

A SIMPLE APPROACH TO HIGH RESOLUTION SEISMIC PROFILING FOR COAL *

BY

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ABSTRACT

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Seismic exploration techniques which have been developed for oil prospecting contribute a valuable means for surveying coal measures. Since the object is to detect minor faults within the first 1500 m, rather than structural features at great depth, the new technique requires much higher resolution in the early part of the traditional seismic cross-section.

Higher resolution means broader bandwidth, which must be obtained by extending the high frequency end of the spectrum. This is achieved (a) by scaling down the explosive charge size and using single geophones instead of groups, and (b) by reducing the sampling interval in space and time. Noise which does not scale down includes static anomalies and ground-roll. The consideration of statics, ground-roll, and the high-cut filtering effect of the near surface layers forces the use of deep shot holes and, where possible, deep detectors. This approach is confirmed by experiments and has been implemented on a regular basis in production.

It is demonstrated that the present technique will clearly resolve faults with a vertical throw of about 5 m at 800 m depth.

I. INTRODUCTION

The National Coal Board's Exploration Programme is designed to prove new coal reserves both for existing and for new underground mines. It also aims to determine the geological structure at both new mine sites and at structurally unproved areas of existing mines. Prior knowledge of geological structure is essential both (a) to ensure that first access to the coal seams is from a place and in a direction which support the easiest mining, and (b) to render economic the mining of unproved seams known to be structurally disturbed. At new mine sites structural information is crucial in determining the location of shaft sites, drifts, and main access roadways. At existing mines, knowledge of geological structure can determine which unworked districts should be mined and, on a smaller scale, within a district, how the

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development of the coal faces should be phased to avoid the effects of geological disturbances. The National Coal Board is investing about £ 10 million a year in exploration for new mines, of which about 10-20 percent is being taken up by seismic reflection surveys.

It costs of the order of £ 20 million per year to run an average 1 million ton/year mine. The only source of revenue is the coal being produced effectively by only two or three coal faces at any moment. Disturbances of the order of seam thickness (say 2 m) are sufficient to halt the progress of a face and lose half or one-third of the revenue for months without change of costs. Thus in these circumstances any unanticipated disturbance to the seam greater than seam thickness can result in losses of the order of £ 1 m. Even when the mine carries sufficient insurance in the form of spare faces, it is unlikely that the losses would be less than £ $\frac{1}{2}$ m. It is discontinuities of this order, therefore, which we should aim to see—with whatever technique—if we are to guarantee the life of a coal face and justify the modern capital-intensive outlay to equip it.

Depths of interest for coal mining are usually not greater than 1200 m in the UK. Therefore all the structure of interest to coal mining engineers would be seen within the first second of the seismic record. The relationship between the coal seismic section and the conventional oil seismic section is illustrated in fig. 1.

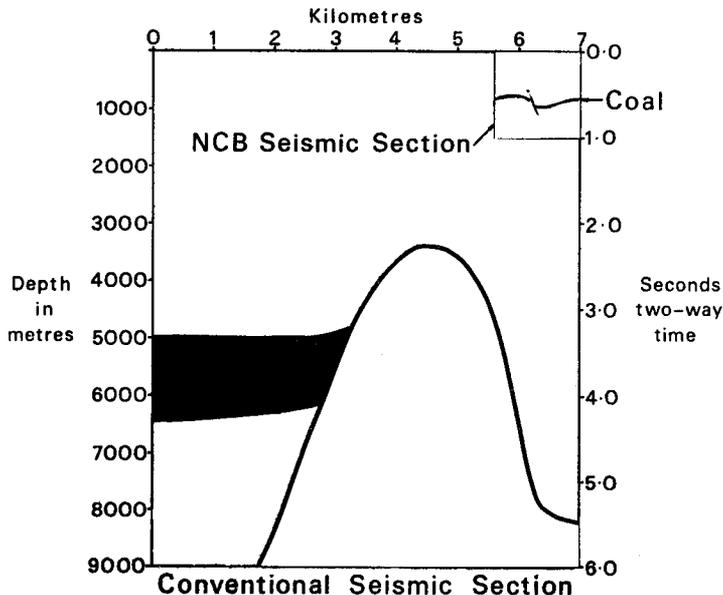


Fig. 1. Comparison of scales: conventional section versus coal section.

For coal mining purposes, it is necessary to be able to magnify the picture normally obtained in the first second of recording. Naturally, the density of information on the space-time seismic section must be increased for the magnification to reveal more detail. It is insufficient merely to sample the data more frequently in space and time, for this will add no further information if the data are already adequately sampled. It is also necessary to introduce more detail into the data.

This can only be done by changing the field technique. To extract detail out of the data is a processing problem; *but to ensure that the detail is there to be extracted is a field problem.*

It is clear that higher frequencies and larger wave numbers (or shorter wave lengths) must be introduced if higher sampling rates in both time and space are to be justified. It follows that the sound source must generate both higher frequencies and larger wave numbers, and the receivers must be sensitive to them.

Our simple approach to the design of a high resolution profiling system, described below, concentrates on land systems with particular reference to those using an explosive sound source. Certain features of our approach will apply equally to land systems using surface sources and to marine systems.

2. THE SOURCE

Let us suppose that we have some seismic data which have been processed in such a way that, within the limits of the data and our processing ability, maximum resolution has been obtained in the zone of interest on the seismic section. In this zone, let us suppose that we are just able to resolve two sub-surface reflectors which are no closer together than Δt in two-way travel time. If this Δt is not small enough for our requirements, we must further contract the seismic wavelets returning from the reflectors. Since we have already done everything we know to contract the wavelets in processing, techniques must be found which will either (a) produce wavelets which are more amenable to contraction in processing, or (b) produce shorter wavelets *before* processing.

One obvious place to look for improvements is in the seismic source and, in this paper, we consider primarily the second of these two alternatives.

The most obvious source to consider is dynamite, because it produces an unrivalled short high-energy pulse, rich in all frequencies of seismic interest. If we are already using well-tamped shots placed at the base of the weathering, the only thing we can do to shorten the duration of the pulse is to use smaller charges. In this section, after making two assumptions, we show that the size and shape of the far-field pulse (in terms of either pressure or particle velocity) are related to the mass M of the explosive charge in the following way:

1. The duration of the pulse is proportional to $M^{\frac{1}{3}}$,
2. The amplitude of the pulse is proportional to $M^{\frac{1}{3}}$,
3. The absolute spectral bandwidth of the pulse is inversely proportional to $M^{\frac{1}{3}}$,
4. The amplitude of the spectrum of the pulse is proportional to $M^{\frac{1}{3}}$.

The two assumptions we make are:

- (a) That the radiation generated by the explosion is spherically symmetric;
- (b) That the fraction of the total explosive energy which is converted into seismic energy is a constant, independent of M , for a given type of explosive in a given medium.

The validity of these assumptions, at frequencies of seismic interest, can probably best be tested by considering their effects on the conclusions of the following argument.

Consider an explosion in an homogeneous medium. In the region close to the explosion the temperatures and pressures in the instants after detonation are very intense. Melting, crushing, fracturing and plastic deformation of the material take place. As the thermal and pressure waves spread out away from the centre of detonation their intensities decrease and the medium is deformed elastically. The deformation of the material which takes place is thus of two kinds: anelastic and elastic; and, invoking our first assumption that the radiation is spherically symmetric, it follows that the region of anelastic deformation is a sphere, whose centre is the point of detonation. Let the radius of this sphere be a .

The total quantity of energy stored in an explosive of given chemical composition is proportional to its mass M . Our second assumption states that the energy contained in the elastic radiation must be a constant fraction of the total amount of energy available. It follows that all the energy *not* contained in the elastic radiation must be proportional to M . But all *this* energy is retained in the sphere of radius a where it is used in anelastic deformation of the material. The capacity of the homogeneous material to absorb energy is proportional to its volume, and, since the volume of the sphere of anelastic deformation is very much larger than the original volume of explosive, it follows that the volume of the sphere is proportional to the quantity of absorbed energy, and is therefore proportional to M . Therefore (see appendix 1)

$$a = KM^{\frac{1}{3}}, \quad (1)$$

where K is a constant which depends on the chemical composition of the explosive and on the physical properties of the medium.

Exactly the same elastic radiation outside the sphere could be obtained by replacing the sphere with a cavity of radius a , at the interior of which is applied a time-varying pressure $P(t)$ equal to the incident pressure wave at a distance a from the detonation. The problem of the generation of elastic waves by a spherical cavity within an homogeneous elastic medium has already been solved.

Sharpe (1942) considered the case where the Lamé constants, λ and μ , of the medium are equal. Blake (1952) solved the same problem for the case where λ and μ are allowed to be unequal. Using either solution, the pressure wave $p(t)$ at a distance r in the "far-field" of the cavity (that is, more than several cavity radii away) can be calculated for any arbitrary pressure function applied at the interior of the cavity. It has the following form:

$$p(t) = a/r \cdot f(\tau/a) \quad (2)$$

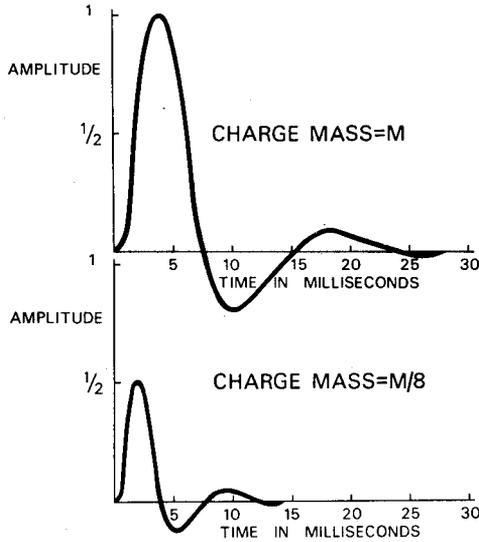
where $\tau = t - (r - a)/c$ and c is the speed of longitudinal waves in the medium. Thus τ is simply time, measured from the instant of arrival of the pulse at the point a distance r from the point of detonation. The variable (τ/a) is scaled time: the shape of the pulse, $f(\tau/a)$, is the same for all values of cavity radius a when plotted as a function of scaled time. (Frasier and North (1976) have shown that the rate at which the energy of the pulse decays at high frequencies as predicted by Sharpe's (1942) model (and therefore by Blake's (1952) model) agrees very well with teleseismic measurements of seismic waves generated by large explosions.) When plotted in *unscaled* time τ , the shape of the pulse is stretched out in proportion to the cavity radius. Substitution from equation (1) into equation (2) yields:

$$p(t) = KM^{1/2}/r \cdot f(\tau/M^{1/2}) \quad (3)$$

This equation embodies our first two propositions, namely, that the amplitude and duration of the pulse are proportional to $M^{1/2}$. The scaling effect of charge size on the shape of the pulse in unscaled time is shown in fig. 2. It is shown in appendix 2 that the energy in the elastic radiation $p(t)$ is proportional to M , which is consistent with our second assumption.

If the Fourier transform of $f(\tau)$ is $F(\nu)$, then the Fourier transform of $f(\tau/M^{1/2})$ is $M^{1/2}F(M^{1/2}\nu)$ (see appendix 3); thus reducing the charge size increases the bandwidth. One might, at first glance, think that one can go on reducing the charge size indefinitely to obtain a broader and broader bandwidth, but this is not the case. If the Fourier transform is normalized such that the normalizing frequency $\nu_0 = M^{-1/2}$, we can write the Fourier transform of the pulse $P(t)$, as

$$P(\nu) = K/(r\nu_0^2) \cdot F(\nu/\nu_0), \quad (4)$$



These Curves Represent Far Field Signals
At The Same Distance From The Source
In The Same Medium

Fig. 2. The effect on signal period and amplitude as the mass of the source is scaled down.

where (v/v_0) is scaled frequency. We now see that the shape of the normalized spectrum is unchanged (just as the shape of the pulse in scaled time is unchanged). As the charge size is reduced, the spectrum is shifted towards the higher frequencies and reduced in level as v_0^{-2} , or as $M^{\frac{2}{3}}$. It follows that the processing signal bandwidth, in terms of octaves, remains the same; but, because of the shift to higher frequencies, a higher resolution section can be obtained.

However, this shift in frequency content is obtained at a cost: the amplitude of the pulse and consequently the level of the spectrum are reduced. Therefore, the ratio of signal energy to background noise energy decreases as the charge size is reduced.

All the above points are illustrated in fig. 3 which shows the effect of reducing the charge size on an eight channel seismic record obtained with single geophones. The geophones were placed 12 m apart and the charges were fired in holes 7 m deep offset 60 m from the nearest geophone. Record (a) shows a strong event at 0.5 s with a charge of $M = 0.45$ kg. As the charge size is reduced, the resolution improves so that on record (c), with a charge $M/4$, the event at 0.5 s clearly splits up into two events; also an event at 0.33 s

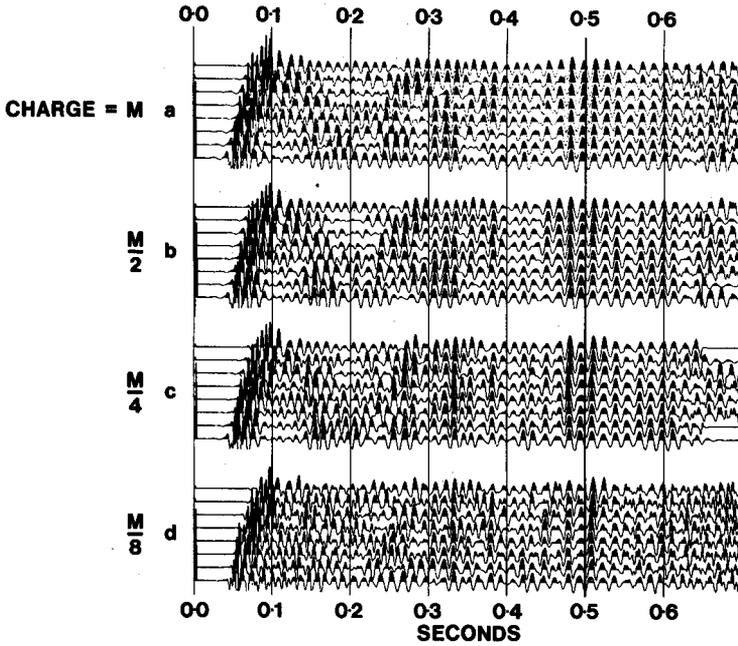


Fig. 3. The effect on a monitor record of decreasing source mass.

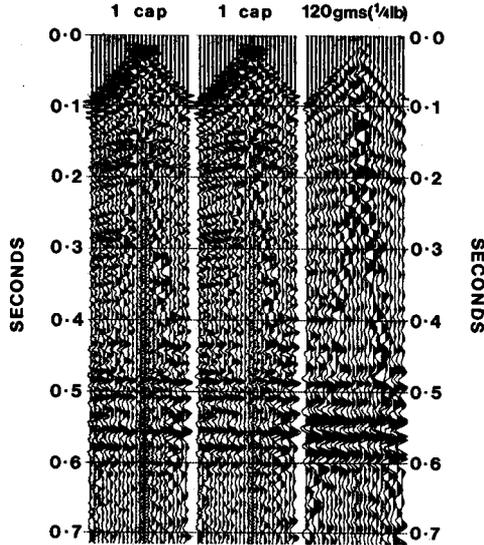


Fig. 4. Monitor records of three shots fired successively in the same 10 m hole. There were 12 m between geophones.

has much better definition and continuity. When the mass is reduced to $M/8$ (0.055 kg) the resolution is very good, but the signal-to-noise ratio is poor. The effect of increased resolution with decreased charge size was noted by Sharpe (1944).

From this analysis we can learn several things:

1. We cannot change the normalized spectrum of the pulse by altering the charge size, but
2. we can shift the spectrum into the most useful band by choosing the right size charge. This is illustrated in fig. 4 which shows successive monitor records obtained with single geophones from three shots fired in the same hole. The first two are single detonators and the third one has a charge of 0.12 kg of dynamite. The zone of interest for coal mining purposes is at about 0.5 s, and it is clear that in this area no explosion bigger than a single detonator is required. It is also clear that the contamination of the signal due to shot-generated noise (mainly ground-roll in this case) is much worse with the larger charge. The ability of the larger charge to excite the ground-roll is enhanced, relative to the detonator, because its spectrum is shifted towards those lower frequencies.
3. If the normalized bandwidth is not sufficiently broad for our requirements, we may broaden it by using charges of more than one size, detonated separately, and then combine the records in processing. This will be discussed in a little more detail later on in this paper.
4. In attempting to improve the resolution of the data at the source by using smaller charges, we will run into signal-to-noise ratio problems. To overcome these it may be necessary to consider vertical stacking. This will also be discussed in a little more detail further on in this paper.

3. THE GEOPHONE STATION

During the Coal Board's experimental work it was found that the highest resolution is obtained from *single geophones* rather than the usual patterns or groups. A typical geophone spread for coal survey is 470 m to 564 m long with only 10 m to 12 m between geophone stations, therefore a 30 m to 100 m array, which would be necessary to reduce ground-roll interference effectively, is out of the question.

Even a short array will act as a filter in which the higher frequencies of the signal are attenuated. To illustrate this, fig. 5 shows how the filtering effect is magnified when the line of traverse is in the direction of dip. The cut-off frequency is proportional to $1/\Delta t$, where Δt is the difference in travel time to the outer geophones. Generally it is assumed that Δt will be small enough to put the cut-off frequency outside the seismic spectrum. But a dipping reflector

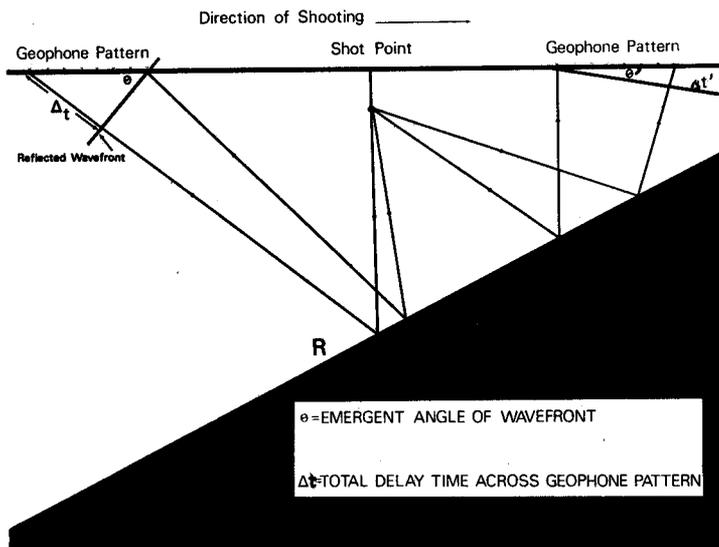


Fig. 5. The effect of dip on total delay across the geophone pattern.

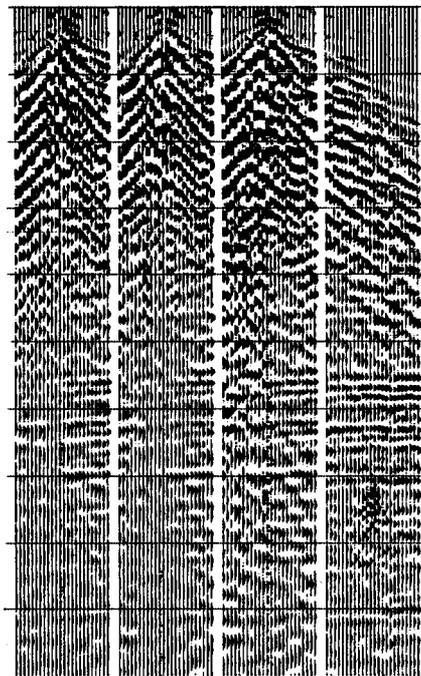
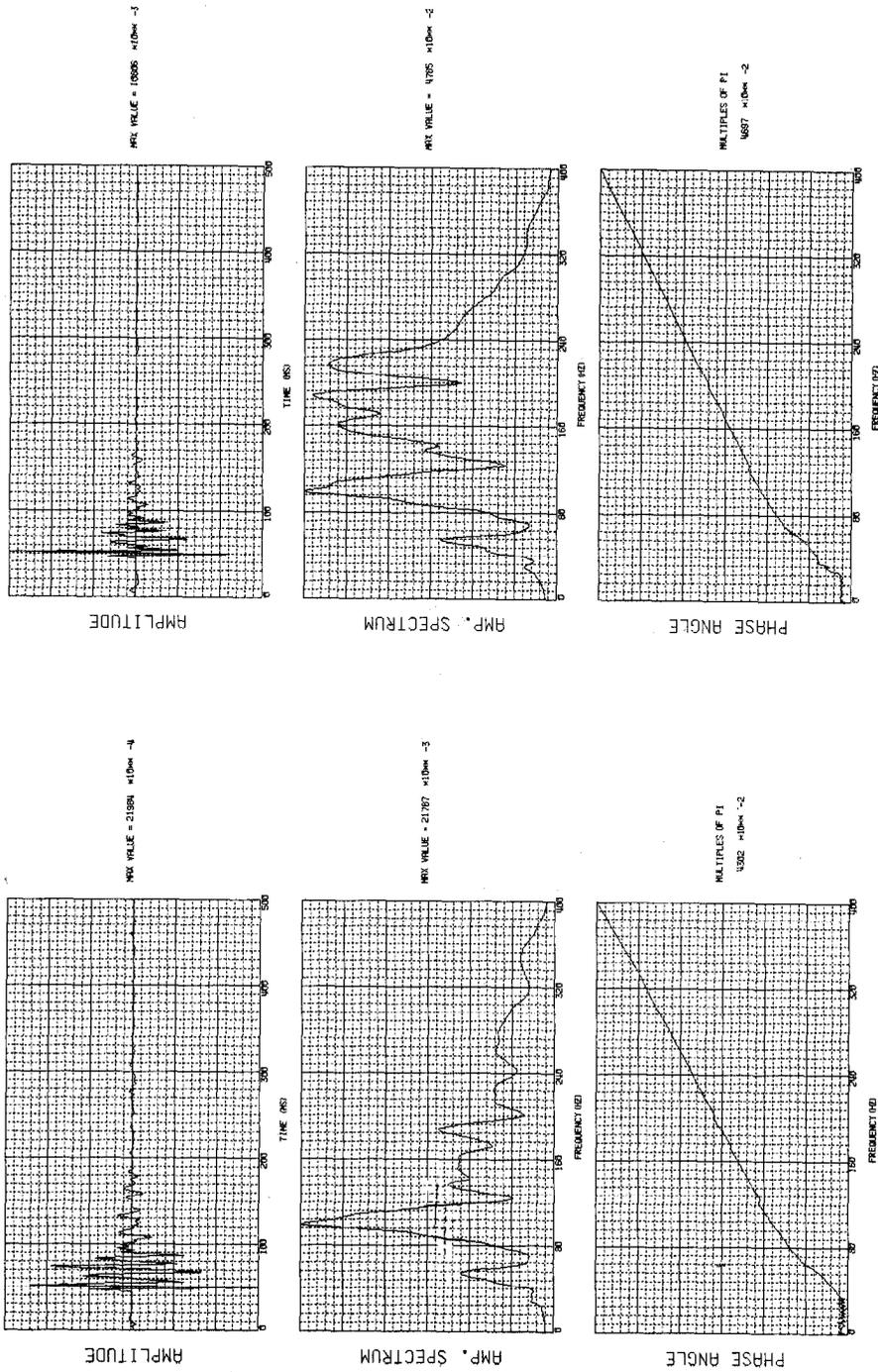


Fig. 6. The effect of the geophone pattern on the reflected signal.



(a)

(b)

Fig. 7. Comparison of (a) a single high-fidelity geophone at the centre of (b) a small circular group of similar phones. The amplitude and phase spectra are of the seismic traces shown at the top.

has the effect of exaggerating the emergent angle of the reflected wave in one half of the spread, which means that Δt is increased and the filtering in that region is severe. Indeed, the overall response of the spread is reduced.

A practical example of this effect is shown on the three straddle-spread records in fig. 6. The event at 0.6 s is strong on the right-hand traces but it fades in amplitude and reduces in frequency towards the left, whereas the skip-spread record on the extreme right shows good continuity in the direction of shooting. It is also worth remembering that Δt may be increased by elevation changes and that it must always increase towards the far traces, even when the reflector is not dipping.

There is also a problem when geophones are planted in a group small enough to avoid the filter effect described above. No matter how carefully they are planted there are unavoidable phase shifts due to slight differences in ground coupling. The higher frequencies are therefore attenuated when the outputs are added. The results of a field test which was designed to examine this effect are shown in figs. 7 and 8.

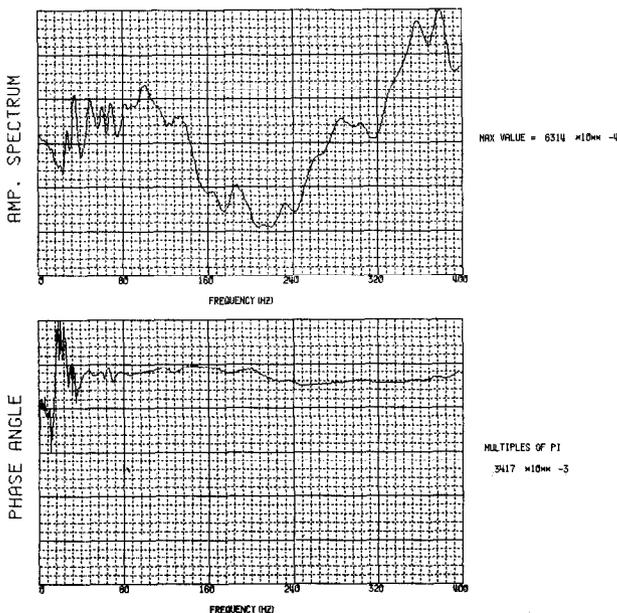


Fig. 8. The spectrum of the seismic trace in fig. 7(a) divided by the spectrum of the seismic trace in fig. 7(b).

During the test, one station in a seismic spread consisted of nine geophones carefully planted in a circle about 1 m in diameter with a single geophone planted in the centre. The nine geophones were connected in series-parallel so that they presented to the instruments the same source impedance as the

single geophone. The two outputs were connected to separate channels and were thus registering the same shot with exactly the same electrical network at the input of each amplifier. Fig. 7a shows the seismic trace from the single geophone with its amplitude and phase spectra immediately below; these can be compared with similar curves in fig. 7b, which were obtained from the group of nine. It will be noticed that both amplitude spectra peak at 100 Hz which was the natural frequency of the high fidelity geophones that were used in this test.

In these results, the true effect of ground coupling is partially masked by the extra damping which is introduced when geophones are connected in series-parallel. Each geophone in the group is in fact looking at additional resistance from the network comprising the other eight in parallel with its own damping resistor. At first sight the group appears to be giving the higher frequency response but this is because the single geophone is the more sensitive near resonance and the peak at 100 Hz is scaling down the rest of the curve. In reality it can be seen that the single geophone presents the flatter response between 200 and 400 Hz.

The curve in fig. 8 shows the ratio of the single geophone response over that of the group. This shows a peak at resonance where the group is heavily damped, but there is a positive slope between 200 and 400 Hz which demonstrates that the single geophone does have the higher frequency response.

Thus, the single geophone has a clear advantage in obtaining bandwidth, but in doing so it leaves the problem of ground-roll to be solved elsewhere. However, the short spread-length lends itself to an alternative method of velocity filtering which will be described later. Nevertheless, the single geophone reveals a new problem concerning its own frequency response which will now be described.

The two curves in fig. 9a are typical for the damped and undamped response which is claimed by manufacturers for the moving coil geophone. The undamped curve peaks at 28 Hz which is the natural frequency of the coil mass supported on its suspension spring. The other curve indicates that, with the appropriate damping, the geophone will give a reasonably flat response from 28 to 500 Hz, and there is no doubt that it is true for vertical motion. However, there is usually at least one more resonance, at a higher frequency than the first, which is caused by a transverse compliance in the suspension spring, and it responds readily to a tap on the side of the case. An example of 220 Hz ringing due to this effect can be seen on the inner traces on the records in fig. 4 where the instrument bandwidth was 40 to 375 Hz. Notice that the interference is more pronounced when the source is reduced to a single detonator, which indicates that the detonator is relatively more able to excite this resonance because its spectrum is shifted towards higher frequencies.

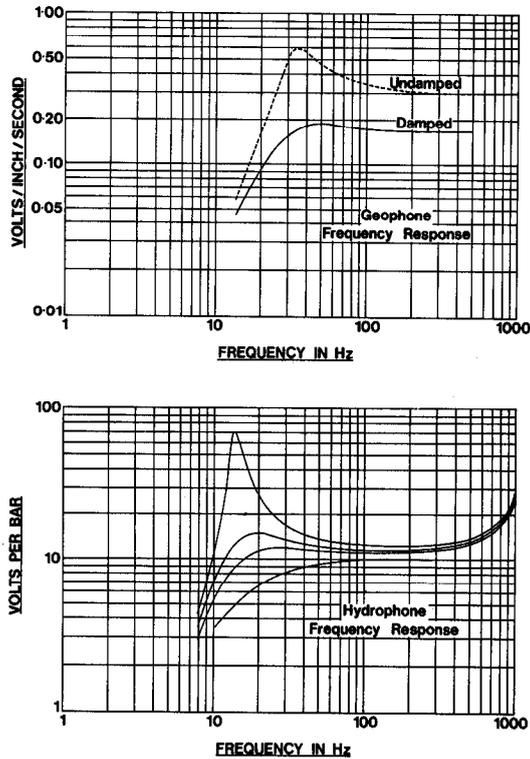


Fig. 9. Manufacturers' curves of frequency responses of a (velocity sensitive) geophone and a (pressure sensitive) hydrophone.

This emphasizes the need for higher fidelity from the single geophone when it is used in this type of survey; to be safe, it should be free from spurious effects up to 500 Hz.

Frequency attenuation in the near-surface is many times greater than the $\frac{1}{2}$ to 1 dB per wavelength in the deeper consolidated layers of the earth, and it is one of the greatest obstacles in the way of high resolution. It would seem logical to plant the geophones deep enough as a matter of course in order to avoid this filtering effect, but, as always, the decision is dictated by practical considerations in the field. The extra cost of drilling is often prohibitive and even when it may be considered worthwhile there are still problems.

A geophone does not give its best performance when it is away from the free-surface where the particle displacement, and hence the velocity, is maximum. The amplitude of the particle velocity of the near-vertically reflected wave is reduced, but not so the horizontally travelling ambient and shot noises, other than the Rayleigh wave; consequently there is a reduction in signal-to-noise ratio in that part of the spectrum which was available at the surface.

The hydrophone is more suitable as a deep detector. However, its use is restricted to those areas where holes will contain water for sufficient time to take a record. It seems likely that this technique is viable only when it is possible to drill below the water table and the holes are filled naturally. Under these conditions the hydrophone performs well; the head of water is not critical provided it is greater than about 3 m. And, of course, another spread dimension must be considered in that the depth of the hydrophones must be known when the static corrections are made.

Regarding the frequency response of the hydrophone, the family of curves in fig. 9b shows the effect of various values of damping resistor. The undamped resonance is an electrical one in this case, due to the capacitance of the piezo-electric crystal element and the inductance of its matching transformer. There is another peak corresponding to the mechanical resonance of the crystal but this is safely up at 1000 Hz. When the appropriate damping is used it can be seen that the response over the band 40 to 500 Hz is effectively the same as that from the vertical component of the geophones. This comparison is made because it emphasizes that the improved resolution on the hydrophone section in fig. 12, over that obtained with surface geophones in fig. 11, is entirely due to the broader band signal which is available at depth, and not to an improved frequency response.

At this point it is appropriate to say something about the value in coal survey of a pre-amplifier at each detector; but first it will help to put its application into perspective if the various noises are clearly defined.

1. Ambient noise depends upon local conditions and varies widely from place to place. It may be due to road traffic, industrial plant vibration or wind moving the trees. It is not truly white and may have its greatest amplitude anywhere in the seismic spectrum. The ratio of signal-to-ambient noise is determined by their particle velocity amplitudes in the ground and will not be improved by amplification.
2. Shot-generated noise includes ground-roll or any near-surface waves; also refractions, reverberations, and reflections from objects other than the required interface. Signal-to-shot noise ratio is again determined at the geophone station and will not be improved by amplification.
3. Cable noise may be due to direct electromagnetic induction into the wires or through leakage paths to ground. The source is usually a power supply line carrying 50 Hz or 60 Hz alternating current. Also, there may be contact noise or microphony in the cable (but it is extremely unlikely that Johnson noise is a problem). Here it is possible to amplify the signal at the geophone to improve signal-to-cable noise ratio, but the dynamic range of the system may now be reduced (when the pre-amplifier has the

- effect of increasing the threshold noise at the input of the main amplifier).
4. Instrument noise: the overall system is designed so that this is less than a typical ambient noise. For example, the noise referred to the input of the main instrument amplifier might be less than 0.5 mV whereas, in the same system, the ambient noise would range from 1 mV on a quiet day to 10 mV when there is a high wind. It is upon this criterion that the main instrument gain is adjusted before taking the record and no advantage would be gained from a pre-amplifier.

Clearly then, the use of a pre-amplifier implies that it is intended to overcome cable noise, since it will do nothing to increase the ratio of signal-to-ambient or shot-generated noise, and the system is already designed to cope with instrument noise. But the requirement for relatively short cables and single detectors will afford a unique opportunity to spend extra money and effort on (a) shielding to reduce electromagnetic pick-up and (b) water-tight connectors to reduce leakage. So the conclusion is that the pre-amplifier has no advantage in coal survey when the seismic detectors are conventional geophones or crystal hydrophones.

4. THE RECORDING INSTRUMENTS

These are typical of the present day recording instruments which have been developed specifically for seismic exploration. Their chief characteristics are:

1. Wide dynamic range, and
2. Extremely fast response to changes in signal level, both of which are achieved by instantaneous-floating-point digital sampling. The sampling rate determines the maximum number of data channels available, which is 48 when the time interval between samples is not less than 1.0 ms and 24 when it is 0.5 ms.

Since the greater number of channels means more efficient operation in the field, some effort has been made to obtain sufficient bandwidth for high resolution from 1.0 ms sampling and forty-eight channels. Field tests were carried out, using wide-band recording with the 0.5 ms sample rate, in order to examine the spectrum of source-generated energy at the time of most interest on the record, which in this case was between 0.3 s and 0.5 s. These tests revealed that the energy at 250 Hz was 20 dB above the background noise, but fell to only a few dB at 500 Hz. Therefore, it was decided that it would be safe to sample at 1.0 ms using an anti-alias filter with a cut-off frequency at 375 Hz instead of the usual 250 Hz. This would preserve the useful part of the spectrum and the 72 dB/octave slope would apply about 40 dB attenuation to the already weak signals at 500 Hz, the Nyquist frequency.

The result of increasing the high-cut frequency in this way can be seen on the Belvoir section in fig. 17 where the dominant period of two events in the region of 0.5 s is 5 ms, which means that they contain frequency components higher than 200 Hz. The improvement is noticeable when fig. 13 is compared with the same section in fig. 11 which was shot before the filter was increased to 375 Hz.

The low-cut filter is selected to attenuate ground-roll and other low frequency interference. The low-cut frequency in most of the examples given in this paper was 40 Hz with 12 dB/octave slope.

In summary then, it is considered that the three octave bandwidth from 40 to 375 Hz is adequate for survey down to one second two-way time, that is, until a method of penetrating with higher frequencies comes along.

5. EXPERIMENTAL WORK

The National Coal Board decided to test these ideas by attempting to improve the resolution in an area where the data were already very good—the Vale of Belvoir. Fig. 10 shows the final twelve fold stacked section of a line in this area which was shot in 1974 using single 0.5 kg (1 lb) charges at a depth of 3 m; the geophones were evenly spaced at 1 m intervals and arranged in groups of twelve; the data were recorded with a twenty-four channel recording system, sampling at 1 ms intervals, with a low-cut filter of 40 Hz and an anti-alias filter of 250 Hz.

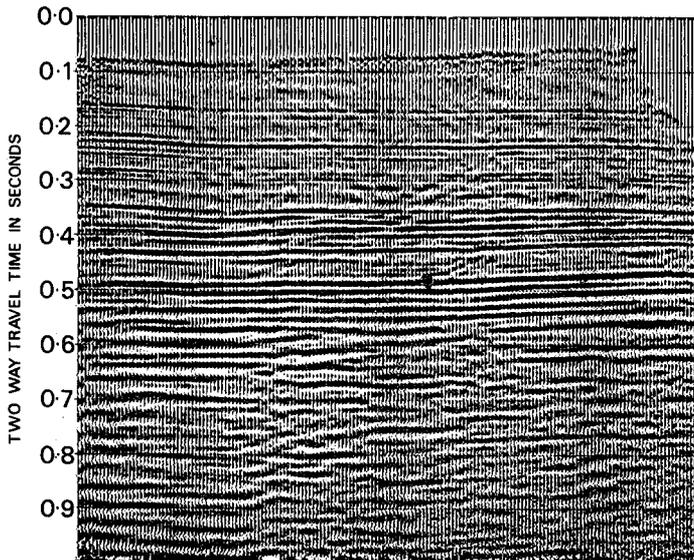


Fig. 10. Section obtained with 0.5 kg (1 lb.) charge at 3 m depth and geophone groups with 12 m between groups.

The unconformity at the base of the Permian can clearly be seen at 340 ms. Beneath this unconformity lie the Carboniferous coal measures. Very large amplitude reflections are to be expected from coal seams because there is a very large acoustic impedance contrast between the coal and the country rock—typically, the density and longitudinal wave velocity of coal are 1.3 gm/cm^{-3} and 2200 ms^{-1} respectively, whereas these parameters for the country rock would probably be about 2.5 gm/cm^{-3} and 3500 ms^{-1} . Reflection coefficients of about 0.5 are normal.

Three experiments were carried out.

1. In early 1976 the section of line shown in fig. 10 was reshot using 0.12 kg ($\frac{1}{4}$ lb) charges at 8 m depth—below the weathering (see section 6 for definition); the geophone groups were replaced by single geophones of the same type at the same 12 m station spacing; the recording system, sampling rate, and filters remained the same. The data thus acquired were processed using the same parameters as for the original line. The result is shown in fig. 11.

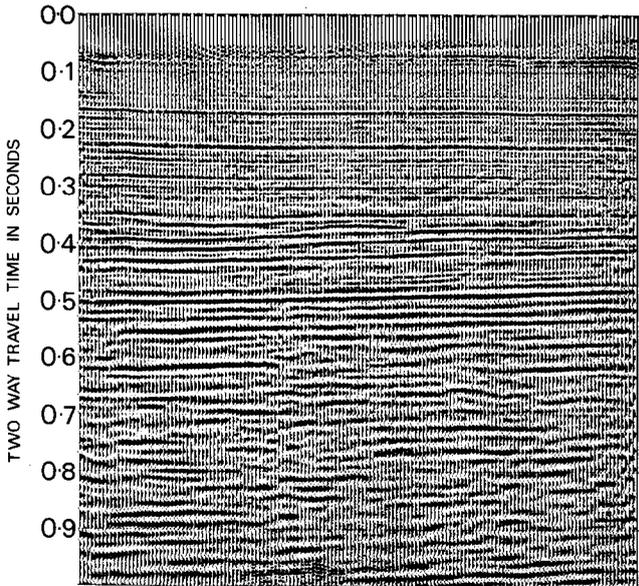


Fig. 11. Same section as fig. 10, obtained with 0.12 kg ($\frac{1}{4}$ lb.) charge at 10 m depth and single geophones at 12 m spacing.

The improvement in resolution obtained with these new field parameters is dramatic: there appear to be approximately twice as many layers visible above the unconformity, while below it—of far more importance to mine planners—there is more detail in the coal measures. In particular, there is a

prominent feature in the middle of the section at 360 ms, which is barely visible (if at all) on the original section.

This bump, about 100 m across, is of great mining significance, for it occurs in the horizon which corresponds to the shallowest mineable seam in the sequence—the “Top Bright” seam. This feature, several miles long, is crossed by about fifteen other lines in The Vale and has a sinuous linear pattern in plan; it always occurs in the same place in the geological sequence—in the Top Bright—and it is tempting to interpret it as an old distributory channel which may be interfacing with the seam in places. To encounter an old distributory channel unexpectedly in the course of mining coal can be very costly (perhaps £ 1 million). And because the locations of such channels are unpredictable, without either uneconomic advanced headings in the seam or a high resolution profiling system, they could cause unexpected losses many times during the life of the mine. The potential savings in mining costs which are achieved by being able to map this feature are therefore enormous.

It should be noted that this improvement in resolution has been obtained without changing the sampling rates in space or time; it was considered that these were already sufficient to prevent aliasing. The costs of this improvement is only the additional cost of drilling the deeper holes which were considered essential (a) to enable accurate static corrections to be calculated, (b) to minimize the low-pass filtering effect of the weathered layer on the downgoing waves, and (c) to minimize the generation of ground-roll. The increased cost of drilling is offset slightly by the use of single geophones instead of groups, and by the use of smaller charges. Incidentally, the static corrections obtained from this experiment were used to improve the original data, and the section shown in fig. 10 contains the improved static corrections.

2. The line was reshot using the same parameters as in the first experiment, but with single hydrophones instead of geophones. The hydrophones were placed at a depth of about 5 m in the shot holes, above the preloaded charges, and the holes were filled with water. The data were processed with the same parameters as before. The result is shown in fig. 12.

There is a further improvement in resolution and, since the response of the hydrophone and geophone are so similar (see section 3), this improvement is entirely attributable to the absence of the low-pass filtering effect of the weathered layer above the hydrophones. There is considerably more detail in the coal measures—another leg appearing in the bump in the Top Bright, for example. In order to obtain the correct correlation between the hydrophone line and the geophone lines, it was necessary to reverse the polarity of the hydrophone data.

3. One final experiment on this line was performed in late 1976 using a forty-eight channel system with the same 40 Hz low-cut filter but with a

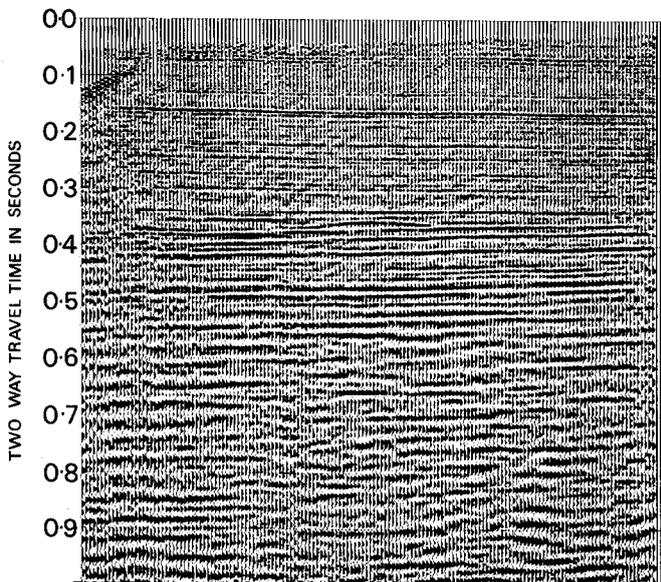


Fig. 12. Same section as fig. 11, using single hydrophones instead of geophones.

375 Hz anti-alias filter. The line was reshot again with single geophones, but this time the geophones were at 6 m intervals. The spread length was therefore the same as before. The shooting arrangements was different: each shot hole was loaded with a string of six charges with about 60 cm between successive charges. The bottom three charges were a detonator, another detonator and 0.12 kg of dynamite. These were fired separately into the spread of geophones *ahead* of the shot, with zero offset; thus the first data channel recorded the uphole time. The top three charges were two detonators and a 0.12 kg dynamite. These were fired separately into the spread of geophones *behind* the shot, with zero offset.

The detonator records were processed separately from the 0.12 kg records. Thus the detonators were stacked vertically first and then the forward and reverse shots were gathered to give a forty-eight fold stack. The 0.12 kg records were stacked to give a twenty-four fold stack. In processing, the same parameters as before were used.

Fig. 13 shows every alternate trace of the 0.12 kg stacked section. This has the same temporal and spatial sampling rate as the previous sections of this line and therefore, apart from the increasing fold of stack (obtained at no extra drilling cost)—forty-eight fold as against twelve-fold—it is directly comparable with the previous sections. This section has higher resolution than the previous single geophone section (fig. 11). The increased resolution can be attributable only to the higher 375 Hz anti-alias filter.

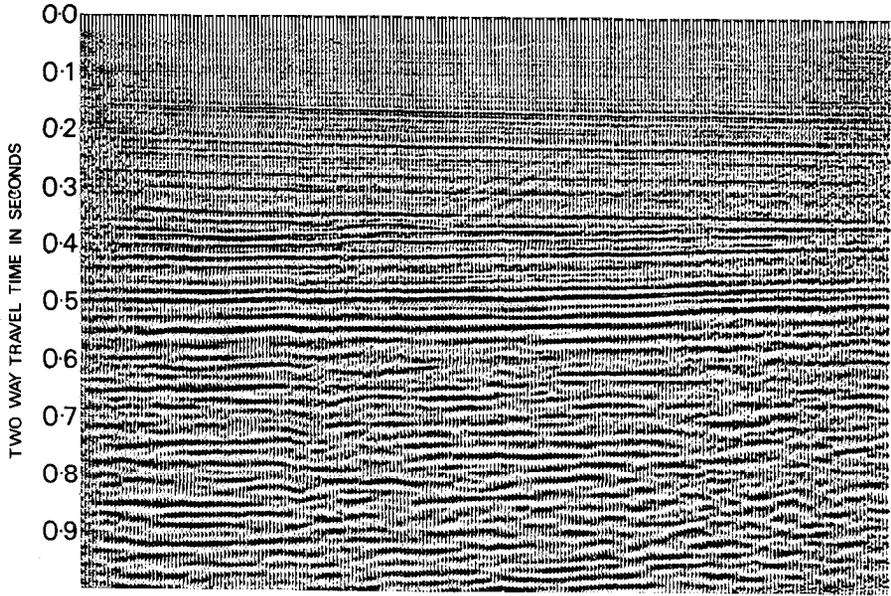


Fig. 13. Same section as fig. 11, using wider bandwidth recording system and two charges per shot hole fired separately into forward and reverse geophone spreads.

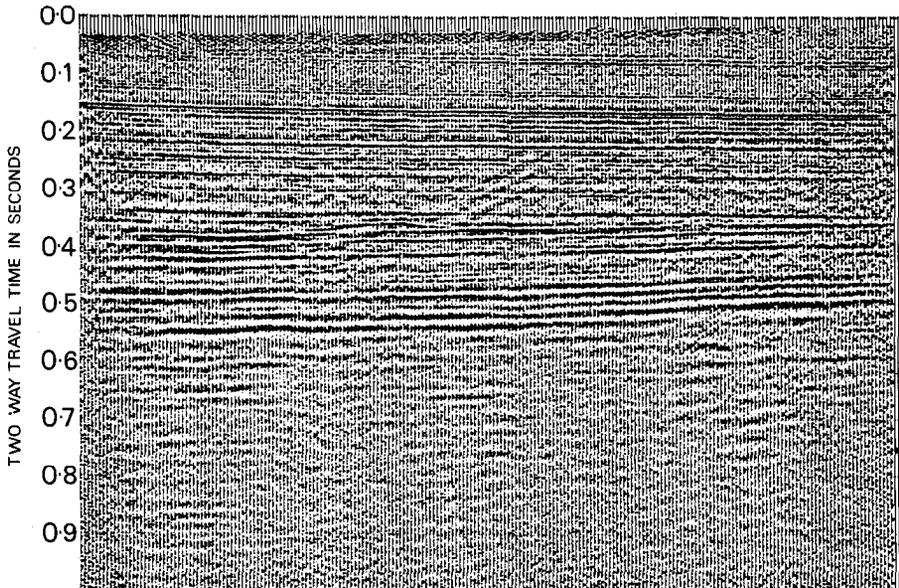


Fig. 14. Same section as fig. 13, using two vertically stacked detonators instead of one 0.12 kg ($\frac{1}{4}$ lb.) charge.

Fig. 14 shows the detonator line with every alternate trace displayed. There is a dramatic improvement in definition of the shallow data above the unconformity. Below the unconformity the signal-to-noise ratio does not compare well with the 0.12 kg line. The lack of reverberation below 600 ms is very noticeable on this section.

We deduce from figs. 13 and 14 that neither the 0.12 kg charge nor the stacked pair of detonators has a broad enough spectrum to give us all the resolution we would like: the small charge lacks high frequencies and the detonator lacks low frequencies. The obvious thing to do is to add the two sets of data. This is shown in fig. 15. A close comparison of figs. 13, 14, and 15 shows that, although fig. 15 is the best section overall, the detonator section has better definition in the very shallow data, whereas the dynamite section has better definition in the coal measures. The background noise on the detonator records is different from that on the dynamite records (see fig. 4). The combined section (fig. 15) contains *all* the noise and is therefore inferior in detail to either the detonator or the dynamite sections, depending on which part of the section is considered.

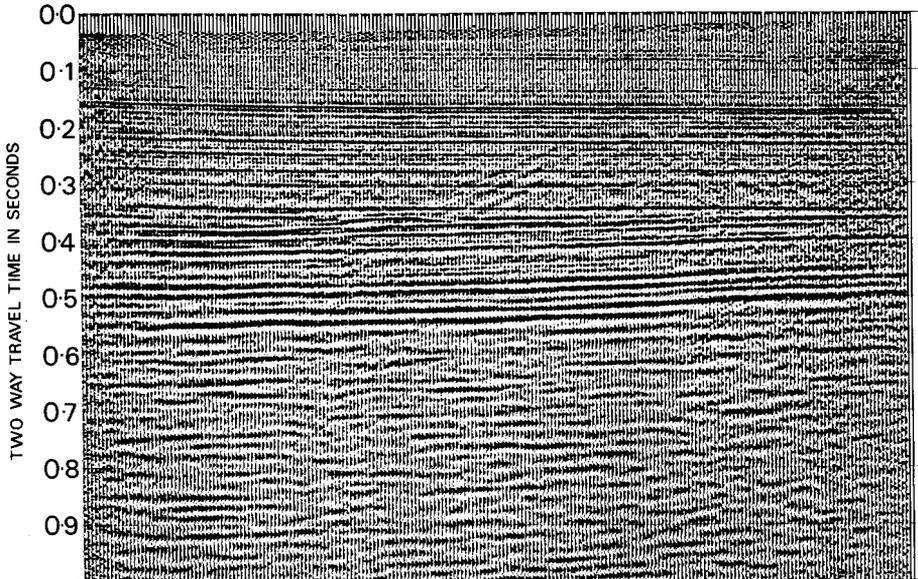


Fig. 15. All data from fig. 13 and 14 stacked together.

The purpose of shooting the line at 6 m intervals was to determine whether 12 m between geophones was adequate. Fig. 16 shows all the data (detonators and dynamite) in a forty-eight fold section with every trace displayed. We

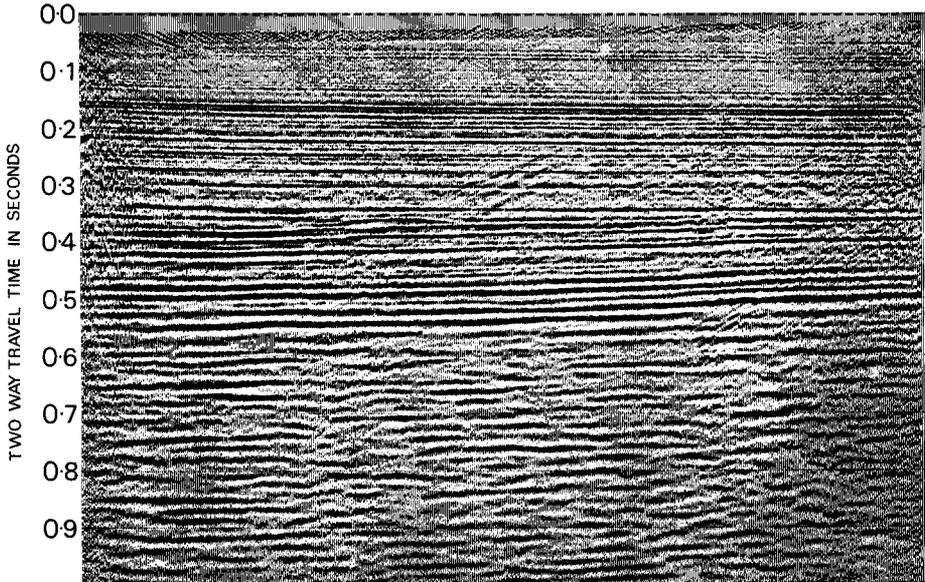


Fig. 16. The same as fig. 15, with 5 m between geophones instead of 10 m.

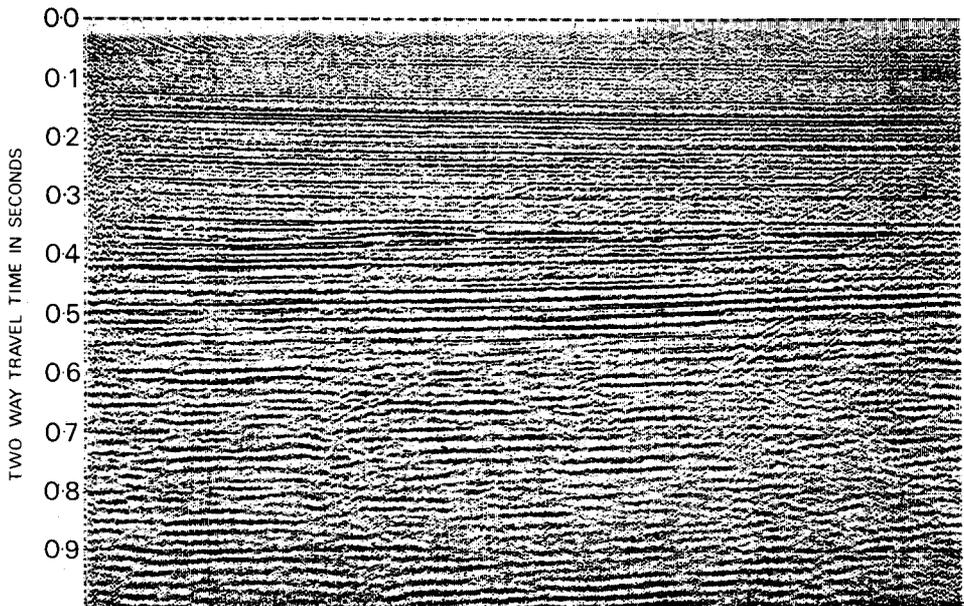


Fig. 17. Same section as fig. 13 with deconvolution after stack.

see that fig. 15 contains just as much information as fig. 16, and therefore 12 m between geophones is adequate.

Purely for interest, we include a further section (fig. 17) which is the same as fig. 13, the dynamite section, but deconvolution has been applied *after stack* (as well as before stack). It is clear that the resolution in the coal measures has been improved: several reflections have split up, notably just above and just below the 500 ms timing line, where the separation of the events is now as little as 5 ms. Deconvolution after stack (DAS) on the earlier sections yields similar increases in resolution, but a comparison of all the DAS sections shows the same progression of increase in resolution with changing field parameters as the figs. 10 to 15.

In summary, higher resolution can be obtained (a) by scaling down the explosive charge size and by using single geophones instead of groups, (b) by reducing the sampling interval in both space and time, and (c) by extending the band width of the recording system at the high frequency end. In the next section, we briefly consider two problems which do not scale down: ground-roll and static errors.

6. TWO PROBLEMS WHICH DO NOT SCALE DOWN

I. *Ground-Roll*

Ground-roll is the name given to the surface waves generated by the shot. Whereas longitudinal and shear waves are generated in the body of the medium and are therefore called body waves, the surface waves can only exist by virtue of the free surface. The character of the surface waves—their velocity and frequency content—is determined by the thicknesses and elastic properties of the material near to the free surface. Thus the velocity and frequency content of the surface waves are independent of the seismic reflection system, and these do not alter when the geometry of the system changes. The only thing which can be changed is the ability of the shot to excite the surface waves: this can be reduced (a) by placing the shot below the weathering, and (b) by using smaller charges whose spectrum is shifted towards the higher frequencies (fig. 4).

The surface waves, for the purpose of the seismic reflection technique, are considered to be noise. The reflections from deep horizons arrive at the geophones in a near vertical direction while the surface waves, travelling horizontally from the shot at a much lower velocity, arrive at the same time. If the frequency content of the reflected signals and the ground-roll differ, they can be separated by band-pass filtering. If their spectra overlap, there will be some degradation of the signal when the ground-roll is suppressed in this way.

In normal seismic reflection surveying, noise analyses are performed to determine the velocity and spectral content of the ground-roll. Geophone arrays are then designed for each geophone station, in order that the array output will be as near zero as possible for surface waves, but will be a maximum for the reflected waves arriving vertically from below. The design of such geophone arrays is possible because the surface waves arrive at successive geophones within the array at successively later times, whereas the reflected waves arrive at all the geophones with the array almost simultaneously.

In the National Coal Board's high resolution work this approach has been discarded because the length of each array would far exceed the distance between geophone stations, and therefore the small changes in move-out which we expect to see from trace to trace would be smeared out and obscured by the averaging effect of the array. Instead the National Coal Board have opted for single geophones. This has the obvious advantage that the planting of geophones is easier and better controlled.

It has the disadvantage that ground-roll is clearly visible on the records.

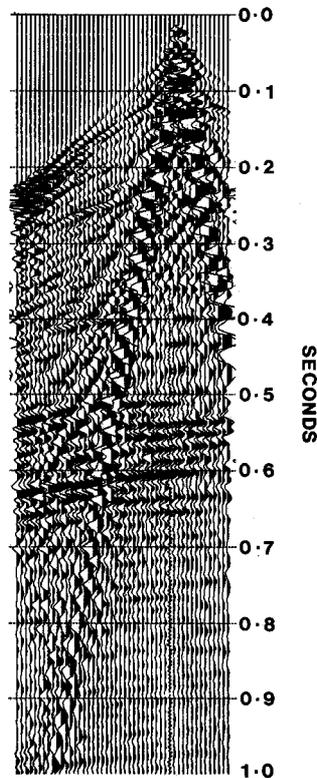


Fig. 18. Monitor record illustrating ground roll.

Fig. 18 shows a typical forty-eight channel record from a good data area. Several modes of surface wave and reverberation are visible. The geophones station interval is 12 m.

The ground-roll has already been reduced in recording by application of a 40 Hz low-cut filter. Further filtering may well damage the data. The National Coal Board are now considering the application of velocity filtering to remove the ground-roll since it is clear from fig. 18 that the reflections and ground-roll must be separable by velocity filtering—perhaps in frequency-wavenumber space. Velocity filters on conventional lower frequency data have not always been successful in the past. We believe that with the geometries being adopted by the National Coal Board, velocity filtering of the data to suppress ground-roll will be successful, especially since there is also a pronounced difference in frequency content between the ground-roll and the reflections.

2. *Static Errors*

One definition of the statics problem is this: Near-surface low velocity layers of variable thickness and velocity slow down the downgoing and returning seismic waves by different amounts in different places. The wavefronts of the seismic waves get distorted, and this distortion is a form of noise: it introduces errors into the time origin of each trace. If these errors are large there can be a problem in lining up reflections from adjacent traces.

These time delays or static errors are clearly determined by near-surface geology. They do not scale down with the scaled-down geometry of the higher resolution seismic system. Static errors are therefore more of a problem for high resolution work than for conventional surveys. Correction of static errors allowing for variations in elevation and in thickness and velocity of the near-surface material is of supreme importance for coal mining seismics. Failure to calculate them correctly will be the limiting factor in the ability of the technique to resolve small faults. The following argument will explain why this is so.

A fault with a vertical displacement of 3 m will typically create a time difference of 2 ms in coal measures between reflection times on opposite sides of the fault. At the surface, velocities can often be as low as 300 ms. An error in the estimation of the thickness of such a surface layer by as little as 60 cm can create a timing error of 2 ms. Introduction of timing errors of this order means that the resolving capability of the system is limited to faults of the order of 3 m.

There are two reasons why the National Coal Board field system appears to magnify static errors:

1. The averaging effect of the geophone pattern is lost.
2. The frequency content and sampling rate have been increased.

The second reason is particularly important. Where an automatic statics programme would have successfully corrected the static errors on low-frequency data sampled at 4 ms intervals, *it fails to correct the same static errors* on higher frequency data sampled at 1 ms intervals.

Fig. 19 shows a static jump rolling through a sequence of monitor records. The time-shift on the reflections at 500 ms is greater than half the period of the wavelet. On much lower-frequency data this static jump could easily be corrected in processing by a computer. With higher-frequency data this problem is less easy to cope with. Once again, a change in field technique is required to improve the information and permit accurate static corrections to be computed.

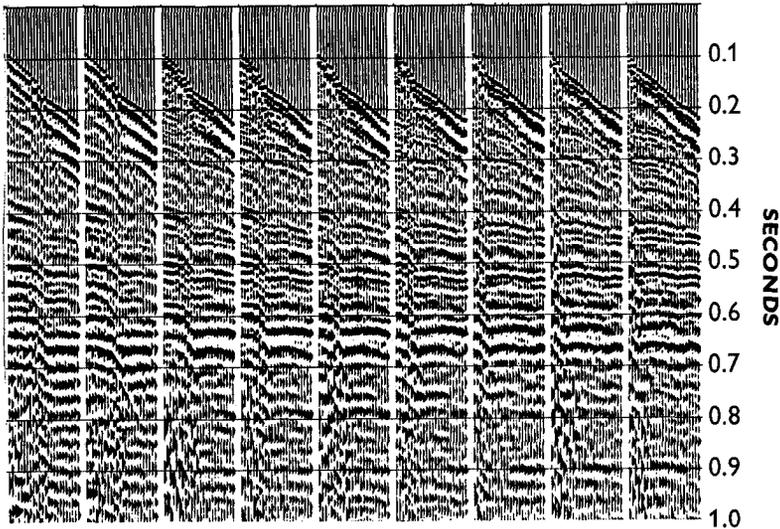


Fig. 19. A sequence of monitor records showing a statics jump rolling through.

The idea behind the National Coal Board approach to this problem is very straightforward. The shots are placed below the weathering (defined as the near-surface material with a longitudinal wave velocity less than about 2000 ms); a standard geophone in the cable is placed above the shot so that the uphole time—the time taken for the sound to travel from the shot to the surface—can be measured and recorded on tape; finally the datum is chosen so that it is close to where the shot is fired. The shot point static correction is given by:

$$t_s = -E_s/V_e \quad (5)$$

where E_s is the elevation of the shot above the datum and V_e is the velocity

of the material at the base of the weathering. The geophone static correction is given by:

$$t_g = - \left[\frac{E_s}{V_e} + t_u \right], \quad (6)$$

where t_u is the uphole time.

There are two key factors in this approach: the drilling and the choice of datum. To ensure that the shot is placed below the weathering—as defined above—it is necessary to carry out continuous refraction surveys ahead of the drills using a separate weathering crew. The weathering crew has only to calculate the approximate thickness of the weathered layer; the drills are then programmed to drill below this.

In a flat area the choice of datum may be no problem. In a hilly area, there is often no horizontal plane which can be chosen such that the static correction will be small everywhere, and, unless the total static corrections are small, the static errors will not necessarily be small. In hilly areas, it may be necessary to make a smooth contoured datum surface which is nowhere so far away from the shot that the static correction exceeds 20 ms. In this way, we hope to reduce static errors to the order of 2 ms, at which point the computer may take over.

Occasionally apparent static problems occur which are no function of timing errors. Fig. 20 shows one of these. There is an apparent statics jump in the middle of the section. When the polarity of the right-hand side is reversed, the two sides appear to match quite well (fig. 21). We have evidence to believe that phase shifts such as this can occur when stringers in the near-surface layers come and go.

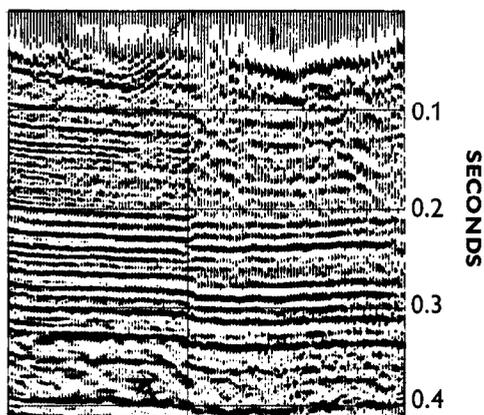


Fig. 20. An apparent statics jump caused by trapped reverberations in the near surface.

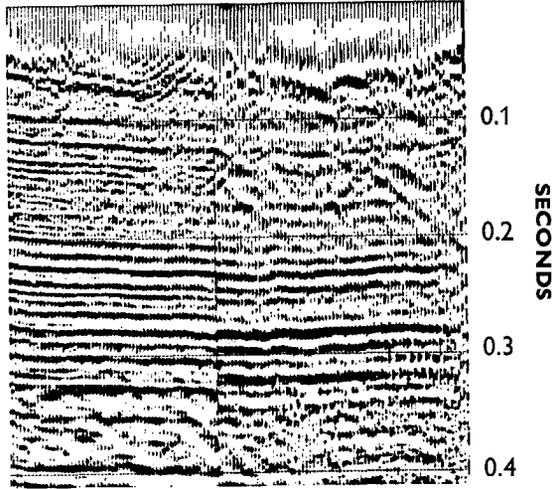


Fig. 21. Same as fig. 20 with reverse polarity on righthand side.

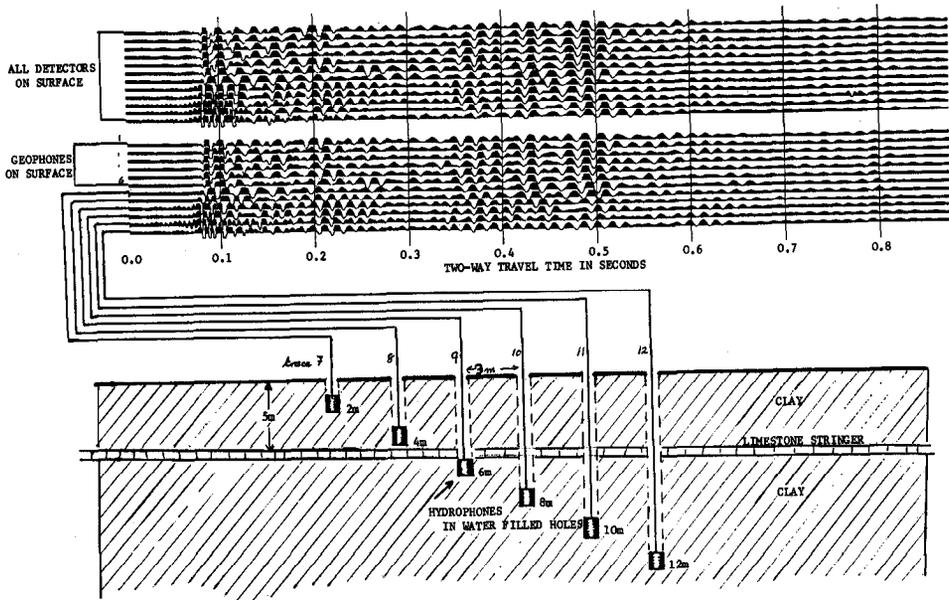


Fig. 22. The effect of a limestone stringer in the near surface upon the phase of deeper events.

Fig. 22 shows the result of an experiment which was carried out in the prospect where the phase-shift occurred. Six holes were drilled in an area where a limestone stringer with thickness of only about 5 cm was known to be embedded in the clay at a depth of 5 m. The holes were spaced 10 m apart and drilled progressively deeper so that the hydrophones could be made to straddle the stringer as illustrated at the bottom of the fig. 22. The lower monitor record shows, on the first six traces, the output from a control geophone (not shown) planted next to each of the holes; the remaining six traces are from the hydrophones as indicated. Notice that there is an abrupt phase change from the hydrophone at 6 m followed by a reasonably good duplication. There is clearly a big difference between the responses above and below the limestone. This indicates the presence of trapped reverberation between the stringer and the free surface. Just to be certain that the phase shift was due to the stringer alone, the record was reshot with all the hydrophones lifted to the 2 m level. This monitor is shown at the top of fig. 22. The phase duplication is now acceptable across the record at 0.4 s and 0.5 s.

It should be noted that phase shifts of this kind can occur anywhere, in conventional seismic reflection as well as in high resolution work.

7. PRODUCTION SECTIONS

The ideas in the early sections of this paper have been put into practice on a production basis. One very important line which was shot as part of a

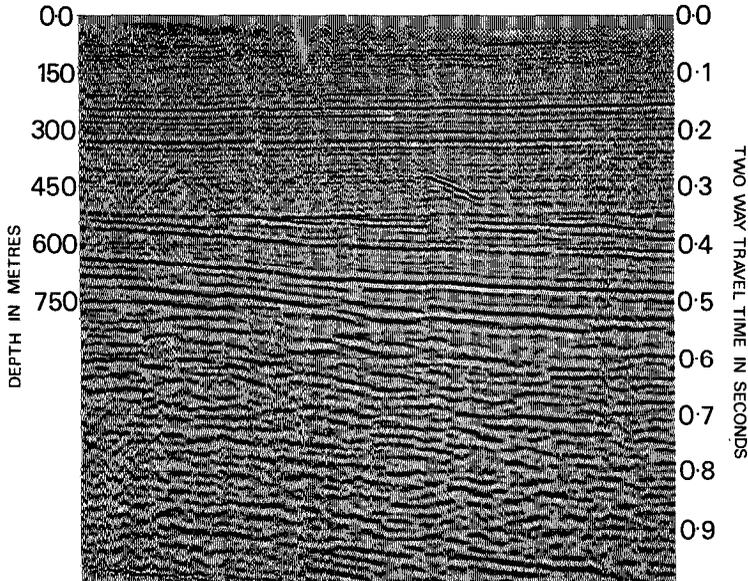


Fig. 23. Production section in the Vale of Belvoir obtained with 0.12 kg ($\frac{1}{4}$ lb.) charges, single geophones and 12 m between phones.

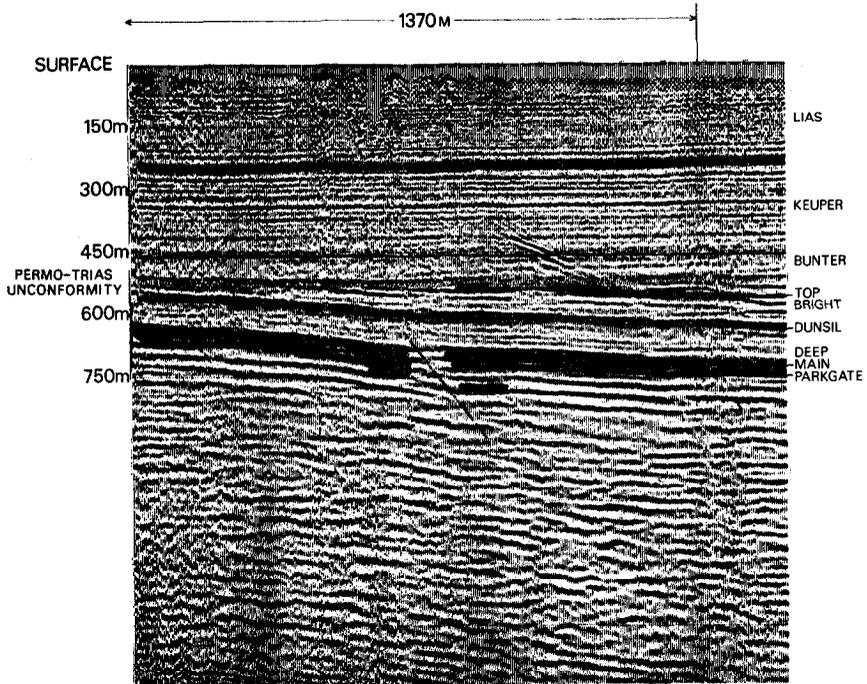


Fig. 24. Interpretation of fig. 23.

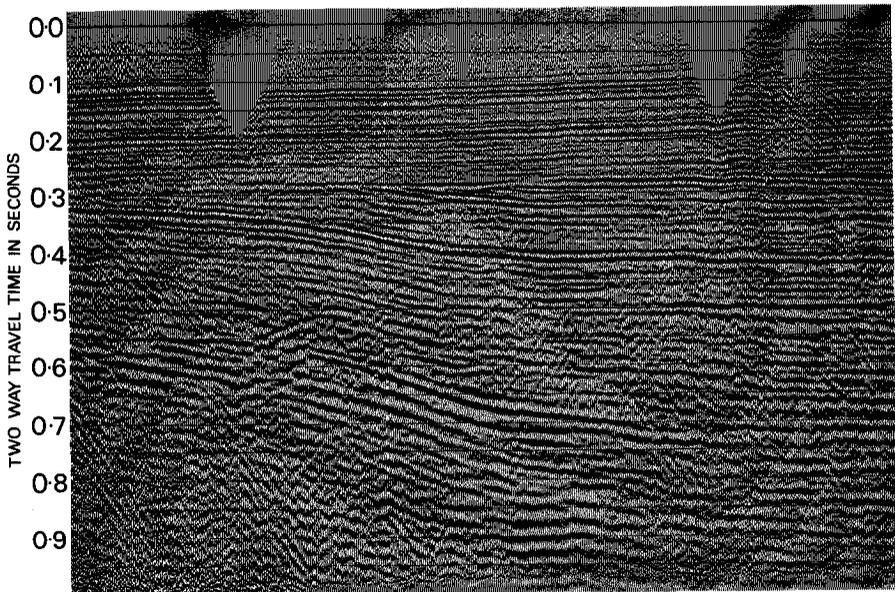


Fig. 25. Typical production section obtained in East Midlands, 1976, using 0.12 kg ($\frac{1}{4}$ lb.) charges, single geophones and twelve fold stack.

survey for a possible shaft site is shown in fig. 23. The line was shot twenty-four fold with a 12 m geophone interval. Shots (0.12 kg) were placed below the weathering and the uphole time at each shot was measured. The static corrections were very accurate.

The interpretation of this line is shown in fig. 24. A borehole on the line at the right-hand edge of the section has enabled the four main coal seams to be identified, and the reflections corresponding to those seams have been marked. An important small fault in the middle of the section at about 500 ms clearly affects the two lower seams, the Deep Main and Parkgate. The throw of this fault is about 5 m.

Finally, a twelve fold production section from another area is shown in fig. 25. This was shot using three shots per hole recorded separately: two detonators followed by 0.12 kg of dynamite. This is the dynamite section. This is typical of the quality and resolution obtainable in this area when the techniques discussed above are employed.

8. CONCLUSIONS

Our approach to designing a high resolution seismic profiling system for coal exploration is, basically, very simple. The ideas we employ are not new. At no point do we require special equipment or special techniques, and we have by no means explored all the possibilities that are available in the field when using small charges of more than one size in each hole.

Nevertheless, with this approach and with some care taken in the field, we have demonstrated that great detail is obtainable in coal measures at depths in excess of 800 m. This detailed structural information allows new mines and new developments of existing mines to be planned in such a way as to avoid major geological disturbances likely to cause excessive financial losses in mining.

It should be recognized that the objective of seismic surveying for coal is not merely the avoidance of large face-stopping disturbances which cost of the order of £ 1 million. The principal aim of far greater value, is to achieve the maximum percentage extraction of coal by constructing a mine which is the best fit to the geology. Clearly, a best fit is unlikely to be achieved if the mine is designed before the geological structure is known.

Finally, we should like to point out that although our approach is quite straightforward in conception, to carry it out in practice is not always easy. The seismic requirements of the coal industry are different from those of the oil industry, because the problem is to get the coal out, not to find it. Many of the ideas discussed in this paper, although not new, are often in direct conflict with the normal approach to conventional surveys for oil or gas—for example, the absence, in the National Coal Board work, of preliminary noise

spreads and geophone arrays. Therefore, to have the work carried out enthusiastically, as it has been, it is vital to convince all the people concerned with the data acquisition that the changes in field technique described above are essential. This is a non-trivial task.

ACKNOWLEDGEMENTS

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APPENDIX I

RADIUS OF EQUIVALENT CAVITY IS PROPORTIONAL TO CUBE ROOT OF MASS OF CHARGE

The total energy E_T stored in an explosive of given chemical composition is proportional to its mass. Thus

$$E_T = k_1 M \quad \text{AI(1)}$$

where k_1 is a function of the chemical composition of the explosive. Let the fraction of this energy which is converted into elastic waves in the medium be β for a given medium. Thus the energy E_E contained in the elastic radiation is

$$E_E = \beta k_1 M \quad \text{AI(2)}$$

where, invoking our second assumption (b), we note that β is a constant, independent of M . It follows that the energy E_A not converted into elastic energy—that is, all the energy absorbed by the sphere of radius a —is given by

$$E_A = (1 - \beta) k_1 M. \quad \text{AI(3)}$$

The volume $4/3 \pi a^3$ of the sphere of anelastic deformation is very large compared with the volume of explosive, and the capacity of the material in

it to absorb energy through anelastic deformation is proportional to its volume. Therefore

$$E_A = k_2 \cdot 4/3 \pi a^3, \quad \text{A1(4)}$$

where k_2 is a constant which depends on the ability of the material to absorb the energy of anelastic deformation.

It follows from equations A1(3) and A1(4) that

$$a = K M^{\frac{1}{3}}, \quad \text{A1(5)}$$

where $K = [3(1 - \beta) k_1 / (4 \pi k_2)]^{\frac{1}{3}}$.

APPENDIX 2

THE ENERGY IN THE ELASTIC RADIATION

The elastic energy which travels across the surface of an imaginary sphere of radius r in the far-field of the explosion and with the center at the detonation is given by

$$E_E = \frac{4 \pi r^2}{\rho c} \int_0^{\infty} p^2(t) dt \quad \text{A2(1)}$$

where $p(t)$ is the incident pressure, ρ is the density of the medium and c is the longitudinal wave velocity. Substituting for $p(t)$ from equation (2) into A2(1), we have:

$$E_E = \frac{4 \pi a^2}{\rho c} \int_0^{\infty} f^2(\tau/a) d\tau, \quad \text{A2(2)}$$

where $\tau = t - (r - a)/c$, and a is the cavity radius. If we substitute $s = \tau/a$ into this equation, we find:

$$E_E = \frac{4 \pi a^3}{\rho c} \int_0^{\infty} f^2(s) ds. \quad \text{A2(3)}$$

However, since s is simply a dummy variable, we can let $s = t$ (time) to yield:

$$E_E = \frac{4 \pi K^3 M}{\rho c} \int_0^{\infty} f^2(t) dt, \quad \text{A2(4)}$$

where we have substituted for a from equation (1).

Since $f(t)$ is independent of M we have demonstrated that the energy in the elastic radiation of Sharpe's (1942) model or Blake's (1952) model is proportional to M , if the cavity radius a is proportional to $M^{\frac{1}{3}}$. This is consistent with our second assumption.

APPENDIX 3

EFFECT OF CHARGE SIZE ON BANDWIDTH

Consider the Fourier transform:

$$F(s) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i s t} dt. \quad A3(1)$$

Let $t = \tau/M^{\frac{1}{2}}$ and $s = \nu M^{\frac{1}{2}}$. Then

$$M^{\frac{1}{2}} F(M^{\frac{1}{2}} \nu) = \int_{-\infty}^{\infty} f(\tau/M^{\frac{1}{2}}) e^{-2\pi i \nu \tau} d\tau. \quad A3(2)$$

Multiplying both sides by $KM^{\frac{3}{2}}/\gamma$, we find

$$(KM^{\frac{3}{2}}/\gamma) \cdot F(M^{\frac{1}{2}} \nu) = \int_{-\infty}^{\infty} (KM^{\frac{3}{2}}/\gamma) f(\tau/M^{\frac{1}{2}}) e^{-2\pi i \nu \tau} d\tau \quad A3(3)$$

Equation A3(3) is the equation of the Fourier transform of our pulse obtained from equation (3). It shows that the absolute spectral bandwidth of the pulse is inversely proportional to $M^{\frac{3}{2}}$ and that the amplitude of the spectrum of the pulse is proportional to $M^{\frac{1}{2}}$.

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