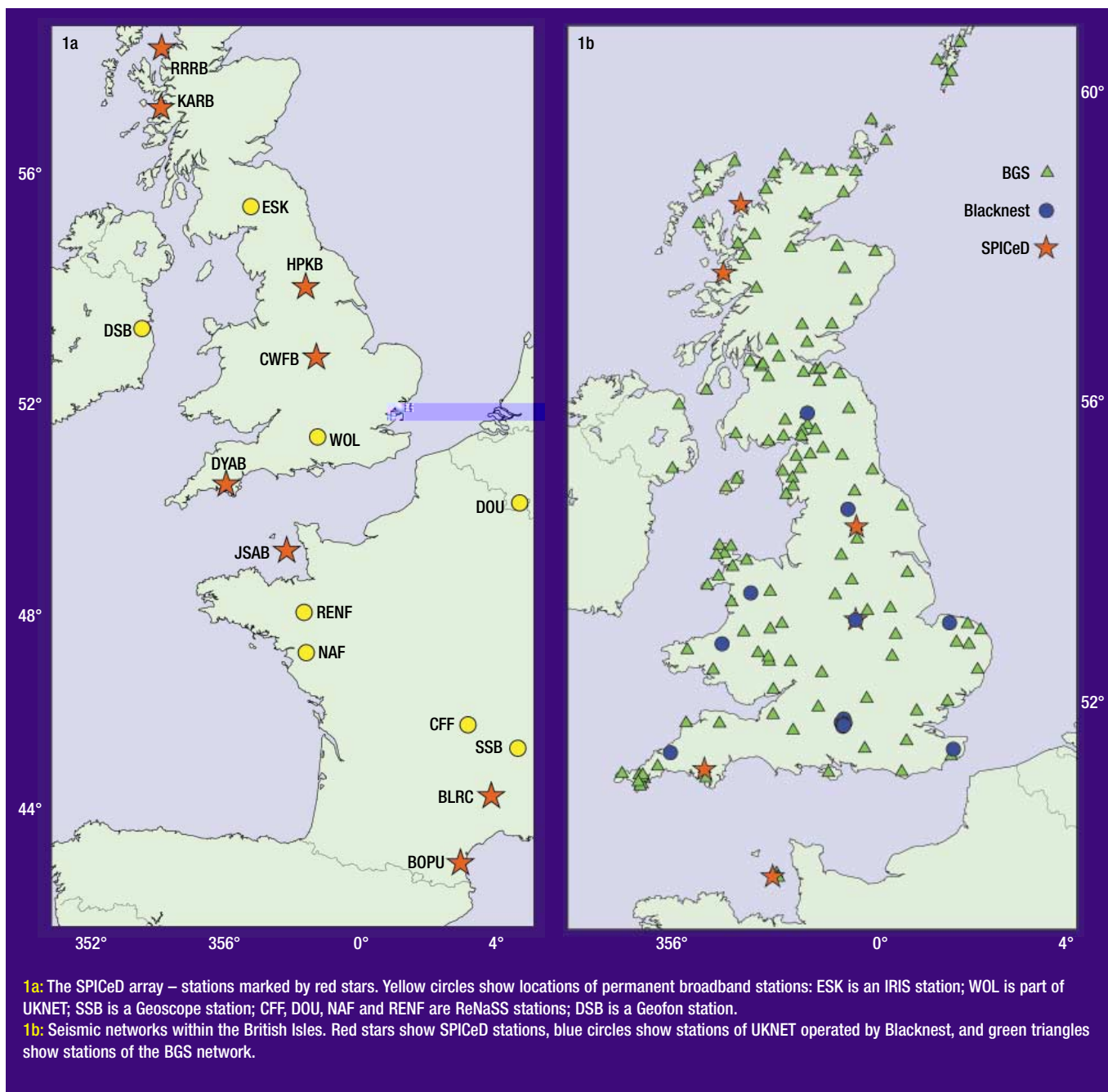
band three-component seismometers (SPICeD) spanning Scotland, England and France has been deployed with the aim of studying these dramatic interfaces within the Earth. A secondary aim of the deployment was to install a working prototype for a permanent three-component broadband seismic network in the UK, as advocated by Alan Douglas in the previous issue of this journal (Douglas 2001).

Imaging the core–mantle boundary

Although K E Bullen coined the term D'' for this layer in the early 1940s, it has only been in recent years that we have begun to realize this is a complex and dynamic region, which is in many ways to the lower mantle what the lithosphere is to the upper mantle. An understanding of the seismic nature of this region is our best aid to understanding the composition and dynamics of the lowermost mantle. The advent of broadband seismology and dense seismic arrays or networks has led to important advances in our knowledge of the lower mantle. We know from tomography that the D'' region is the site of the largest lateral variations in velocity structure below the 660 km discontinuity (Masters *et al.* 1996). We also know that velocity heterogeneity in the region exists on length scales from tens of kilometres

(scatterers) (Hedlin *et al.* 1997) to continental size structures. In many regions the top of the D'' region is bounded by a seismic discontinuity which is on average 260 km above the CMB, but shows variations in thickness of ± 150 km (Wyssession *et al.* 1998). More recently, Garnero *et al.* (e.g. 1998) have shown evidence for an ultra-low velocity zone at the base of the D'' region. Finally, there is mounting evidence for seismic anisotropy in the lowermost mantle (Kendall and Silver 1996), the character of which varies globally and appears to be connected to the dynamic nature of the mantle. For example, the style of anisotropy in regions of downwelling or paleo-slabs is quite different from that in regions of upwelling and possible plume formation.

The interest in the properties of D'' stems from the possibility that they could be mani-



festations of either chemical interaction between the metallic core and the silicate mantle or compositional heterogeneity in the mantle (Lay *et al.* 1990). The former suggests that the core and mantle are not in chemical equilibrium, whereas the latter means that it reflects the convective style of the mantle. Compositional heterogeneity in D'' affects Earth dynamics through changes in the morphology of the geomagnetic field (Bloxham and Jackson 1991), the length of day and, indirectly, the heat flux from the core into the mantle.

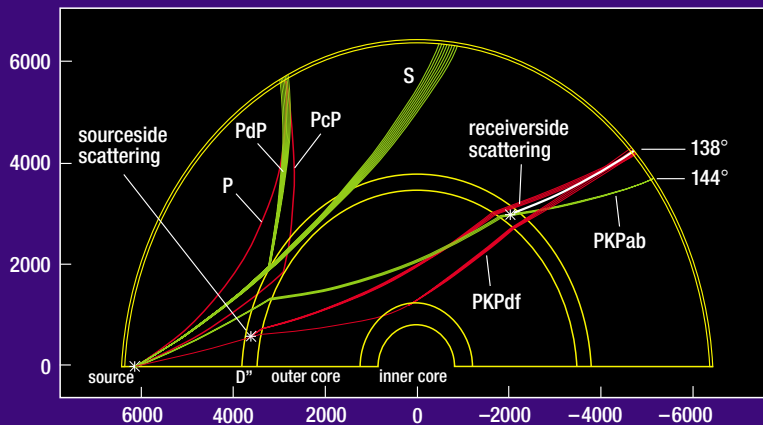
Preliminary analysis has been devoted to a region of the CMB beneath northern Europe and Asia, where we see considerable variability in the topography of the seismic discontinuity or reflector which lies atop the D'' layer. Figure 3 shows records for a large (M_b 7.2),

deep (565 km) earthquake beneath the Russia–China border (130.35°W and 43.61°N). A clear signal intermediate to the S-phase which turns in the lowermost mantle, and the ScS phase, which reflects from the CMB, is interpreted as a reflection from the D'' discontinuity. From this profile it is apparent that there is some variability in this reflector's distance from the CMB. In collaborative work with Tine Thomas at Leeds, a migration scheme similar to that more commonly used in exploration seismology is being used to study lateral variations in the D'' reflector.

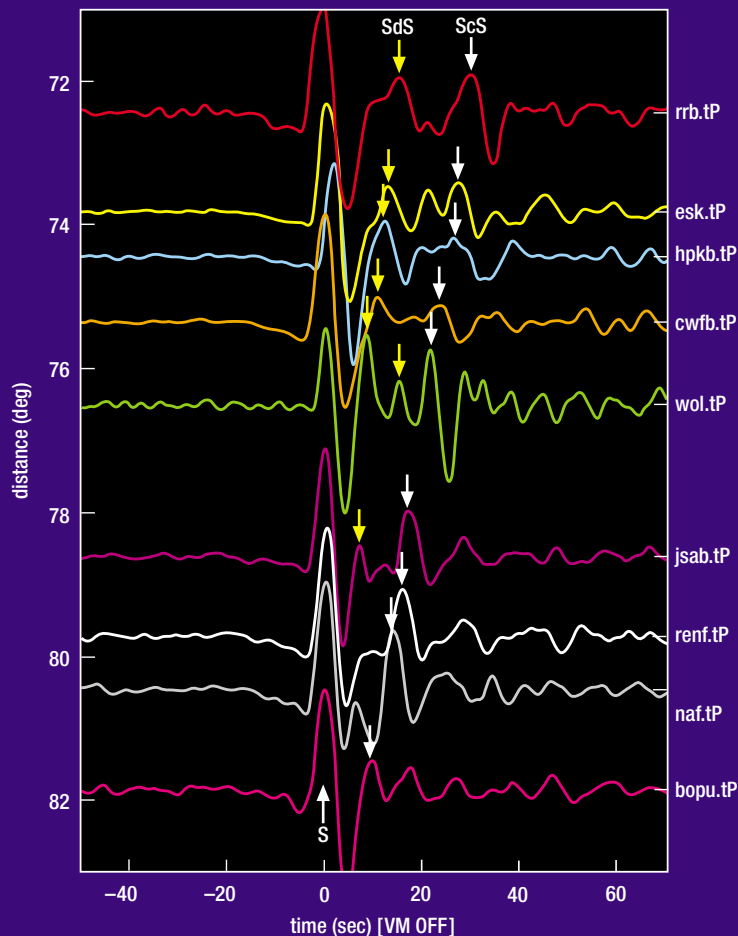
The inner-core/outer-core boundary

Aside from the ocean's shores and the atmosphere's base where we stand, the inner-core/outer-core boundary is the most dynamically active interface in the Earth. Here the

liquid outer core is freezing to a solid as the Earth slowly cools. As the outer core solidifies, it expels elements that are not compatible with the solid-state structure of the inner core. (This flux releases gravitational potential energy that is one source for powering the geodynamo responsible for the Earth's magnetic field.) Consequently, the inner-core's surface grows slowly, but is in contact with the outer core, which convectively flows at speeds of kilometres per year. The interplay between crystallization, element expulsion, and outer core flow expresses itself in unusual inner-core properties. First, seismic waves travel faster through it north-to-south than they do east-to-west (Creager 2000). The pattern of wave speed differences is approximately cylindrically symmetric around the Earth's spin axis, and may indicate texturing of the growing surface



2: A sketch of the seismic phases that can be used to analyse the Earth's core–mantle boundary and inner-core boundary regions. A discontinuity at the top of the D' layer will reflect P- and S-waves. Typically this is best observed at epicentral distances between 70° and 85° and is characterized by an arrival, PdP (SdS), which lies between the lower-mantle turning P-wave (or S-wave) and the core reflection PcP (ScS). S-waves between 90° and 105° transit the D' region considerable distances. Should this region be anisotropic, significant amounts of shear-wave splitting will be generated. The inner core is sampled by the phase PKPdf. Finally, precursors to the core phase PKP provide evidence of lower-mantle scattering. The scattering may occur in the mantle at the source side or the receiver side.



3: An example of seismic data recorded by the SPICeD array. The event (M_b 7.2) is located 565 km beneath the Russia–China border and occurred in April of 1999. This images the lowermost mantle beneath northern Russia. The transverse component seismograms are aligned on the S-phase which turns above the CMB. The ScS phase is a reflection from the CMB and the SdS is a reflection from the region a few hundred kilometres about the CMB. Standard reference Earth models do not predict the occurrence of the SdS reflection.

by core flow, or preferential growth of the inner core in the polar regions with subsequent solid-state flow equatorward. Secondly, the inner core is not homogeneous even in its average seismic structure. Seismic wave speeds in its quasi-eastern hemisphere (from about 40–180°E longitude) are slower than the remainder. Lastly, in addition to this large-scale heterogeneity, the inner core has smaller-scale heterogeneity on 10 km length scales (Vidale and Earle 2000).

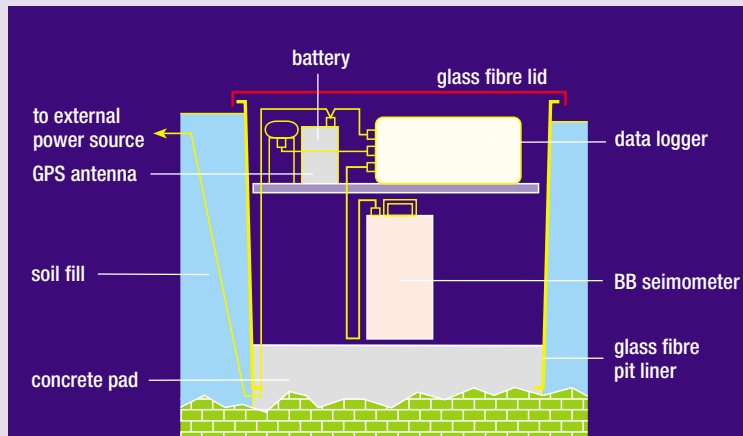
All these features are unexpected seismological findings of the past 20 years. What they represent is information about the behaviour of this remotest of boundaries in the Earth. With the SPICeD array we are gathering more inner-core observations, to decide whether the small-scale heterogeneity in the inner core is due to the presence of liquid inclusions in the solid core or whether it is due to differences in the solid itself. The two models have different signatures in the frequency content decay with distance of seismic waves that travel through the inner core. Only broadband instruments have the fidelity to detect this signal.

A prototype network

A secondary aim of the SPICeD deployment was to develop a prototype for a three-component broadband (BB) network in the UK. As reported in a previous issue of *A&G* (Douglas 2001), the existing single-component BB array, UKNET (figure 1) run by the Blacknest group and funded by the UK Ministry of Defence, will be disbanded soon.

The other seismic network in the UK is operated by the British Geological Survey (figure 1). The aim of this network is to primarily monitor local seismicity within the UK and offshore waters, determine locations and magnitudes for local earthquakes and make assessments of seismic hazard in the UK. Over 140 short-period stations are grouped into regional subnetworks. Continuous data from each outstation are telemetered to a central recording station in each subnetwork where it is stored in a ring-buffer for around 14 days. A detection algorithm operates on all incoming data and event data are also recorded. Triggered events are automatically transferred to Edinburgh for analysis and archiving. Within each subnetwork there is at least one three-component sensor, usually at the base station. The surrounding outstations generally have a single vertical-component sensor. Only the first four or so minutes of data are recorded, yielding only short-period P-wave first-arrivals for teleseismic data.

While the station coverage of the BGS network rivals that of networks in California, there is limited wider scientific application of this data due to the limited duration of the archived data and the fact that the sensors are



4: Station pit design. Instruments are housed in a fibreglass box mounted on a poured cement pad. The seismometer sits on the concrete. The data logger, battery and GPS antenna are housed on a shelf above the seismometer. Dave Francis is shown installing the station at Arisaig, Scotland.

First dig your hole...

The deployment of the Leeds-owned equipment started in July 1998 and the last instrument was removed in September 2000. The broadband (10 Hz to 120 sec) seismometers include six Guralp CMG-3T and two Guralp CMG-40T three-component sensors. Data were recorded by four 24-bit Orion3 data loggers made by Nanometrics and four 16-bit Mars88 data loggers made by Lennartz Electronic.

The instruments at DYAB, JSAB, HPKB, CWFB were housed in existing vaults or

buildings. One of the more interesting sites was located within a network of underground tunnels built in occupied Jersey during World War II. The instruments at RRRB, DYAB, KARB, BLRC and BOPU were placed in lined pits constructed from purpose-made fibreglass boxes. The station-pit design is shown in figure 4. The seismometer sat on a poured concrete base and the data logger and battery (which was continuously trickle charged) were above on a false shelf. The stations in Scotland, England and Jersey were colocated with BGS sites with mains power provided to each. The

two stations in southern France had power provided from solar panels. These stations were maintained by Guilhem Barruol at the University of Montpellier.

Nearly 700 events of body-wave magnitude greater than 5.4 were recorded and the array operated with a nearly 80% data recovery rate. Instrument problems included a station in Scotland being hit by lightning, which required repairs to both the seismometer and data logger. A Y2K problem with the GPS clocks attached to the Lennartz Mars data loggers produced errors in the timebase at these stations after 1 January 2000.

short-period and primarily single-component. More continuous data from this network predates digital recording and was archived on tape in analogue format. Some of these data have been digitized and used in other studies (Helffrich 1995; Collier & Helffrich 1997; Kaneshima & Helffrich 1999), but it is a cumbersome process to retrieve them.

The way forward

Both the BGS network and UKNET are in need of modernization in terms of instrumentation, data transmission and data archival. Data from UKNET is transmitted to Blacknest via phone lines which is costly. Data from the BGS network is telemetered, but there isn't sufficient bandwidth with this system to telemeter BB data. When UKNET closes, the UK will be one of the few European countries without a permanent BB seismic network.

Academic research interest motivated the SPICeD deployment, but its data is of value to treaty verification efforts as well as national hazard assessment. This underscores the wide applicability of broadband instrumentation to national endeavours. However, the equipment's full benefit is not realised unless all of the seismic wave field is recorded as well as all

the components of ground motion. Many phenomena of interest lie in the later portions of the wave field and in the shear wave arrivals. The short segment following the first-arriving P-wave and the vertical component of ground motion are no longer adequate for state-of-the-art research. Any follow-on use of the infrastructure built by SPICeD should look to the future of seismological research and monitoring capability and aim to serve the broadest interest base among seismological data users.●

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● *Many people contributed to the smooth running of the SPICeD experiment. Dave Francis at Leeds coordinated the deployments and data retrieval. Stations in France were maintained by Guilhem Barruol at the University of Montpellier. Paul Denton at Leicester University changed disks at the Charnwood Forest site. In Jersey, Phil Johnson and Paul Aked at the Jersey Meteorological Department looked after the equipment and did the disk changes. They were especially helpful in getting the equipment going again after a power cut in the tunnel. Dai Stewart and coworkers from the BGS*

helped at each station where BGS hosted the equipment (RRRB, KARB, DYAB and JSAB). Fran and Chris at Rubha Reidh Lighthouse Hostel provided friendly accommodation and electric power for the battery charger. Devon SW Water gave permission to host the site at Watercombe Water Treatment Works, and provided power.

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