IN-SEAM SEISMIC EXPLORATION TECHNIQUES

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Introduction

It was about 1960 when I was told about the difficulties arising in the working of coal in deep mines if the seams are interrupted by small faults or other minor irregularities. I was asked whether reflection seismics, carried out at the surface of the earth or within the mines using normal seismic body waves, could detect faults with a throw of say 3 to 6 feet (1 to 2 meters) only. Of course, I had to negate this question. In reflection seismics from the earth's surface the smallest possible wave lengths would still be far too long (Figure No. 1) . In fact, they are about 120 to 160 feet (40 to 50 meters), and body waves produced and observed underground within the mines at a face or in a gallery would have bad chances of being efficiently reflected from a fault plane, because reflected energy would only arise from the narrow strips where coal is adjacent to country rock, and this would only be a small percentage of the fault plane (Figure No. 2). Only unhealed fractured zones in the vicinity of the fault plane would improve the reflectivity as a whole.

After having studied the physical properties of coal and rock a little, I realised that coal has a low velocity and low density, as compared to the country rock, at least in the Ruhr area, and it

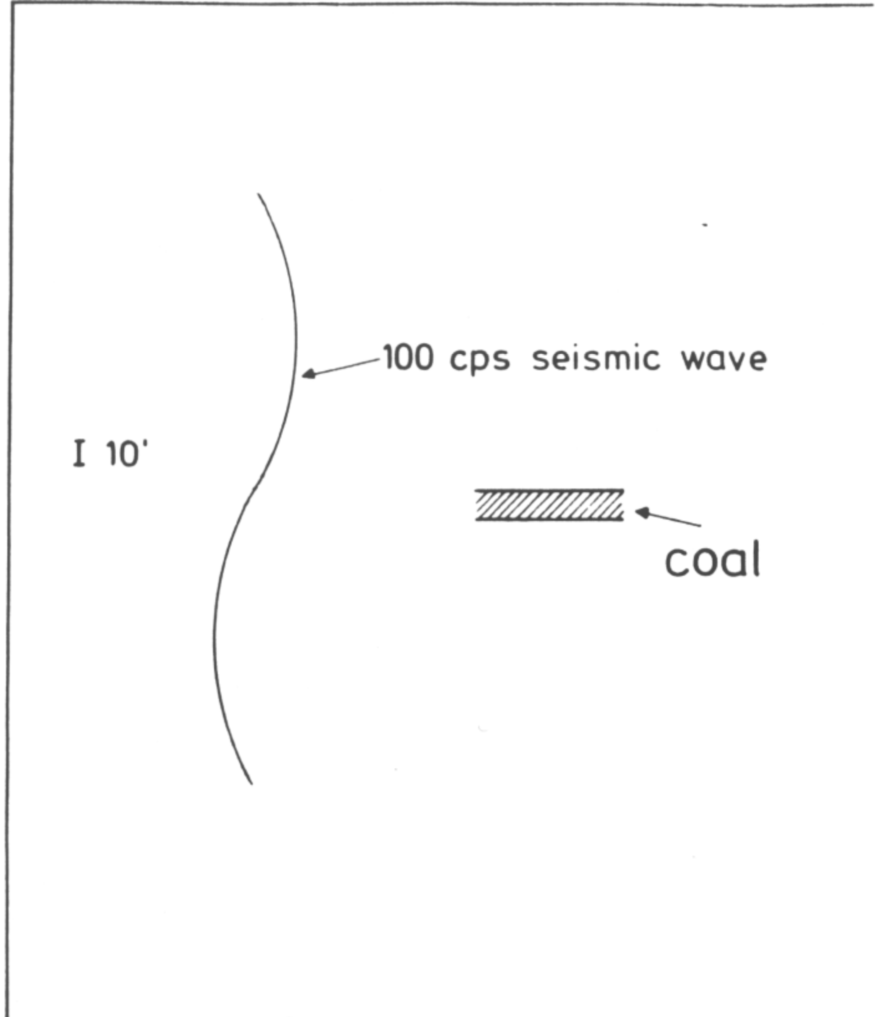


Figure No. 1

Comparison of the dimensions of a typical Ruhr area seam and a 100 cycles per second seismic wave originating from a shot at the surface.

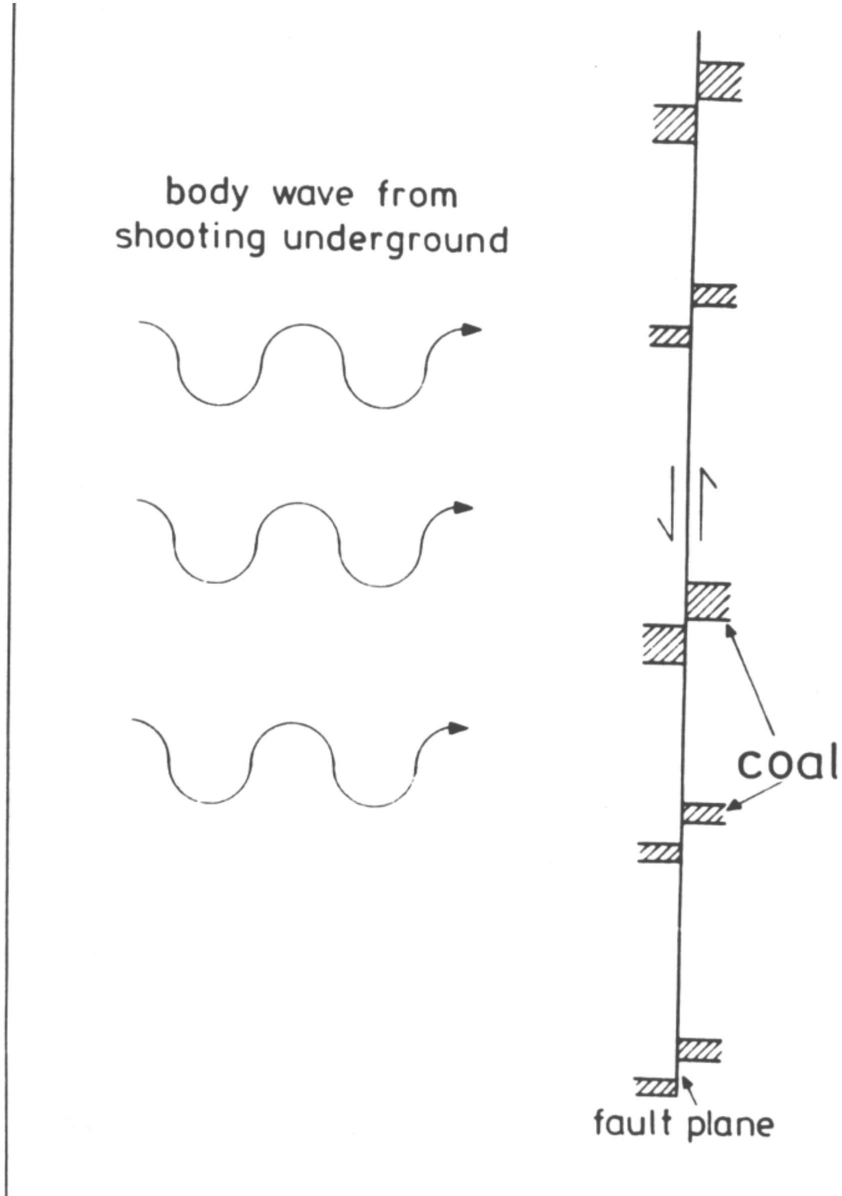


Figure No. 2

Typical distribution of seams on both sides of a fault plane of minor throw. Total thickness of seams is about 10 percent of total rock thickness.

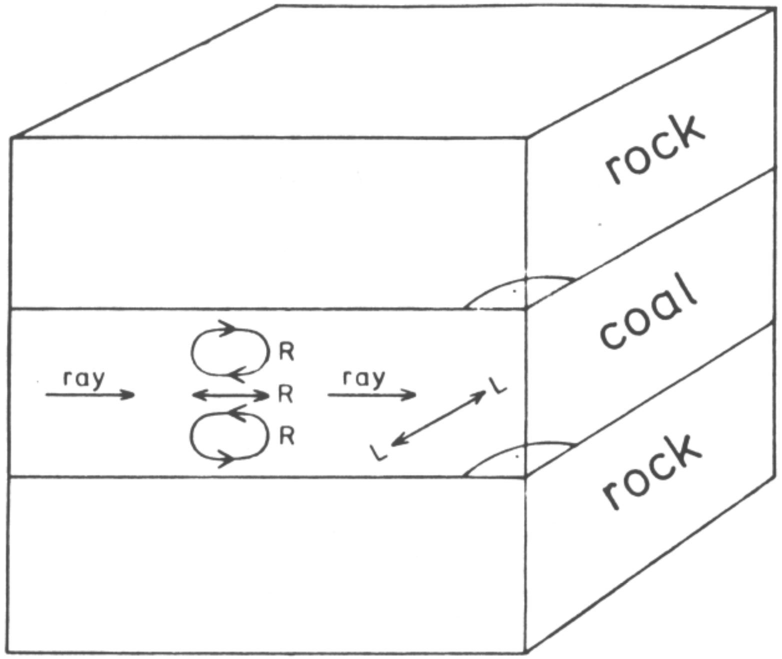


Figure No. 3

Movement of particles in the case of Love-type seam waves (L) and Rayleigh-type seam waves (R) .

occurred to me that a coal seam should be a wave guide, at least for waves of Love type, where rock and coal particles move parallel to the seam and perpendicular to the direction of the rays, i.e. the moment occurs within the wavefronts, which are vertical to the seam and to the rays (Figure No. 3).

Such guided waves have their largest amplitudes in the seam. In the adjacent rock the amplitudes decay exponentially with the distance from the seam. This decay depends on the wave lengths, on the frequencies as can be seen in Figure No. 4, which refers to the so-called fundamental symmetrical mode. This mode is the most important one in the following. Obviously, the higher the frequency the more rapid is the decay. This involves another important fact in the percentage of energy within the seam increases with the frequency. Another important feature of guided waves is dispersion (Figure Nc which results in typical long wave trains as a response to short imps sources (1) .

There is still another type of waves guided in seams, i.e. the Rayleigh type (Figure No. 4). In this case rock and coal particles move in a plane perpendicular to the seam and to the wave fronts. These waves have similar qualities as those of Love type as far as dispersion and exponential decay of amplitudes off the seam are concerned. But genuine guided waves of Rayleigh type, i.e. so-called non leaking modes which do not permanently lose energy into the country rock, can only exist when the shear wave velocity of the country rock exceeds the dilatational velocity of the coal, and this condition is not always fulfilled (2).

Period of Tests

My feeling at that time was: Waves guided by a seam, or simply seam waves, should be reflected by faults more effectively body waves because the percentage of energy in the seam is much higher in the case of seam waves.

A series of underground test surveys in mines was agreed up first with Tasch, Rheinstahl, then with Kneuper, Saarbergwerke, finally with Brentrup, Steinkohlenbergbauverein, Essen. The second test ordered by Saarbergwerke and carried out with governmental financial assistance first proved the existence of seam waves, and reflected such waves could be observed too (Figures Nos. 6, 7)

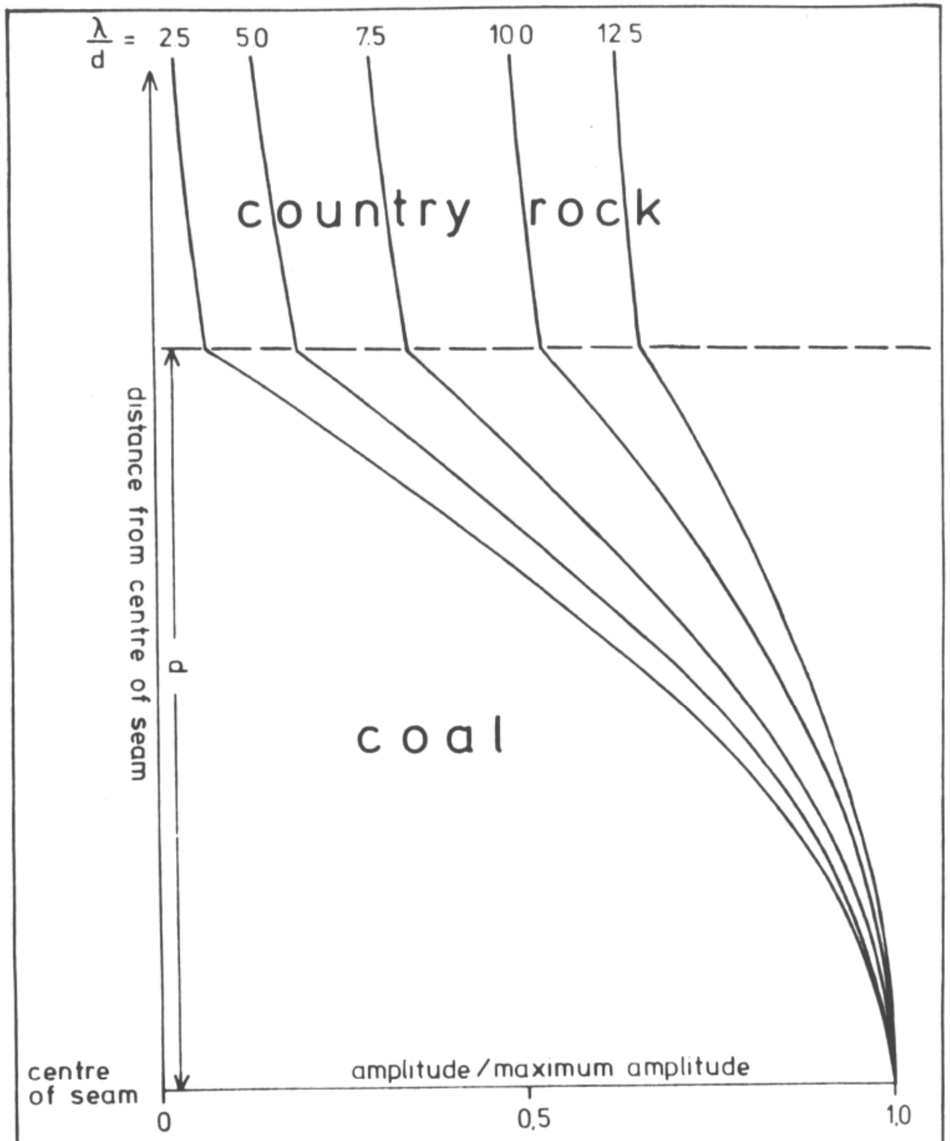


Figure No. 4

Relative amplitudes of seam waves of the Love-type fundamental symmetrical mode for various wave lengths λ .
d = half seam thickness.
Ratio of velocities 1 : 2.
Ratio of densities 1 : 2.

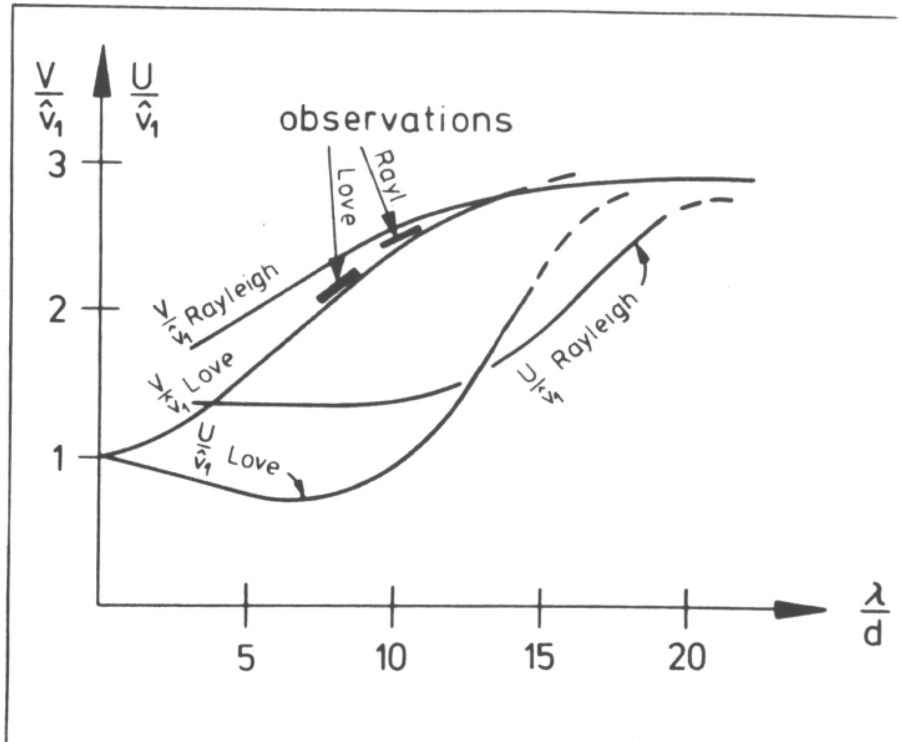


Figure No. 5 (from(1))

Dispersion curves of seam waves of fundamental symmetrical mode.

λ	=	wave length
d	=	half seam thickness
V	=	phase velocity
U	=	group velocity
$\hat{v}_1$	=	shear velocity in coal

ratio of coal to rock density 1.1 : 2.6
ratio of coal to rock velocity 1 : 3
Poisson's ratio = 0.25.

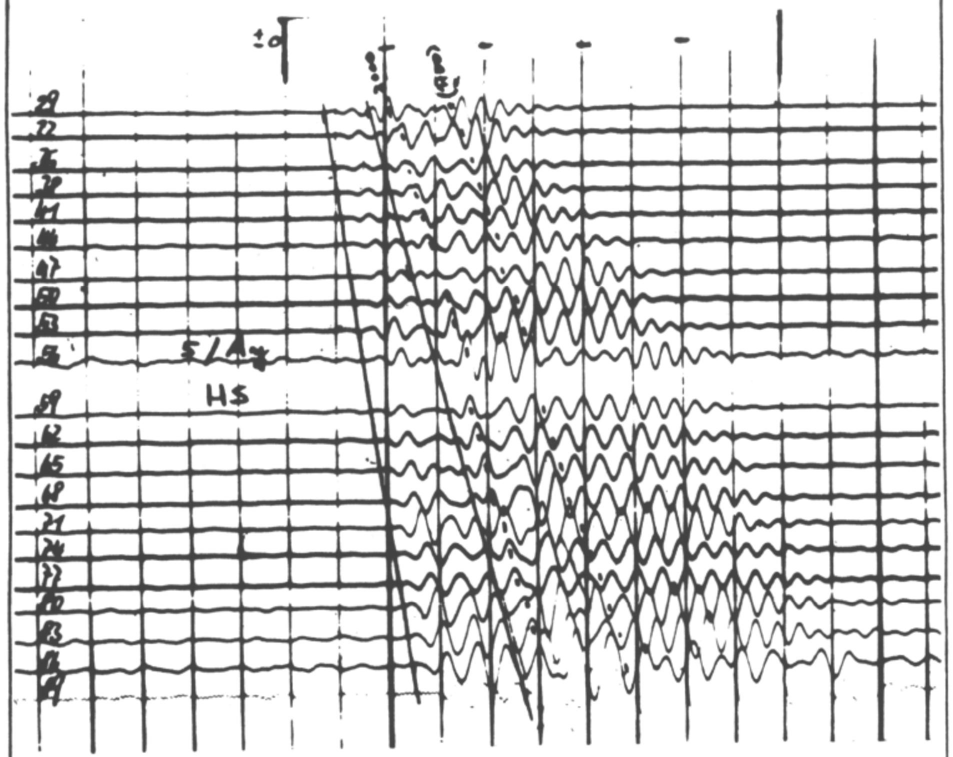


Figure No. 6 (from (1))

Love-type seam waves resulting from a hammer blow.

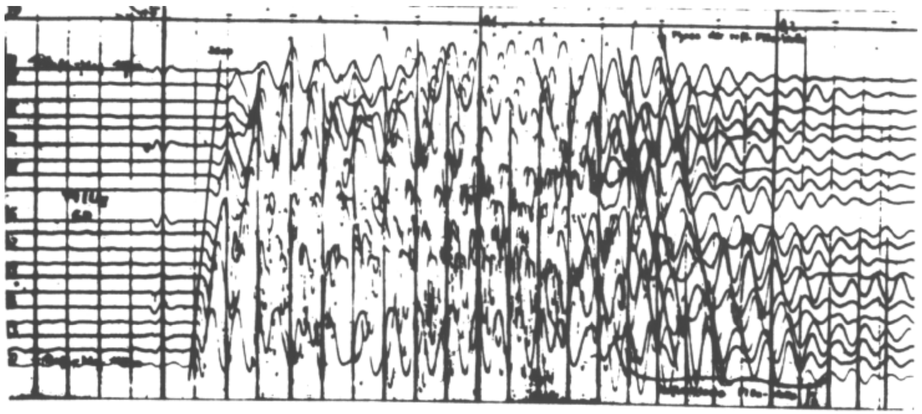


Figure No. 7 (from (1))

Dynamite shot with first observed reflected Love-type seam wave.

(3), (1), (4). Therefore it was decided to build a recording unit which could be testified to be fire-damp proof. Much to our regret this took several years. But then, in 1966, we could start the 3rd series of tests in the Ruhr area by order of Steinkohlenbergbauverein, also financially assisted by the government. Seam waves and reflected seam waves could be observed in most cases. Agreement between predicted and observed faults was 66 percent according to Brentrup's investigations (5). This means, interpreted reflections were counted positive when they coincide with a fault which lies within an errorzone of + one wave length. All others and missing reflections at a place of fault were counted negative provided the throw of the fault was at least about equal to the thickness of the seam. Distances from the site of measurement which exceeded 100 times the thickness of the seam were excluded from this comparison. The result of 66% was quite encouraging, but not perfectly satisfying.

Very soon it was found out that seam waves could be used in yet another manner, i.e. as transmitted waves (Figure No. 8) ;(5), (6). In case an area of seam, planned for being worked is partly surrounded by either two parallel galleries or by a working face and a gallery more or less at right angles, the continuity of seam waves transmitted through this area can be checked. Seam waves are not observed or become very weak when a fault displaces the seam between source and receiver by an amount greater than or comparable to the seam thickness. The percentage of positive predictions of faults by transmitted seam waves was 83 as stated by Brentrup (5) . This was still more encouraging than the reflection results.

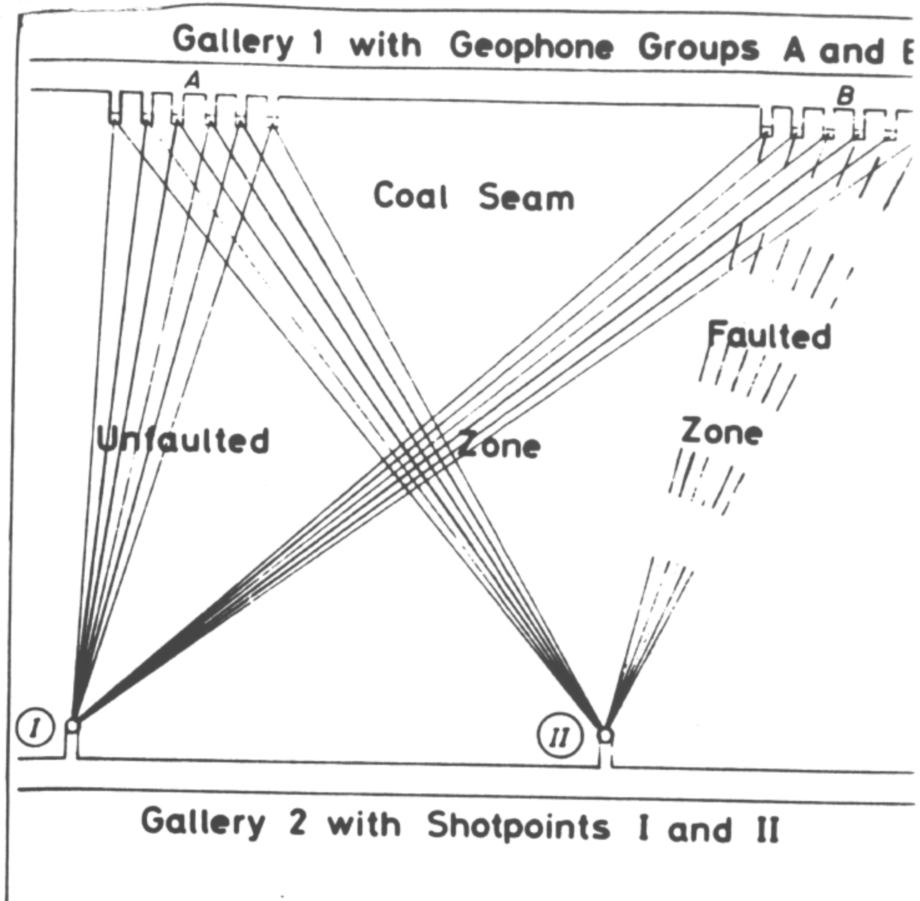


Figure No. 8

Principle of transmission surveys.

No seam waves pass through the faulted zone.

Routine Surveys

As a consequence of these tests some 250 routine surveys have currently been carried out underground in many mines in France, Great Britain and Germany since 1967 by SEISMOS GmbH and PRAKLA-SEISMOS GmbH. Both, reflected and transmitted seam waves were used for these investigations ahead of face (5) , (6) , (7).

Before presenting to you some case histories of this activity the main technical details of this seam-wave method should be outlined in short

The seismic source is normally a shot fired in a hole drilled to a length of 6 to 10 feet (2 to 3 meters) in the centre of the seam and parallel to the seam. In preference explosive of low detonation velocity is used. But also hammer blows upon a bar put into the "shothole" are effective in many cases. Pairs of moving coil geophones of a natural frequency of about 27 cycles per second are also planted in holes in much the same way as the shots. They are sensitive for two directions parallel to the seam but perpendicular to each other. Thereby it is possible to discriminate between the various kinds of waves observed, e.g. whether they are of Rayleigh or Love type.

The recording unit (Figure No. 9) used hitherto has 24 amplifiers, and wiggle trace paper seismograms are produced by an oscillograph of 24 traces. Frequency range is up to 500 cycles per second, and 5 high and 5 low-cut filter settings are possible with 2 slopes . No magnetic recording, either analogue or digital, was used due to the difficulties in making such equipment fire-damp proof and due to the lack of commercial availability of smaller sampling rates than 1 millisecond.

In Figure No. 10 you see the interpretation of a seam-wave survey using reflected waves, mainly of Love type. The faults encountered when working the coal agreed pretty well with the locations of the reflecting planes. This includes the splitting of the extended fault running nearly parallel to the gallery of measurement. Reflections from this fault zone are partly masked by other reflecting faults.

In certain mines of northern France working of coal can be seriously impaired by a special kind of washouts called "puitsnaturels". Here predictions by transmitted seam waves were quite successful. According to Figure No. 11 an area of seam planned for being exploited was nearly completely surrounded by roadways. Thus, the transmission method could well be applied. In this figure the space between shot-point and geophones is bounded in different manners according to the quality of the transmitted seam waves observed. Straight lines stand for good, dashed lines for fair, dotted lines for questionable to not observed. Areas through which good to fair transmitted waves never passed point to serious discontinuities of the seam, either to faults with a throw comparable to the seam thickness or higher or to "puitsnaturels" as in the present case. Such areas are indicated in Figure No. 11 by heavy and minor dotting. Figure No. 11 shows too that the exploitation of the area really encountered 2 "puitsnaturels", as indicated by hatching and N.Sch., at about the predicted locations. Here, too, the seam waves used for interpretation were mainly of Love type (8).

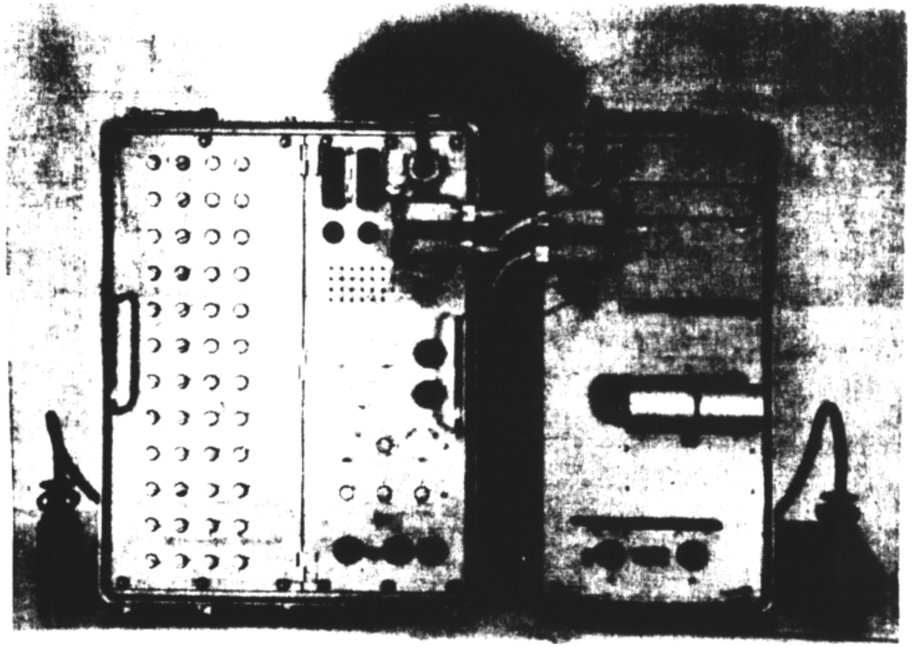


Figure No. 9

Fire-damp proof seismic recording unit GSU, constructed by SEISMOS GmbH.
Left side module of 24 amplifiers, right side oscillograph.

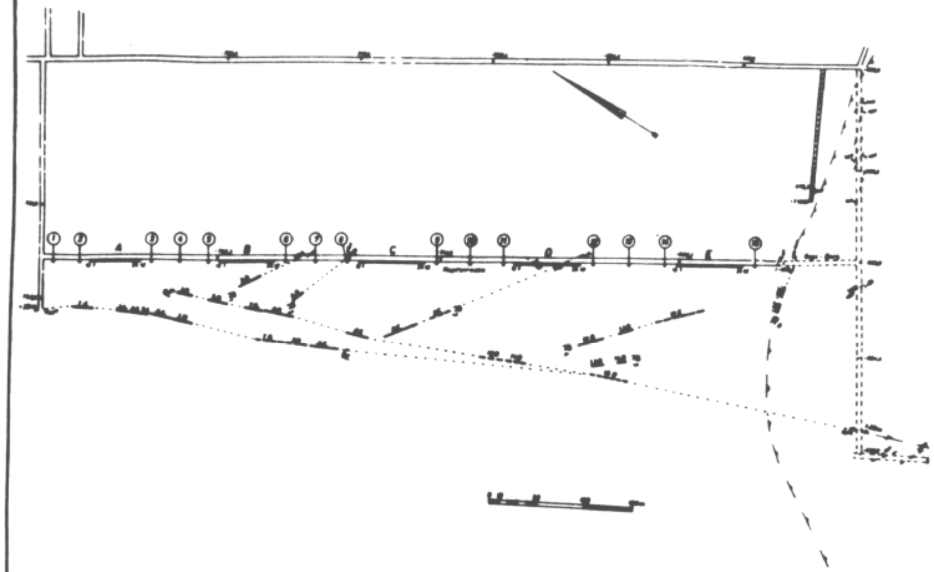


Figure No. 10 (from (6))

Exploration of a zone ahead of face by reflected seam waves. As to details see text.

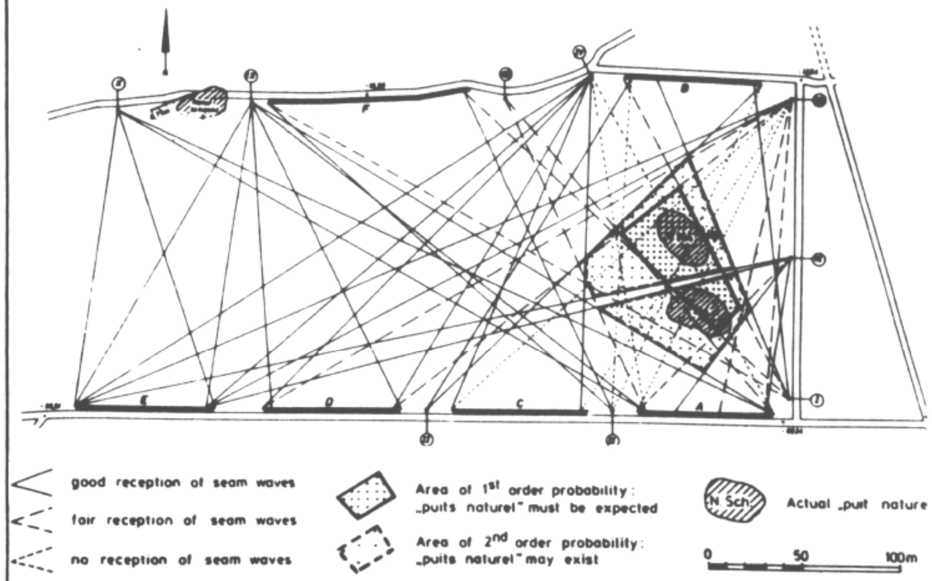


Figure No. 11 (from (6))

Exploration of a seam area by transmitted seam waves using three road ways.

Figure No. 12 presents an example of a combined reflection and transmission survey. In the left part of the figure several reflections detected a fault which proved to be an overthrust with a throw decreasing towards the right. Obviously the transmission of seam waves to spread C was impaired to a certain degree. Here, the throw of the fault mentioned sti I I comprises about ha 1 f the th I cknes s of the seam,

Transmission of guided waves cannot only be used from gallery to gallery or from gallery to face, but also from a hole to a face or from hole to hole. Several years ago we carried out a transmission survey in the Saar region from a hole to a gallery (9) . The hole had been drilled from the surface to a depth of about 3700 feet (1100 meters). The gallery was at a distance of ~ 4000 feet (1200 meters) from the hole and at a depth of about 2500 feet (750 meters). A seam encountered at the bottom of the hole was believed to be identical with that which was worked at the face. Shooting was carried out in the hole and geophones had been planted in the gallery in such a manner that the reception of Love type guided waves was favoured. Some geophones, however, were enhancing Rayleigh-type waves for comparison purposes. The result of the survey was that a pronounced transmission of guided waves could be observed. The upper part of Figure No. 13 shows a transmission seismogram shot in the rock of the borehole about 100 feet (30 meters) above the seam. No seam waves of appreciable amplitude can be recognized. In the second seismogram the shot was fired in the central part of the seam. Seam waves of Love type appear pretty well between 525 milliseconds and 650 milliseconds in spite of a considerable amount of noise. For comparison purposes you **see** in the lowest part of Figure No. 13 how seam waves look at corresponding distances when transmitted from gallery to gallery through a fault-free part of the same seam.

Thus it could be concluded with a high degree of probability that the seam in the hole and the seam in the gallery were identical and that no faults would interrupt the continuity of the seam between the two locations. In the meantime this conclusion has been proved by the mining activity, but by the way, when proceeding beyond the hole without applying any additional geophysical measurements a bad fault **was** struck which gave the miners some serious problems due to water invasion. The fact that guided waves did not appear when shooting in the country rock at a certain vertical distance from the seam (Figure No. 13 upper part) agrees well with result of the doctor thesis of Guu (10).

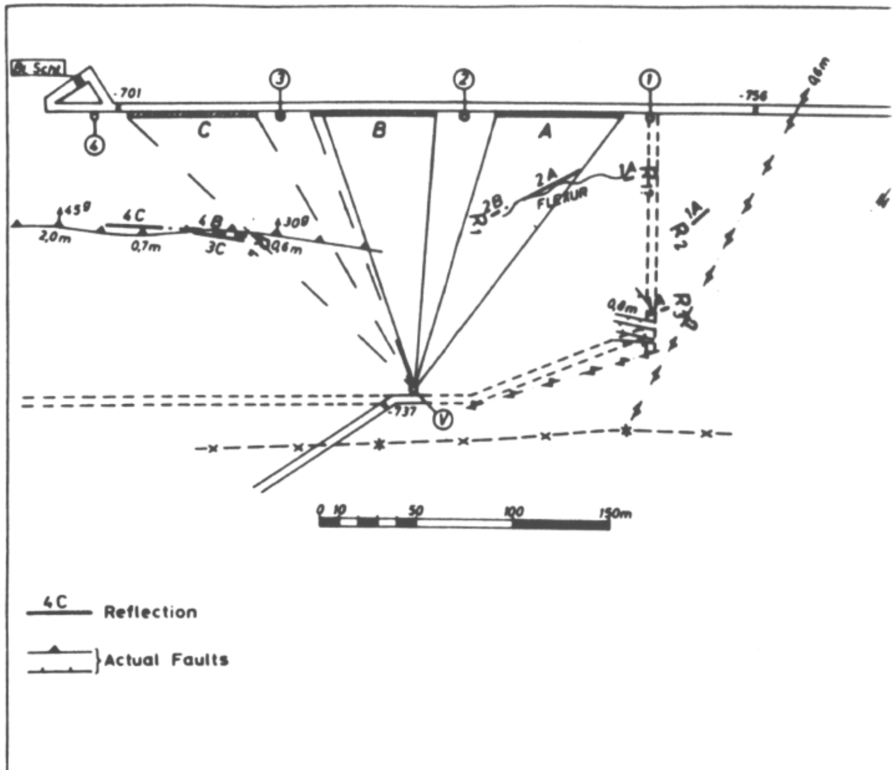


Figure No. 12 (from (6))

Combined reflection and transmission survey.
As to details see text.

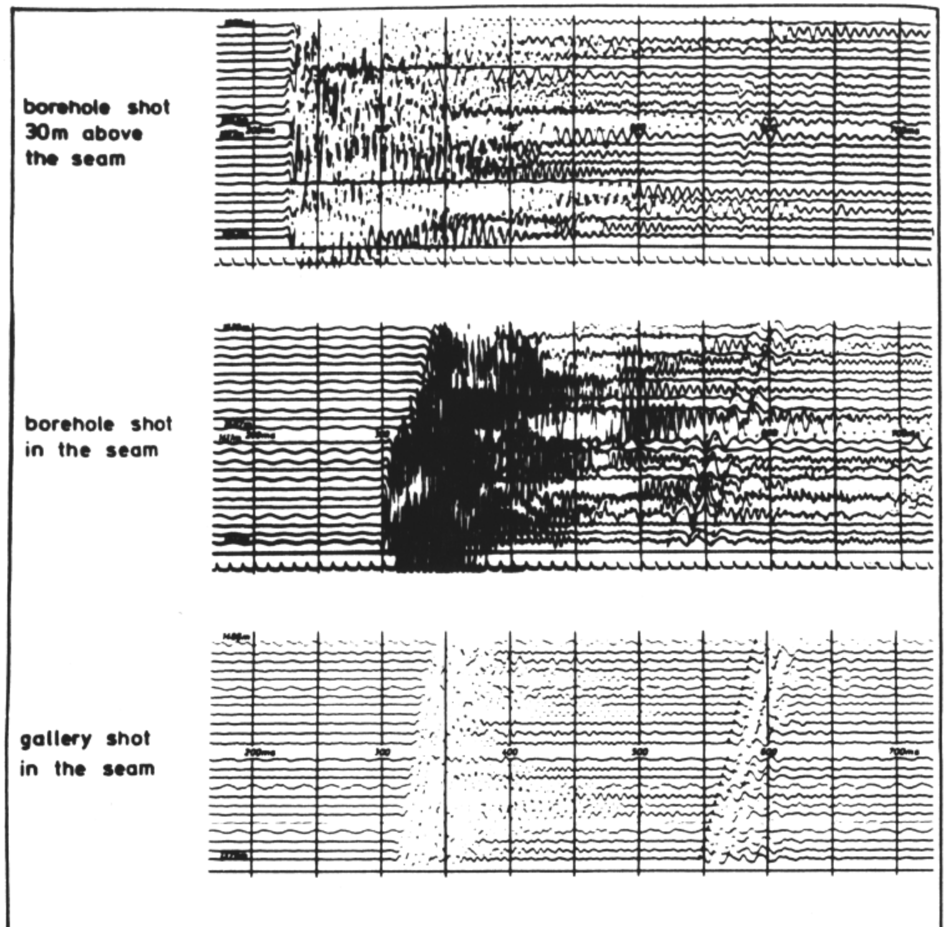


Figure No. 13

Various transmission records.

Geophones in the seam of a gallery.
Uppermost record shot in a borehole from about 100 feet (30 meters) above the seam. Central record shot in the same borehole from the central part of the seam.
Lowest record shot in a gallery from the central part of the seam.

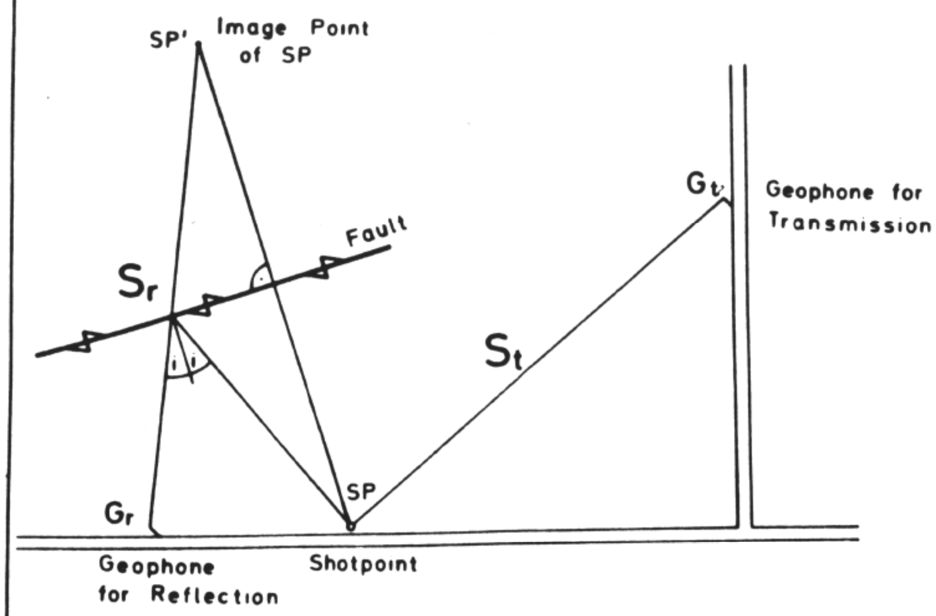
<u>Some Problems Connected with the Method</u>

After having realized the merits of seam waves in the planning, of the exploitation of coal, we now draw our attention to deficiencies and limits of the method, and then we shall discuss what is going on an what can still possibly be done to improve the method.

When assessing the precision of any seismic method we have first of all to consider the effects of diffraction, which depend mainly on the wave length. According to our observations these wave lengths are of the order of 20 to 80 feet (6 to 25 meters). This implies uncertainties in the positioning of discontinuities of the seam of about a similar order of magnitude, though there is always an important dependence on the geometry of the special case at hand too.

Another problem arises from the dispersion of guided waves, i. the velocity of seam waves is a function of frequency. Therefore it is difficult to determine a precise arrival time for transmitted and reflec seam waves, and the question is : which velocity has to be attributed it. One approach to the problem is deconvolution as favoured by our British colleagues (personal communication of Clarke , National Coal Board (NCB)). Arnetzl and myself (11) tried to crosscorrelate transmitted and reflected seam waves with each other provided that both events have approximately the same traveltime. The small difference of the traveltimes should then be equal to the time delay at which the maximum crosscorrelation value occurs. The length the reflected raypath S_r (Figure No. 14) would then be equal to the length of the transmitted raypath S_t augmented by the product of the time delay -r just mentioned and the velocity V, but now this velocity must be known approximately only because it is multiplied with a rather small time delay. Therefore any average phase $velocity_{phase}$ can be used. Of course, such processing presupposes digital recording for routine application. An additional advantage of such a procedure is that it should also improve the recognisability of reflected seam waves because it is nothing else but matched filtering. A drawback is that transmitted seam waves must perhapt additionally be observed at the desired distances, as indicated in Figure No. 14.

We could test this crosscorrelation method at some sites of the Ruhr area, partly after digitizing paper records, which is rather trouble some, partly after digital recording at a place free of CH_4-gas, but this was with a sampling rate of 1 millisecond only. The results were



$$S_r = S_t + \tau_{max} \cdot \bar{V}_{phase}$$

S_r	length of reflection ray path
S_t	length of transmission ray path
τ_{max}	time of maximum crosscorrelation amplitude
$\bar{V}_{phase}$	average phase velocity

Figure No. 14 (from (11))

Determination of the lengths of reflection ray paths by means of cross-correlation.
For details see text.

partly encouraging (Figure No. 15) and partly not too promising. The reason is probably a considerable frequency dependence of the reflected energy of seam waves as proved explicitly with the help of physical models by Dresen (12) . Thus, crosscorrelation can probably become more effective when combined with additional filtering by which the reflected energy is enhanced.

We shall now give some more consideration to the reflected energy as a function of frequency. Let us suppose that a seam ends at a major fault and that discontinuous physical properties are only occurring where the seam ends and nowhere else at the fault plane. Then it is quite suggestive that the percentage of reflected energy is mainly dependent on the percentage of energy travelling within the seam, and this percentage increases with frequency as mentioned earlier (Figure No. 4). On the other hand, the attenuation of seismic waves is frequency dependent too, higher frequencies show stronger attenuation than lower ones. Thus, both effects act in opposite direct resulting in an optimal frequency range for reflected seam waves. Thi optimal frequency range is, of course, dependent on the length of th4 reflection ray path, i.e. there is on unfavourable shift towards lower frequencies with increasing length of ray path. These facts are probak the main reasons why reflected guided waves could never be disceme(when the reflecting discontinuity, say fault, was farther away than 6(to 900 feet (200 to 300 meters) from the shot-geophone array, even with 3 geophones per trace and 3 hole shots. On the other hand fro mitted seam waves can be observed up to a considerable distance fron the source, say 6000 feet (2 kilometers). These observations refer 1.4 seam thickness of 6 to 8 feet (2 to 2.5 kilometers).

There is another point which calls for being improved, i.e. the source of seismic energy (11). The main useful seam waves are the fundamental mode of the symmetrical Love-type wave. But, with normal shooting in a single hole the percentage of this desired energy is small very often at the beginning. But we found out that subsequent shooting in holes at a distance of 2 to 3 feet (50 to 100 centimeters) from the first shot hole resulted in higher amplitudes of the Love-type seam wave probably because the first shot destroyed the cylindrical symmetry of physical properties around the second shot hole. This technique can o principal be extended to the enhancement of higher modes too, if desired. E.g. (Figure No. 16), when the first higher symmetrical Love type mode is to be enhanced, 3 holes for the production shot are arranged in a row perpendicular to the seam at those places where the am-

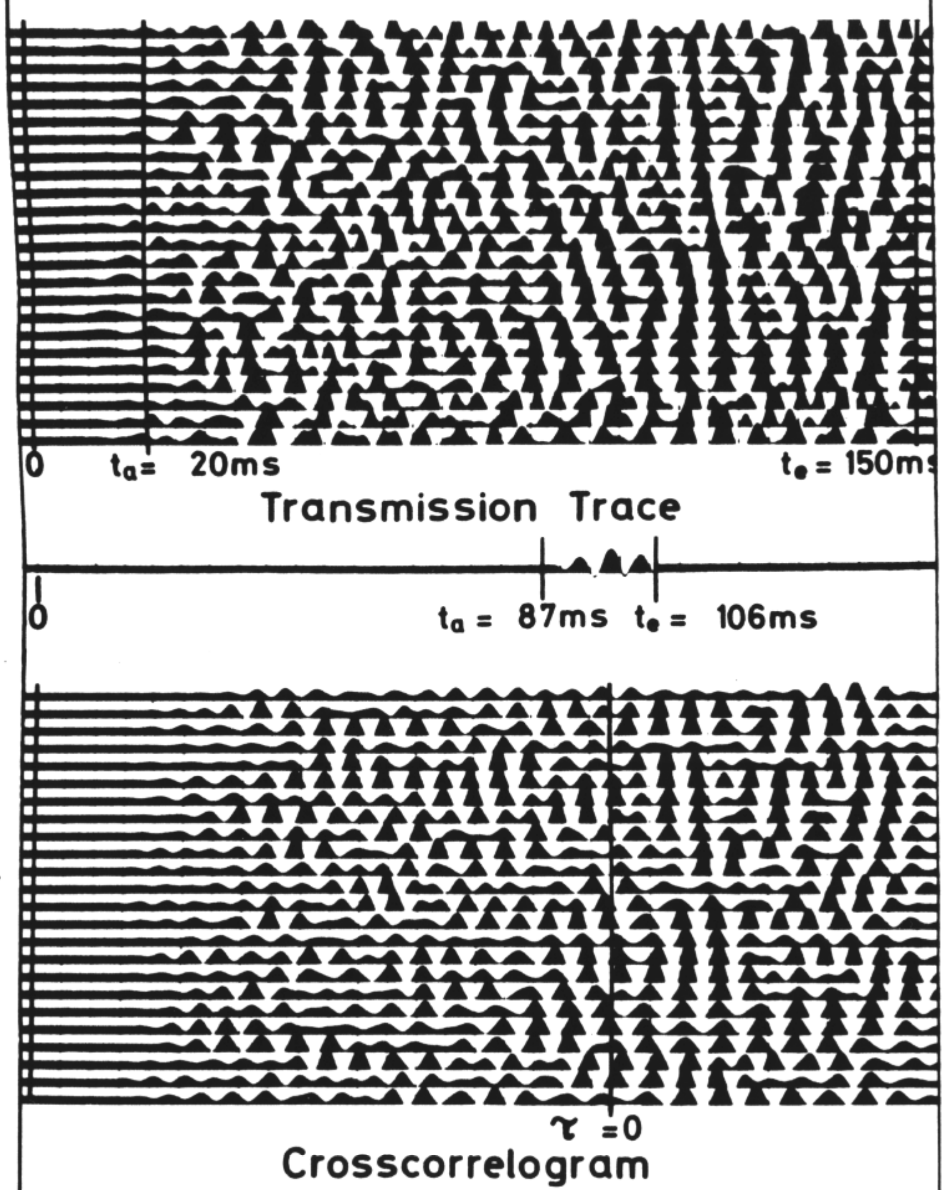


Figure No. 15 (from (11))

Cross-correlation of reflection traces with a transmission trace.

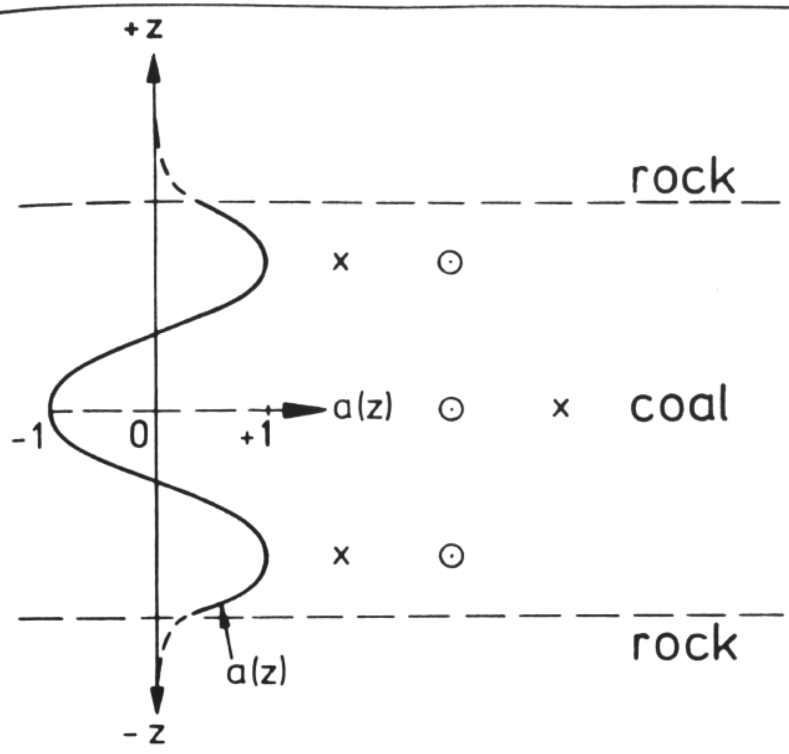


Figure No. 16

Enhancing the first higher Love-type symmetrical mode.

X = hole for preparatory shot

⊙ = hole for genuine production shot

a(z) = amplitude of desired mode as a function of the distance z from the centre of the seam.

plitudes of the desired first higher mode exhibit extreme values. Then 3 preparatory holes are drilled at the same distances from the centre of the seam as the production shot holes but with a lateral offset of say 2 feet (0.6 meters) applied alternatively to the left and right side of the production shot holes. After having shot the 3 preparatory holes with the purpose to produce the desired inhomogeneities the production shot should preferably produce the first higher mode.

Trends for Improving the Method

Now, what can be done and what has been done to improve the efficiency of the seam wave method ?

As to the detection of reflected waves it is obvious from the preceding considerations that digital recording with a sampling rate of 0.5 milliseconds or less is necessary for any progress. This unit must be fire-damp proof.

The National Coal Board in Great Britain was the first to build such equipment. The main features of this unit are preamplification, multiplexing and frequency modulation underground, transfer of the data by wireline to the surface of the earth with different carrier frequencies then analogue to digital conversion and digital recording in real time. It is possible to have a sampling rate of 0.8 milliseconds . (Personal communication of Clarke, NCB.)

In Germany the Steinkohlenbergbauverein at Essen started another development. A DFS V instrument from Texas Instruments, which enables the recording of 24 traces with a sampling rate of 0.5 milliseconds, is being made fire-damp proof by PRAKLA-SEISMOS GMBH, Hannover, and will probably be used underground in the autumn of this year (1976). This development is sponsored by the government of Nordrhein-Westfalen and the European High Commission.

The additional possibilities arising from the introduction of this digital equipment do not only comprise filtering and crosscorrelation, as mentioned earlier, but also horizontal and vertical stacking, two-dimensional, i.e. inseam, migration, migration-stack, deconvolution and many others. It is hoped that the signal-to-noise ratio can be

effectively improved for reflected seam waves and that the range of the detectibility of such waves can be increased from 600 to 900feet (200 to 300 meters) now to 1000 to 2000 feet (300 to 600 meters) in future. Much to our regret the demands of our mining clients have increased too in the meantime, i.e. to 3000 to 4000 feet (900 to 1200 meters). Experience will have to show whether this range can E reached by the reflection method in future. Anyhow such distances are within the range of observable transmitted waves.

Little has been done to improve the efficiency of the source. Hasbrouck from the US Geological Survey in Denver, and Guu, Colorado School of Mines, developed a mechanical device to enhance Rayleigh-type seam waves in vertical holes drilled from the earth's surface into a seam (13).

It would, of course, be very thrilling to use the Vibroseis method underground at the faces with vibrations parallel to the face and to the seam. The sweep could then be adapted to the range of maximum amplitudes of the reflected Love-type seam waves. The main difficulty would be to build such a vibrator and to make it fire-damp proof.

As to geophones a considerable progress has been achieved quite recently. Ruter of the Westfdlische Berggewerkschaftskasse in Bochum, Ruhr area, developed a two-component system measuring the total movement parallel to the seam. This system is planted in holes which are 2 meters long and parallel to the seam. The diameter of the hole has to be about 2 inches (50 millimeters). The geophone is clamped to the wall of the hole by compressed air. The improvement effected by the new system can be seen in Figure No. 17. We hope that this new geo phone and digital recording will render a considerable progress in the utility of the seam-wave method.

Rüter also carried out experimental investigations underground attributing much to understanding the nature of seam waves (14),(15)

I am very glad that much laboratory and mathematical research too has been carried out as to the topic of seam waves. This activity is still going on and will hopefully continue. I can only mention some of it.

Tests with physical models were carried out by Klusmann (16), Freysttitter (17) and Dresen (12) in Western Germany and are going on in Great Britain (Clarke (NCB) , personal communication). They proved the existence of waves guided by a seam as well as the possibili

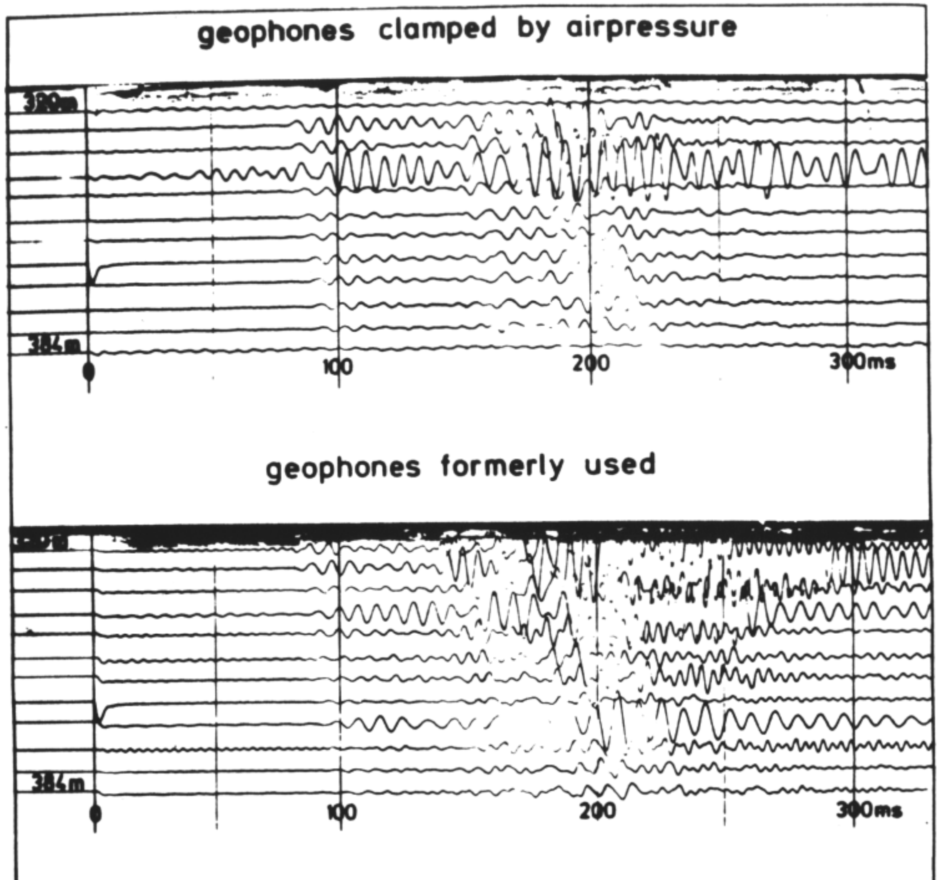


Figure No. 17

Comparison of new geophones (upper 12 traces), clamped by airpressure, with geophones formerly used (lower 12 traces).

of getting reflected such waves. The vanishing of seam waves behind a fault could also be shown. But these tests also point to the fact that the reflection amplitude is depending on frequency as mentioned already (12).

Model computations using the finite difference method were carried out by Guu (10). They proved that •transmitted seam waves con well be used to test the continuity of a seam.

Mathematical investigations were carried out by Masson (18) in France and by Halliday at the NCB Great Britain, and are going on in London at the Imperial College (Clarke (NCB), personal communication).

Summary

In summarizing, seismic waves guided by a seam, especially waves of Love type, have proved to be useful in the planning of working coal. They have currently been applied in underground seismic surveys for a decade. Both, reflected and transmitted waves have been interpreted. Scientific research and technical progress will certainly improve the method in the future, just as normal exploration seismics carried out at the earth' s surface has undergone a tremendous development, and yet it has been useful right from the beginning.

Acknowledgment

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