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The first lecturer in exploration geophysics in Australia – later to become a world renowned seismologist

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Figure 1. *'Hal' Thirlaway taken, it is thought, just before he arrived in Australia. Reproduced from* The Guardian *newspaper, 20 January 2010.*

The first full-time university lecturer in Australia in exploration geophysics was Dr Henry Ivison Shipley Thirlaway, who was appointed to the position in the University of Sydney's Department of Geology in 1949. Dr Alan Day (1966) reports that the only teaching in geophysics before this was in 1931, when E. H. Booth gave a series of lectures, demonstrations and three days field work in geophysical prospecting 'under the auspices of the Extension Board of Sydney University'[1].

Thirlaway only held the position in Sydney from October 1949 to April 1951, and on return to the UK in 1960 he went on to become a leading expert in detecting illegal underground nuclear testing. Figure 1 is a photo of him, probably taken just before he came to Sydney.

An obituary of Thirlaway in the *Guardian* newspaper (Davies, 2010), states that 'Hal', as he was known to his colleagues, graduated in geology from Durham University in 1938 and completed his PhD in 1950 in the Department of Geodesy & Geophysics of Cambridge University under the supervision of Edward ('Teddy') Bullard[2].

According to Dr David Branagan (pers.comm.) who was an honours student in the Department in 1950, Thirlaway was appointed when Professor C. Marshall was Head of Department from 1949 to 1973, as part of Marshall's efforts to re-invigorate the Department as he had found on his arrival that 'much of the teaching was out-of-date' with a need for 'new staff experienced in 'practical' geology' and more funding[3]. Marshall set about acquiring new staff and, recognising the need to include geophysics, made Thirlaway the first ever academic geophysicist. In Branagan's view, Marshall would have liked to have had a Professor of geophysics at this time but it could not have been Thirlaway as he lacked the appropriate qualifications; he was only 32 at the time[4]. At least, as Branagan points out, Marshall was able to have the department named the Department of Geology and Geophysics. In 1951, a Chair in Geophysics was established at the Australian National University but only for graduate studies.

According to Dr Alan Day (pers. comm.) who was one of four honours students in the Department in 1951, Thirlaway gave a one-term segment on geophysics in the honours year using as textbook 'Geophysical Prospecting for Oil' by Nettleton (Nettleton, 1940), which Day states was heavily favoured at the time for its emphasis on seismology. Thirlaway's teaching method, according to Day, was to require his students to read one or two chapters of Nettleton each week, which led Day to conclude that he hadn't 'had much contact' with pupils at that stage. While Thirlaway only stayed in the position for one full year and two part years, Day (1966) claims that Thirlaway 'successfully pioneered both teaching and research' in Australian universities. Doyle (1987) makes a further point in relation to the consequence of Thirlaway's appointment; that the spread of geophysics courses to other universities was gradual and 'mostly single appointments were made at first, (thus) restricting research possibilities'.

After Thirlaway's departure in 1951, lecturing in geophysics in the Department was continued by Hari Narain, who came from India in 1950 on a UNESCO Fellowship. At first, he was a Teaching Fellow (1952), then a Temporary Lecturer (1953–55), and finally Lecturer (1955–56). In 1955 Narain was awarded the first PhD in Geophysics in the Department (and possibly, therefore, in Australia)[5].

The *Guardian* obituary of Thirlaway (Davies, 2010) reports that he moved from Sydney 'to Pakistan to help UNESCO establish

[1]Edgar Booth was on the staff of the Physics Department from 1915–1937 where one of his interests was geophysics. The Extension Board provided courses to non-students of the University.

[2]Bullard, who was an 'early researcher on the dynamo theories of Earth's magnetic field' (Turner, 2010) became head of the Department in Cambridge in 1956 and Professor in 1964.

[3]Branagan (pers.comm.) noted that the Department had become overwhelmed from 1947 by the huge increase in student numbers due to ex-service men and women enrolling.

[4]Branagan (pers. comm.) suggested that this desire at this time would have most likely met with opposition from the Department of Applied Mathematics of the University, which conducted research in global geophysics under Professor Keith Bullen.

[5]Narain returned to India in 1956, where he later became Surveyor-General of India

a geophysical observatory in Quetta. He remained Head of the Observatory there until he moved to Blacknest'. Blacknest, in Berkshire, was where, from 1961 to 1982, he was head of a research group that was an offshoot of the British Atomic Weapons Research Establishment (AWRE) at nearby Aldermaston, 75 km west of London. The group's main function was to develop and maintain expertise in using seismic techniques to detect and identify underground explosions.

According to Davies (2010), this group was deliberately an unclassified research arm, separate from AWRE, which 'meant that [the purely scientific] work at Blacknest could be discussed openly with seismologists from around the world, including the Soviet Union'[6]. No doubt it was hoped this would engender similar openness from the Soviets, as it did on occasions.

Thirlaway was a rare seismologist in the group at a time when seismology was riding a wave of new-found use in enabling the detection of underground nuclear tests[7]. He had just published an article in *New Scientist* in May 1963 (Thirlaway, 1963) entitled, 'Earthquake or Explosion?', in which he was able to show different seismic characteristics between earthquakes and those of underground tests. In particular, he showed that the original idea of distinguishing explosions from earthquakes based on differences in direction of first motion was unreliable. His group developed a better way to improve signal quality using crossed seismic lines of both vertical and horizontal geophones, summing the signals to produce a combined trace of each line and then correlating both lines. The resulting 'correlograms' showed clearer differences between the two types of signal (see Figures 1 and 2 of Thirlaway, 1963). A copy of Thirlaway's *New Scientist* article is appended to this paper.

In 1972 Thirlaway was awarded the Gold Medal of the Royal Astronomical Society (RAS) for, firstly, his team's development of large seismic arrays able to act as tunable filters and, secondly, for initiating the recording of data directly onto magnetic tape[8].

The following highlights of Thirlaway's career at Blacknest were obtained from 'Geophysics in the Affairs of Mankind' by Lawyer et al. (2001), in which there are seven references to him over a 24-year period.

Thirlaway showed, by late 1963, that seismic signals in a zone 3000 to 9000 km from the source were less complex and distorted and, therefore, it was a better region in which to carry out analysis.

In April 1964, he represented Great Britain, in Paris, at a UNESCO organised; 'First Intergovernmental Meeting of Experts in Seismology and Earthquake Engineering', at which representatives of 33 countries participated including a Soviet delegation. Before this, in early September 1961, the Soviets had broken the test ban and this supposedly non-political conference may have been a means to discuss the matter scientifically. Later Thirlaway held a seat on a UN Disarmament Committee as a scientific expert representing Great Britain.

In 1984, Thirlaway was a keynote speaker at a USA Project review meeting in Santa Fe, New Mexico where he was described as 'one of the Western World's leading forensic seismologists'[9].

Finally, quoting from the Obituary again (Davies, 2010), 'Thirlaway's success can be attributed mostly to his ability to work effectively with ….his staff, university academics, and seismologists from abroad, as well as diplomats and politicians' (Davies, 2010).

Thirlaway died in 2009 at the age of 92, survived by his wife, Billie, and their two daughters.

Acknowledgements

I thank Dr David Branagan and Dr Alan Day for their generous time in sharing with me their irreplaceable memories.

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[6]David Davies, the author of the obituary in the *Guardian*, was a contemporary of Thirlaway.

[7]A partial test ban treaty in 1963 banned atmospheric testing but not underground testing. An agreement was not reached on the latter for a further 33 years.

[8]The gold medal of the RAS was awarded for achievement in astronomy or geophysics. Professor Bullard was also awarded one in 1965.

[9]Thirlaway had himself coined the term 'forensic seismology' in 1961 for its application in legal matters and especially in detecting test-ban treaty violations.

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Earthquake or explosion?

With his task of distinguishing between small earthquakes and nuclear test explosions, the new seismologist has to be far subtler than his predecessors. The rate of arrival of energy in the first minute after the initial shock, together with indications of the depth of the "event", provides clues for identifying its character

by Dr H. I. S. Thirlaway

UK Atomic Energy Authority, Blacknest

EARTHQUAKES and explosions are frequently in the news these days, and seismology is flourishing as never before. This situation has arisen from what at first seemed to be an easy problem: that of distinguishing man-made explosions from earthquakes for the detection of nuclear weapons tests. On closer examination, the problem proved to be difficult, because of the need to achieve 100 per cent success in identifying the few hundred earthquakes which may occur each year in the areas of interest. Research has been directed to (1) the refinement of instrumentation, (2) a search for new principles, and (3) the application of new processing techniques to well-known principles. The first and last of these approaches have been particularly rewarding, and this article outlines some of the progress by the United Kingdom Atomic Energy Authority in this field.

Earthquakes have been studied for many years by British seismologists. For example, John Milne in Tokyo invented a seismograph which formed the basis of the first network of seismographs organised by the British Association in 1896, and R. G. Oldham, in India, was the first to demonstrate that certain impulses on a seismogram were in fact the records of elastic waves travelling through the Earth. They were of two kinds: the compressional, or P, waves analogues to sound waves, in which the ground movement was of the push-pull variety; and the slower-travelling shear, or S, waves, analogous to the motion of a vibrating string in which ground movement was perpendicular to the direction of travel of the waves.

Up till now, however, the best experimental work by British seismologists has always been done while they have been located in seismic areas. In Britain itself there has never been any serious interest in experimental earthquake seismology because the dramatic effects of earthquakes do not occur here. Even the largest earthquakes in the British area, for instance the Dogger Bank earthquake of 1931 or the Midlands earthquake of 1957, have rarely caused injury. In the whole of the recorded history of earthquakes in the United Kingdom, only one person has been killed and only four injured. Compare this with, for example, the Quetta earthquake of May, 1935, which, within the space of a minute, killed 30 000 people, most of whom had to be left buried among the ruins for the whole of that summer and winter because of the impossibility of digging them out. The chaos was such that rebuilding did not start seriously until 1939, after major decisions had been taken about building designs for the new Quetta, and in fact about whether the town should be rebuilt at all. In 1960, when I last visited Quetta, it was still possible to see earthquake ruins, and to meet people whose entire families had perished on that fearful morning.

The impression I have of moderately sized earthquakes is one of almost continuous activity for several hours after the first major shock. Even the first frightening shake seems to be anything but a single impulse and in fact most earthquakes of this size are multiple events which can be easily identified instrumentally even at long range. The difficulty that arises when one tries to identify small earthquakes, of energy equivalent of a few kilotons of explosive, is partly that some of them are very simple shocks and partly that the subsequent activity is at a very low level.

Detection.—The first problem in the new seismology, therefore, is to be able to detect small earthquakes. This was not a requirement in classical seismology, since large earthquakes, recorded by many hundreds of observatories using standard seismographs, provided all the data required for understanding the major internal structures of the Earth. However, at ranges between 5000 and 10 000 km, an earthquake with the energy of a few kilotons of explosive (the smallest disturbance in which we are interested) gives a ground displacement of not more than about 1 millimicron (the diameter of a 'flu virus is about 50 millimicrons) at a frequency of about 1 cycle per second. Small, random Earth disturbances, "Earth noise", of the same frequency has, in the quietest parts of Britain, an amplitude of about 10 millimicrons, so that the signal of a small, distant event recorded on a single seismometer would be overwhelmed by Earth noise. It is possible to reduce the effect of random noise by summing the signals from a number of seismometers. The improvement is proportional only to the square root of the number of instruments used, so that, in Britain, to record a millimicron signal with a signal-to-noise ratio of 3, about 1000 seismometers would be required even in the quietest parts.

Fortunately, most of this noise originates in the oceans and, as one moves inland from the coastal areas, it is rapidly attenuated. Locations in the hearts of continents with Earth noise amplitudes of 1 millimicron at 1 c/s are reasonably common, provided one goes well away from industry and traffic. In such places, 100 seismometers will give a maximum signal-to-noise ratio of 10 from the smallest events in which we have a practical interest.

Identification of earthquakes.—One of the first methods suggested for distinguishing earthquakes from explosions was to note the initial direction of movement detected by the seismograph. The scheme shown in the upper circle on the left-hand side of Figure 1 is based on the observation that the overwhelming majority of earthquakes are generated by shearing blocks of rock: that action will compress the rocks in some directions while expanding them in others. Thus some recording stations will show an initial ground motion away from the origin of the earthquake (+) and others will display one towards the origin (−). Explosions, on the other hand, produce compressions in all directions and positive first motions at all stations (lower circle, Figure 1).

Unfortunately, the first motion is the smallest signal in the seismogram, and nothing that anyone has been able to do instrumentally has improved the situation

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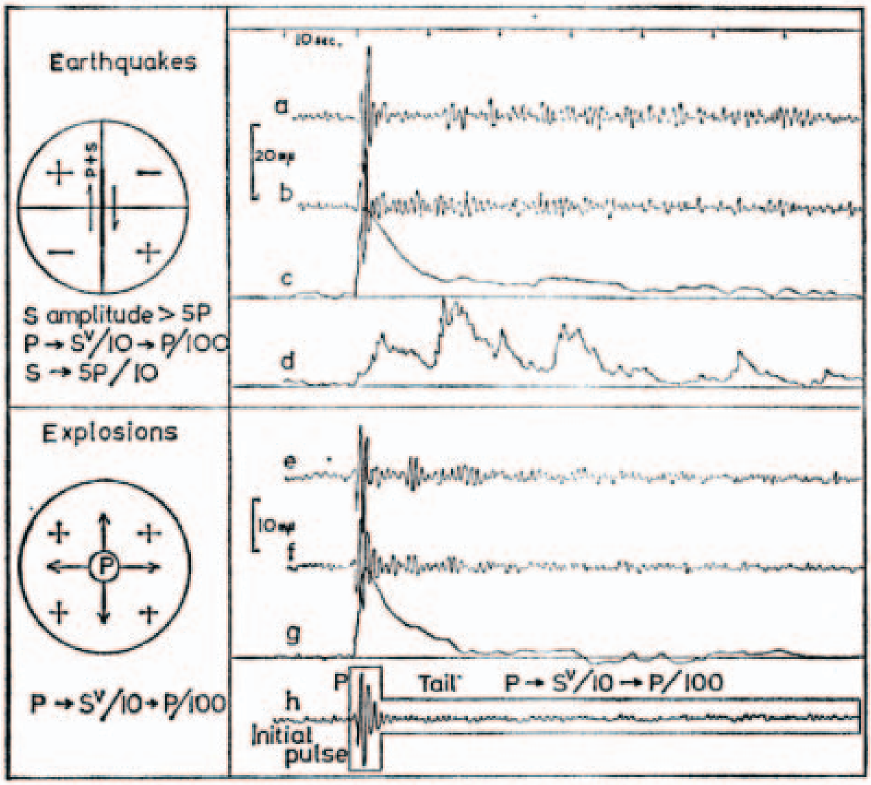
Earthquake or explosion? *continued*



a. *Conventional record of the P waves from a simple earthquake combined from one line of seismometers*

b. *Conventional record from the same earthquake combined from the other line of seismometers*

c. *Smoothed curve obtained by correlating the two lines of seismometers*

d. *Smoothed curve for a typical complex earthquake*

e. *Record of an explosion, combined from one line of seismometers*

f. *Record of the same explosion, combined from the other line*

g. *Smoothed curve obtained by correlating the two lines of seismometers*

h. *Idealised seismogram of explosion deduced from g; the random signals in the tail have been eliminated*

FIGURE 1. *How earthquakes and explosions may be distinguished. An early idea was to exploit the difference indicated in the two circles at the left, that at some stations the very first motion detected from an earthquake is a "pull" (−), while from an explosion all stations will record an initial "push" (+). However, as the traces a, b, e and f show, the initial movement is weak, which makes the method unreliable. A better method uses crossed arrays of seismometers to obtain smoothed, correlated curves c and g. The initial pulse of the earthquake is followed by a relatively strong "tail" (of P waves generated from S waves near the site of the earthquake) while in the record from an explosion, which does not in principle produce S waves, the tail is missing or very weak.*
Note: The untransformed S waves do not appear on these initial records because they travel more slowly.

during the last three years. The size of this first motion relative to the rest of the signal is well illustrated for both an earthquake and an explosion in Figure 1. So, even if one is on a "1-millimicron" site with 100 seismometers, the first motion of a small event will be barely distinguishable from Earth noise. One cannot be really certain about the direction of motion until it is three or four times greater than the background noise; therefore, in practice, only earthquakes of moderate size, equivalent to a few tens of kilotons of explosive or more, can be identified with certainty by this technique.

Another idea is to make use of the ratio of "transformed" seismic waves. If a compressional (P) wave strikes a rock boundary at an angle, part of its energy is transformed into an S wave (with vertical motion) designated Sᵛ. Conversely S waves may be transformed to P. In 1899, C. G. Knott showed that the energy ratio (and therefore the relative amplitudes) of these transformations can be calculated. It turns out that, at the small angles of incidence observed at ranges greater than

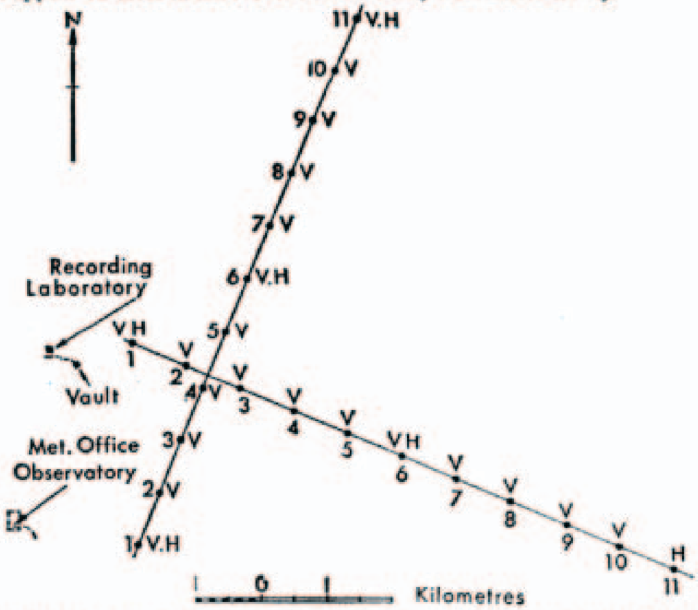


FIGURE 2. *Layout of the cross array of seismometers at Eskdalemuir. Both lines contain instruments, V and H, that record vertical and horizontal displacements of the Earth's crust. The vault is for a long-period seismometer.*

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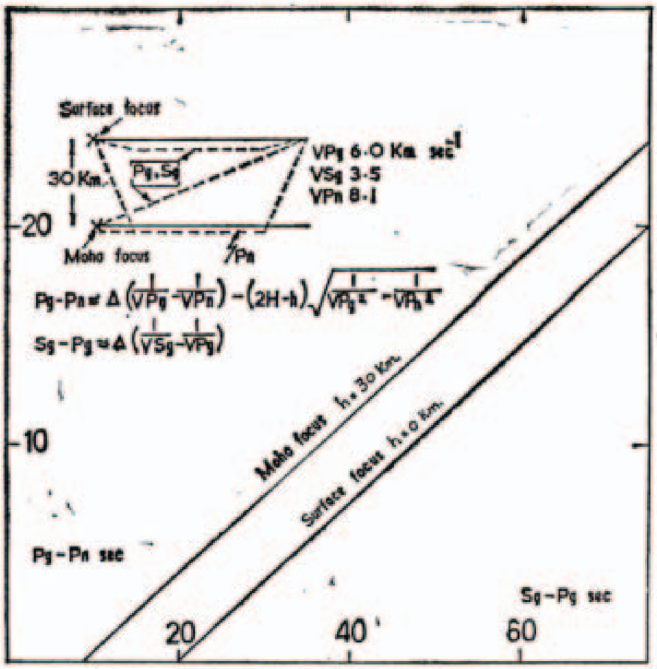

FIGURE 3. *The method of estimating the depth (h) of an "event" within the Earth's crust using the delay in the arrival of the P waves which travel via the "Moho"—the boundary between the crust and the underlying mantle. The equations relate observed time differences to observed velocities (VP_g, etc.) to the depth to the Moho (M), focal depth (h) and range (Δ). P_g and S_g stand for the P and S waves that travel by direct route from the event to the detector.*

5000 km, the amplitude of the transformed waves are only one or two tenths of those of the incident waves. Transformations of the type P→S^v→P from explosions and earthquakes are therefore not likely to be recorded at long range above the ambient noise level. However, earthquakes *generate* S^v waves which are observed, at close range, to be five to ten times the amplitude of the initial P wave. Transformations of the type S→P should therefore be recorded at long range and, if suitable rock boundaries are present to a depth of 250 km below the event, the P signals resulting from the S^v→P transformations should arrive at the recording station for at least a minute after the initial pulse. No S signals will be recorded in this time interval since the velocity of S waves is little more than half that of P waves.

Explosions, on the other hand, do not in principle generate S energy, and records of explosions at short range generally show that the S^v energy (which must be due to transformation of P energy at rock boundaries near the source) is only two or three times that of the energy in the P group. This hypothesis therefore suggests a possible discrimination technique based on the analysis of the first minute or so of the seismogram of a long-range event. It can be summarised as follows:

1. P→S^v→P transformations occur in both earthquakes and explosions but the resulting P waves are very weak at long range.

2. S→P transformations occur with earthquakes and the resulting "tail" of transformed P waves should be a considerable fraction of the initial P.

Unfortunately, when conventional long-range ("teleseismic") seismograms of explosions and earthquakes were examined the signal amplitudes following the initial impulse proved to be similar, as a comparison of Figure 1a with Figure 1e will show. Last year, however, we recorded two fairly large underground explosions on a cross array of seismometers similar to that at Eskdalemuir (Figure 2). The arrangement is similar to that described by Mr I. Maddock in the *Journal* of the British Institute of Radio Engineers (June, 1962, pp. 415-427) in which the linear dimensions are comparable with the longest wavelength of the signals of interest—about 25 km for P signals recorded at 10 000 km range. This type of array, with its associated analysis system, enables us to sum and cross-correlate the recorded signals.

Figures 1a and 1b, for example, are conventional seismograms of a teleseismic earthquake after the two lines of seismometers have been separately phased and summed. Figures 1e and 1f are the equivalent seismograms of one of the explosions of similar magnitude recorded at a similar range. In Figures 1c and 1g are the smoothed curves obtained after point-by-point multiplication of the pairs of traces from the seismometers. These curves show the variation in the rate of arrival of correlated energy.

It is at once apparent that, although the

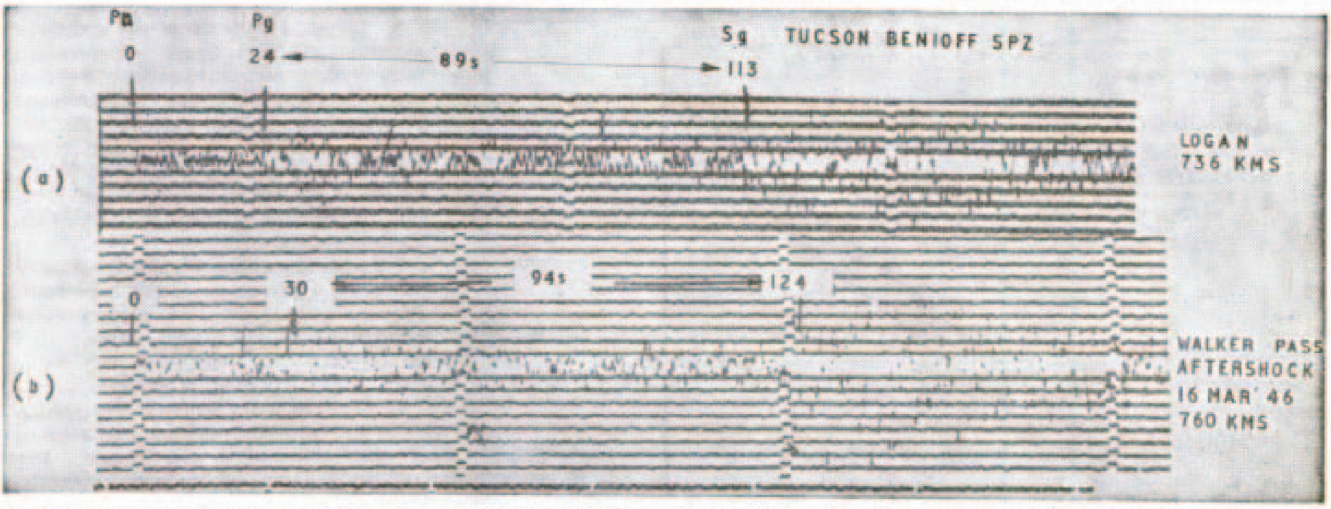

FIGURE 4. *An example of the use of P_n delay time showing that the earthquake* (b) *occurred at a greater depth than the explosion (Logan,* a). *Compare the complexity of these short-range records with the relatively simple long-range records in Figure 1.*

Earthquake or explosion? *continued*

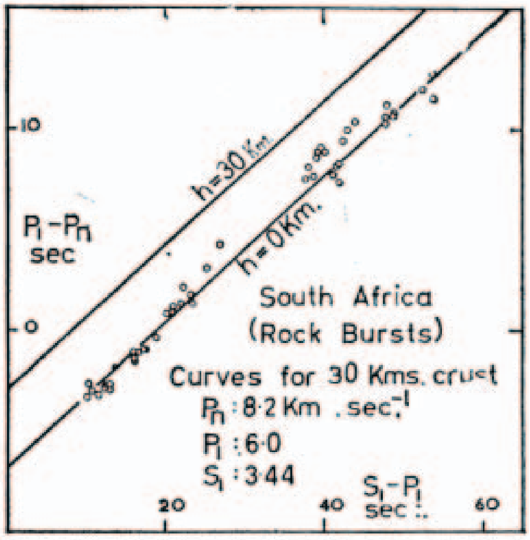

FIGURE 5. *Readings from seismograms of mine rock-bursts. After Hales and Willmore.*

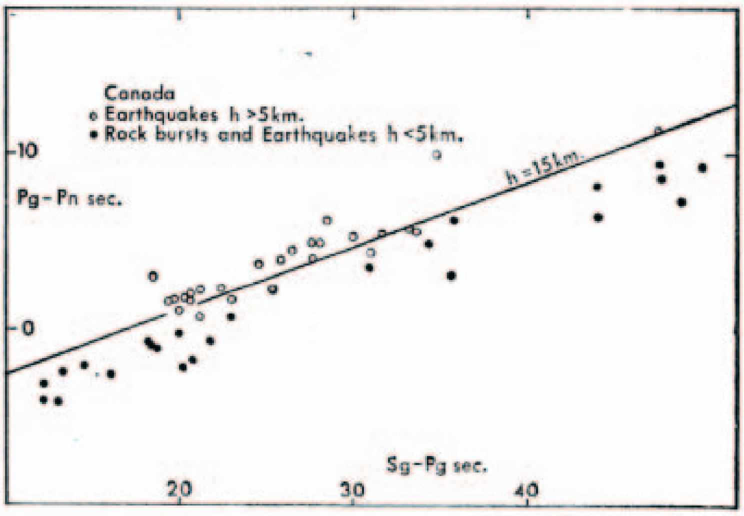

FIGURE 6. *Readings from Canadian records. After Brune and Hodgson.*

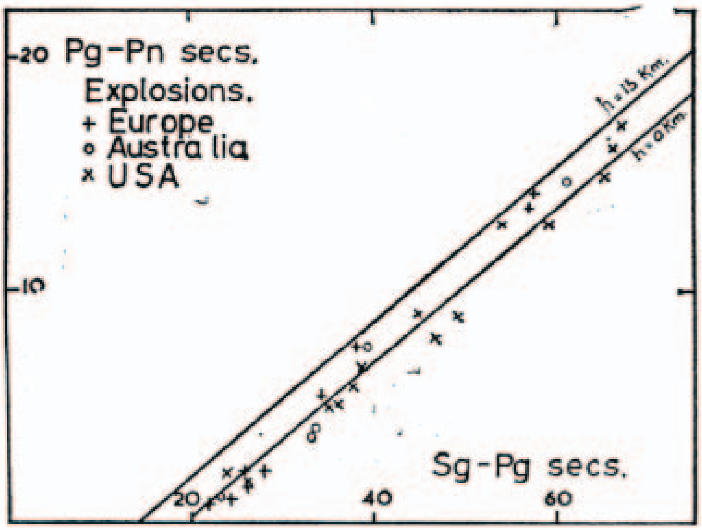

FIGURE 7. *Readings from records of chemical and nuclear explosions.*

initial pulses are indistinguishable, the subsequent rate of arrival of energy is higher in the case of the earthquake—as predicted by the hypothesis. This must mean that the earthquake signals are more strongly correlated across the array. Figure 1h is an *idealised* seismogram of an explosion based on the correlator output 1g. I think that the *observed* signals in the tails of explosion seismograms are generated by random transformation and scattering of the initial pulse as it enters the complex structures in the Earth's crust underlying the recording station. These signals would be poorly correlated across a large array. They may be analogous to shock-generated noise identified by oil prospecting seismologists who have used linear arrays for many years. Records of random signals from both explosions and earthquakes are "cleaned" by the correlation process to leave only signals which originated near the source.

The hypothesis predicts that the rate of arrival of energy in the tail will decrease with time since the number of $S^v \rightarrow P$ transformations will decrease as the signal travels by longer paths through deeper and more homogeneous regions of the Earth's mantle. This effect can be observed in Figures 1c and 1g. By the same token, it predicts that, as the depth of the event increases, so the rate of arrival of energy will decrease because the environment of the source becomes more homogeneous. This effect has also been observed experimentally using linear array processing techniques.

The results to date are clearly interesting enough to follow up in more experimental and theoretical detail. At the moment only two distant explosions have been recorded in the form required for processing by the technique described, and, though these were fired in two different continents, we have enough experience of the enormous variability of seismic signals to be prepared for a third to upset the hypothesis. Furthermore, the events illustrated in Figure 1 are of magnitude greater than the smallest events of interest. It will therefore be appreciated from a study of Figure 1c that the amplitudes of transformed signals from small events will be equal to or less than the ambient noise.

Further research on this idea is evidently necessary, firstly to prove the hypothesis, and secondly to improve the signal-to-noise ratio in the detection system, before the technique can be applied with confidence to the identification problem.

Fortunately, it is possible to concentrate effort on that fraction of the total number of earthquakes which are "simple". The majority are more or less complex events. Figure 1d, for example, is the smoothed, correlated curve for a typical earthquake which occurred in the same general area

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as that represented by 1c. I think event 1d is a series of four "aftershocks" which follow so closely on the first onset that the conventional seismogram (not illustrated) has the appearance of a single event with related but unidentified phases. The after-shock hypothesis fits in with the subjective impression of people experiencing an earthquake and with commonsense thinking on the way a fault must move in an environment as complex as that of the Earth's crust.

Depth of events.—Sometimes the initial P wave of an earthquake at long range is complicated by a signal (pP) which is reflected at the Earth's surface near its site before being propagated to the recording station. Deeply buried explosions will give a double pulse effect for the same reason. When such a signal is seen, the time delay relative to the onset is a sensitive measure of depth at long range. As the depth of the earthquake increases, the surface reflected signal arrives progressively later than the initial signal until two well defined signals are seen on the seismogram. Correlation of two groups of seismometers separates this signal from unwanted signal and noise with great clarity. I am sure, however, that the depth indicator pP is often confused with a pulse generated by aftershocks.

This technique begins to break down when the depth of the event is less than 30-40 kilometres as the surface reflection, pP, follows so closely on P that the two signals may be confused.

At ranges of a few hundred kilometres, another depth indicator for events occurring within the Earth's crust (which is 25-50 km thick) is the delay of the P signal (P_n) refracted by the Mohorovicic discontinuity ("Moho") where the crust meets the underlying mantle, relative to the direct P signal (P_g). If the direct S signal (S_g) can also be identified, the depth of the event is determined by a single station. The principle is illustrated in Figure 3, which shows the paths of the signals concerned both for a surface event and for one at the base of the crust. For the surface event, P_n takes some 4 seconds longer than for an event at the "Moho" to reach the recording station. At ranges greater than 150 km, the P_g and S_g travel times are, within the required accuracy, independent of depth, but with increasing depth P_n will arrive earlier relative to P_g.

The two seismograms in Figure 4 demonstrate this effect for an explosion and an earthquake. This figure also serves to show the inherent difficulty in identifying the required signal components when confused by other signals. The principle has been recognised for some 40 years but it has never been seriously used by seismologists for depth studies because of this problem.

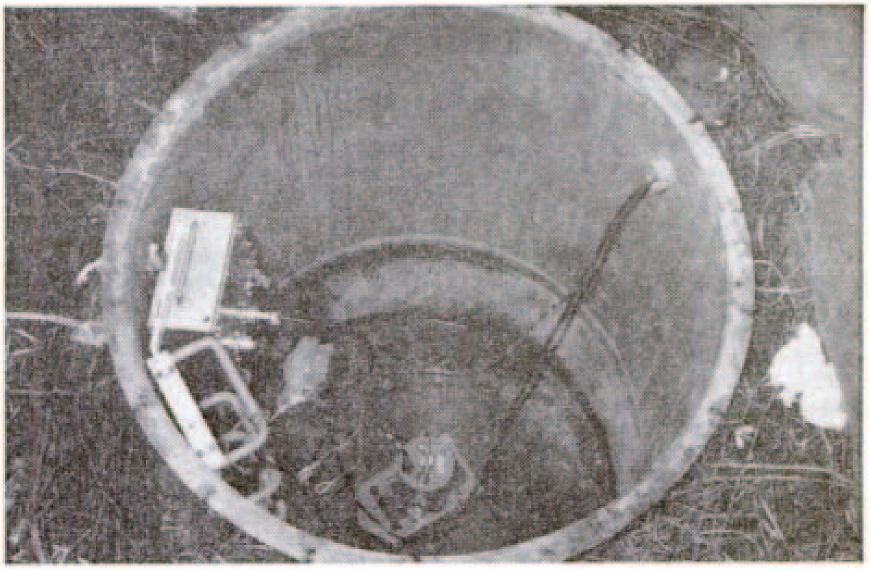

FIGURE 8. *An instrument pit at Eskdalemuir, showing seismometer and preamplifier.*

The use of a linear seismometer array, however, enables us to pick out and enhance a selected component of the signal.

Figures 5, 6 and 7 show some results of depth studies in several continents using conventional seismograms. The range in kilometres can be roughly estimated by multiplying S_g—P_g by 8. As might be expected, the best results to date are from continental shields where the crust is, seismologically speaking, a good deal simpler than mountainous areas. It is also interesting that the most consistent results are those of the South African rock bursts in Figure 5, where the measurements were made with nine seismometers in groups of three, each group being separated by some 400 metres. It was therefore possible to select the signals more certainly by eye. The signals for Figures 5 and 6 were picked by independent observers; those in Figure 5 designated P_1 and S_1 by Hales and Willmore are evidently equivalent to P_g and S_g.

Allowing for observational uncertainties we could confidently identify all events below 15 km as earthquakes in these regions. In mountainous areas, where the crust is more complex, detailed knowledge of the area would be necessary before the method could be reliably applied.

Future of arrays in general seismology.—A new way of studying earthquakes has thus been created by a group of UK Atomic Energy Authority scientists and engineers who, only two years ago, were complete strangers to seismology. During the course of the next year they plan to publish the theory and practice of their systems and processing techniques.

It is already evident from the results arising from this research that the new methods of recording and processing will have a wide application in the whole field of seismology. Using reflected and refracted body waves it looks as though a few arrays around the world could throw light on, for example, the energy and numbers of earthquakes, the nature of the Earth's inner core, the detailed structure of the Earth's crust and upper mantle, and the distribution of earthquakes in depth. They will be able to select the relatively small number of larger, single shock earthquakes which are worth detailed study using the existing network of conventional seismographs. Arrays set up in the earthquake zones themselves could record, in a form capable of precise analysis, the large number of very small, near shocks which must be carefully located before useful seismo-tectonic maps can be drawn—these are base maps for civil engineering development in such regions. Had such maps been available at the time, the first Quetta garrison would either have been built some 25 miles north of the present town, or would have used reinforced construction on more consolidated ground.

At present there are five seismological arrays in the USA, one in Canada and one in Britain. They were built to seek the scientific data required to further the conclusion of a treaty to end nuclear weapon testing. Whatever happens politically in the future, the seismological results are promising enough to warrant a special effort to make sure that the arrays are maintained by interested research groups for many years to come.