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# A TECHNIQUE FOR CONDUCTING SEISMIC REFRACTION EXPERIMENTS ON THE OCEAN BED USING BOTTOM SHOTS: FIELD PROCEDURES

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## CONTENTS

## INTRODUCTION

Bottom shots recorded by ocean bottom seismographs (OBS) provide an important technique for studying the seismic velocity structure of the immediately subjacent ocean bed. Such experiments are akin to a profile on land with a seismic source and geophone at or near the land surface. The alternatives at sea, which involve near-surface shots and/or receivers, all suffer from the well-known geometrical constraint which means that bodywave arrivals from the top few hundreds of metres below the sea bed are, almost generally, not first arrivals and frequently therefore are obscured by preceeding arrivals.

The earliest experiments with bottom shots and receivers were carried out in 1937 and 1938 (Ewing & Vine, 1937; Ewing et al. 1946). These, and later experiments by Shorthouse (1963), all suffered from the practical difficulty of achieving the required relative positions of the shots and receivers over spreads of only a few kilometres particularly when the technique involved the deployment of several geophones along the bottom by means of a cable attached to the research ship. Davis et al (1976) used OBS and free-fall shots to fire a 20km long line on the Juan de Fuca Ridge but encountered problems of shot reliability and adequate source-level.

Ideally, to prevent spatial aliasing, traces on the eventual (composite) record-section should be about a half-wavelength apart (say 15m). An attempt to approach this ideal situation was made by Koelsch et al (1986). They lowered a large framework to the sea bed which was charged with 48 shots. The shots were dropped at regular acoustically-navigated intervals, along lines 1 to 2 km long and on command from the ship, and were fired in the water near the bottom. In fact spatial aliasing is rarely avoided even with near surface shots yet useful results are commonly obtained by such techniques.

A similar but less bulky device, loaded with up to 8 charges, was used by Dorman et al (1987) to detonate shots on the sea bed on command from the ship under acoustic navigation control. In this experiment propagation over 15 km was achieved.

In this paper we describe a technique using OBS and bottom charges deployed from the surface under acoustic navigation control. This enabled us to obtain regularly-spaced traces 200-300 m apart along bottom profiles up to 4 km long. In addition it proved possible to determine shot-receiver ranges with an accuracy of ±7.5m and shot instants to within a few milliseconds. The data were obtained at six sites in the Norwegian Sea in depths of 1500 to 3900 metres.

## DESIGN OF THE BOTTOM CHARGES

The construction and use of explosive charges for this type of experiment required careful consideration. Due regard was paid to the following points.

(a) The charge should generate sufficient energy with a suitable, not too high, bubble pulse frequency in water depths of up to 4000 m.

(b) All components of the bottom charge should be capable of operating reliably in the proposed water depth.

(c) Explosive charges should be prepared and deployed with proper regard to safety principles and regulations. For these reasons the charge and electrical detonator were designed to be lowered from the ship on 100 metres of shot firing cable before the detonator-initiation device (an electronic timer) was connected to the firing circuit.

(d) Preparation and deployment of charges should not be too time-consuming to avoid tiring the shotfirers and to enable reasonably rapid execution of the experiment.

(e) Detonation time should be fairly precise to avoid wasting recording capacity. Bottom charges may be only one of several energy sources recorded during an OBS deployment and the necessarily high sampling rate required means that bottom shot recordings consume a disproportionate amount of recording capacity.

(f) Commercially available components should be used wherever possible to reduce the unit cost of the charge.

Given the approach described above it was necessary to design a charge which was relatively simple and fast to assemble and which would free-fall to the sea bed relatively fast (to avoid sideways drift due to currents) and at a speed greater than the terminal velocity of the timer pressure-case (to prevent mid-water tumbling and to avoid the heavy charge falling on the timer or its cable).

The basic components of the charge were chosen from those generally available in U.K. The explosive is ICI Powerprime 400, a cast PETN/TNT primer charge obtainable in 400 gram sticks, which is designed to be initiated either by an electrical detonator or by detonating cord. A pair of holes runs the length of each stick for this purpose. However high pressure electrical detonators suitable for depths of a thousand metres or more are too wide to be safely inserted in these holes and so instead we used 16 grams/metre RDX detonating cord manufactured by Ensign Bichford. Lastly high pressure electrical detonators, supplied by Jet Research Centre, were chosen to initiate the cord.

To ensure the high terminal velocity referred to above, a long narrow cylindrical charge shape was preferred (Figure 1). A 165 mm diameter standard plastic drainpipe was located within which four packages, each of 7 Powerprime sticks, would fit snugly end to end (providing a total charge of 11.2kg). The design allowed for a length of detonating cord to be passed down one set of holes in the Powerprime and up another set with the two free ends at the top of the charge (the holes were to be aligned by a rod passing the length of the charge). One end was to be capped with a rubber sleeve and the other was to be crimped into a sleeve in the detonator and taped to the alignment rod. A handle and lid were provided at the top of the charge and 8.6 kg of steel discs were added to the base to provide hydrodynamic stability and to ensure sufficient terminal velocity. The overall length is 0.91 m.

As we were unable to find any economical commercial source of suitable timers we designed and constructed them at IOS. We required a current pulse of at least 0.25 A after a selectable time delay in hours from 1 to 9 (± about 0.5 sec). The timer had to be able to be reset from either a logic level pulse or a contact closure enabling synchronisation with the shipboard master clock and indirectly with the OBS clocks. Each timer circuit, with power-supply and detonator-firing batteries, was housed in an aluminium alloy pressure case. Electrical connections were made through the single end cap of the pressure case using a two-pin Marsh and Marine plug to which a suitably terminated 100 metre long shot firing cable could be attached.

The timer itself consisted of a 4.1943 MHz crystal oscillator, frequency divider circuitry and a low on-resistance (0.15Ω) F.E.T. electronic switch all mounted on a small printed circuit board. Power to the circuit was supplied by a single 9V manganese alkaline PP3 battery. This same battery, with three more in series, provided the current to fire the detonator. Hard-wired links were used to select the desired firing-pulse delay for our experiments. The simplicity of the timer circuitry and the small batteries enabled the dimensions of the pressure case to be restricted to 5 cm internal diameter and a length of 40 cm. Pressure cases and end caps (rated to 6000 m) were machined from high strength aluminium alloy (7075T6) bar stock. The end cap was sealed by two piston 'O' rings. As the timers were disposable items the pressure cases were not protected from corrosion by anodising, thus reducing production costs. The firing cable was ordinary 4 Ω/100 m 2-core electrical cable with a breaking strain of about 45 kg.

A characteristic of bottom shots is their relatively high bubble-pulse frequency (typically 100 to 215 Hz, for depths of 1500 to 4000 metres respectively, for an 11.2 kg shot) with significant energy at even higher frequencies. For this reason we chose to pass the seismic signals through a 400 Hz anti-alias filter and sample the output at 1000 samples/sec per channel. As will be seen later this high sampling rate allowed very precise shot instants and ranges to be calculated. Recording windows were started early enough to allow for the ± 0.5 sec uncertainty in the timers. The window lengths were chosen long enough (40 secs) to record 30 m $s^{-1}$ surface-waves out to a range of 1000 m.

## OPERATIONAL EXPERIENCE AT SEA

Deployment of the bottom charges involved the efforts of three groups of people. On the Bridge acoustic navigation, with a 'real time' VDU display, was used to ensure that the ship was at or very close to the correct position for each charge. Electronic engineers in the lab area checked, reset and assembled timers in their pressure cases. The shotfirers, working from the stern of the ship, concentrated on assembling, priming and deploying the charges. This approach of dividing the work amongst 'specialist' groups proved very efficient and successful.

### Assembly of the Charges

After some early misfires and subsequent experimentation the charges were assembled in the following manner which provided a total weight of 10.0 kg of explosive (Figure 1). The procedures required are listed step-by-step.

1. Three packs, each of seven Powerprime sticks, were tightly bound together with pvc tape. A further pack of four sticks was also made up.

2. A ca. 2 m long loop of strong twine was threaded through two holes in the sticks of the first pack, which was gently pushed to the bottom of the shot case. Another pack of seven sticks was threaded onto the free ends of the twine loop and pushed down into the case.

3. Next a 2.5 m length of detonating cord was sealed at one end by double crimping a metal cap in place. Cow-gum was smeared around the outside of the joint and then a two-inch square of 3M mastic pad was carefully moulded over the whole sealing cap and cap-detonating cord join.

4. This sealed end was taped to the side of the pack of four Powerprime sticks, and the detonating cord wound around the pack in a tight spiral for five complete turns. Strong wide tape secured the cord to the pack.

5. The two free ends of the twine loop were then threaded through holes in the primer sticks and the four-stick pack was pushed into the charge case.

6. A final pack of seven sticks was inserted into the case after the twine and free end of the detonating cord had been fed through holes in the primer sticks. The twine was drawn tight and knotted to secure the four packs of Powerprime sticks tightly together.

7. The lid of the shot case was secured by screws, the free end of the detonating cord having been threaded through its centre hole.

8. A rope loop with a pvc bobbin threaded on it was attached to the top of the shot case to act as a lifting handle.

9. Finally the free end of the detonating cord was sealed with a rubber cap and cow-gum to prevent ingress of moisture.

10. Further charges were prepared in this manner and stored in a secure magazine until needed.

Shotfirers were able to prepare the required number of charges a day before they were to be deployed thus spreading their workload and reducing their exposure to often inclement weather conditions.

**Preparation of the Timers**

The timers were hard-wired to give the required delay, the batteries were connected and the divider chains checked with a frequency counter. Operation of the F.E.T. switch was also tested.

An hour or so before the first shot deployment all timers were reset using the shipboard clock to which the OBS instruments had previously been synchronised. Resetting the timers was carried out at ten minute intervals (the chosen shot-firing interval), enabling each timer and battery pack to be checked and safely inserted in its pressure case before the next timer was reset. End caps were sealed in place and a check for no voltage was carried out on the timer output pins before they were sent to the shotfirers for deployment.

Each timer was numbered sequentially, and the time of firing was written on the pressure case, to enable the shotfirers to deploy them in the correct order. This was necessary to avoid confusion, as timers could be prepared at a faster rate than the shots could be deployed.

**Overside Deployment of the Charges**

Two wooden tables (1.32 L x 0.76 W x 0.76 H metres) were used as shot preparation platforms. These were securely bolted fore-and-aft to the deck at the stern of the ship. One table was made with a hinged clamp to secure the shot tubes in the horizontal or vertical positions. A second table provided a clear working area and a fixing point for a small hand operated winch. Holders for ten prepared charges and cable drums were situated under the tables.

The hand operated winch served two purposes. Shot-firing cable was supplied on flimsy cardboard drums so the wire on each drum had to be transferred to a more robust drum, made from polypropylene, secured to the winch. This was done simply by reeling the wire onto the winch drum by hand. As these drums were removable, shot-firing cables could be wound in advance onto separate drums ready for the next set of deployments. The second use of the winch, during deployment, was to lower the charge away from the ship on its 100 m of shot firing cable until the electronic timer could be attached.

The deployment procedure is described below step-by-step.

1. About 20 minutes before each deployment an assembled charge was laid on the wooden shot-preparation table.

2. A 100 metre drum of shot-firing cable was mounted on the small hand winch. The end of the cable was drawn from the drum, through a block mounted over the stern of the ship, then back to the charge. Several turns of the cable were wound around the bobbin on the rope handle of the charge case and secured by tape. A pair of wire tails was left to allow for later connection to the detonator.

3. The detonator was attached to the end of the detonating cord. The cord protruding from the shot case was cut back to a stub 8 cm in length which was immediately sealed with cow-gum. A high-pressure detonator was pushed over the end of this stub and secured with a double crimp using proprietary crimping pliers. Cow-gum and a square of 3M mastic pad were again used to seal the detonating cord-to-detonator joint.

4. Connections between the detonator wires and the shot firing cable were made by twisting them carefully together. The two joints were insulated and waterproofed using mastic pads and then taped to the top of the charge alignment rod to prevent any strain being placed directly on the detonator wires.

5. A length of rope attached to the charge lifting handle was used to lower the charge to the sea surface. Once the charge was in the water the rope could be let go leaving the charge supported by the shot-firing cable.

6. By releasing the winch brake and paying out the cable, the charge was lowered to a depth of 90 metres below the stern of the ship. Whilst one of the shot-firing team held the weight of the shot, the remaining cable was unwound from the drum and passed through the block.

7. A shorting plug could now be removed from the end of the cable and, after the cable and detonator had been checked for continuity using a current limited resistance meter and a final check made that there was no voltage present on its output terminals, the cable was plugged into an electronic timer.

8. The cable was then looped back along the length of the timer pressure case and taped to it to prevent strain on the connector.

9. The charge could now be let go by hand once the navigating team were satisfied with the ship's position.

## Acoustic Navigation

Accurate relative navigation was required for the deployment of OBS and bottom charges. At each experimental site three Oceano acoustic transponders were laid with baselines between them 4 to 5 km long. Next the ship steamed around the work area to obtain a set of ranges from the transponders which were processed to provide a very precise relatively calibrated network. The two OBS were deployed and bottom charges were laid with a precision of a few metres.

After practise with this system the ship could be manoeuvred to within about 30 metres, or better, of the required position, even though weather conditions were never ideal.

The table shows that there were problems with early shots at Sites 4 and 6. Most of the apparent misfires were detected by an overside near-surface hydrophone, suggesting that the detonator had fired, but that it was failing to initiate the detonating cord. Another possibility was that the cord was being fired by the detonator, but poor coupling of cord to the main charge was preventing the latter from detonating. Further steps were taken to seal the detonating cord-to-detonator connection, as described earlier, to prevent absorption of moisture by the cord. Wrapping the cord tightly around the third pack of charges ensured that the main charge would be initiated should the detonating cord fire. The greater success rate achieved during the last five sets of shots (Table 1) indicates that the major problems had been solved by the shotfirers.

## RESULTS

### Reliability of Detonations

Table 1 shows details of the shots fired throughout the cruise.

TABLE 1

Summary of bottom charge deployments

| Site | Date | No. Charges | No. Fired | No. Misfires |
|---|---|---|---|---|
| 4 | 25 July (206) | 8 | 4 | 4 |
| 6 | 27 July (208) | 10 | 7 | 3 |
| 5 | 29 July (210) | 5 | 5 | 0 |
| 5 | 30 July (211) | 5 | 4[1] | 1 |
| 3 | 1 August (213) | 10 | 9 | 1 |
| 2 | 4 August (216) | 9 | 9[2] | 0 |
| 1 | 5 August (217) | 10 | 10 | 0 |

1 One shot fired 3 minutes late

2 Two shots fired 12 minutes late

There was a total of three 'late' shots two of which, because they occurred exactly 12 minutes late, clearly indicated problems with the electronic timers. The cause of these problems was attributed to failure of a divider stage to reset properly. In future a minor redesign of the timer circuit should enable all stages to be easily checked after reset.

**Shot Instant Calculations**

The timers cannot provide shot instants more accurate than about ±0.5 secs, although this is sufficient to locate the shots within the recording windows. The acoustic navigation cannot be used either to compute accurate shot-receiver ranges, even though the surface deployment positions are known within ±3 metres, because of unknown sideways drift during the descent of the charges and OBS.

We therefore used classical techniques based on water-borne arrivals, picked to a precision of ±1msec, to determine the shot-receiver ranges and then the shot instants. Several approaches can be taken but the most sensitive method is to use the travel-time difference between the direct and surface-reflected water-waves to calculate range (Figure 2). Given the echo-sounder depth of the shot and the OBS and the soundspeed structure throughout the water column (obtained from contemporary XBT's and historical water-bottle data) it is straightforward to devise an iterative computation from which horizonal range can be calculated once the calculated time-difference (based on ray-tracing) and the observed time-difference agree within 0.2 msec. The shot instant is then calculated from the slant range, sea-bed soundspeed and direct water-wave arrival time.

Before the experiments described here it was not sure that a sea bed hydrophone would detect the direct water-wave from a shot at about the same depth; theoretically the hydrophone lies in an acoustic shadow zone. We initially included a buoyed hydrophone 40m above the OBS to overcome the shadowing effect but in practice this was unnecessary since sufficient energy was detectable by the sea bed hydrophone and the geophones out to 5km range.

Results obtained so far with the above technique are very encouraging. Since two OBS were deployed to record the bottom shots at each site two independent estimates of each shot instant are available. Generally these estimates agree with ±5 msec implying a range accuracy of ±7.5 metres. Further, the OBS separation (range difference) calculated from the more distant shots agrees within 16 m with that calculated from surface airguns fired along the same azimuth.

A typical hydrophone record-section, based on shot instants and ranges calculated by the above method, is shown in Figure 3. Sedimentary compressional wave arrivals are clearly seen. In Figure 4 normally dispersed surface-waves and shear bodywaves can also be seen. Interpretations of these, and other similar, record sections will be published later.

**Cost**

The cost of the bottom shots described above is given in Table 2, broken down into three main parts.

TABLE 2

Itemised costs of a 10.0 kg bottom charge

| | | £ |
|---|---|---|
| 1. | Explosive | |
| | Powerprime 400 (10.0 kg) | 88 |
| | 2.5 m RDX Detonating Cord (16 gm $m^{-1}$) | 3 |
| | HP Detonator (type D1012) | 20 |
| 2. | Electronics | |
| | Timer Circuit | 25 |
| | Batteries & Connectors | 8 |
| | Shot Firing Cable (100m) | 35 |
| | 2-pin Connector | 20 |
| 3. | Hardware | |
| | Timer Pressure Case | 85 |
| | Explosives Case + Steel Disc | 25 |
| | Total cost per shot | 309 |

## CONCLUSIONS

1. A relatively simple technique has been developed and tested of deploying 10kg shots from the surface which detonate reliably on the sea-bed in depths of up to 3900 m. No deep-towed device is needed.

2. The technique relies on very accurate relative navigation of the ship (such as is provided by acoustic bottom transponders) in order to deploy the OBS and shots in the required pattern.

3. Electronic timers with an accuracy of just a few seconds over several hours are sufficient to initiate the shots.

4. Ranges and shot instants, accurate to $\pm$ 7.5m and 5msec respectively, can be reliably determined after the experiment from differences in the observed water-wave arrival times provided the direct-sound arrival can be identified. We observed this arrival for OBS-to-shot separations of up to 5km.

5. Our experiments were conducted over a level sea-floor. In principle,. provided the sea-floor relief does not block the direct water-wave, the technique should succeed in areas of substantial relief since no knowledge of the bathymetry between the OBS and the shot is necessary.

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## REFERENCES

**DAVIS, E.E., LISTER, C.R.B. & LEWIS, B.T.R.** 1976 Seismic structure of the Juan de Fuca Ridge: ocean bottom seismometer results from the median valley.
Journal of Geophysical Researches, 81, 20, 3541-3555.

**DORMAN, L.M., HILDEBRAND, J.A., CORNUELLE, B. & HAMMER, D.T.C.** 1987 Seismic study of the interior of Jasper Seamount (abstract).
EOS, 68, 1372.

**EWING, M. & VINE, A.C.** 1938 Deep-sea measurements without wires or cables.
Transactions of American Geophysical Union, 19th Annual Meeting.

**EWING, M., WOOLLARD, G.P., VINE, A.C. & WORZEL, J.L.** 1946 Recent results in submarine geophysics.
Bulletin of Geological Society of America, 57, 909-934.

**KOELSCH, D.E., WITZELL, W.E., BRODA, J.E., WOODING, F.B. & PURDY, G.M.** 1986 A deep towed explosive source for seismic experiments on the ocean floor.
Marine Geophysical Researches, 8, 345-361.

**SHORTHOUSE, J.M.** 1964 Seismic measurements on the deep-sea bed.
Unpublished Ph.D. thesis, University of Cambridge.

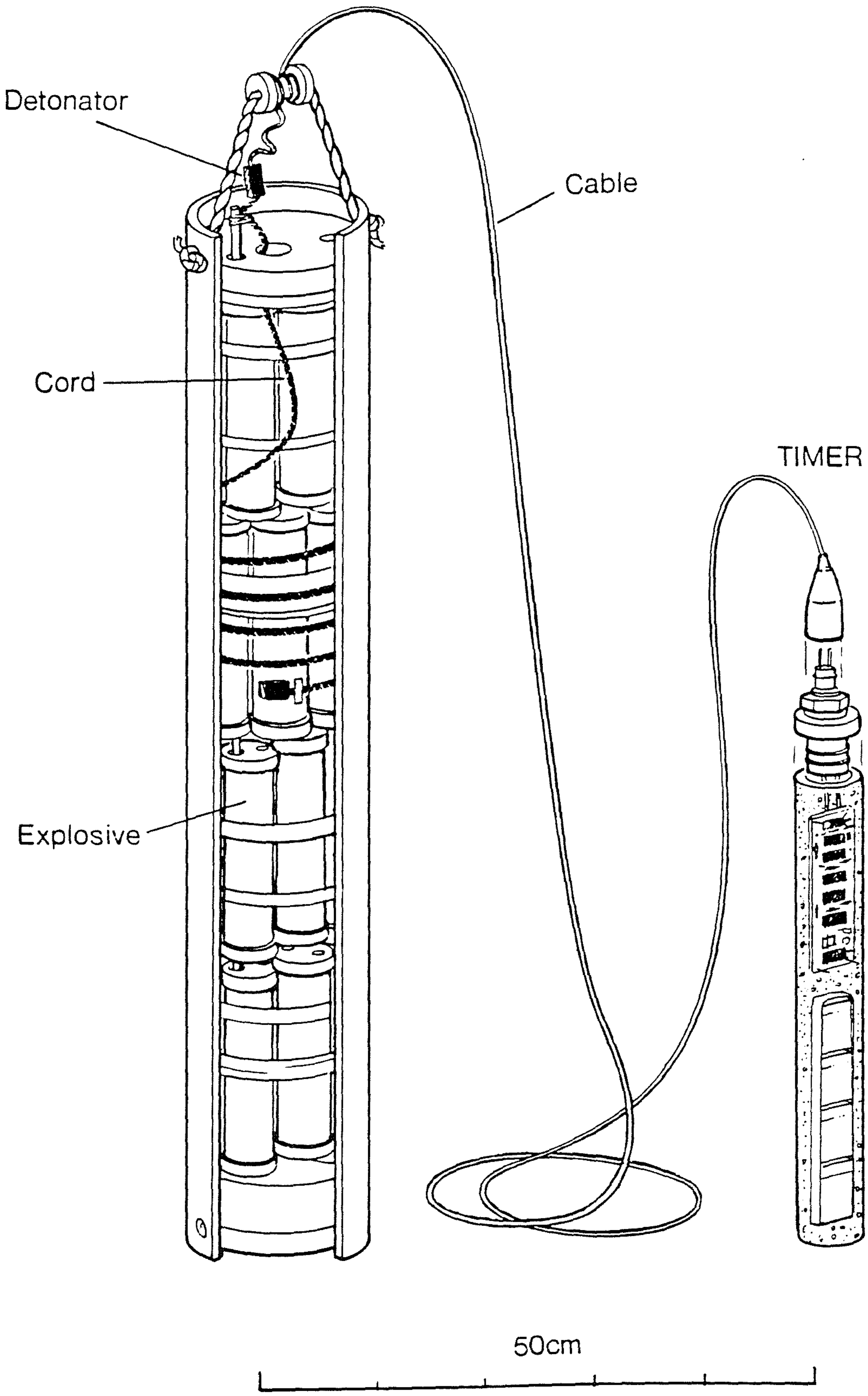
## FIGURE CAPTIONS

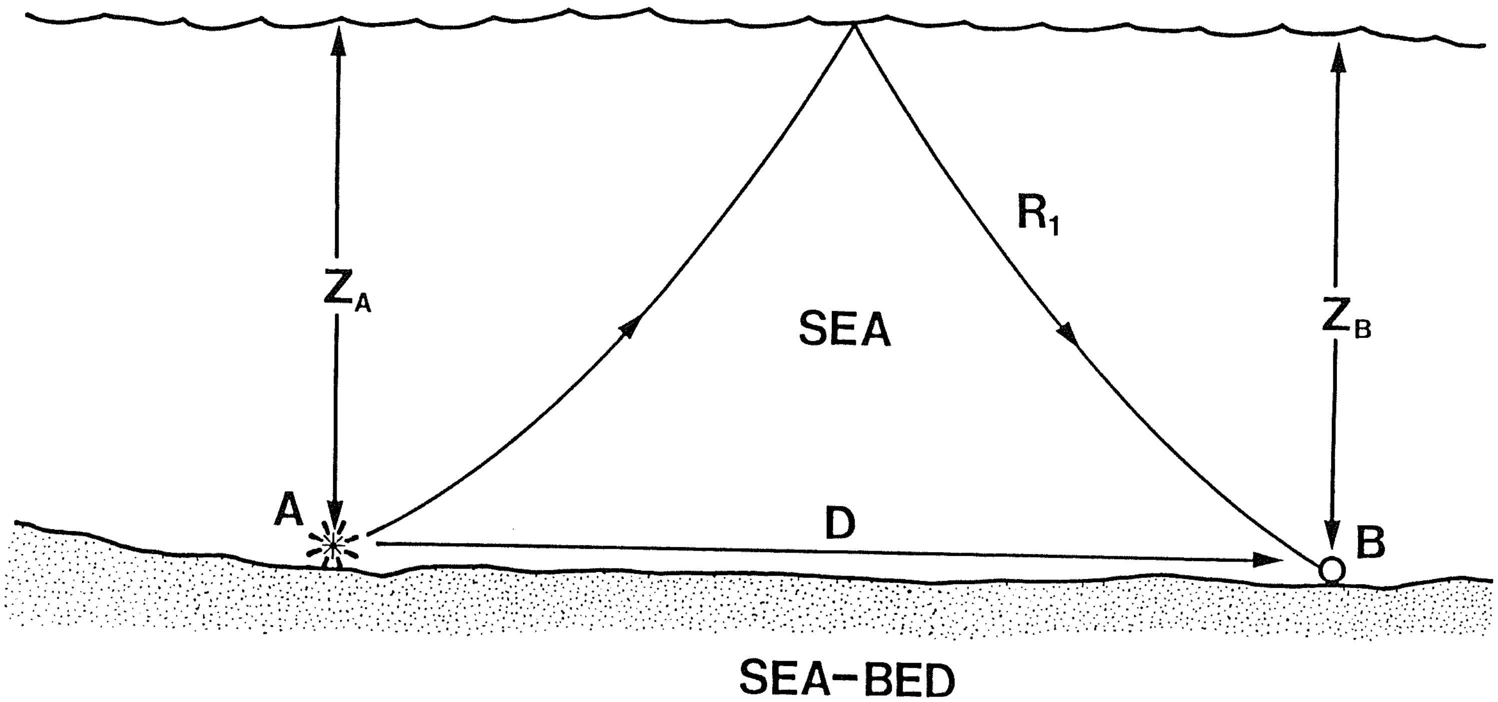
Figure 1. Schematic cut-away drawing of the bottom charge assembly with timer pressure-case and firing cable. See text for a fuller description.

Figure 2. Sketch of the water-wave paths used to compute the horizontal shot-to-OBS distance A-B. The technique relies on a knowledge of the soundspeed structure from surface to sea-bed, the echo-sounder depths of the shot and OBS ($Z_a$, $Z_b$ respectively) and the difference in arrival time of the D and $R_1$ water-waves.

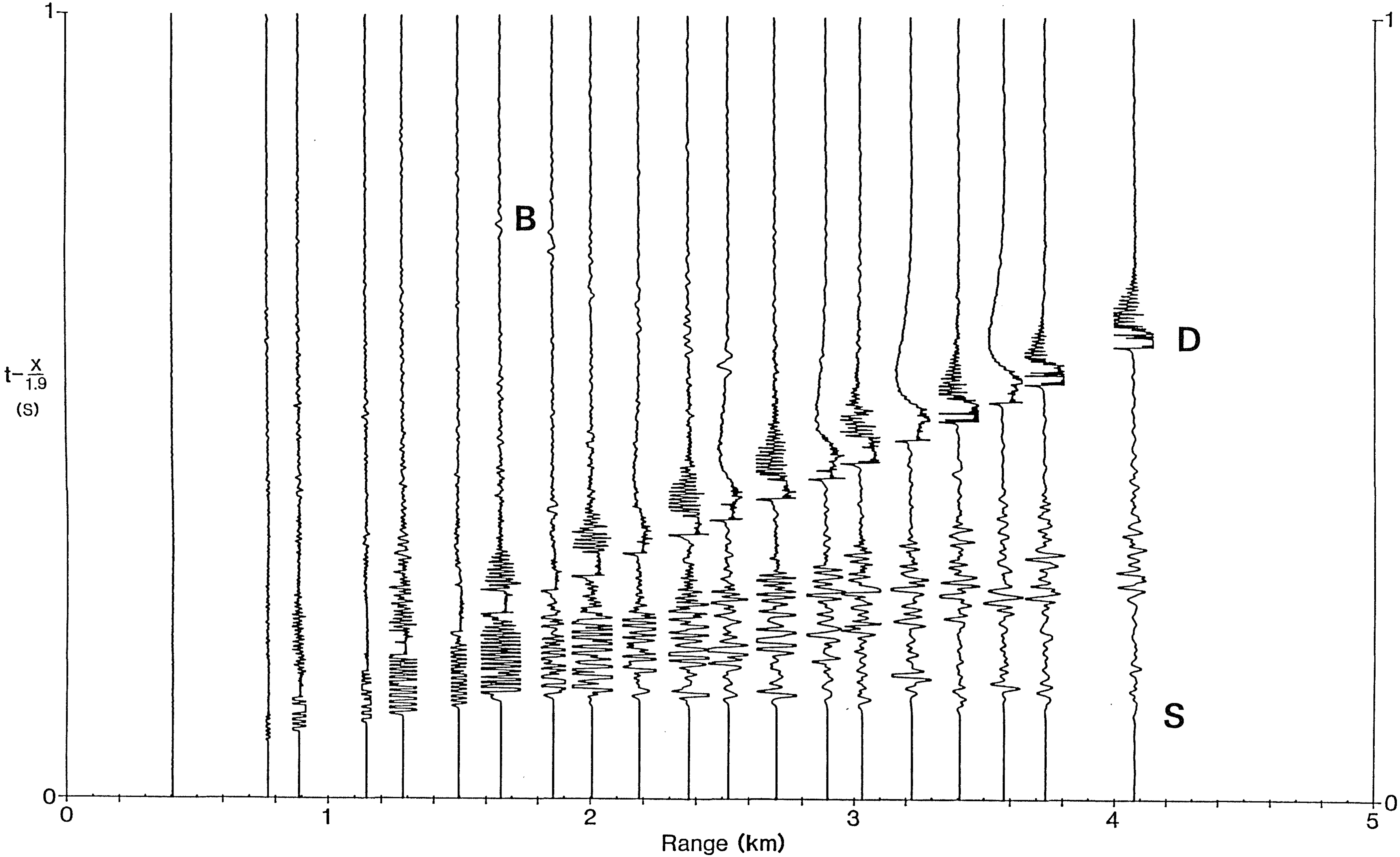
Figure 3. Record section of the combined hydrophone traces recorded by two OBS from ten shots (reduction velocity 1.9 km $s^{-1}$). Clear sediment first arrivals (S) can be seen as well as the direct water-wave (D). A weak basement reflection (B), with an intercept of over 1 second, is also visible.

Figure 4. Record section of vertical geophone traces recorded by one OBS (reduced to 200 m $s^{-1}$). The figure shows possibly two shear body-waves ($S_1$, $S_2$) with velocities of about 140 and 130 m $s^{-1}$ respectively plus, at the shortest range, dispersed Scholte surface-waves (Sch).


Detonator
Cable
Cord
TIMER
Explosive
50cm



$Z_A$
$R_1$
SEA
$Z_B$
A
D
B
SEA-BED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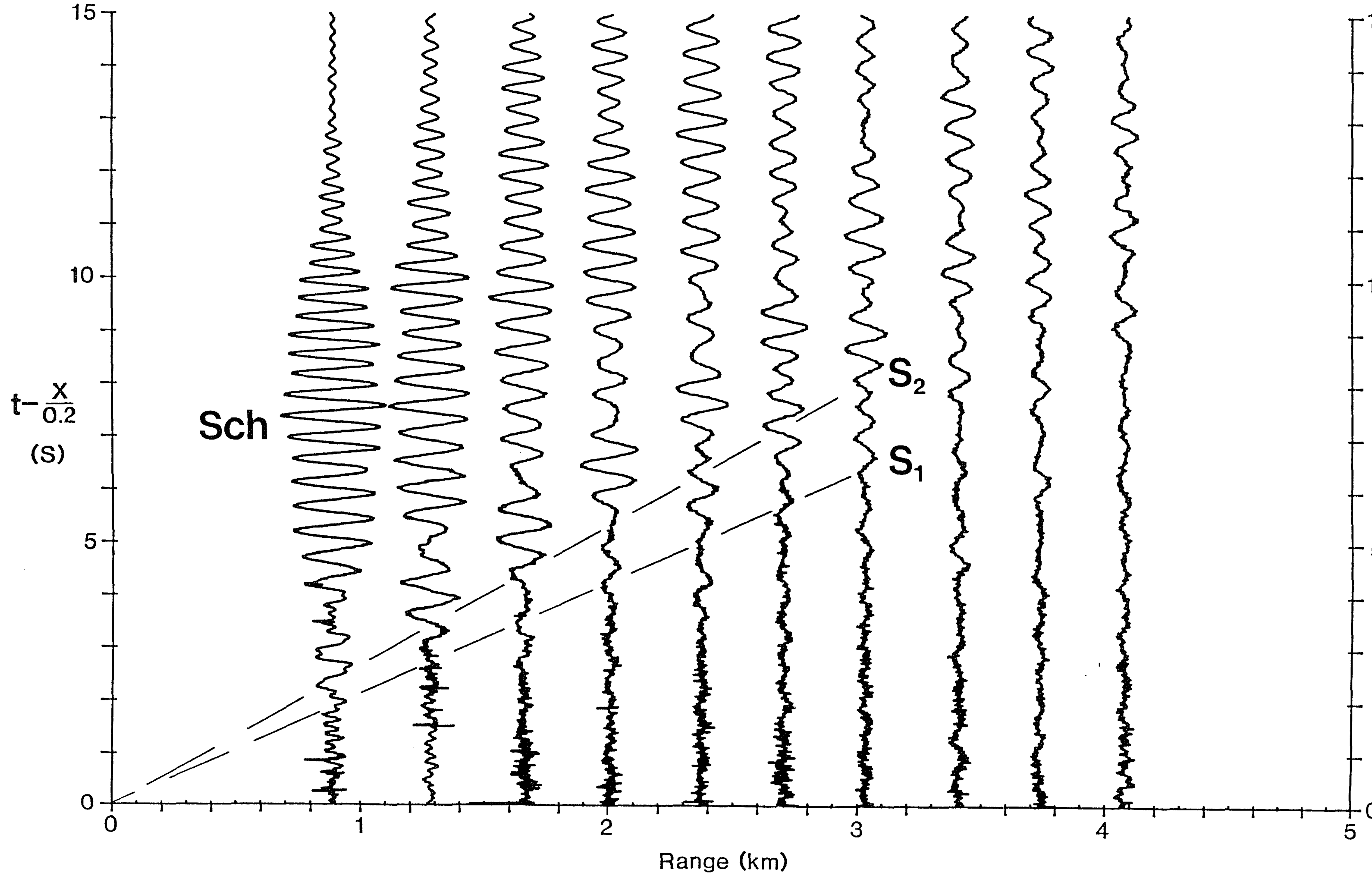
Range (km)



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S2
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15
10
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