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Aspects of seismic reflection prospecting for oil and gas

P. N. S. O'Brien *Manager, Geophysical Technical Services, BP Exploration, Britannic House, Moor Lane, London EC2Y 9BU*

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Summary. Seismic reflection survey is a technology which has made, and is making, rapid advances by means of continuous marginal improvement over each of its subdivisions of data acquisition, signal enhancement and geological interpretation. It is wedded to the digital computer and as long as the real cost of digital computers and their peripherals continues to fall so long, at least, will reflection seismology continue to advance – for there are many algorithms waiting only for more (at the right price) computer power before they are implemented. The essence of the technique is simple echo-sounding combined with large data redundancy and (fairly) complex signal enhancement and imaging procedures. On land the source is normally a few kilograms of high explosive and at sea it is usually an array of airguns, which is a device for releasing into the water a few litres of air at high pressure. Particle velocity detectors are used on land and pressure detectors at sea, their output is digitally recorded on magnetic tape with a total dynamic range of some 180 dB, though resolution is limited to 14 bits. Arrays of sources and detectors are used and the first 10–12 stages in the signal processing chain are devoted to producing a record as close as possible to the hypothetical record which would have been obtained if the source and detector had been coincident on a horizontal datum plane and if there had been no noise and no multiply reflected echoes. Once the best such 'zero-offset' record has been obtained an imaging algorithm, based on the acoustic (not elastic) wave equation, is used in order to bring into focus as sharply as possible the seismic image of the subsurface. This is normally done for vertical slices through the Earth but increasingly attempts are being made to produce proper three-dimensional images. The models of the Earth which underlie signal enhancement procedures are grossly simplified versions of reality. A major development effort in iterative and interactive model fitting is just beginning with the aim of allowing more plausible models to be used. Interpretable echoes are commonly obtained from depths in sedimentary rocks of 5 km and more. Absorption limits penetration of the higher frequencies so that it is rare for echoes from the greater depths to have appreciable energy above 25 Hz. Some information on the nature of the rocks and their depositional environment

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may be obtained from the reflections but essentially nothing may be deduced about whether their pores are filled with water, oil or gas. Colour graphics work stations are just being introduced to aid in the geological interpretation of the computer enhanced signals but it will be some time before they can call up fast enough and display adequately the quantity of data involved in an average survey (10^{10} bits).

1 Introduction

As illustrated in Fig. 1 seismic reflection prospecting is simple echo-sounding. This is normally carried out at intervals of about 25 m along straight lines and a better than average result is shown in Fig. 2. By obtaining a set of such records (we call them seismic sections) over a grid of lines covering the area of interest, contour maps of the subsurface reflectors may be built up and predictions made of the subsurface geology. Measurements of the amplitudes and waveforms of the echoes may help in geological predictions but only to a minor extent. The predictions are then tested by the drill and are usually proved correct. This confident and encouraging statement should not be taken to imply that all is well because, by-and-large, the predictions made fall very far short of what is needed for the next stage in the investigation. In civil engineering, they do not extend to estimates of shear strength, plasticity, or other useful mechanical properties; in hydrocarbon exploration they do not (except under very restricted conditions) indicate whether or not hydrocarbons are present; in coal production planning they do not define minor faults; in hydrogeology they do not tell you whether the water is fresh or saline. Further, in many areas of the world, particularly on land, the reflection sections obtained are more like the one shown in Fig. 3. With such sections, where clear echoes are not detected, the uncertainty estimates attached to predictions are so large that, even if the prediction (which, of course, includes the uncertainty estimate) is correct, its use is lessened.

This paper is mainly about technical principles and therefore may have some relevance to all uses of the seismic reflection method. However, the discussion and examples all relate to exploration for oil and gas, which is the field where the method exhibits its highest degree of sophistication. It has established an indispensable place in hydrocarbon exploration due to the combination of three factors. One, there is no present method for detecting oil or gas at depth from measurements made at the ground surface. Two, oil and gas occur in sedimentary rocks which by-and-large are sub-parallel and therefore well suited to being mapped

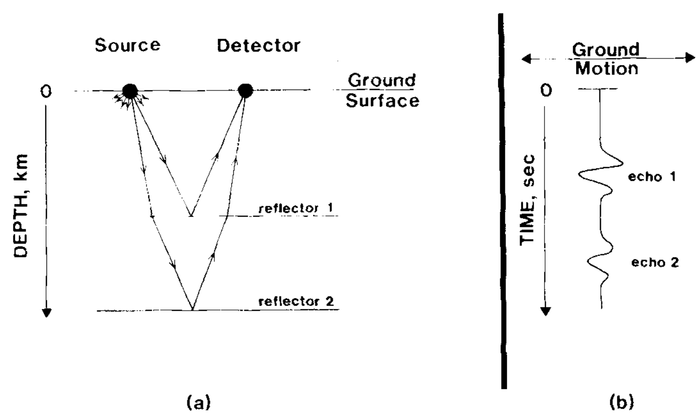

Figure 1. Seismic echo sounding. (a) Idealized Earth section. (b) Idealized reflection record.

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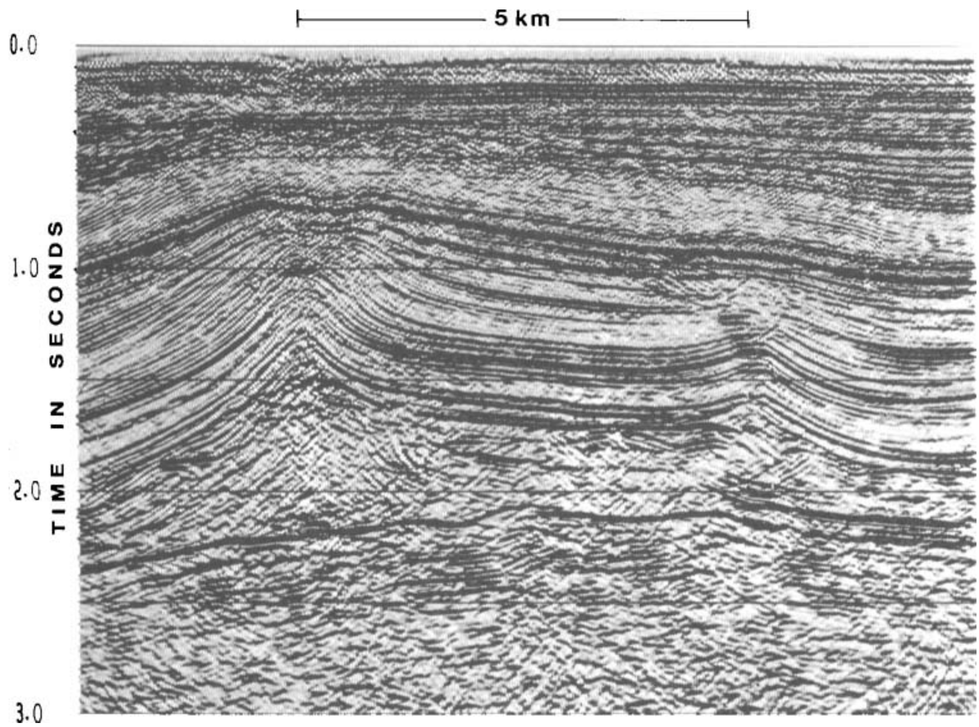

Figure 2. A better than average seismic reflection section.

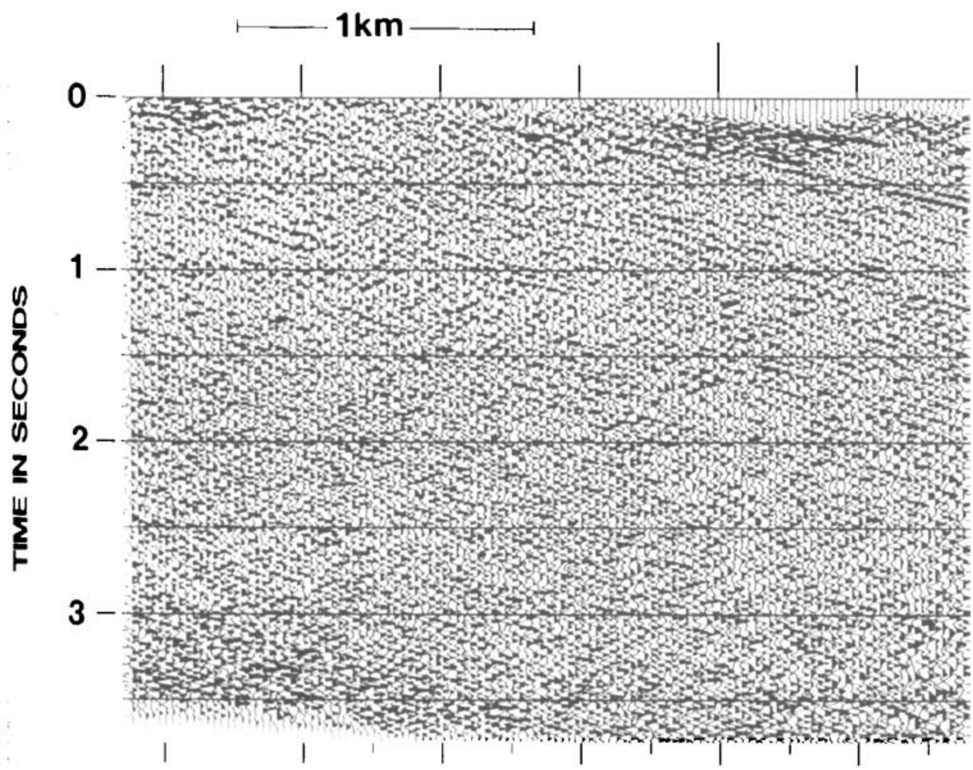

Figure 3. A worse than average seismic reflection section.

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by echo-sounding. Three, oil and gas occur at depths of a few kilometres and drilling holes to those depths – which is the preferred method for most aspects of sub-surface exploration – costs several millions of pounds per hole. If cost and time were no object there would be a great many more holes drilled and a lot less seismic reflection surveying. When the depth of investigation is shallow and the information provided is further removed from what is required – as in engineering geophysics – then the need for a seismic reflection survey is much reduced.

In the non-communist world there are about 1000 seismic land crews plus about 100 seismic ships engaged in hydrocarbon exploration. They each gather data at an effective rate of about 10^8 bits km^{-1} at a cost varying widely according to local conditions but generally between £2000 and £10 000 line-km^{-1} on land and between £200 and £1000 at sea. The subsequent signal processing costs are around £500 line-km^{-1} on land and £250 km^{-1} at sea. The cost of geological interpretation, which is more manpower intensive but relies increasingly on interactive computer technique, is small in comparison, amounting to perhaps another £20 line-km^{-1}. The communist world has more land-crews, but fewer ships.

Like any technology, seismic reflection prospecting is intensely specialised, as was illustrated by a recent recruiting advertisement which listed seven different types of exploration seismologist, each of whom would be expected to stay within his own speciality throughout his career. Consequently, this review makes no claim to cover the whole of the subject, nor even that the aspects treated are those of most importance. Mainly, they are constrained to those aspects for which illustrative material is least difficult to obtain.

In spite of the listing of seven specialities as mentioned above, this paper retains the time-honoured division into Data Acquisition, Data Processing and Interpretation – it being understood, of course, that each speciality interacts significantly with the others.

2 Data acquisition

Data acquisition divides naturally into two parts, the equipment and its deployment. We start with equipment which we treat in three sections covering the source, the detector, and the recorder.

2.1 THE SOURCE

On land the archetypal source consists of a few kilograms of high explosive fired some 10–20 m below ground surface. At least one-half of all land surveys use such a source. Fig. 4(a) shows a typical example of the signal radiated from a buried explosion, the negative reflection which occurs about 20 ms after the signal onset comes from a reflector lying between the explosion and the ground surface. The next most popular source is a truck or tractor mounted vibrator, hydraulically driven and electronically controlled to radiate a signal lasting 10 s or so, with an instantaneous frequency varying from about 10 Hz to about 60 Hz. The overlapping complex of recorded echoes is then cross-correlated with the radiated signal (as in CHIRP radar) to compress the original 10 s signal to a pulse with a duration of about 0.1 s, thus enabling resolution of echoes to the same extent as if the radiated signal had been of that duration. Fig. 4(b) shows a measurement of such a compresssed pulse. These recordings were made with a detector buried 300 m below the surface (Sixta 1982). Under survey conditions the received echoes will have travelled a few thousands of metres through the absorptive Earth with the result that the explosive and vibrator pulse shapes become broadly similar, as indicated in Fig. 4(c and d), and are virtually indistinguishable when displayed on a section such as those shown in Figures 2 and 3.

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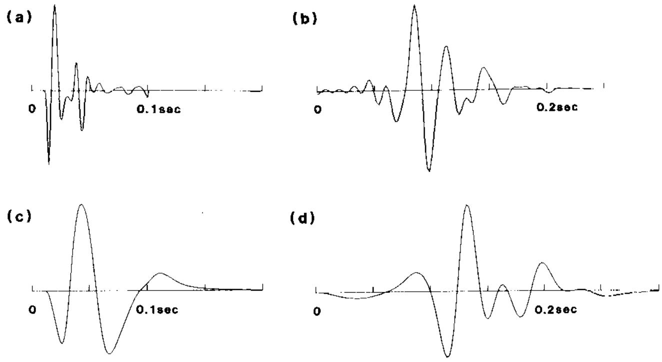

Figure 4. Radiated and received signals. (a) and (c) Radiated and received signals from 2 kg of explosive detonated at 30 m. (b) and (d) Radiated and received signals, after correlation, from a surface vibrator.

Vibrators currently provide a peak force of some 10^5 N which is insufficient to obtain detectable echoes from the greater depths and so three or four of them are operated in synchronism, each unit being activated several times. The resulting signals are then added together to overcome ambient noise. Unfortunately a very large amount of the energy radiated by a surface source is constrained to remain close to the ground surface (mainly Rayleigh waves). Consequently, the individual vibrators have to be suitably spaced to form a linear array with which to reduce the horizontally travelling waves without adversely affecting the near-vertically travelling echoes. A similar array is required at the detection location, not only for surface vibrators but for all types of source.

The geophysical literature contains a reasonably extensive treatment of the seismic signals radiated from buried explosions both theoretical (e.g. Jeffreys 1931; Blake 1952) and experimental (e.g. Sharpe 1942a, b; O'Brien 1969; White & O'Brien 1974). All those who have read that literature can be in little doubt as to the nature of the explosion radiated signal in so far as it relates to seismic prospecting. This is not the case with vibrator signals. A few papers provide analytical treatments of an ideal vibrator exciting an elastic half-space (e.g. Miller & Pursey 1954; Pursey 1956) while Lerwill (1979, 1981) uses physical insight to develop equivalent electrical circuits as analogous of the vibrator–ground interaction. However, there is not yet any consensus on what constitutes a realistic model of a practical vibrator, nor any detailed treatment of the relevant mechanical properties of those most imperfectly elastic materials – near surface soils and rocks.

There exist not a few latent PhD topics in this general area, including ones which cover the detailed specification of where sensors should be placed in order to estimate from *surface* measurements the equivalent (i.e. compressed) radiated signals (several types of wave are radiated) and their directivity patterns. But, of course, none of the results will be worth a row of beans unless the analysis is supported by appropriate measurement. In addition to Lerwill (1981) an introduction to practical vibrators is given by Waters (1978). There are a number of other land sources, most of them designed to impact the ground surface. They mainly radiate relatively low energies and therefore are useful only in areas of low ambient noise or for small depths of investigation.

Condensed explosive is now rarely used in marine reflection survey, its place having been taken by the air-gun. This is a device which, under command of the ship's position fixing equipment, releases into the water, at intervals of about 10 s, a given volume of air, typically a few litres, at a given pressure, typically 14 MPa. The immediate consequence of releasing the high pressure air is the radiation of a pressure pulse. This is followed by rapid expansion and contraction of the air bubble with the consequent radiation of a train of secondary

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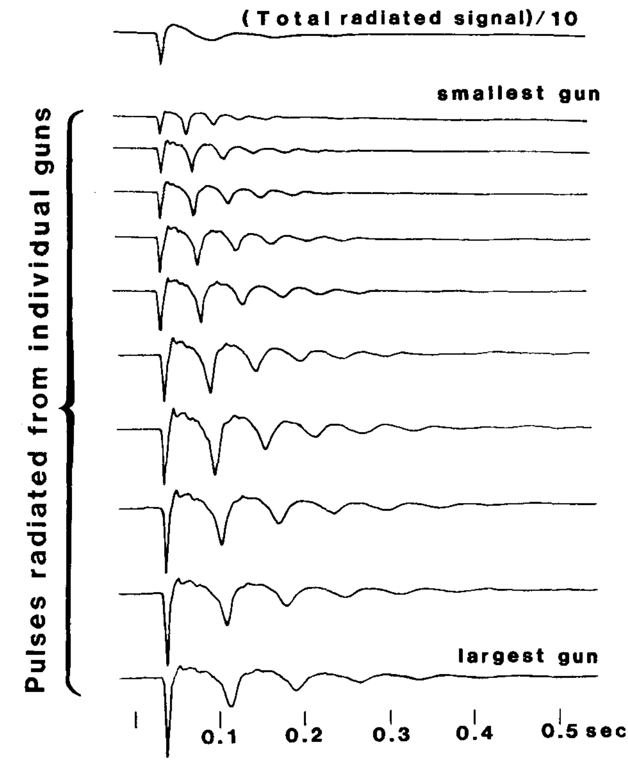

Figure 5. Design principle of an air-gun array (after Edelman 1975).

pressure pulses whose time intervals depend upon the energy in the bubble. The total radiated signal lasts 0.5 s or so and needs to be compressed in order to obtain optimum resolution of the returning echoes. This could be achieved by standard numerical techniques (signature deconvolution). However, since a single gun does not generate sufficient energy, a number of them – perhaps 20 or more – have to be used in synchronism and virtue is made of this necessity in order to reduce the duration of the radiated signal. The technique is illustrated in Fig. 5, where the radiated signals from each of 10 differently sized air-guns are shown. The upper trace is constructed by the superposition of the 10 individual traces and so corresponds to the overall vertically radiated signal, provided, of course, everything is linear. By choosing the gun volumes correctly and ensuring synchronism of firing, the initial pressure pulses add constructively while the secondary pulses add destructively, so generating a suitably short pulse. Of course, the waveforms radiated at large angles to the vertical are not so simple but this is though to be a relatively minor problem. There has been quite a lot written on air-guns, much of it rather removed from practicality. The papers of (Giles & Johnston 1973; Nooteboom 1978; Safar 1976; Ziolkowski *et al.* 1982) give a good idea of the state of the art.

There are other marine sources for which water guns, steam guns, propane-oxygen explosions in 'elastic' bags, and mechanically induced implosions are all used to some small degree. These, and some others, are described by Lugg (1979).

It is perhaps of interest to indicate the amount of energy in the seismic bandwidth which needs to be released in order to record readable echoes. Later echoes are obviously smaller than earlier ones. Their reduction is due largely to wave-front divergence (roughly inversely

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proportional to distance travelled) and absorption and scattering (very roughly 0.25 dB/wavelength travelled in porous sedimentary rocks), though reduction with depth of typical reflection coefficients plays a small part. In practice, for reflections from 1 km, and after allowing for current techniques in signal-to-noise enhancement, we need maybe 50 kJ, whereas for 10 km penetration we need maybe 50 MJ for a similar bandwidth, but only one-tenth as much for an acceptable one (say 15 Hz). These figures which, since noise characteristics are so variable are not to be taken too seriously, apply to useful energy radiated by the source into the interior of the Earth. Since surface sources radiate most of their energy as surface waves, they need to generate more energy than downhole sources (explosives). The usable seismic bandwidth is controlled entirely by earth absorption and noise, and varies from about 100 Hz at 1 km to about 25 Hz at 5 km – there is no possibility of recovering significant spectral amplitudes at 100 Hz from depths of 5 km in porous rocks.

2.2 THE DETECTOR

On land, detectors are electro-magnetic, moving coil, geophones with sensitivies of about $10\,\mathrm{V\,m^{-1}\,s^{-1}}$; at sea they are piezoelectric, ceramic, hydrophones with sensitivities of about $0.1\,\mathrm{mV\,Pa^{-1}}$. Both types are cheap and robust – two vital characteristics when crews, far from any supplier, will be deploying a few thousand detectors. The large numbers occur because at each recording station, of which there are commonly 96 but maybe more than 1000, an array of 10–50 detectors is laid out in order to reduce horizontally travelling coherent noise. This coherent noise is mainly source generated on land and mainly ship generated cable snatch at sea; it is often 10 times the signal amplitude and may reach 100 times, proving to be a major limitation to the seismic method.

From time-to-time new detectors become available which claim to produce less distortion, fewer spurious resonances, or to have improved technical performance of one sort or another. The claims are mostly true but, equally, are mostly of little importance since the governing conditions are the quality of ground coupling and the stability of response after some tired, heavy booted, 16 stone geophysicist has walked all over them. What has just arrived (Klaassen & van Peppen 1982) is the 'electronic' geophone which by combining a higher sensitivity with lower output impedance should appreciably reduce the ever-present scourge (even in the desert!) of electromagnetic pick-up. It may also appreciably reduce harmonic distortion which, with conventional detectors, produces noise in the signal bandwidth by distorting the low frequency surface waves. On land accelerometers have the appealing property that they discriminate against the low frequency surface waves. At sea velocity sensitive hydrophones have the apparently equally appealing property that they give larger output when placed at shallower depths (the output of pressure detectors decrease as they become shallower). Neither type is much used!

It is still the norm for the detector arrays to be connected to the recording instruments via conductor pairs, even when there are 240 of them! However, more and more the signals are coded at the detector location and sent multiplexed down a cable containing a very few wires, or very occasionally sent by radio. At sea – where all the hydrophones, electronics and conductor wires are contained within a neutrally buoyant tube some 3–4 km long and of 10 cm diameter – the first fibre optic link in seismic prospecting came into operation in mid-1982. Fibre optic links on land followed close behind. Telemetry strikes another blow against cross-feed and pick-up and may remove any practical advantage of the electronic geophone mentioned above.

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2.3 THE RECORDER

Of course, the signals (but mainly noise!) are recorded digitally on magnetic tape. Since I am not an electronic engineer I shall do no more than list some of the major specifications. The bandwidth is 2–500 Hz, the overall dynamic range is 180 dB and the magnetic tape packing density is usually 1600, but increasingly 6250 bits per inch. The incoming signals are band-pass filtered to reduce noise and prevent aliasing of the high frequencies, and then input to an amplifier whose gain varies sample-by-sample, commonly at 4 ms intervals, in steps of two or four. The amplified signal thus keeps within the dynamic range of the analogue-to-digital converter and, since the gain steps are also recorded, overall dynamic range is considerably increased, although the resolution is fixed as that of the converter, which is typically 14 bits. The signals are multiplexed before recording and this multiplexing normally takes place after some fixed gain pre-amplification. There are several auxiliary channels for recording other relevant information and the daily, weekly and monthly instrument checks are often under microprocessor control. There are also multichannel cameras of one sort and another for immediate visual inspection of the records.

On land the total cost of geophysical equipment for a 96 channel crew might be about £1M whereas it would be about £2M for a marine crew.

2.4 EQUIPMENT LITERATURE

Detector design is covered well, e.g. for geophones (Dennison 1953) and for hydrophones (Bruel & Kjaer; Luehrmann 1972). The rest of the equipment is covered only in manufacturers' brochures though the second edition of volume 2 of *Seismic Instruments* (Evenden & Stone 1971; under revision) should to a large extent rectify this.

2.5 MARINE POSITION FIXING

We need to know the relative positions of the ship to within a metre or two over periods of minutes and to within 5–10 m over the long term. We need the latter accuracy in absolute measure so that uncertainty in position fixing may be ignored when comparing the results of one survey with those from another or when using them to locate a drilling barge. Unless there is line-of-sight radio positioning these accuracies are usually missed by a factor of 10 or more. The ship will carry receivers to make use of the US Navy navigation satellite system, at least one, often two, and sometimes three ground based radio navigation systems, and possibly an inertial system of some sort. All these are tied together in a computer whose output steers the ship and activates the source and recording system – say one 5 s record every 25 m.

2.6 EQUIPMENT DEPLOYMENT

Choice of equipment and how to deploy it are obviously a vital part of pre-survey planning. Type of source, size and shape of detector arrays, sampling interval, source-detector spacing, sign-bit recording, etc., all require consideration. Since sign-bit recording is probably the least familiar phrase in that list I will say a little about it.

In conventional equipment each sample of the signal is recorded as a 19 bit word – one bit for direction of earth movement (up or down) and 18 bits to specify the amplitude of movement. In sign-bit recording the 18 bits are ignored and only the sign bit is recorded. That is, the record only indicates whether the ground moves up or down, not by how much it does so. Obviously, if we can get away with that we can use much simpler instrumentation

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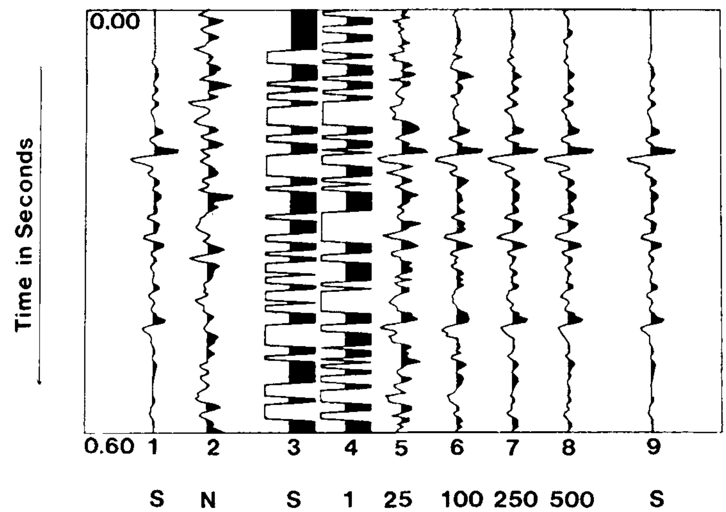

Figure 6. Sign-bit recording with a signal-to-noise ratio of 1:2. Traces 1, 3 and 9 are of the noise-free signal. Trace 2 is noise alone. Trace 4 is a single record of signals and noise superposed. Traces 5–8 are summations of 25–500 individual sign-bit records with constant signal but varying noise.

and record many more detector locations for each source location, so enabling more elaborate signal processing in the computer. When noise is a severe problem these extra detector locations may be a boon. Current sign-bit crews record from 1024 detector locations rather than the more normal 60 or 96.

Imagine that, prior to activating the source, the Earth's surface is perfectly motionless. Suppose an impulsive source is activated with the consequence that traces 1 and 9 in Fig. 6 represent the sequence of band-limited echoes that would be recorded with conventional equipment. Trace 3 would be the equivalent trace as recorded by sign-bit only. Note that all the amplitudes are now equal and no one reflection stands out from another. Suppose a whole sequence of impulsive sources are activated one after the other at the same location on an otherwise motionless earth, individually sign-bit recorded, added together after allowing for differences in source activation times, and then plotted out. Apart from a scaling factor the resulting trace will be identical to trace 3 – no additional information has been obtained. Now imagine the experiment repeated with a very low energy source activated on the real Earth whose ground surface is in continual motion. The resulting sign-bit record (trace 4) will be a similar looking train of constant amplitude, variable polarity, spikes which, if the source generated echoes are small enough, will essentially represent the ambient ground motion of the Earth – that is, noise dominates signal. Suppose the experiment to be repeated many times. Each record will contain the same amplitude very small echoes at the same times after time-zero but the ambient ground motion will differ. Addition of all the individual records, all referenced to their source activation time, will now emphasise the constant time reflections at the expense of the noise. Note that this is a non-linear process (not a linear $\sqrt{n}$ process) and that as more and more traces are added together the output will tend toward the true reflection sequence, giving relative amplitudes as well as polarity, as typified by trace 1. A few minutes' calculation adding constant amplitude bias to sets of random numbers will soon convince you that that is so. Traces 5 to 8 in Fig. 6 show how well trace 1 may be recovered when the signal-to-noise ratio for a single record is 1:2. Figures 7 and 8 allow a comparison between full-bit and sign-bit records using a vibrator

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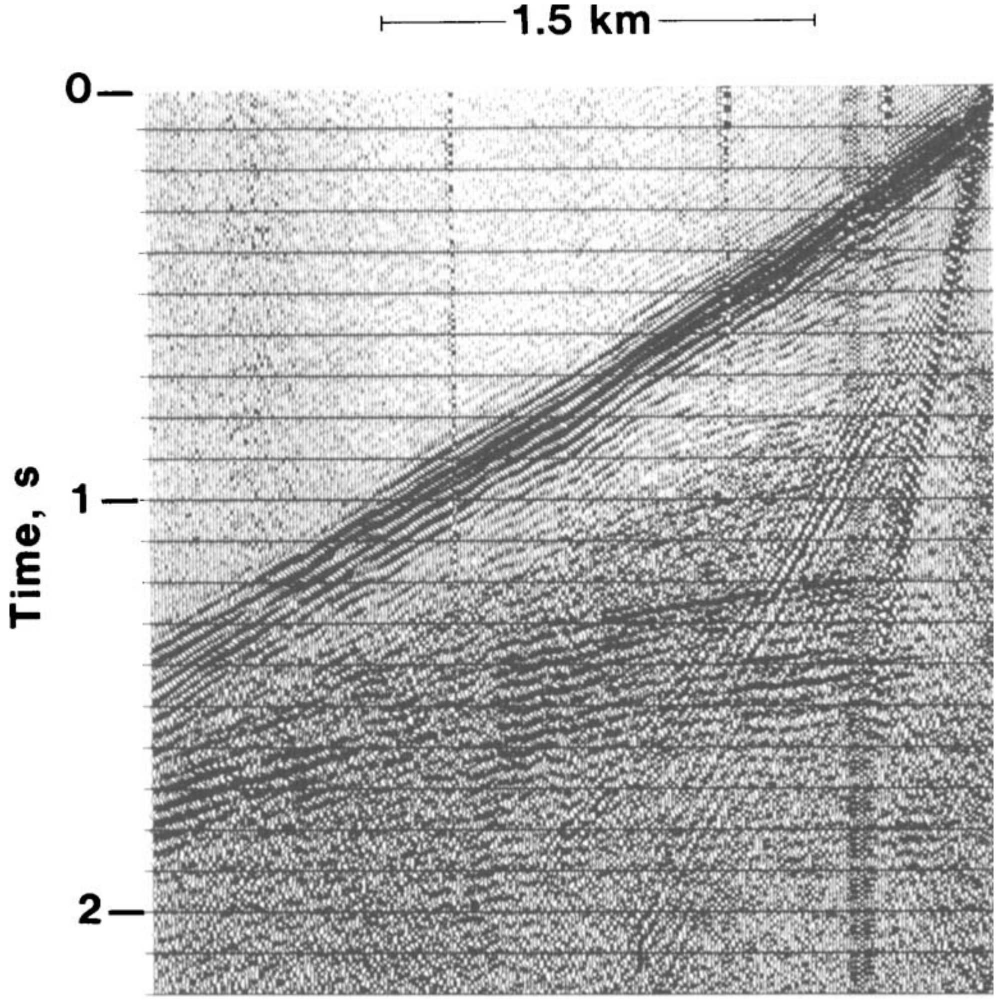

Figure 7. Vibrator source, correlated output after sign-bit recording. (Courtesy of Sohio Petroleum Company.)

source. Note that because the radiated vibration signal is long compared with its auto-correlation a single sign-bit record after cross-correlation with the VIB sweep, already looks like a full-bit record. Although sign-bit recording has been used with an impulsive source there seems little merit in so doing.

Figs 9 and 10 compare fully processed seismic sections with the full-bit section being clearly inferior. Sign-bit recording is a temporary phenomenon due to the fact that full-bit instrumentation is not yet sufficently miniaturized to handle 1000+ traces. O'Brien *et al.* (1982) give a fuller discussion.

3 Seismic data processing

There are some 12–15 separate operations in data processing, each of which requires human intervention for parameter choice and quality control. Essentially, their main purpose is

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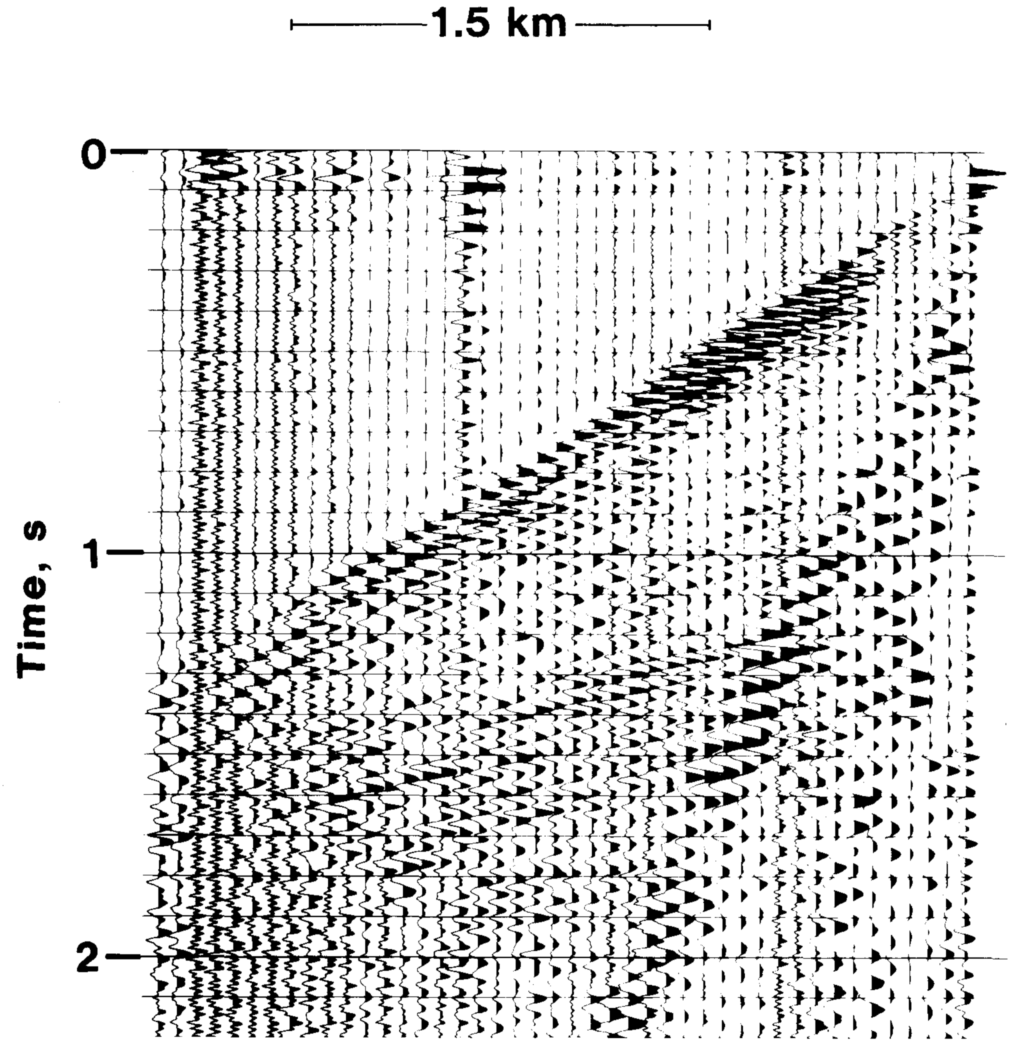

Figure 8. Vibrator source, correlated output after full-bit recording. This record and the one in Fig. 7 were both taken at the same location. (Courtesy of Sohio Petroleum Company.)

signal-to-noise enhancement, it being understood that the noise is mainly source generated and cannot be adequately reduced by field techniques. This signal-to-noise enhancement is achieved mainly by spectral analysis with subsequent 1- and 2-dimensional filtering and by exploiting measurement redundancy via the use of simple ray theory (geometrical optics). Redundancy has increased from nil in the mid-1950s, when common mid-point stacking was introduced (Mayne 1962) up to 100 and more today, though of course a factor of 100 is neither economically possible nor technically necessary under all conditions. A redundancy factor of 100 means that each reflection from an elemental portion of the sub-surface is recorded 100 times, each time with a different shot-detector spacing. This enables coherent noises of one sort and another to be reduced by multichannel filters based on ray-tracing principles. The archetypal ray-trace filter is the 'common-mid-point stack' based on 'move-out' analysis.

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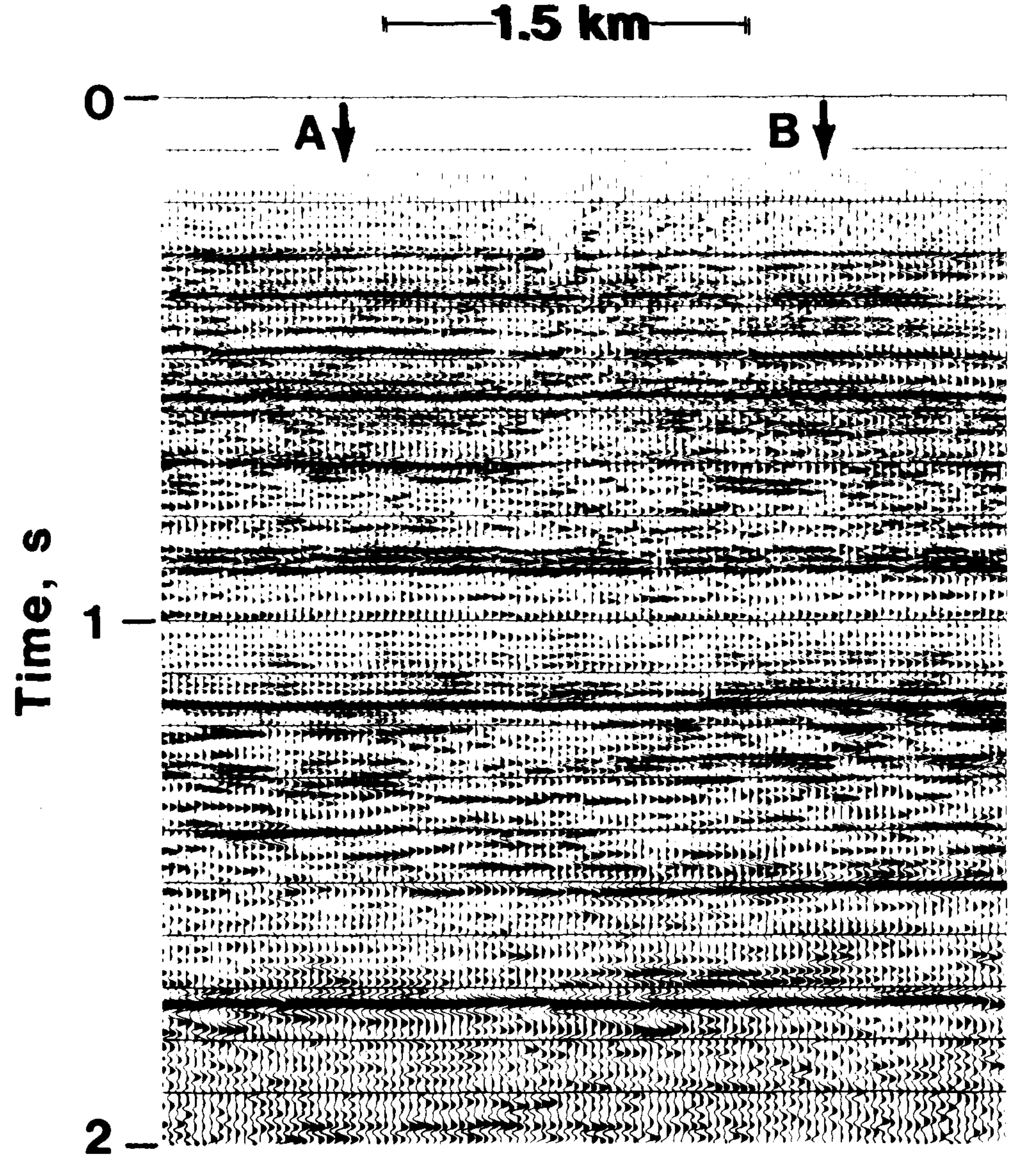

Figure 9. Sign-bit section. Eleven-fold summation after 60-fold CMP stack (Courtesy of Sohio Petroleum Company).

3.1 CMP STACK

'Common mid-point' and 'moveout' may be understood by reference to Fig. 11. A record is made with a source and detector each positioned a distance x_1 either side of the mid-point, M. Additional records are then taken with the source and detector spaced x_2, $x_3 \ldots x_m$ either side of M, which explains why it is called the *common mid-point.* For each record the reflection comes from the common *depth*-point, D. As the spacing increases so will the reflection times obviously increase, as indicated in Fig. 11. The increase in time with horizontal distance is called the moveout. Removal of the moveout time in the computer enables a simple superposition (stacking) of the traces to increase the amplitude

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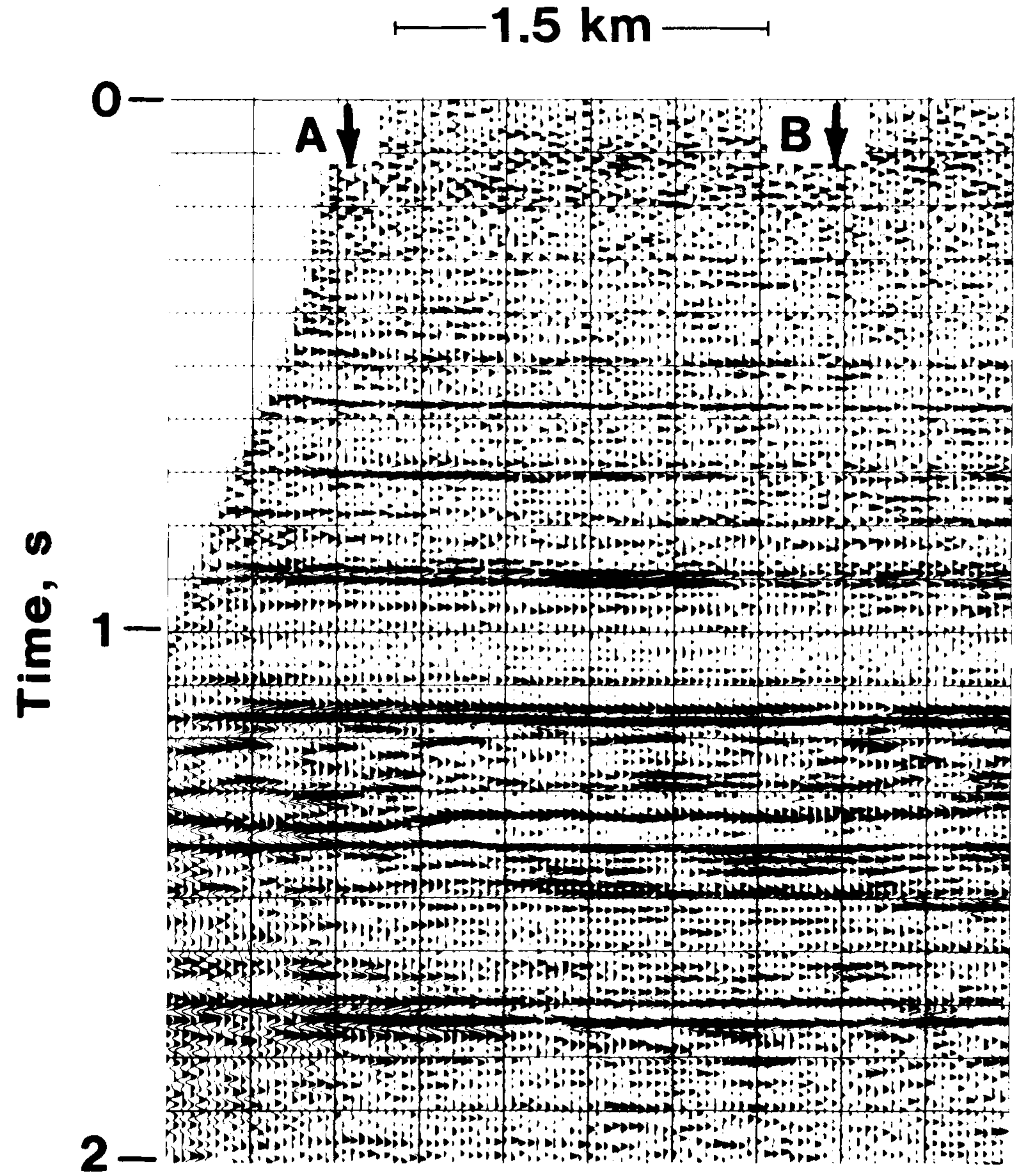

Figure 10. Full-bit section. Twenty-four-fold CMP stack for the line shown in Fig. 9 (Courtesy of the Sohio Petroleum Company).

of the reflection at the expense of any coherent noise following a different moveout curve. The moveout is measured with respect to the time which would be recorded with a coincident source-receiver pair, i.e. $x = 0$, and it is this 'zero-offset' time which is plotted on the seismic section. The mechanics of carrying out this elegantly simple and amazingly powerful technique are described in several texts (e.g. Waters 1978; Telford *et al.* 1976) as are the details of analysing the data to determine the required moveout functions (see also Schneider & Backus 1968). Fig. 12 illustrates the power of the technique. I will not attempt to run through all the other processing procedures, which are mostly described in the texts mentioned above but will select just one, record section migration.

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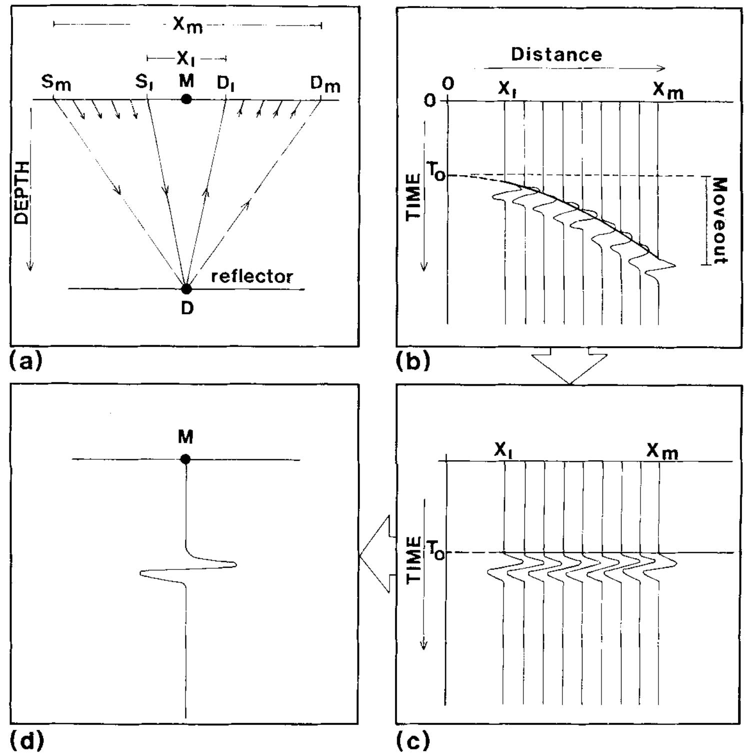

Figure 11. Common mid-point (CMP) stack. (a) Ray diagram; S = Source, D = Detector, (b) CMP record, note that each trace comes from a different field record. (c) CMP record with moveout removed. (d) Summation (stack) of all m traces.

3.2 RECORD SECTION MIGRATION

Seismic wave propagation is governed by the elastic wave equation. However, unlike earthquake seismologists, few exploration geophysicists would recognise the equation if they saw it and fewer still could make any use of it. Except in the trivial sense that it underlies geometrical ray theory it, as yet, plays little part in seismic prospecting. A major exception to this generalisation is record section migration, of which theoretical reviews are given by Hood (1981) and Berkhout (1980) and a philosophy of usage is given by Hosken & Deregowski (1982).

A minor application of the equation is to use it to calculate the ground motion which would be recorded at a given detector location when a given source excites a prescribed earth model. The result is called a synthetic seismogram and the procedure is illustrated in Fig. 13. It is equally possible to solve the wave equation with time running backwards and so estimate the unknown earth section from the recorded reflection time section. This latter procedure is known as record section time migration – 'record section' because that is the starting point of the process, 'migration' because the reflecting 'points' are said to 'migrate' from their recorded ground position (x) and echo time (t) to the horizontal location (x_m) of their point of origin on the reflector and the vertical travel time (t_m) to that point. And 'time' migration because the velocity function for the procedure is expressed in terms of two-way vertical travel time (t_m) and not depth.

Note first, that before the observations can be migrated it is necessary to stipulate the velocity and density functions. Of course, if we knew these precisely, we would not be carry-

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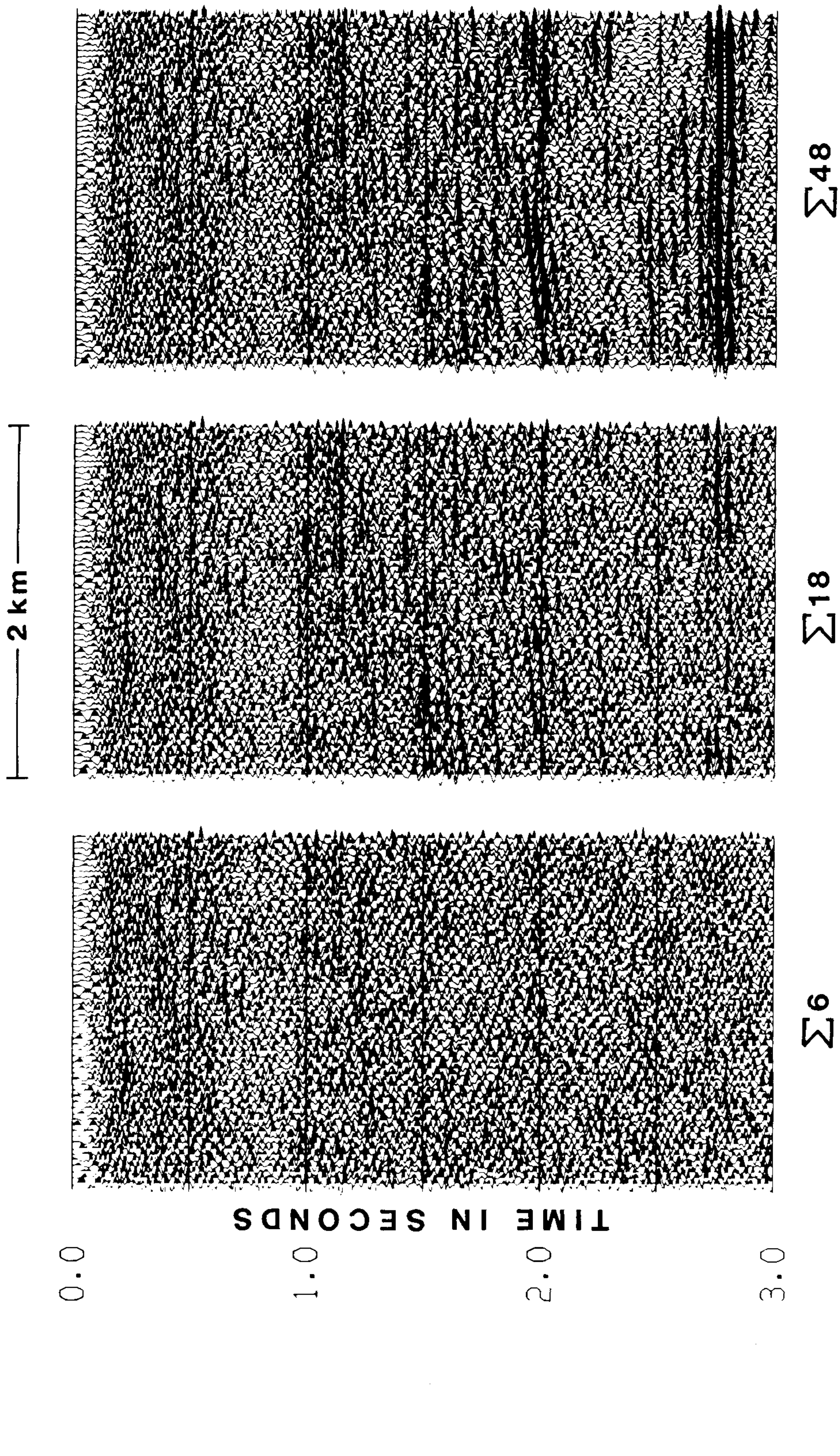

Figure 12. Results of common mid-point stacking.

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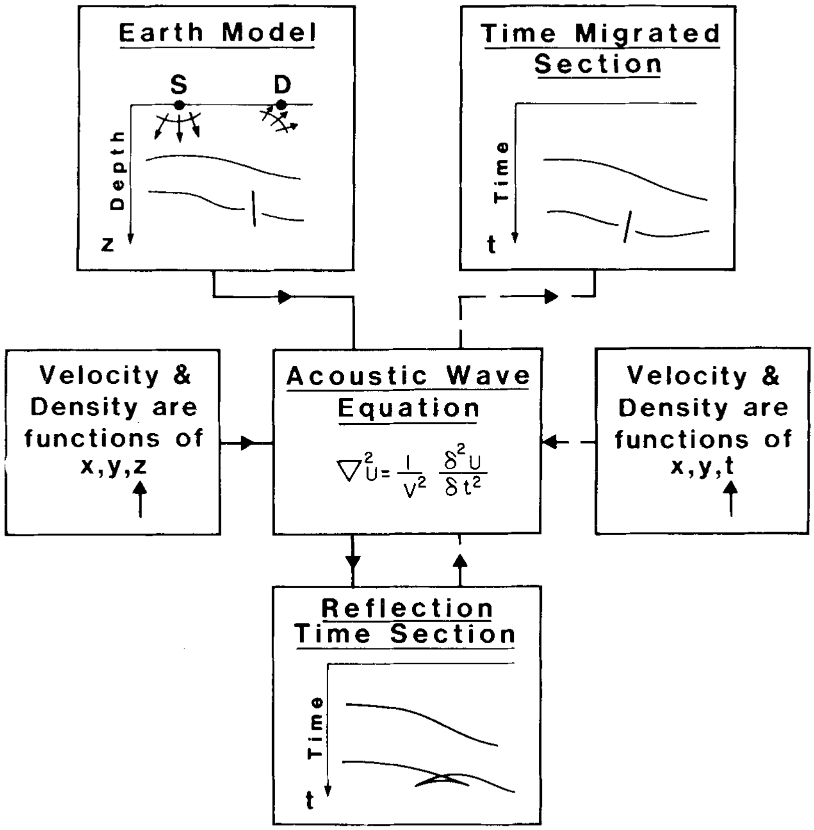

Figure 13. Seismic modelling. Down the solid line – forward modelling, depth-to-time. Up the dashed line – time migration as inverse modelling, time-to-time.

ing out a seismic reflection survey since the spatial variations in velocity and density are all that can be deduced from measurements of mechanical reflections. In practice, we make an estimate of the gross features of the velocity variations as a function of travel time (an observable) from prior data analysis or by extrapolation from nearby borehole information, ignoring variations in density, and are agreeably surprised that 9 times out of 10, the images on the migrated section are very much clearer and interpretable than their equivalents on the unmigrated section. Figs 14, 15, 16 and 17 show typical examples. The essence of the improvement is that the geometric forms of the reflections are more correctly presented on the migrated section – migration gives no significant additional information on velocities and densities, nor will it do so in my lifetime, except in the limited situation of extrapolation away from a well – a confident statement which many research workers are endeavouring to prove wrong and which I make with the hope that it may irritate others and so spur them in the attempt. What will be achieved in the next few years is a closed loop, interactive, computer graphics, modelling system which will iterate on a gross *spatial* velocity function and control record section migration to achieve clearer and more correctly positioned geometrical images of the subsurface. The reason I doubt that development of the method will allow significant velocity/density information may be summed up in two phrases – 'noise' and 'signal waveform'. If more research was carried out on the properties of source-generated noise instead of making the ludicrous assumptions that it is white, random

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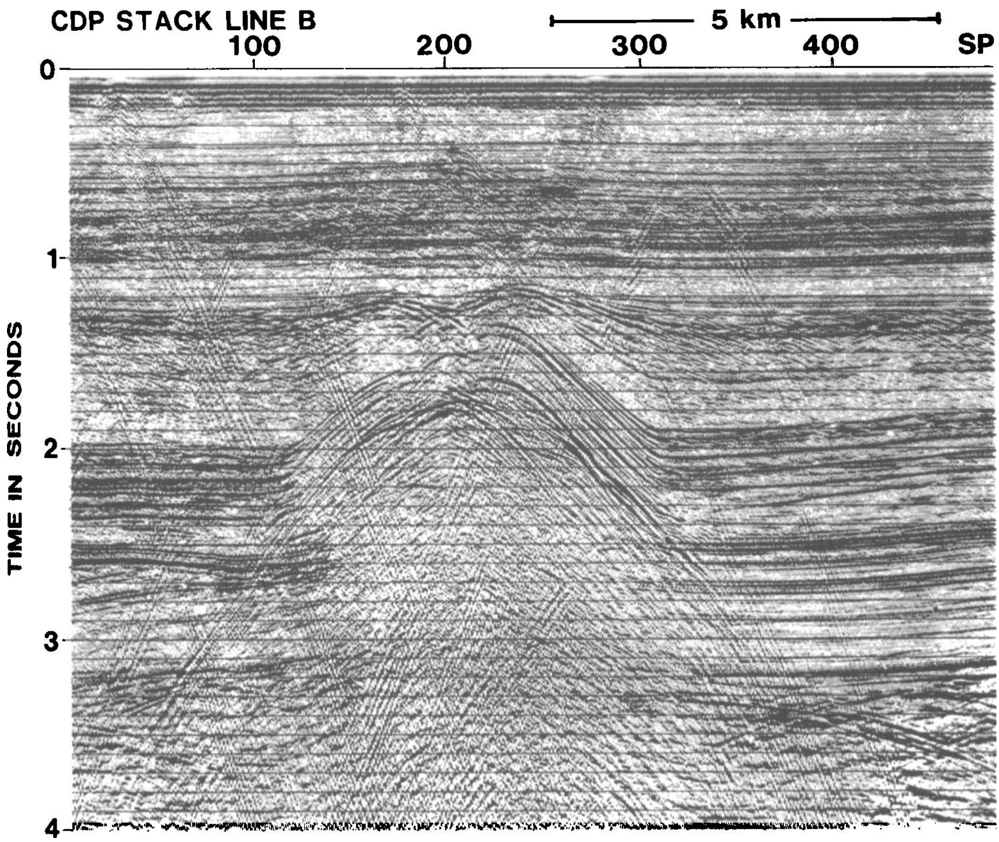

Figure 14. A seismic section before migration.

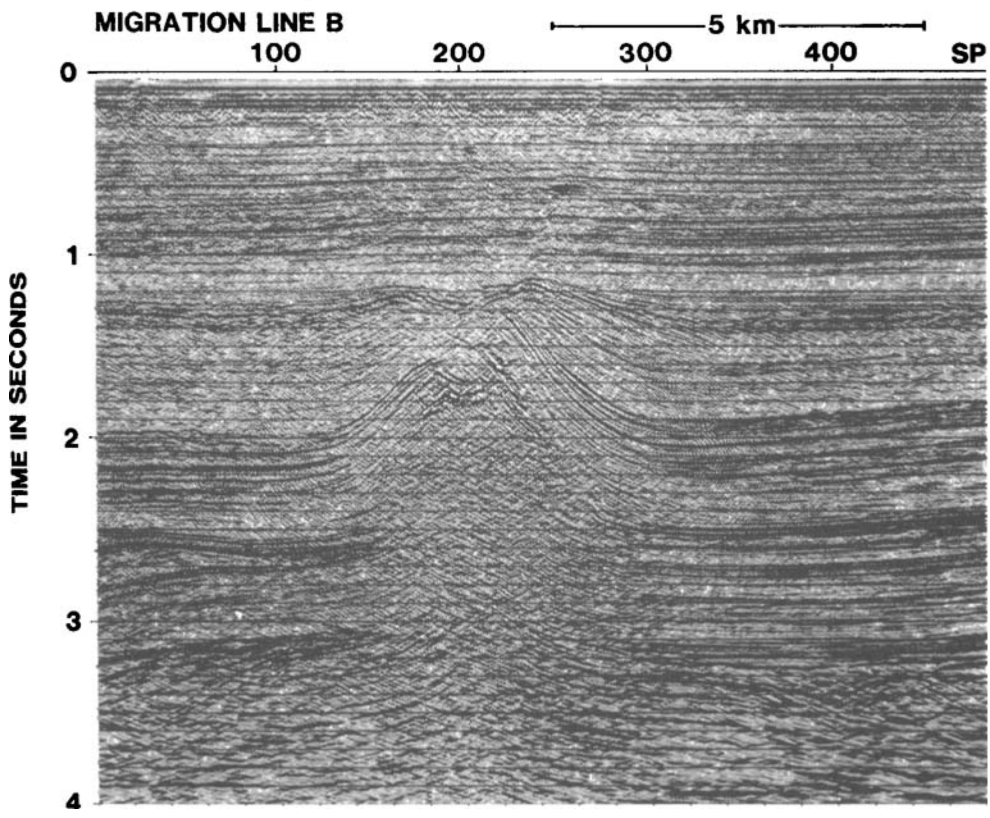

Figure 15. The section in Fig. 14 after migration. Note the narrowing of the salt dome and the clarification of the collapse structures on its peak.

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and Gaussian, then faster progress might be made. In principle, the waveform radiated by the source may be precisely measured, and at sea this will 'soon' be achieved. But the waveform required for detailed unravelling of the velocity and density functions is that of the recorded echo, and in the absence of a well this can be estimated only by (spectral) analysis of the recorded traces; and 2–3 s of data, even if noise free, is not enough for a sufficiently accurate estimate.

All current algorithms are based on solutions of the *acoustic* wave equation, so shear waves are ignored. It is also assumed that density is constant. Further, the records to be migrated are assumed to contain no echoes which have been reflected more than once. Since the original field records are often full of multiply-reflected echoes this means that the multiples must have been considerably reduced by pre-migration processing (deconvolution and CMP stacking). It is also normally assumed that the CMP stacked trace (Fig. 11) is equivalent to the trace which would have been recorded if the source and detector had been co-incident (zero-offset).

Most migration procedures then make use of the 'exploding reflector' hypothesis. This hypothesis may be understood by reference to Fig. 18. Fig. 18(a) illustrates a physically possible experiment in which a coincident source-detector pair are moved incrementally along a line, recording a single trace at each location. Plotting these traces side-by-side will produce the seismic section illustrated in Fig. 18(c). Consider now the result of the hypothetical experiment in Fig. 18(b) where a line source (a sheet in 3D) is initiated at time zero. Suppose that at each point along the line the source strength is proportional to the amplitude and polarity of the reflection coefficient at the corresponding position in the real Earth. The wave travelling up from the 'exploding reflector' will reach the ground surface at times equal to exactly one-half of those recorded on the surface-to-surface CMP record section. If we have a lot of reflections, as we do, we may solve the wave equation for each in turn and, since it is a linear equation, superpose the solutions and double all times to obtain the recorded section. So, if we can obtain the appropriate exploding reflector model this will be identical to the actual distribution of reflectors (and diffractors) in the real Earth.

This is done by making use of the Kirchoff Boundary Integral to carry out inverse modelling – that is, to proceed from the zero-offset (CMP) time section to the sought- for exploding reflection model. Refer to Fig. 19. P is an elementary point source at a distance R from an observation point on the free surface. It may be shown (e.g. Hosken 1981) that the strength of the source, u, at position $P(x_1, y_1)$ is given by

$$u(x_1, y_1, Vt_0) \simeq -\frac{1}{2\pi} \cdot \frac{t_0}{V^2} \int_S \frac{1}{t_1^2} (\partial u/\partial t)_{S,\, t_1}\, dS \tag{1}$$

where x, y and z are rectangular co-ordinates with z vertically downwards, V is the acoustic wave velocity, t_0 is Z_1/V, t_1 is R/V, S is the surface defined by the ground and an infinite hemisphere.

Since values on the infinitely distant hemisphere make a negligible contribution to the integral, u_P may be calculated from the ground surface observations – provided V is known.

In practice, it is assumed that the earth section is invariant in the y-direction and the surface integral then reduces to the line integral:

$$u(x_1, y_1 = 0, z_1) \simeq \frac{1}{\pi} \int_0^\infty \frac{t_0}{V^2 t_x^{3/2}} [f(t_x) * u(x, 0, 0, t_x)]\, dx, \tag{2}$$

where $*$ denotes convolution and

$$f(t_x) = (2\,|t_x|)^{-1/2}\, \delta(t) - (2\,|t_x|)^{-3/2}\, [1 - H(t)],$$

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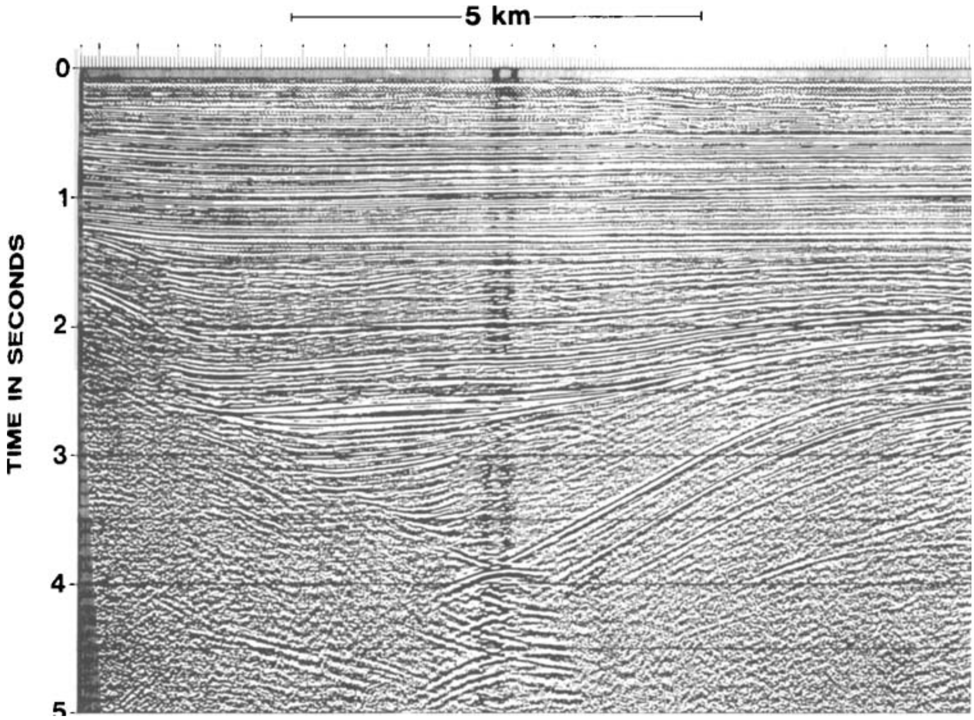

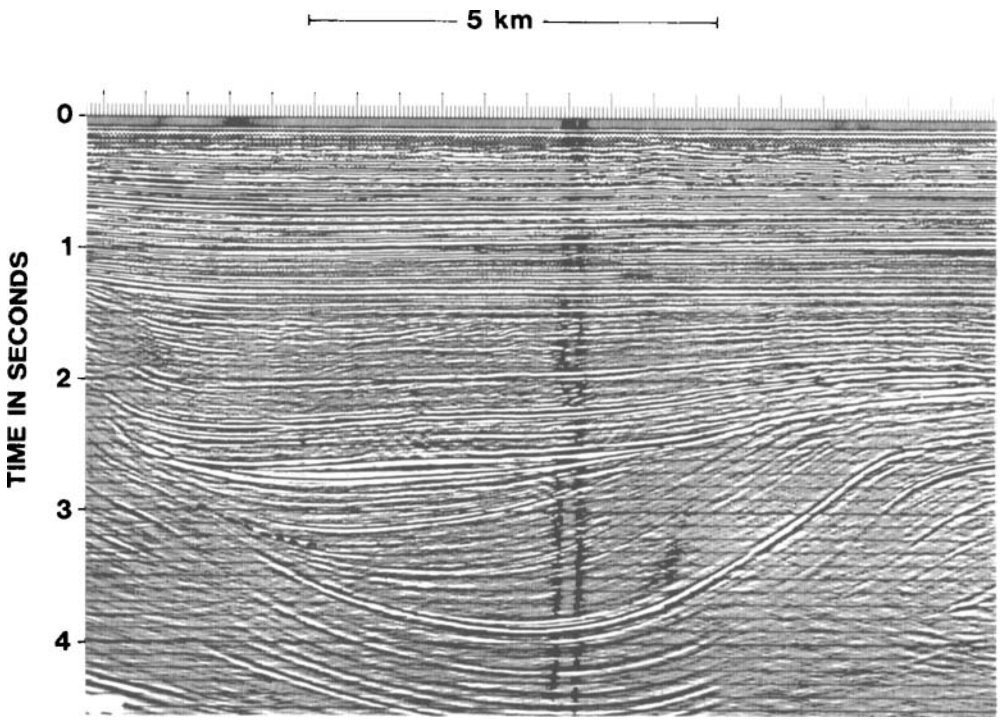

Figure 17. The section in Fig. 16 after migration. Note the broadening of the syncline and the improved clarity of the reflection terminations.

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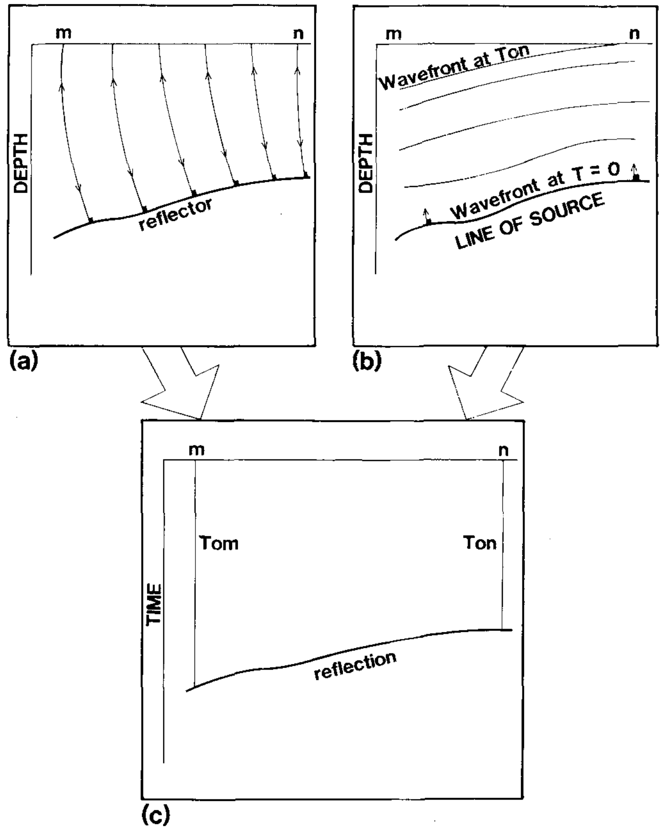

Figure 18. Imaging principle – the exploding reflector hypothesis. (a) The real experiment with co-incident source and detector. (b) The hypothetical experiment. The medium is identical to that in (a) except that all velocities are halved. (c) The zero-offset section. Note that (a) and (b) are not equivalent if there are extreme lateral variations in the medium.

where $\delta(t)$ is the Dirac impulse and $H(t)$ is the Heaviside unit step. $f(t_x)$ is a maximum-phase, half-differentiating filter operator, giving 45° phase lag and a 3 dB per octave increasing amplitude with frequency. The integral in equation (2) is approximated by a summation and carried out in the computer as indicated diagrammatically in Fig. 20. The curve along

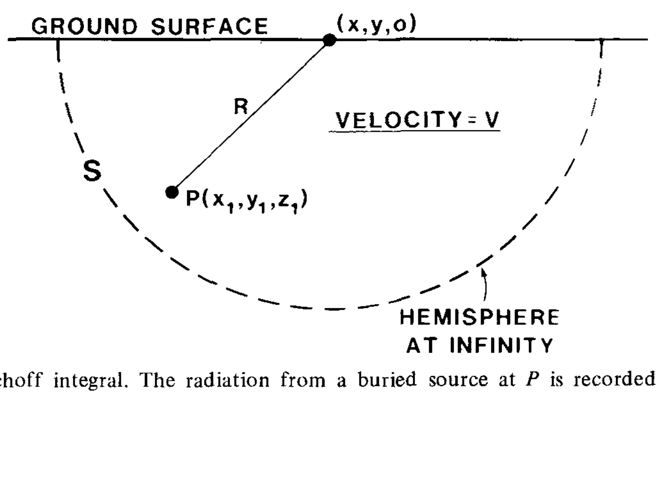

Figure 19. The Kirchoff integral. The radiation from a buried source at P is recorded on the ground surface at $(x, y, 0)$.

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which the samples are 'gathered and summed' is that relating t_x to t_0, i.e.

$$t_x^2 = t_0^2 + (x - x_1)^2/V^2$$

and is therefore a hyperbola. If V varies with depth only equation (2) may still be used, and the summation curves remain closely hyperbolic, though V is now replaced with its time-averaged, root mean square value $V_{\mathrm{rms},t}$. If V varies only slowly with x, then summation curves which are easy to implement in the computer can still be defined, but as soon as lateral variations in V become large the procedure, while still being useful in that it clarifies the image, will position that image incorrectly. This mislocation of the image was first discussed by Hubral (1977) who introduced the concept of image rays and indicated how they might be used to remove the mislocation error, a subject elaborated upon by Hatton (1980) and Larner *et al.* (1981). Image rays are used extensively when accurate positioning is required, such as when locating a well, but normally this is done only after the number of samples on the record section has been drastically reduced (by up to a factor of 1000) by identifying a few key reflections on each trace, representing them by a single sample at the appropriate time and replacing all other samples by zeros.

It has been implied in the previous paragraph that migration will appreciably clarify the image even if the velocity field is not known very accurately. This is an advantage in that it means that worthwhile signal processing can proceed without detailed knowledge of the velocity. On the other hand, it means that measurement of image clarity will not lead to accurate velocity estimates and accurate velocities are in many cases what are needed for the proper location of wells and the detailed mapping of potential hydrocarbon reservoirs, even when the image ray distortion mentioned above is negligible. As a simple example consider the problem illustrated in Fig. 21. It is desired to test the indicated fault block. Referrring to Fig. 26 and putting $V_1 = V_2 = V_3 = V$ it may be seen that the lateral migration shift of a reflection segment is given by $VT_n \sin\theta/2$, which is proportional to V^2. A 10 per cent error in V will therefore give a 20 per cent error in lateral shift, which could result in the well being located outside of the edges of the fault block.

The most popular migration algorithms are based on finite difference schemes for the solution of the wave equation, not the boundary integral method outlined above. Their

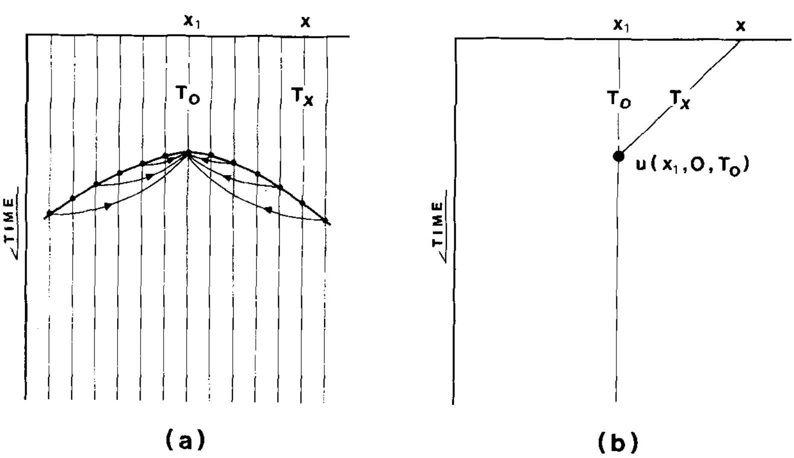

Figure 20. Migration by Kirchoff summation. (a) Zero-offset field (CMP stacked section). Integration of the integral is carried out by summing together, after scaling and filtering according to equation (2), all the u values which lie along the hyperbola. This summation, which takes place over a few hundreds of traces, is output at x_1, T_0 as indicated in (b).

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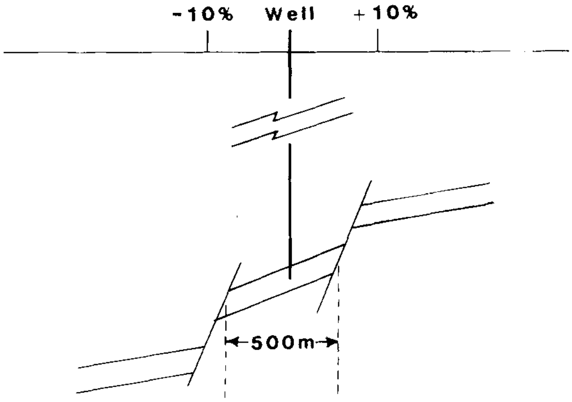

Figure 21. Migration positioning error. Errors of ±10 per cent in velocity will not strongly affect clarity of the image on the seismic section but may result in a well missing its target.

introduction was due to Claerbout (1971, 1976), who also introduced a frame of reference which moved upwards with the average wave velocity with the consequence that in the calculations any downward moving energy (i.e. multiples) was rapidly attenuated. The scheme is less demanding of computer time than the Kirchoff method and is therefore cheaper, it also has the surprising advantage of being more effective because it is less accurate! This is because of the presence of noise. The Kirchoff method is accurate even at very large dips so that noise spikes – which, of course, the algorithm treats the same as signal – are smeared out over large circular arcs producing the well known 'smiles', much as may be seen within the salt of Fig. 15. The finite difference operator does not deal so well with large dips and therefore does not organize the noise to nearly the same extent. Of course, if reflectors with large dips are present then Kirchhoff Summation may be preferable to the Finite Difference method.

The fastest algorithm of all makes use of the Fourier transform to carry out its manipulations in the time-frequency spatial wavenumber domain. As introduced by Stolt (1978), it is exemplary if velocity is constant (it never is), adequate if velocity varies only with depth and poor if the velocity varies laterally. Because of its intrinsic speed, many researchers are endeavouring to modify it to handle lateral velocity variations; if they succeed it will no doubt become the preferred method. In passing, it may be noted that migration is no longer reserved for sections which exhibit severe geometrical complexity but is being used more and more to remove scattered energy and to clarify reflector terminations at unconformities and faults. This is due in large measure to the impetus given to the introduction of migration as a routine procedure as a result of the *cheapness* of *f–k* migration (Stolt 1978).

Migration as described above starts with a zero-offset reflection section. Such a section could be obtained by surveying with source and receiver placed very close together but the signal-to-noise ratio would normally be so poor that reflections would be largely invisible. A CMP stack is required to raise the SNR to an acceptable level. Fortunately such a stack normally approximates closely to a zero offset section which, via the exploding reflection hypothesis, is taken to be a solution of the wave equation. Nevertheless, when reflector structure is complex a CMP stack does not approximate a zero offset section, nor is it a solution of the wave equation since it results from a superposition after the *non-linear* CMP processing of the individual solutions (the input shot records). Consequently an inverse modelling procedure (migration) based on the wave equation will not work. There are

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various ways of 'fudging' the migration procedure to handle such data but the only satisfactory procedure is to go back to first principles, keeping the high degree of redundancy necessary for signal-to-noise enhancement, while applying wave-equation processing to individual shot records, each of which is obviously a solution to the wave equation since it is the result of an actual experiment. Such a scheme has been described by Schultz & Sherwood (1980). In their procedure each field record is taken separately and the wave equation used to compute what the record would have been if the detectors had been placed a small distance (say 50 m) below the ground surface. This is illustrated diagrammatically in Fig. 22. The data are then sorted into records, each of which relates to a single detector but all the sources. Reciprocity is invoked to say that detectors and sources may be interchanged, with the result that the record may be treated as if it were the result of a single shot (replacing the single detector at 50 m depth) and a number of detectors (replacing the several sources on the ground surface). The wave equation is then used to compute the record which would have been obtained with the 'reciprocal detectors' placed at the –50 m level. These two steps result in obtaining a set of records which would have been obtained if both the sources and detectors had been 50 m beneath ground surface. This two-stage procedure is continuously repeated and on each occasion the reflection times with respect to the lowered recording level become earlier and the reflected energy moves inward from the larger offsets (source-detector distances) toward zero-offset. As the revised reflection time reaches zero, so does the reflected energy reach the zero-offset trace; the procedure is stopped for that (time, energy) pair and the sample is output to form part of the output migrated record section (Fig. 23). Assuming that reciprocity applies sufficiently well, which is somewhat uncertain, each 'downward continued' record is a true solution to the wave equation which, in the case of Schultz and Sherwood, is obtained by means of a finite difference scheme. Although their paper was called 'Depth Migration before Stack' no

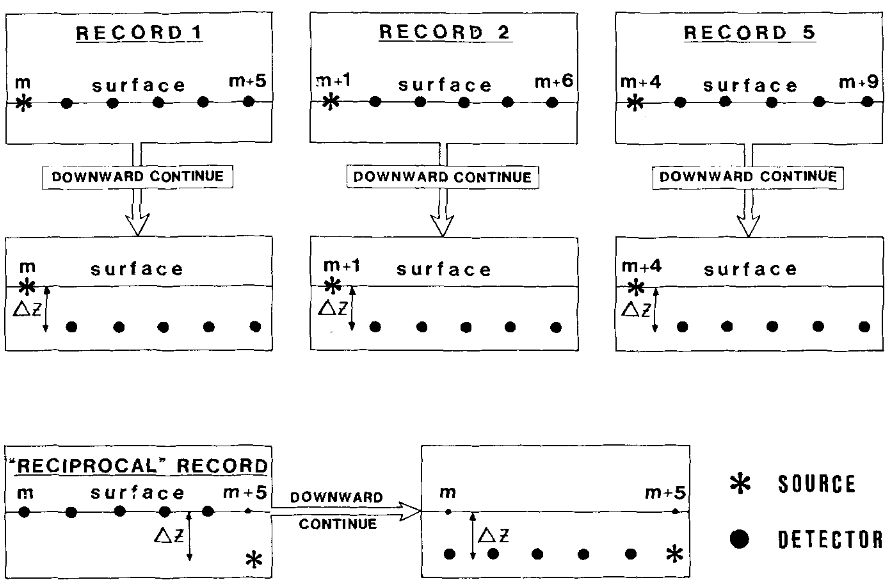

Figure 22. Downward continuation. By invoking reciprocity it is possible to calculate the records which would have been obtained at depths of Δz, $2\Delta z \ldots n\Delta z$. In this illustration the source and five detectors are equally spaced and successive records are taken after moving them along the line by increments of one spacing interval.

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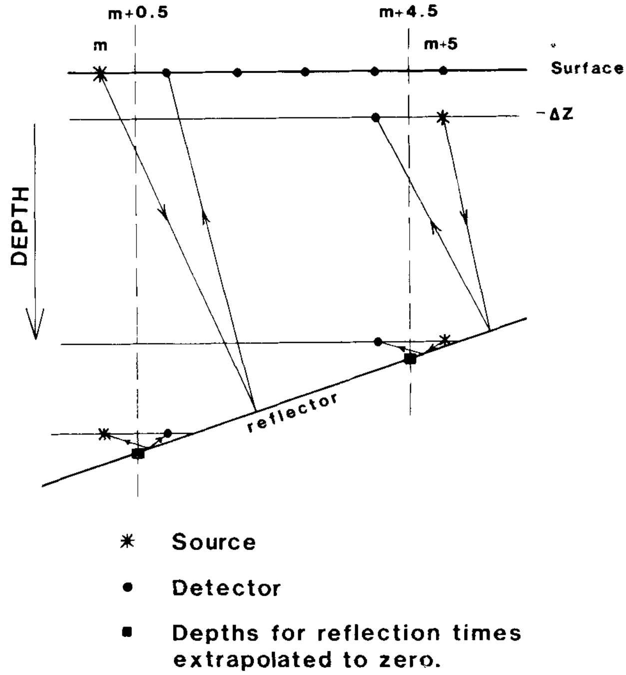

Figure 23. Downward continuation. As the hypothetical recording level is lowered the reflection (and diffraction) times become less and less. When an event time reaches zero the 'recording' level has been lowered to the reflector (or, diffractor) position. Note that the output is a depth section and this requires the velocity field to be specified as a function of space (2 or 3D), not time.

subsequent stacking procedure is required since the technique implicity allows for moveout correction and stacking at the same time as it migrates.

This downward continuation procedure is predicated upon a velocity–*depth* model and hence is called depth migration. The procedures outlined previously require velocity–*time* models as input and hence are called time migrations. In depth migration the initial velocity–depth model is obtained from interpretation of a CMP stacked section or from a time-migrated version of it. This initial model is then changed interactively and iteratively until the resulting depth migration is judged by some set of criteria to be an optimum. Since depth migration works on the individual field records, it has to process 20–100 times as much data as the conventional time migration, for which the input is the CMP-stacked section. Also, because it honours a velocity–depth model of arbitrary complexity, it uses a more complex algorithm. Consequently, it is 100 times or more as costly as time-migration and is rarely used. Hosken & Deregowski (1982) discuss the principles of decision making when moving from less accurate to more accurate migration procedures – there are many more choices than I have mentioned – and give a practical example.

The first paper on seismic record section migration was probably that by Rockwell (1971). It rapidly became the most active area of research into seismic data processing and continues to be so. But we need a lot more attention paid to ensuring that the earth models used and noise properties assumed are reliably accurate idealisations and a lot less (or, at any rate, a little less) attention paid to purely algorithmic development. Of the many post-war improvements in seismic reflection data processing, record section migration ranks third after CMP stacking and statistical deconvolution.

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4 Interpretation technique

Interpretation is concerned with turning seismic record sections into geological ones and then using these to deduce basin history as it relates to petroleum generation, migration and accumulation. Stage one, therefore, is concerned with getting as good a description of today's geology as possible. In decreasing order of reliability one obtains structure including faults, unconformities, lithology, depositional environment and stratigraphy. The last three items are particularly dependent on well information and may be put in different orders by different geophysicsists. No mention has been made of direct detection of hydrocarbons: it can be done – but rarely. Stage two, obtaining the petroleum-related history of the sedimentary basin obviously moves into the area of mainstream geology and so falls outside the scope of this article.

Just as there are chrono-stratigraphy, bio-stratigraphy and litho-stratigraphy so too there is seismo-stratigraphy. This is concerned mainly with mapping unconformities and with identifying and interpreting offlaps, onlaps, bottom laps and related reflector terminations. The principles involved and a self-contained and largely accepted terminology is given in a series of papers by Vail *et al.* of the Exxon group (e.g. Vail *et al.* 1977). Although the industry concerned itself with these matters before the publications of the Exxon group, there is no doubt that they raised seismic stratigraphy almost to a separate discipline by their series of outstandingly innovative contributions. Their 'invention' of seismic stratigraphy certainly rates in importance with that of seismic migration.

But the bulk of seismic interpretation is concerned with structural mapping, an example of which is given in the next section.

4.1 RAY TRACE MODELLING

The CMP stacked section in Fig. 24 shows a series of reflectors terminating against the flank of a salt wall on the left hand side of the figure. Fig. 25 shows a contour map at potential reservoir level prepared from a number of such sections. The next step is to choose a well location to test the reservoir for the presence of oil. It must be located so that the well meets the reservoir sand just outside the salt wall but remains inside the shaded area which indicates the maximum possible lateral extent (closure) of any oil accumulation. Reflect*ion* (x, t) segments measured on Fig. 24 must be accurately migrated to reflect*or* (x_m, z_m) pairs as indicated in Fig. 26. Record section migration as described in Section 3.2 is as yet neither sufficiently accurate nor sufficiently flexible to 'solve' the problem. Instead, we turn to a much simpler technique, ray trace migration. Referring to Fig. 26, and remembering that Fig. 24 shows a *zero-offset* section, it may easily be seen that at the surface the angle of approach of the zero offset ray, θ_1, corresponding to the reflection recorded at time t at location x is given by the equation

$$\sin\theta_1 = V_1 \cdot \partial t/(2\partial x);$$

∂t and ∂x may be measured off the seismic section so that, if V is known, the ray may be traced backwards into the earth model, refracting it at each velocity contrast, calculating the travel time $\Sigma(L/V)$ and terminating the procedure when it equals one-half of the observed reflection time. The reflecting element may then be drawn as a small segment perpendicular to the ray end. This procedure starts with the shallowest reflector, in this case the sea-bed, and maps in successively deeper reflectors until all the reflections have been migrated. Fig. 27 shows the reflection segments which were 'picked' on the CMP stacked section shown in Fig. 24 and Fig. 28 shows a near final result of ray trace migration.

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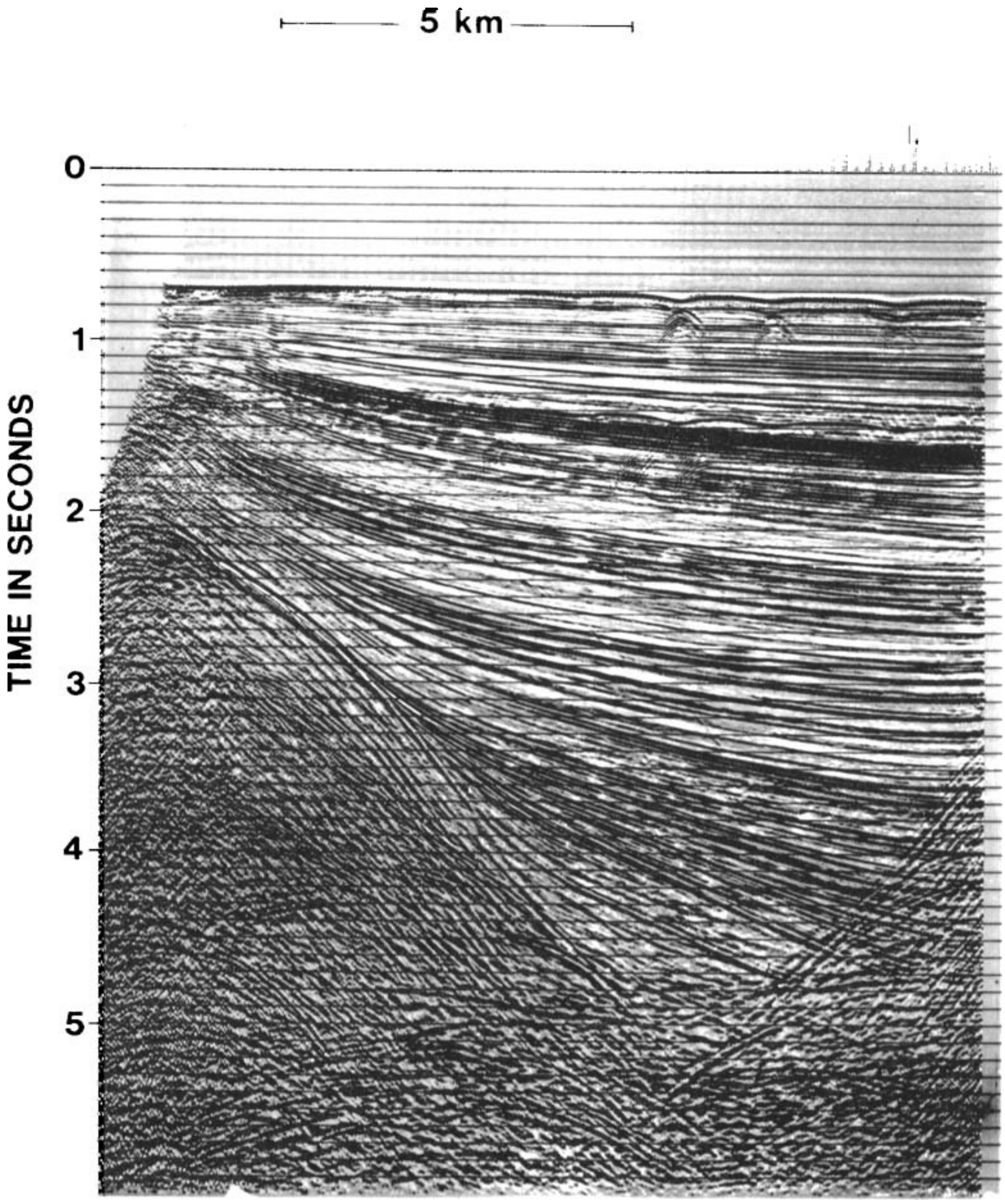

Figure 24. CMP stacked section in a salt province. Note reflections terminating againat a salt wall on the left. There is also a deeper salt feature on the right.

Segment numbering informs the interpreter which reflection segment defines which part of the structure so that if he does not like the migrated result he can assess whether or not it is permissible to alter his initial x, t 'picks'. Note in this case that segment 11 is decreased in spatial extent and moved laterally by about 4.0 km, while segment 10 is increased in spatial extent and reversed in curvature. Note also that in spite of continuous dense recording on the ground surface significant gaps occur in coverage on the reflector.

An exact depth model depends upon exact velocities. These mainly come from analyses of CMP gathers controlled, whenever possible, by measurements in wells. Reference to

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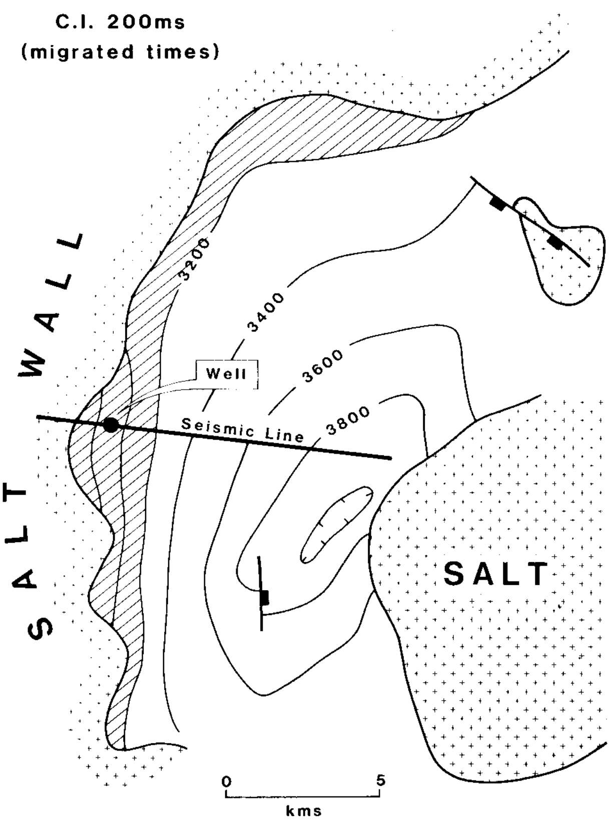

Figure 25. Isochrons at reservoir level.

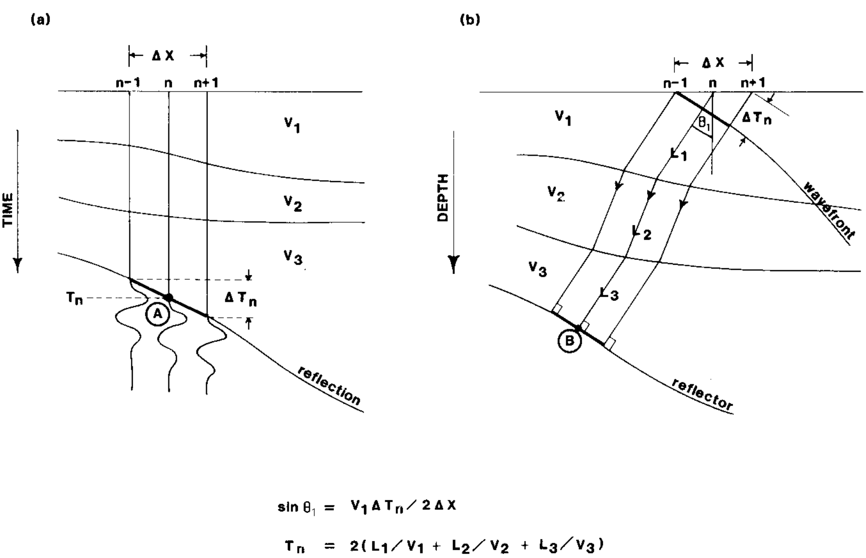

Figure 26. Ray trace migration. (a) Zero-offset (CMP stack) section showing reflec*tion* segment A. (b) Depth section. Reflec*tor* segment B is the origin of A, its accurate location demands accurate knowledge of the velocity field.

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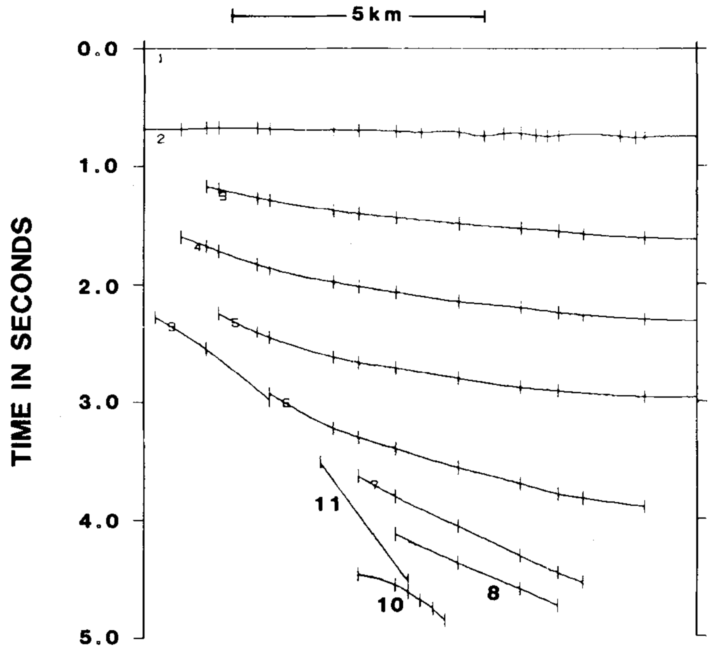

Figure 27. 'Picked' reflections. This is an interpreted overlay to the CMP stacked section of Fig. 24.

Section 3.1 and Fig. 11 makes it obvious that the reflection moveout measured on a CMP gather is directly related to velocity. In fact, for the ideal case of a constant velocity, V,

$$t_x^2 = t_0^2 + x^2/V^2.$$

So, by analysing observed moveout times layer velocities may be estimated. Note that an estimate may be obtained at each common mid-point that is, at 25 m intervals in this case.

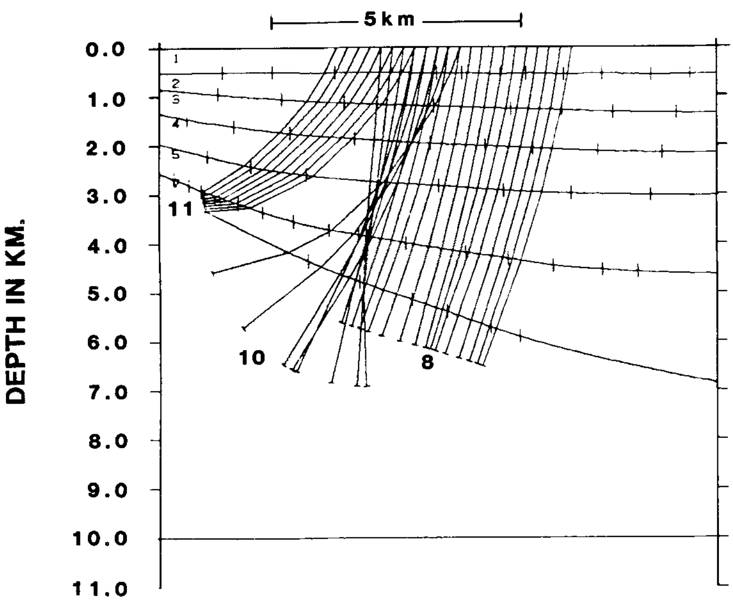

Figure 28. Depth section from ray trace migration. The ray ends 8, 10 and 11 originate from the correspondingly numbered reflection segments in Fig. 27.

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Since layer velocities vary laterally due to lithologic changes and vertically due to changing overburden pressure, this essentially continuous velocity estimation procedure is essential. Constant velocity layers do not exist or, at least, only very rarely.

So the final depth model, obtained after several iterations, satisfies not only the t, x pairs on the CMP stacked section but also the moveout functions from each primary reflection on the individual CMP records. The result, in this case, was a mean depth error of around 0.75 per cent. Unfortunately, as with the results from 54 other wells drilled in the same sedimentary basin, no commercial oil was found!

Note that this graphically interactive ray trace procedure starts from the CMP stacked section, which is the basic result of a seismic survey, and ends with a depth model. It is also possible to start with a depth model and compute zero offset section by ray tracing. This would then be compared with the observed CMP section and the depth section altered iteratively until the simulated and real sections agree. This latter procedure founders on the difficulty of generating the initial depth model so, while many programs have been written which start from a depth model, few have had significant use.

5 The future

Though the principles remain essentially the same, the pace of technological change advances the practice of seismic reflection survey with unabated speed. Mainly this relates to the gathering of increased data volumes and the use of digital computers to handle them. The increased data volume is due partly to an increase in the data redundancy factor as a means of combating shot-generated noise and partly to decreasing the line-spacing in the survey. The latter is necessary in order to enable us to drop the over-simplifying assumption of a 'two-dimensional' subsurface, which currently underlies the vast majority of seismic data processing. Digital computers and related equipment continue their rapid improvement in cost effectiveness but the day is still far off when their power will be cheap enough to warrant application of signal enhancement and imaging algorithms which are already definable. In fact, it will still be a long time before the computers are large enough, much less cheap enough.

1983 is the year of the colour graphics work station. These are of use when interpreting seismic sections (such as those shown in Figs 2 and 3) after they have undergone the full range of signal enhancement procedures. Current work stations can neither store, nor call-up, nor display, nor provide hard copy of enough data fast enough, nor cheaply enough, for ubiquitous use. But in five years they will – and then the seismic interpreter will no longer need to handle paper?

In 1982 the first commercial service was offered for satellite transmission of seismic data from the survey area to HQ. The maximum transmittal rate is 56 kbaud, which is sufficient for many quality control purposes. A rate of 1.544 Mbaud is promised which would enable *current* data acquisition results to be transmitted in real time. HQ processing and interpretation will then have the challenge of reacting fast enough to modify the survey specification during the data acquisition period, even for fast moving marine surveys. It will not happen.

From a purely technical viewpoint it might be better to aim at moving the computer power to the acquisition ship or base camp – something which has been talked about for a long time and is gradually being achieved – but, even if computer developments make this worthwhile, the desire to get data back to the safety of HQ, where it can be more easily integrated with all the other exploration and commercial considerations, will always be a strong counterforce.

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There are a number of peripheral seismic techniques and measurements which have been in R&D for many years and one day may survive in the harsh environment of the real world. Shear wave reflections may give added useful information, particularly if we can devise worthwhile numerical models for those rock properties which tell us something we need to know; attenuation – a very blunt tool indeed – may some day be worth measuring; and more measurements with detectors and/or sources down deep holes may occasionally be of benefit. One of the great unsolved problems in seismic prospecting is mapping the near surface sufficiently well to reduce significantly its masking effect on the deep subsurface. Perhaps this problem may be alleviated by making better use of interface modes of propagation, though we shall certainly have to drop the laughable assumption that the Earth consists of plane, parallel, layers.

At present the earth models underlying acquisition, processing and interpretation form an hierarchy of increasing complexity. Attempts are underway to dispense with the simpler models and to use, iteratively and interactively, the most complex of these models to control acquisition and processing parameters in addition to its current role in providing a drilling location. We know what we want to do – we merely need cheaper and bigger computers and display devices in order to do it.

Whatever may be thought of it in other fields, Marshall Macluan's dictum 'The medium is the message' certainly applies to seismic prospecting. To unravel the message we must study the medium, or at any rate our model of it. If we do so it is just possible that eventually, and before the oil and gas 'run-out', we will be able to detect hydrocarbon accumulations from surface seismic measurements as a matter of routine, though not in my lifetime.

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