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RECORDS

1958, No.44

METHODS OF IMPROVING THE QUALITY OF SEISMIC REFLECTION DATA

by

K.R. VALE

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CONTENTS

ILLUSTRATION

1. INTRODUCTION

The following discussion presents conclusions arrived at, by the author, partly from reading of geophysical literature but, more particularly, from discussions with geophysicists in the United States, England, France and Italy during a tour overseas between February and May, 1957. However, most points covered by those discussions are also covered in the literature. The real value of the discussions lies in the fact that the author obtained a large number of opinions on the relative importance currently being placed by the geophysical industry on the numerous techniques that are continually being proposed for improving the quality of seismic data. This, in turn, has greatly assisted in appreciating the literature. Reference throughout the following discussion is made to a fairly comprehensive bibliography presented at the end.

A seismic reflection record contains many seismic waves, of which only a few are required for analysis. Those waves which provide the required sub-surface geophysical information are known as the signal; the others are classified as noise. A seismic reflection signal is mechanically generated by the shot and transmitted through the ground, giving rise to reflections at certain discontinuities. These reflected signals return to the surface and are detected by electro-mechanical detectors giving an equivalent electrical signal which is amplified and filtered and finally displayed by optical means on a photographic record. Improvements in the quality of the data obtained may be made either at the mechanical (i.e. the ground motion), the electrical, or the display stage.

Methods of improving the quality of seismic reflection data may be divided into two major groups:-

(i) Improving the signal/noise ratio on the seismogram.
(ii) Final display of the data.

2. IMPROVING THE SIGNAL/NOISE RATIO.

A. Frequency Discrimination.

Frequency discrimination is a term applied to the conventional method of using a band-pass amplifier to reduce noise by filtering. This method depends on the fact that the signal/noise ratio is greater in certain discrete frequency bands than it is in the remainder of the seismic spectrum.

Simple constant-K filters are commonly used with independently variable low and high-cut sections. The more modern amplifiers usually have two sections each of low and high-cut, giving attenuation of the order of 24 decibels per octave (1). By far the most elaborate filters currently offered as standard equipment on any of the commercial amplifiers are those of the HTL 7000B amplifiers, of which the Bureau has a 12-channel set in use at Mawson, Antarctica.

One company is currently producing a set in which the cut-off frequency is altered by varying the inductance of a toroidal coil in the filter circuit. This is done for all amplifiers by a central, remote control. By means of a trip and decay circuit, the centre frequency of the band-pass can be varied by any desired amount during the running of a record.

Phase shift is a problem associated with filters which is causing some concern at the moment. This concern follows from the work of certain experimenters who are studying the possibility of making use of phase and frequency relationships for the investigation of small structures, reefs, lenses, pinch-outs etc. Elaborate linear phase-shift filters have been designed for laboratory and central office computing systems designed to process magnetic tape recordings (2).

A time-delay filtering system is currently offered on the market in which the original signal is fed on to a revolving magnetic disc and then picked off by 18 heads positioned around the disc so as to give any desired band-pass. Reinforcement and cancellation of frequencies is achieved as a result of time (or phase) differences between the various pick-up heads (3,4).

B. Phase Discrimination.

There are several methods of improving signal/noise ratio that can be grouped under this heading. They all aim at reducing the recorded strength of horizontally-travelling waves which normally produce a major portion of the noise recorded on a seismogram. In addition, they aim at reduction of noise which is random with respect to individual geophone and charge locations. This reduction of random noise automatically follows from any set-up of multiple geophones, multiple holes or multiple charges within a hole and will not be discussed further.

Phase discrimination is involved in the following techniques:-

(i) Multiple geophone arrays.
(ii) Multiple hole shooting.
(iii) Mixing
(iv) Spaced charges within a single hole, and long, low-velocity charges.
(v) Record stacking simulating either (i) or (iv) above and with different spreads for different holes.
(vi) Weight dropping.

(i) Multiple Geophone Arrays.

The technique of using more than one geophone per station has now become the first step towards improving results in any area where the quality of reflections is not first-class. It is now rare for less than four geophones per station to be used. Nine geophones per station is very common practice. Groupings of up to 100 per station are also common, the larger groupings usually being used in conjunction with multiple holes or charges. Groupings of up to 20 are often laid out along the line of the traverse. Large groupings, and sometimes smaller groupings, are laid in areal patterns, oblong, diamond and star grids being the most common (5,6,7,8).

Two schools of thought prevail with regard to multiple geophone arrays. One school believes that the essential factor is diversity of recording stations. A geophone separation of 25 feet or more is selected and a broad area is covered so that the geophones simulate a single geophone whose base contact with the ground would cover the same area. The types of noise which this arrangement aims to reduce are:-

(1) That which bears a random relationship to the actual positions of individual geophones,

and

(2) That which is distributed over a broad spectrum of frequencies for waves that travel horizontally and have a broad spectrum of velocities.

If these unwanted signals are regarded as coming directly from the shot point the geophones may be confined to in-line spreads. If, however, a substantial proportion of them is considered to consist of secondary waves resulting from primary waves (i.e. directly from the shot point) passing or being reflected from irregularities in the ground to the side of the traverse, then an areal pattern is used. The "diversity factor" governing improvement in a random set-up is more or less proportional to the square root of the number of geophones.

The second school of thought believes it is possible to detect in the noise a dominant wave of specific frequency and velocity. In this case the geophone pattern is designed to give maximum attenuation for this wave and all other noise is still reduced by reason of the diversity factor. A further stage in this theory is to arrange the geophone pattern to give a specific attenuation band of frequencies for a specific velocity at which the noise may pass through the pattern (7). If a range of likely velocities can be determined and if the spectrum for the best signal/noise can be determined for single geophones then a geophone pattern can often be determined that will give attenuation of all frequencies within the best signal/noise spectrum, that pass the pattern at all likely velocities. Theoretical attenuations of between 12 db and 24 db are usually aimed at. In practice the theoretical attenuation band is usually made to coincide with the amplifier filter pass band.

(ii) Multiple Hole Shooting.

This is normally treated in a manner analagous to that of (i) (5,6,7). However, multiple shot holes effect improvements under certain conditions which have no analogies in the case of multiple geophones. This is so if much of the noise is considered to be associated with the precise location of the hole and some of it travels vertically downwards and is reflected back to the geophones. It is also true if some individual holes are likely to have much poorer characteristics than others for transfer of the required seismic energy into the ground. Moreover, if the signal/noise ratio is likely to decrease with increased charge, multiple holes may be used to detonate the required total charge in smaller units, thus giving better noise attenuation.

For more or less vertically travelling noise, increase in the signal/noise ratio is obtained with multiple shot holes only by virtue of the diversity factor. However, for horizontally travelling noise, attenuation is effected as a result of both the diversity factor and characteristics common to both shot hole and geophone patterns. These patterns may be designed to attenuate certain dominant waves of surface noise by making use of phase relationships. More generally, and particularly in areas where "ground roll" is serious, shot hole patterns are arranged to give an attenuation band of somewhat lower frequency than that of the geophone pattern.

The diversity factor for a combination of multiple holes and multiple geophones is proportional to the square root of the product of the number of holes and the number of geophones. In general, economic factors determine the proportion of holes to geophones in an arrangement designed to achieve a certain diversity factor.

In areas where drilling is difficult, multiple shallow holes, which give comparatively poor signal/noise ratio, are used to achieve results equal to, or better than, those obtainable from single deep holes drilled to the optimum depth for maximum signal/noise ratio. Examples can be quoted where 30 to 50 holes of 6 to 10 feet depth give, with the same total charge, very much better records, at much lower cost per record, than single holes of 250 feet depth. In such cases the gain in signal/noise due to diversity and pattern is substantially greater than the loss due to shallow shooting (9).

When using multiple holes and multiple geophones, care must be taken to ensure that they do not cause any appreciable reduction of the signal strength of shallow reflections.

(iii) Mixing.

Mixing has always been a controversial technique. It is essentially a method of increasing the diversity factor independently of the use of additional geophones and holes. However, the equivalent geophone pattern and its theoretical rejection band should be considered. The two most common forms are termed unilateral and bilateral mixing. In the past, mixing has been carried out almost entirely in the output circuits of the seismic amplifiers. In unilateral mixing, trace 2 on the seismogram is derived from 50 per cent of the signal from geophone station 2 and 50 per cent from geophone station 1; trace 3 is derived from 50 per cent of the signal from geophone station 3 and 50 per cent from geophone station 2, and so on. This is termed 50 per cent unilateral mix. Other percentages are of course possible and the direction of mixing may be reversed. Bilateral mixing is of the type in which trace 4 on the seismogram is derived from 50 percent of the signal from geophone station 4, 20 per cent of each of geophone stations 3 and 5, 4 per cent of each of geophone stations 2 and 6 and one per cent of each of geophones stations 1 and 7. This is termed 20 per cent bilateral mix. Other percentages are possible and common.

The principal objections to mixing have derived from the fact that in certain areas weathering and elevation corrections introduce sufficiently large time differences between traces to cause the apparent line up after mixing to "jump a leg" across the record. False phase line-ups after mixing sometimes result from phase shifts between stations due to other causes. In general, mixing smoothes out small phase differences between traces. In some areas, however, considerable diagnostic importance is placed on relatively small phase shifts across a record. Another objection to mixing is that the signals from shallow or steeply dipping reflectors are often nearly 180 degrees out of phase on adjacent traces and may undergo near-cancellation on mixing.

Some of the above objections can be removed if magnetic recording is adopted and both static and dynamic corrections are introduced on play back. The use of magnetic tapes has in fact led to the development of newer forms of mixing in order to build up very high diversity factors (2,4). Much experimental work is now being done, using fully corrected tapes, with progressive overlap input mixing. For example, in an 8/6 progressive overlap mix the corrected signals from the first 8 geophone stations are added and displayed as trace 1. The corrected signals from geophone stations 3 to 10 are added and displayed as trace 2, and so on.

When mixing of this nature is employed in conjunction with multiple holes and multiple geophones, very high diversity factors become possible. Some spectacular results have been achieved in this manner but the following points should be borne in mind when using such techniques:-

(a) Special records, and sometimes special shots, are necessary to make adequate weathering and elevation corrections.

(b) Phase shifts of diagnostic importance are often lost.

(c) False line-ups, quite unrelated to reflections caused by relatively large noise pulses coming from two or three widely separated geophone stations, are possible.

As indicated, special shots may be necessary to overcome (a) above. Point (b) cannot be overcome. For (c), special criteria must be laid down and satisfied before a line-up is accepted as a reflection. Usually, the criterion is adopted that an event be continuous for a certain minimum distance across a section before it is accepted as representing a reflecting horizon. However, much useful information is now being obtained using pattern and mixing techniques in areas that were previously labelled "NR". The dangers are serious only where considerable detail is required for the investigation of very small structures and location of faults with small displacements.

(iv) <u>Spaced Charges Within a Hole and Long Low-Velocity Charges</u>.

The use of spaced charges within a single hole (10) or of long low-velocity charges (11) constitutes a single shooting technique. When spaced charges are used they are connected by "cordtex" or similar detonating fuse so that the charges are detonated successively down the hole to simulate a long charge with a low velocity of detonation. It is necessary, therefore, to consider only the case of the long charge.

The velocity of detonation of the charge is selected so that it is approximately the same as that of the seismic velocity of the material in which it is being detonated. The object of this is three-fold:-

(a) To reduce strength of horizontally-travelling waves.

(b) To eliminate ghost reflections.

(c) To increase the vertically-travelling energy in the seismic P (or compressional) wave.

With regard to (a) and (c) above, the long low-velocity charge performs a function similar to that of a pattern of shot holes with more or less point charges. The elimination of ghost reflections is more easily achieved with the elongated charge than with the point charge. The above objects are achieved in the following ways:-

1. The strength of certain horizontally-travelling waves is reduced by interference of waves originating from different points along the length of the charge.

2. Ghost reflections are common when a point charge is placed well below the base of a clear-cut weathering layer. Upward travelling energy is reflected from the base of the weathering. The wave front from this interface follows the primary wave down through the earth and gives rise to a second "ghost" reflection from each reflecting horizon. These secondary reflections are not required; they confuse the record and may mask important diagnostic reflections, particularly when such reflections are relatively weak and follow closely on strong ones such as may occur at an unconformity. With long charges partial cancellation of the unwanted waves again tends to occur.

3. As each successive point on the charge detonates it adds to the energy of the downward-travelling wave front provided it is being detonated in material whose P velocity is approximately equal to that of the velocity of detonation. As some interference occurs in other directions between P waves originating from different points along the charge, a directional effect is obtained. As the detonation rate of the column is lowered relative to the side wall velocity, the directivity increases and the downward energy decreases. In practice, the optimum balance of these factors is a detonation rate about 4/5 of the side wall (P wave) velocity (11, p.81). It does not appear to be critical that the charge should extend up into the weathering, though this may cause some difficulty in calculations regarding weathering.

(v) Record Stacking.

Record stacking is a technique that has followed the introduction of magnetic recording (3).

If a large number of holes is shot and a tape record taken for each, then the signals from the various holes can be added together on to new tapes and eventually displayed on conventional records. Depending on the number and distribution of holes shot, any number of desired patterns can be tried by stacking records without the necessity of reshooting. Furthermore, repetition of tapes simulating charges detonating at the same point with specific time intervals can be experimented with. If several charges are fired in the same hole, the time intervals separating them in stacking can be made to simulate long charges with different velocities of detonation. Hence, with a relatively small amount of initial field work a considerable amount of laboratory experimentation can be carried out to determine the best field technique in a difficult area. Techniques can be developed which would otherwise be difficult to achieve without the assistance of magnetic tape recording. One technique is to add fully corrected tapes recorded from the same sub-surface strata that have been obtained with different hole and geophone locations. Endless variations are thus possible.

(vi) Weight Dropping.

Weight dropping is another technique that has followed from magnetic recording (12,13). In this technique seismic signals of low signal/noise ratio are generated but enormous diversity factors are possible. Outstanding success has been achieved by the method in areas where elaborate but more conventional techniques of multiple holes and geophones have failed. At the centre of the spread a patch of geophones numbering 300 to 1000 is placed at 25-foot intervals. A 3-ton weight is dropped in patterns (or in line in good reflecting areas) at the various stations normally occupied by geophones along the spread. Up to 100 drops per station are common. The signal picked up by the geophone patch from each weight-drop is recorded on a single track on the magnetic tape. All tracks relating to one station on the spread are added together to give a single track on a second tape. The final record is obtained after all the tracks on the secondary tapes have been fully corrected and a series overlap mix is applied. If 1000 geophones are used and 100 drops made per station then the diversity factor is the square root of 100,000 n where n is the number of tracks added during the series overlap mix. It may be possible to achieve equivalent quality for the final record from a similar series overlap mix applied to magnetic tapes derived from large patterns of shallow holes and multiple geophones, even though the diversity factor may be much lower. This depends on the signal/noise ratio of a single weight-drop compared to the signal/noise ratio of a shallow hole. Sufficient work has not yet been done to determine this comparison, or, if it has been done, the results are not generally available.

The weight-drop technique presents a major problem for adequately solving weathering corrections. A special series of recordings from certain drops detected by a single geophone or a small closely-spaced group of geophones is taken to determine first breaks when necessary. This complicates the procedure. As in multiple hole and geophone arrangements, care must be taken to ensure that serious partial cancellation of shallow reflections does not occur. Moreover, the dangers of large patterns and heavy mixing forcing erroneous line-ups on reflections or completely false line-ups due to noise and unrelated to reflections must be constantly guarded against during interpretation. Similar dangers also exist when narrow pass band, steep cut-off filters are used in frequency discrimination. They are, consequently, ever present in difficult areas where extreme methods are employed to obtain useful results.

3. FINAL DISPLAY OF THE DATA

This discussion is limited to the cross-sections and records from which the interpretation is made. The conventional form of display which has been used for many years is the wriggly line seismogram (usually 24 trace) from each shot. This is used in conjunction with, and as the source of data for:-

(a) Correlation cross-sections, on which the reflections are represented as straight lines drawn vertically beneath the spread. An indication of the quality or "grade" of the reflections is usually given.

(b) Dip cross-sections, on which the reflections are represented as straight lines drawn at a location estimated to be the true position of the reflecting horizon where the reflection occurs, assuming that the traverse is normal to the strike of the reflecting horizon. Again, an indication of grade is usually given.

(a) aims at presenting all the useful data on the seismograms in a form in which it can be studied as a whole. It is not possible to realize this aim completely and frequent reference to the seismograms is usually necessary for detailed study. The correlation cross-section gives a good indication of structure and also the degree of correlation of events from record to record. It indicates those portions of the section where detailed structure can be studied on the basis of continuous reflecting horizons or where the drawing of phantom horizons is necessary.

(b) gives a more accurate representation of structure, particularly in areas of steep dip. It is frequently, but not always, the type of section employed when calculating phantom horizons. Contour maps are usually prepared, if possible, from continuous reflecting horizons. The data are drawn from the correlation section, and, if necessary, a displacement correction applied. If continuous reflecting horizons are not available, phantom horizons are used.

Some companies have for several years, either replaced or supplemented correlation cross-sections with record sections. Before the advent of magnetic tape and variable density recorders the sections were usually compiled by pasting records side by side and photographically reducing the complete section. These were extremely useful but required that the speed of the camera producing the record be kept within very close tolerance limits. The practice is still very common. These sections are used for detailed study of a large number of seismograms simultaneously.

With the advent of variable density, magnetic tape and clipped trace (Reynolds) recording (see Plate 1) it became possible to correct the seismograms fully before, or during, the preparation of the record sections. It was thus possible to incorporate all the advantages of the plotted correlation section into the record section. Production of sections obtained from magnetic tape recording will now be considered (3,14,15,16,17,18).

Starting with magnetic tape recording it is possible to produce sections identical to those obtained using variable density and/or clipped trace recording techniques, but not necessarily vice versa.

Data display in the form of record sections may now be obtained in the following forms:-

(a) Wriggly line.
(b) Clipped trace.
(c) Telescopic trace.
(d) Variable density.
(e) Coded variable density.
(f) Full wave variable area.
(g) Clipped wave variable area.

Other forms are possible but the writer is not familiar with them. Most of these various forms are shown in Plate 1. Each form has its supporters, but with the possible exception of the wriggly line, the various forms do not usually find favour until the seismologist has become accustomed to them as a working medium. The wriggly line appears to hold its popularity because seismologists are so accustomed to it.

Those who have been obliged by the organisation for which they work to become accustomed to another form of display nearly always develop a high regard for it. Currently, the most popular form, apart from the wriggly line, is variable density. This presents the section in the form of light and dark shading. The intensity of the shading corresponds to the amplitude on a wriggly line trace. Light and dark lines across the section correspond to line-ups of peaks and troughs respectively on a wriggly line section. The variable density form of section makes the line-ups of even weak events very obvious and easily seen and appreciated even by the untrained eye. It is thus an excellent method of presentation for discussions with management or with geologists not familiar with seismology. It is also excellent for showing diffraction patterns associated with faulting. Such diffraction patterns frequently cannot be seen on the wriggly line form of display.

Advantages similar to the above are claimed for the other forms of presentation. For example, clipped wave variable area looks like a high contrast variable density form with the slope of the edge of the light and shade indicating amplitude. Telescopic trace is excellent for management presentation and also enables both high and low energy events to be studied in detail without the need for a fast A.G.C. in the amplifier to try to balance the amplitudes on the seismogram. Full wave variable area is claimed to have all the detail of wave form that wriggly line has and also the advantages of variable density. It is desirable to have equipment so designed that sections can be provided to suit the tastes of the particular interpretation group and to satisfy the requirements of presentation to the management. There is no reason why this should not be possible at reasonable cost.

There is no doubt that record sections in their various forms greatly increase the accuracy of seismic interpretations, as all the information available is displayed on the section. It is not subject to individual selection of what should be transferred from the record to the section. The section obtained is a complete trace analysis. The human factor operates only in the corrections applied and not in the data selected. A greater number of people are able to study the interpretation without having to tediously examine numerous records to see how they were treated. However, with the greater amount of data available for consideration in interpretation it is doubtful if the use of these sections effects any appreciable saving in time.

The record sections mentioned above replace only the correlation sections; dip sections must still be drawn. The function of a dip section when used in conjunction with the newer record sections, is to clarify the structure and certain other points requiring analysis. The record can be used to determine those events which may be best used for the construction of dip sections. If a light table is used it may be convenient to construct the dip section on the back of the record section. When working from record sections in this way, events used for "migration" need not be confined to original single records but may extend over some distance, thus giving a more accurate determination of dip.

A new machine has recently been developed for the construction of dip sections, working from single records (19). The record is laid on a table against a time scale, and a cursor is laid across the record at an angle appropriate to the time step out due to the dip of the reflection under study. By means of servo motors, a plotting arm on an adjacent plotting table swings through an appropriate dip angle and a marker bar moves to an appropriate depth. The reflection is then marked on the cross section. This machine will be of greatest advantage when used with fully corrected records. It will probably also be readily applicable to record sections.

4. DEVELOPMENTS IN THE DESIGN OF SEISMIC AMPLIFIERS

In conclusion, some comments on current developments of seismic amplifiers and their significance are warranted.

Factors governing the development of modern amplifiers are demands for:-

(i) A broader spectrum of working frequencies (20).
(ii) Greater and more rapid attenuation of frequencies outside the selected pass band.
(iii) More flexible A.G.C.
(iv) More accurate picking of first breaks.
(v) More rapid changing of amplifier settings.
(vi) A reduction in power consumption.

(i) Broader Spectrum

The demand for a broader spectrum follows from the introduction of high-frequency techniques for shallow prospecting. The techniques do not appear to be as generally applicable as was at first thought. Many sets of amplifiers with the broad spectrum provision have probably never used it on survey. This requirement also followed from the original specifications put on magnetic tape equipment that it should be capable of recording all frequencies between 2 and 500 cycles. This was more of a laboratory requirement than a field requirement, but as the industry is still not sure of its true requirements these specifications still tend to remain, although they are being relaxed in some quarters.

(ii) Filter Attenuation

As the need for investigation of "difficult to work" areas becomes more urgent, greater efforts are being made to improve signal/noise ratio. Frequency discrimination has always been one of the methods employed to this end, so the more difficult areas have led to demands for more flexible and efficient filtering systems (1). As the phase discrimination methods are developed and relatively wide band recordings are taken on magnetic tape, the demands for more frequency discrimination on field amplifiers is being relaxed.

(iii) More Flexible A.G.C.

The demand for a more flexible A.G.C. arose from (a) the requirement of a very fast A.G.C. to gain rapid control over the level of the traces following the first breaks when investigating very shallow reflections, and (b) the requirement in certain areas for rapid release of A.G.C. control to raise the recorded level of a weak reflection following a strong reflection. With the advent of some of the recent data display systems and the use of magnetic tapes this requirement can be relaxed for field amplifiers used in conjunction with these systems.

(iv) More Accurate First Breaks

More accurate first breaks are required in the investigation of very small structures, when the most accurate weathering control is essential. The necessary accuracy is achieved by eliminating filtering while the first breaks are being recorded. Its value is probably limited as there are so many features in the ground that normally cannot be fully accounted for.

(v) Rapid Changing of Amplifier Settings.

Rapid changing of amplifier settings arises from the use of magnetic tape reoording in which the same amplifiers are used for recording and monitored play back. Teohniques available on some systems include grouping of filters with ganged control, step switches on filter controls, the use of variable reluctance toroid coils in filter circuits with a single control for all coils, and the use of A.G.C. type circuits with a single control for gain variations.

(vi) Reduction in Power.

With the introduction of magnetic tape systems, variable density recorders, etc. the power requirements for the equipment in some of the most modern seismic trucks are becoming excessive. All firms are experimenting with transistors in an effort to reduce the power requirements.

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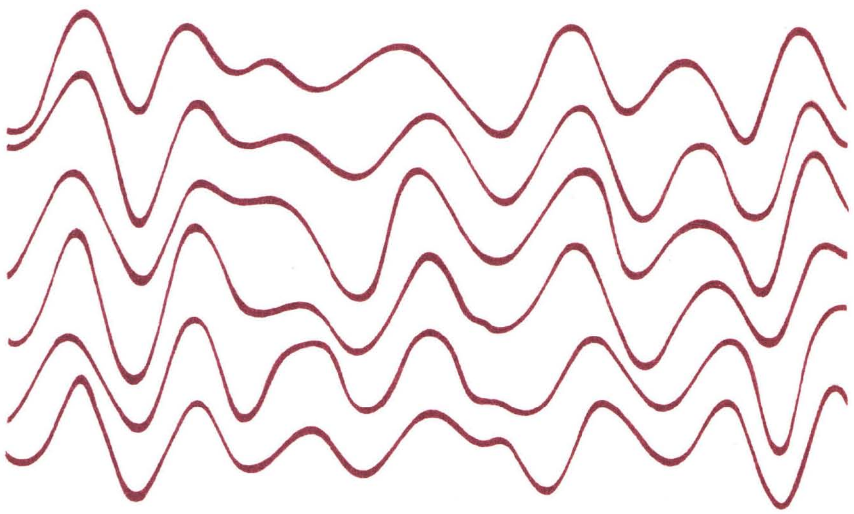

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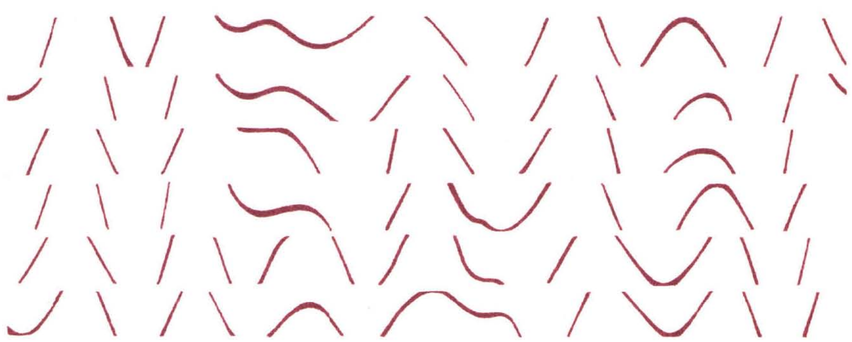

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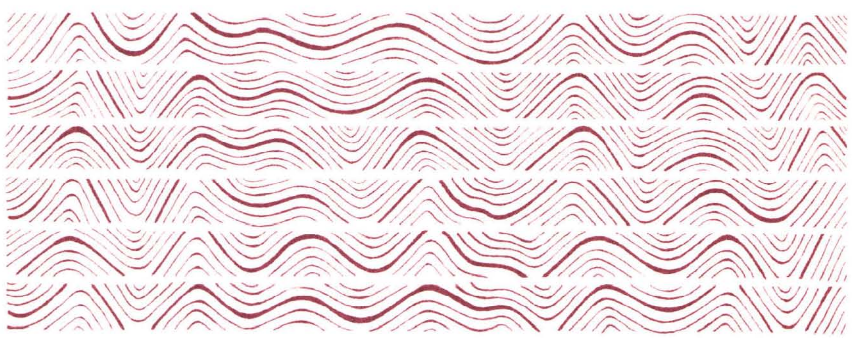

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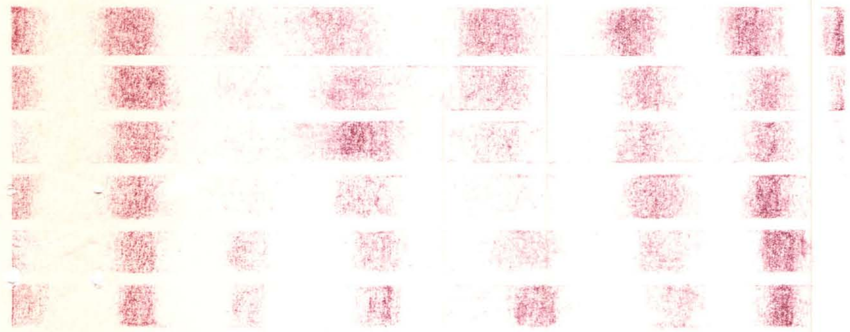

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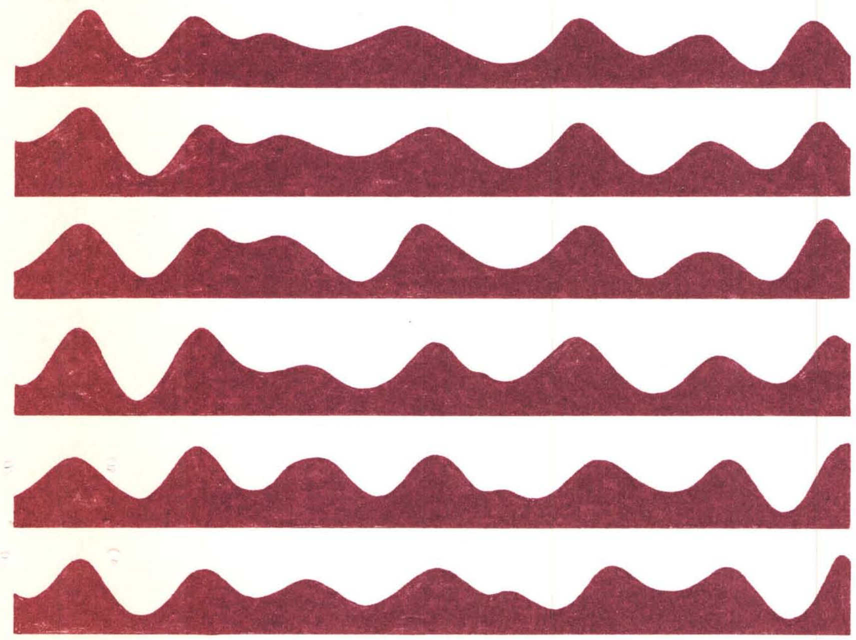

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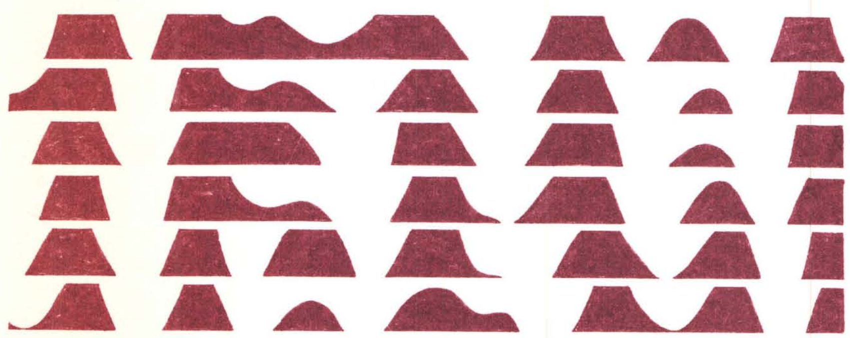

6. CLIPPED VARIABLE AREA

ALTERNATIVE METHODS FOR PRESENTATION OF SEISMIC REFLECTION RECORD SECTIONS