REEF INTERPRETATION BY FREQENCY ANALYSIS

by

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ABSTRACT

The increase in velocity and decrease in bedding thickness often present in sediments deposited directly above a reef body can give rise to a detectable increase in the frequencies of reflections recorded over a reef. Such anomalies can be conveniently observed on the optical frequency spectrum of a time interval selected just above the reef level. The absence of anomalous increases in the spectra of time bands positioned below and above the influence of the reef can help confirm that the observed increases stem from conditions associated with reefing. Frequency spectra can thus provide an additional tool for improving the confidence level of reef interpretation.

INTRODUCTION

The success of seismic exploration efforts in Canada depends to a great extent on the correct interpretation of reef structure. On seismic cross-sections reef evidence, such as draping, diffractions, velocity pull-up and the termination or disappearance of reflections, is often quite subtle. When noise or multiple reflections obscures such evidence, it becomes difficult to interpret reefing with confidence. It is thus important that new aids to interpretation be sought to help raise this confidence level. Recently developed optical techniques show definite potential in the detection and definition of reef structure. The purpose of this paper is to discuss one of these approaches: the application of optical frequency analysis to the reef interpretation problem.

The basic parameters of seismic energy include arrival time, phase, amplitude and frequency. At the present state of the art, our interpretations are based primarily on observed arrival time and phase relationships. The use of binary gain ranging amplifiers, which record seismic amplitudes accurately, will permit better application of amplitude to interpretation. Although frequency has received attention in the literature in problems concerning noise and filtering, its application as a parameter in interpretation has had little consideration. This is surprising in view of the importance and usefulness of frequency spectra in other technical fields. Perhaps we may attribute this relative neglect to the difficulty and expense that were previously encountered in presenting seismic frequency data in a manner convenient for study. Modern digital and optical techniques now make frequency spectra readily available. It is becoming increasingly apparent that frequency is an important interpretive parameter which should be studied routinely by the geophysicist in his efforts to reach a better understanding of his seismic data. The results of processing nearly one hundred cross-sections over known and suspected reefs have indicated that important diagnostic evidence for reefing is often present in the frequency domain.

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THE PARAMETER OF FREQUENCY

That the frequency of seismic energy relates to the subsurface is not a new idea. There are many references in the literature to this subject. Shugart (1944) described the influence of the near-surface on the seismic waveform. Clewell and Simon (1950) compared the earth to a band-pass frequency filter, noting that attenuation and scattering coefficients of formations might be measured and used in interpretation. Jakosky and Jakosky (1952) described the reflection generation process as an interference phenomenon, whereas Woods (1956) discussed model experiments which showed the relation of bedding sequence to the frequency of reflected events.

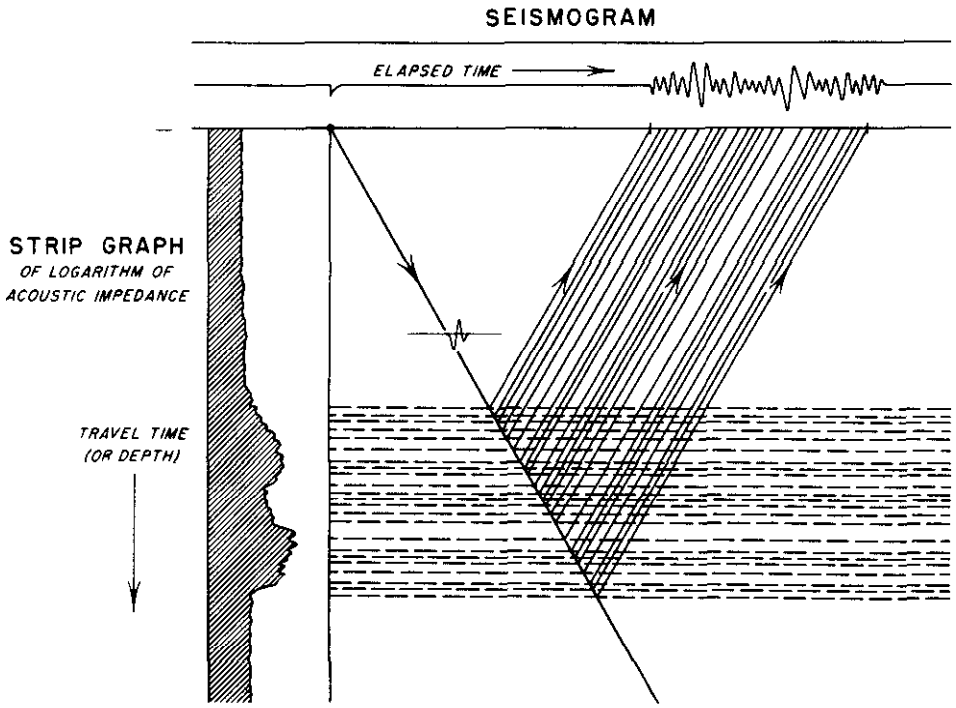

FIG. 1.—Schematic illustration of the reflection of a seismic pulse from an acoustic impedance distribution.

In their paper on the synthesis of seismograms Peterson, Fillippone and Coker (1955) demonstrated how reflections are generated by layering in the earth. Let us consider for a moment an ideal reflection cross-section, such as one produced from a group of synthetic seismogram traces without multiples. Each trace will be made up of a series of pulses corresponding to a large number of acoustic impedance changes within the earth, as illustrated in Figure 1. We may assume that the

layering sequence is essentially random for a large sample so that the distribution of reflection periods (and the frequency content) is in the form of a bell-shaped curve, effectively flat within the pass-band of the recording instruments. The optical spectrum of such a cross-section will be white, as shown in Figure 2a.

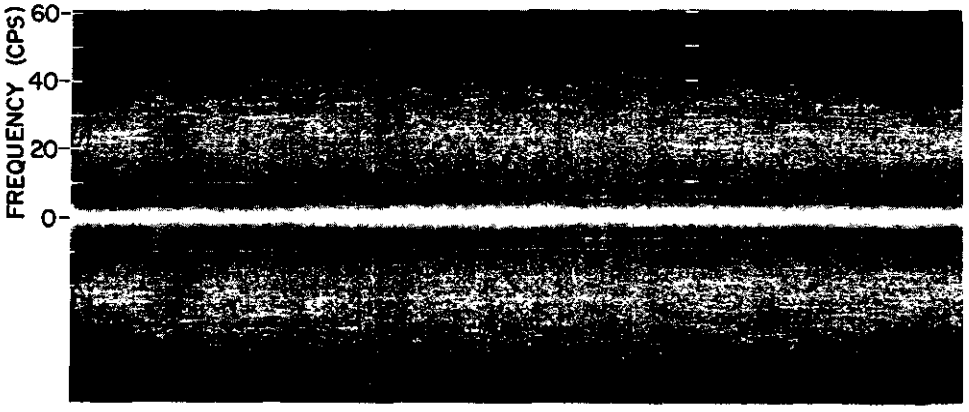

FIG. 2A.—Optical spectrum of full-length section showing uniform frequency distribution.

If now we reduce the length of sample, for example to about one-half second, the spectrum of this sample may show certain dominant frequencies relating to the preferred spacings of the layering within the corresponding geologic section. This effect is illustrated in Figure 2b.

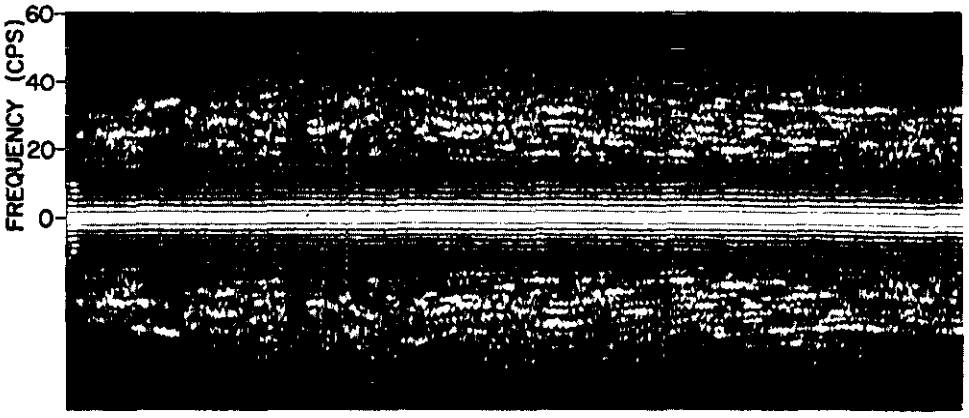

FIG. 2B.—Optical spectrum of zone between 0.55 and 1.1 seconds of same section.

Frequencies will be higher with velocity increases and lower with velocity decreases. A lateral velocity change, due to differential compaction or to a change in lithology affecting an appreciable section thick-

ness, will appear on the spectrum as a frequency shift. Similarly, if a significant stratigraphic thinning or thickening occurs within this interval the spectrum will show corresponding frequency changes. Note how the different bed spacings at positions I and J in Figure 3 generate higher and lower frequencies, respectively. The frequency spectrum of a restricted time interval on a seismic section can thus give information about appreciable changes in bedding thickness or velocity taking place within the corresponding geologic section. This spectrum is analogous to a detailed isochron plot of the selected interval and thus is potentially important in all types of problems where the isochron map is used.

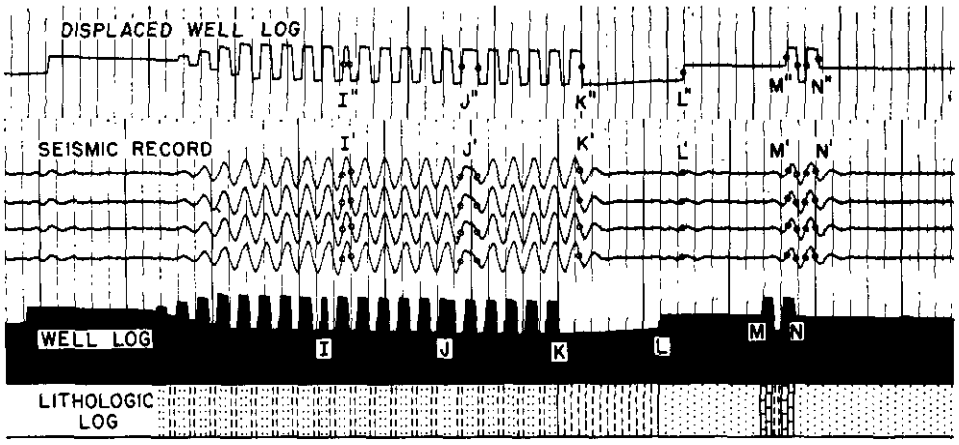

FIG. 3.—Hypothetical well log and corresponding seismogram illustrating frequency dependence on layer thickness.

We have considered an idealized noise-free cross-section, produced by a sharp impulsive source. Seismic sections are generally much more complex. The source may be a broad pulse, as produced in a clay medium, giving a predominance of low frequency data. It may be a sharp pulse from a limestone medium resulting in a high frequency record and poor energy penetration. In addition, seismic frequency spectra may be influenced by various types of random and coherent noise, multiples, and near-surface filtering effects. If these undesirable influences are too strong, the results will be poor in the frequency domain just as they are in the time domain. There are notable exceptions: if poor quality is due to conflicting events such as coherent noise or multiples, the frequency bands resulting from these events are often separated on the spectrum of restricted time intervals permitting their identification and interpretation. In the event that poor record quality is caused by improper static corrections, the information in the frequency domain will not be impaired.

Strong near-surface filtering effects can cause difficulty in the interpretation of frequency spectra. Ringing, ghosting, or shallow multiples will usually show on the spectrum of the full section as prominent bands.

Such a banded spectrum resulting from ringing is shown in Figure 4. It is doubtful in this case that usable information could be retrieved from the interval spectra without prior digital deconvolution.

FIG. 4.—Optical spectrum showing ringing frequencies in offshore data.

In the frequency domain, as in the time domain, interpretation based on a knowledge of the behaviour patterns of noise is the principal means of combatting such interference problems. Most of our seismic frequency data from Alberta and Saskatchewan are readily amenable to interpretation, as will be illustrated later in this text.

THE OPTICAL SPECTRUM

The LaserScan* optical system which was employed in this work is described by Dobrin, et al; (1955). Although this system is used primarily for frequency and directional filtering of seismic data in cross-section form, it also provides by means of the simple insertion of a cylindrical lens a convenient method for obtaining the frequency spectrum of any selected time interval on a variable-density or variable-area seismic section. Jackson (1964) first described the techniques for constructing such spectra and Fitton and Dobrin (1967) have discussed the basic principles for the use of frequency data in seismic interpretation.

The frequency spectrum formed in the LaserScan system may be viewed directly on the television monitor or photographed on Polaroid or film. Figure 5 shows an example of such a channel-by-channel spectrum and its relationship to the original seismic data. The optical spectrum consists of a horizontal axis of undiffracted light at zero frequency and two symmetrical data clouds which present mirror images of the frequency distribution of the seismic data, trace-by-trace, laterally across the section. The brightest areas on the spectrum correspond to diffractions from dominant frequencies. The darker areas indicate frequencies with a relative sparsity of energy. Since frequency is proportional to the vertical distance from the zero axis, a calibration scale may be attached.

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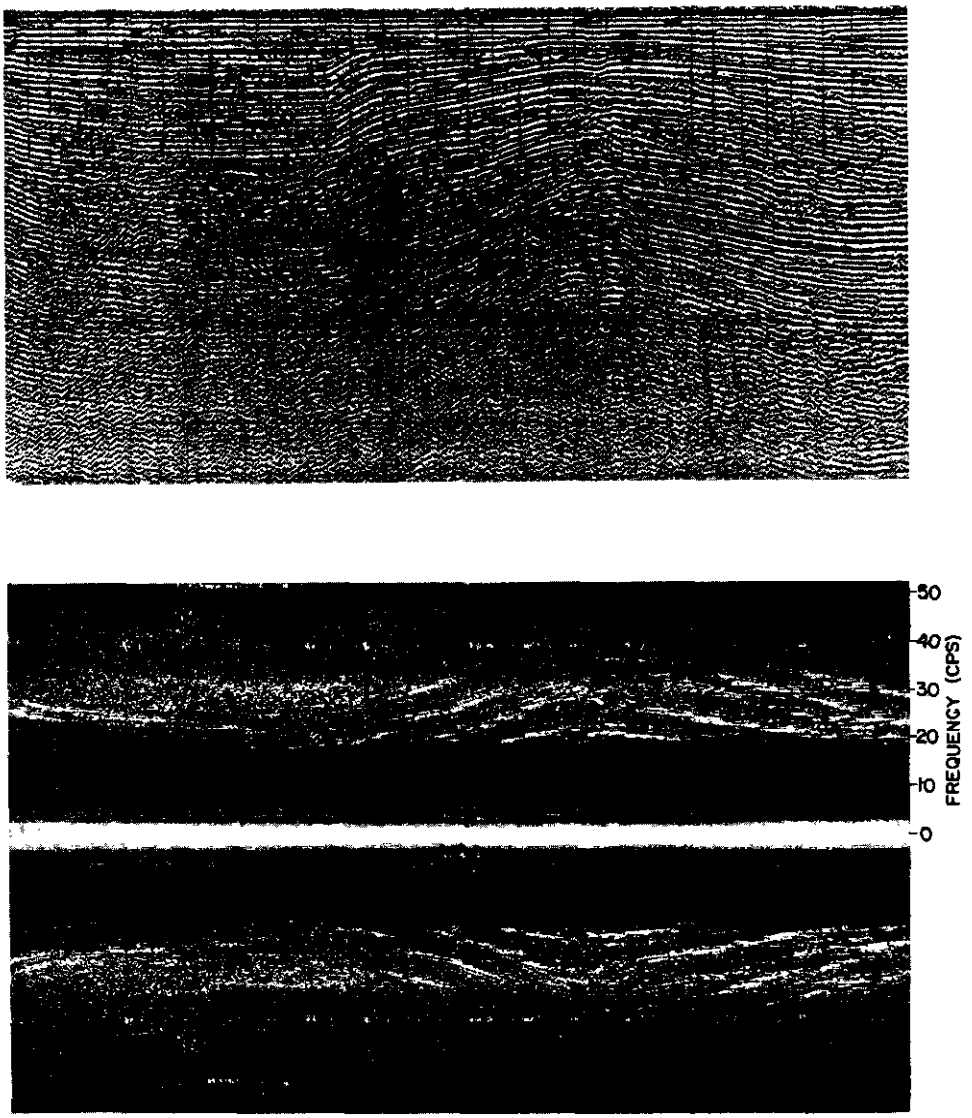

FIG. 5.—Seismic cross-section across faulted anticlinal feature with its optical spectrum showing trace-by-trace frequency distribution.

It is important to note that the spectrum of any selected time band on a section may be obtained simply by isolating the part of the section we wish to analyze; that is, by masking all the rest of the section. Such a window can be moved up and down the section or changed in width. Variations in frequency may be observed directly on the television monitor during the windowing process. This optical spectrum

presentation is effectively the same as that obtained when the power density spectrum is calculated by a digital computer to an accuracy of better than one cycle per second and the results are plotted in variable-density mode in a presentation similar to that of a record section. At the present time optical techniques for frequency analysis are far more economical than digital and more convenient due to the monitoring capabilities inherent in an optical system. The dynamic range of digital results is, however, superior to that obtainable by optical processing. We may asume that in the future, high speed convolvers and display programs may make digital channel-by-channel frequency analysis economically feasible.

THE EFFECT OF REEF STRUCTURE ON SEISMIC FREQUENCIES

The thinning of beds as well as the velocity variations which are found over many reefs can often cause observable differences between the frequencies of seismic data recorded across a reef and those recorded above off-reef sediments. We have seen such differences in studying a great many seismic sections over known Canadian reefs. Figure 6 shows a schematic section depicting a typical reef. Because of differen-

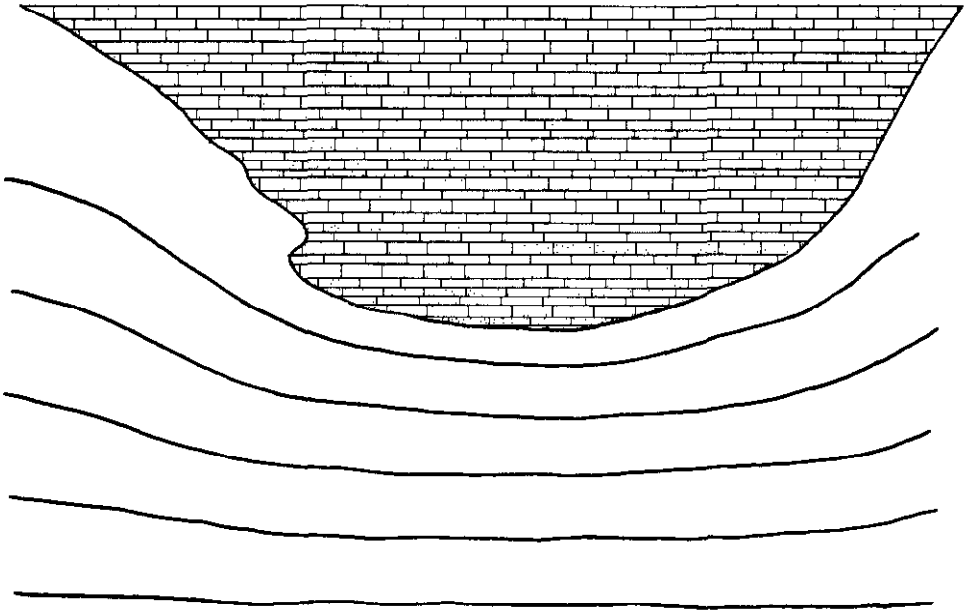

FIG. 6.—Typical reef structure showing stratigraphic thinning above reef.

tial compaction, erosion and deposition the beds above the reef normally are thinner and may also have a higher velocity than those over the off-reef facies. Reefs, consisting of organic limestones built up above the bottom of the sea by vertical growth, typically have rigid skeletal

structures. Deposits laid down over reefs tend to drape across the reef edges. Differential compaction usually occurs when the rigid reef material is overlain and surrounded by muds, shales, silts, and sands. We would thus expect from a statistical view point that reflections from the zone just above the reef would show a generally higher frequency over the reef body than above its flanks, an effect which usually diminishes rapidly with shallower time intervals. Below the reef the sedimentary sequence should be normal and no frequency anomaly would be expected.

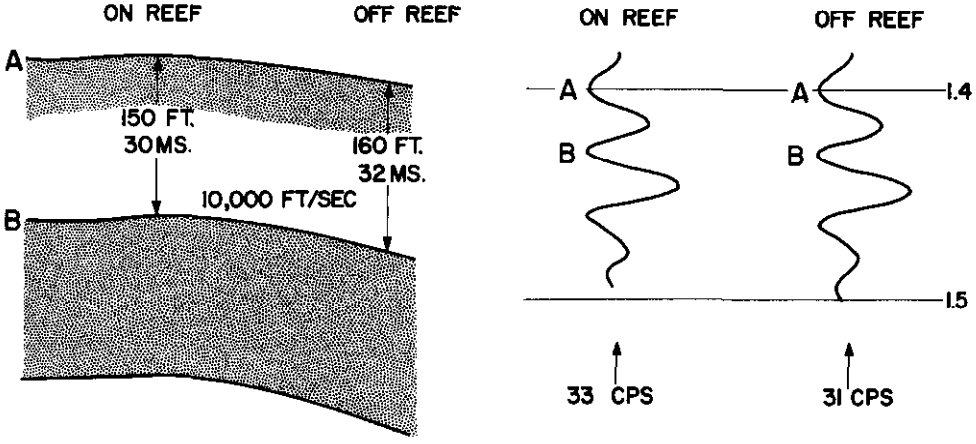

FIG. 7.—Relationship of reflection frequency variations to thickness changes resulting from compaction and thinning over a reef.

The amount of thickness variation which will produce observable anomalies is quite small. In Figure 7 an example is shown in which we have postulated a pair of layers 150 feet apart increasing in thickness by ten feet from over the reef to above its flanks. If we assume an interval velocity of the order of 10,000 ft./sec., the reflections from directly above the reef have a frequency of 33 cps as against 31 cps reflections from the same formations above the off-reef facies. This means that a frequency anomaly of two cycles is associated with the reefing in this example.

Another factor, not shown here, which would act in the direction of increasing the frequency anomaly is change in velocity. In addition to the thinning over the reef we might expect an increase in velocity due to differential compaction. Assuming that the 10,000 ft./ec. velocity increases only 2% to 10,200 ft./sec. over the reef, then the round trip time for the 300 foot on-reef interval would be reduced from 30 to 29.4 milliseconds and the frequency generated would be 34 rather than 33 cps. The total frequency anomaly would then be three cps rather than two.

Changes of the magnitude of two or three cycles per second would not be easily discernible on the time section. On a one-dimensional

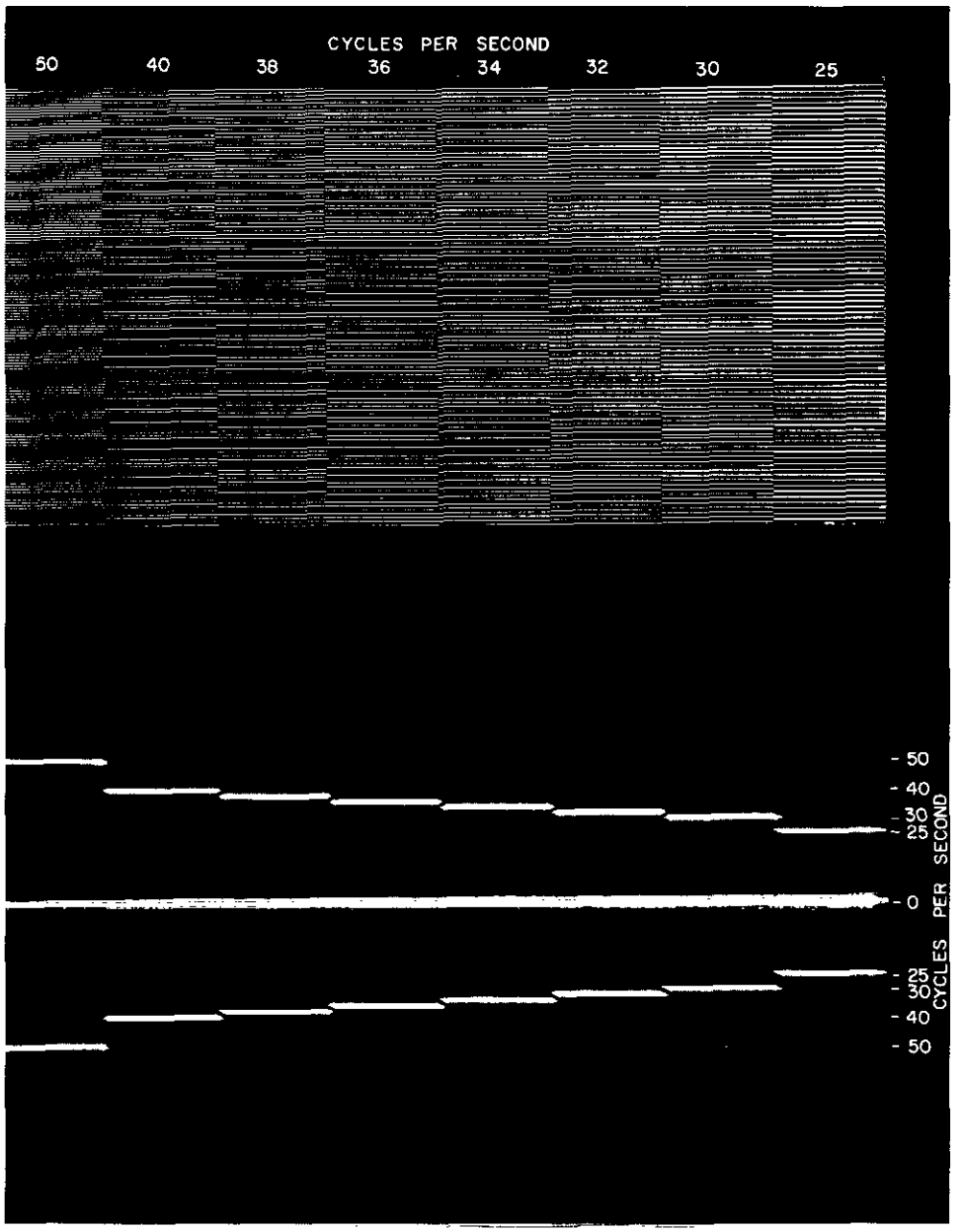

FIG. 8.—Chart showing frequency decreases in steps from left to right and its optical spectrum with two cps differences clearly visible.

optical spectrum, however, such changes are readily apparent. Figure 8 shows the input and the spectrum of a step frequency chart in which frequencies change in discrete steps as noted. On the spectrum the

increments corresponding to five two cycle steps stand out clearly. The frequency spectrum is independent of apparent dip on the time section, as illustrated by Figure 9. Here a low frequency reversal, obscured by horizontal high frequency interference, gives a spectrum with two constant frequency bands.

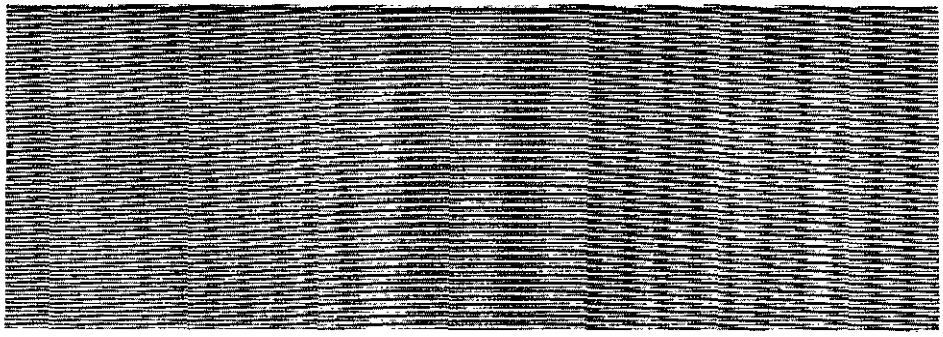

FIG. 9a.—Hypothetical low frequency reflections from anticline obscured by high frequency horizontal interference.

FIG. 9b.—Optical spectrum demonstrating separation of frequencies and independence of frequency from apparent dip.

FREQUENCY ANALYSIS AS A TOOL FOR FINDING REEFS

Experimenters have long sought anomalies in gravity or in velocity measurements which might be indicative of reefing. The frequency of seismic reflections is influenced not only by velocity and density increases, but also by the thinning of sedimentary layers, all of which might be expected over reefs. Thus the frequency domain presents a different and potentially important way of detecting reefing from seismic data. Let us now consider some actual field examples involving reefs and examine the type of reasoning which might be used in the interpretation of the associated frequency spectra.

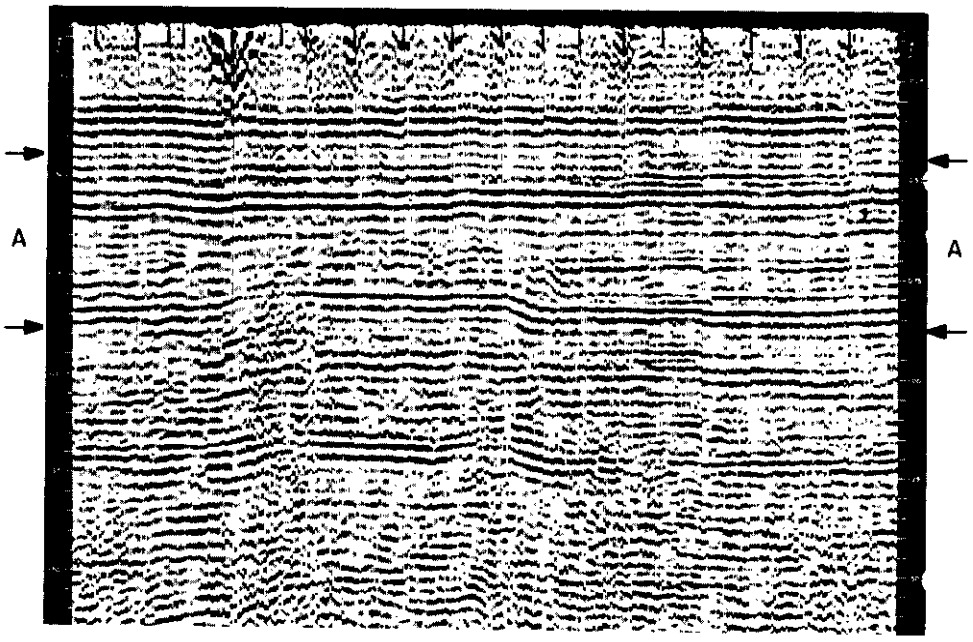

FIG. 10a.—Seismic section across typical Alberta reef showing well-defined reef edges.

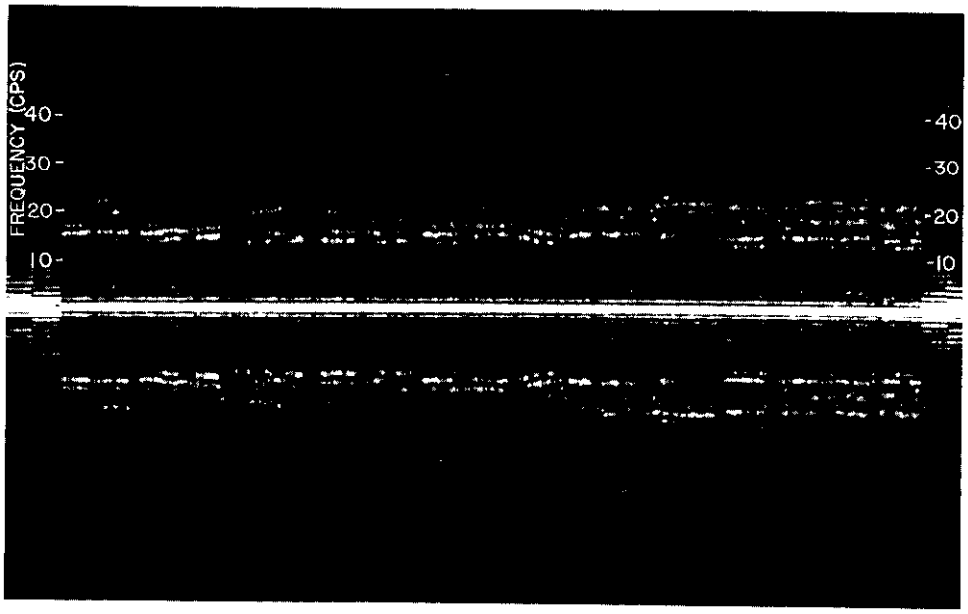

FIG. 10b.—Optical spectrum of zone "A" displaying sharp frequency increase over reef.

Figure 10a is a classic seismic section over a known Alberta type reef. Velocity pull-up provides evidence on the time section for both reef edges. Window "A" has been selected by monitoring to include the reef level and an appreciable interval above the reef. The one-dimensional spectrum of window "A" (Figure 10b) indicates a pronounced frequency increase, just as theory predicts, when one crosses the reef rim toward the reef from either side. This anomaly suggests that compaction and thinning in the bedding over the known reef result in an increase in the frequency of reflections returned from above the reef level. Note also the abundance of high frequency energy on the right side of the section. This zone might be associated with the lagoonal side of the reef, whereas the thicker, homogeneous, seaward sediments may give rise to lower frequency energy. Such a frequency shift may serve as an added criterion in the interpretation of reefing.

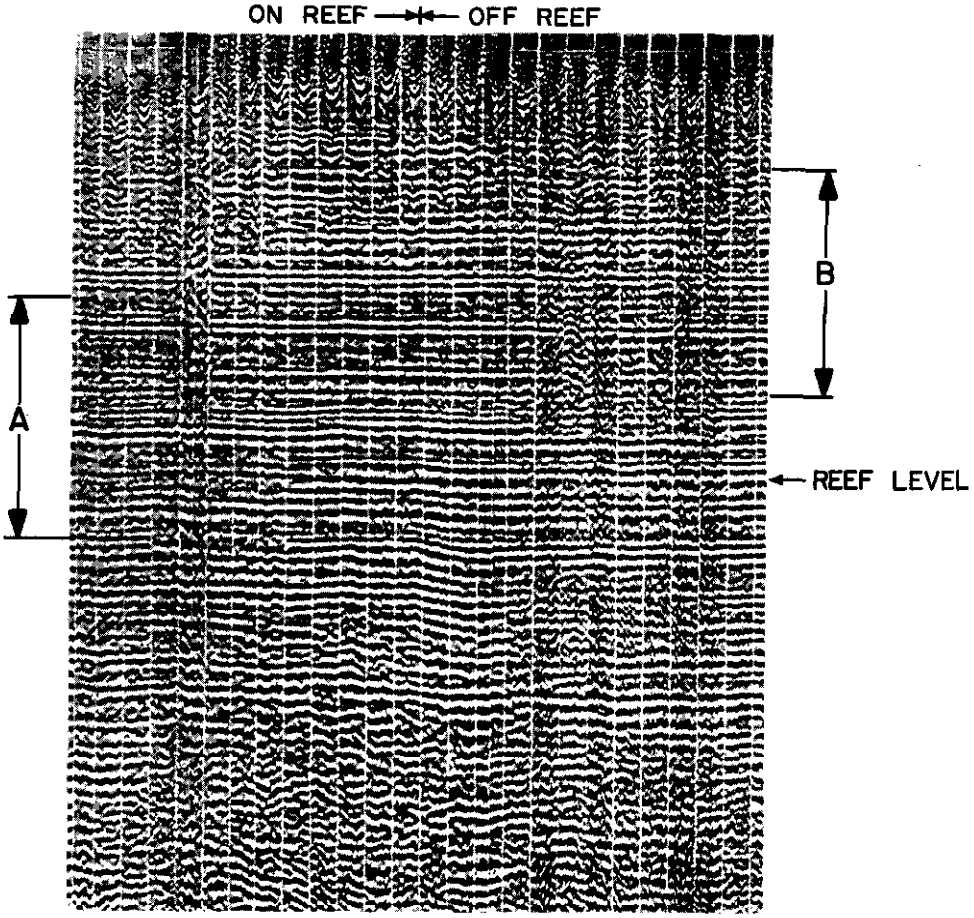

FIG. 11.—Alberta reef section showing interference by interbed multiples.

Figure 11 shows reef evidence which has been obscured to some extent by interbed multiples. The reef level is in the lower third of window "A." An examination of the spectrum of window "A" (Figure 12),

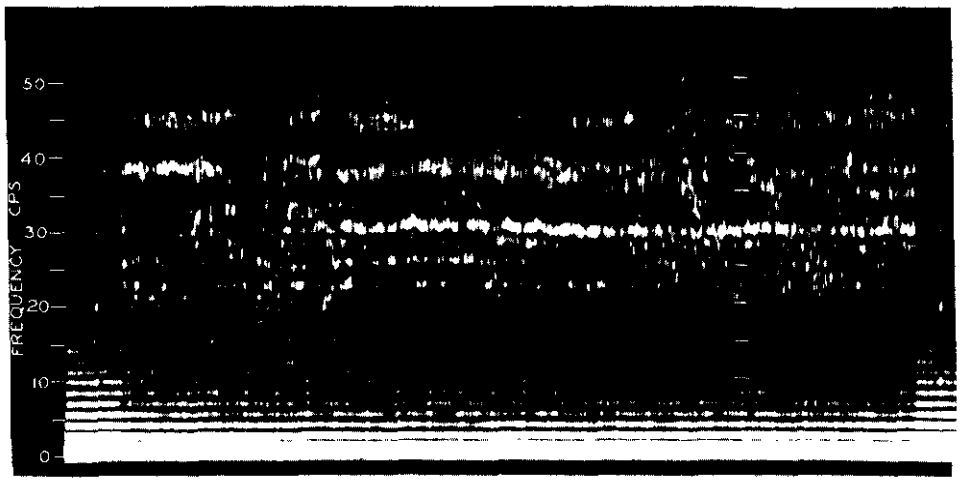

FIG. 12a.—Optical spectrum of zone "B" on Figure 11 showing a frequency anomaly of one cps.

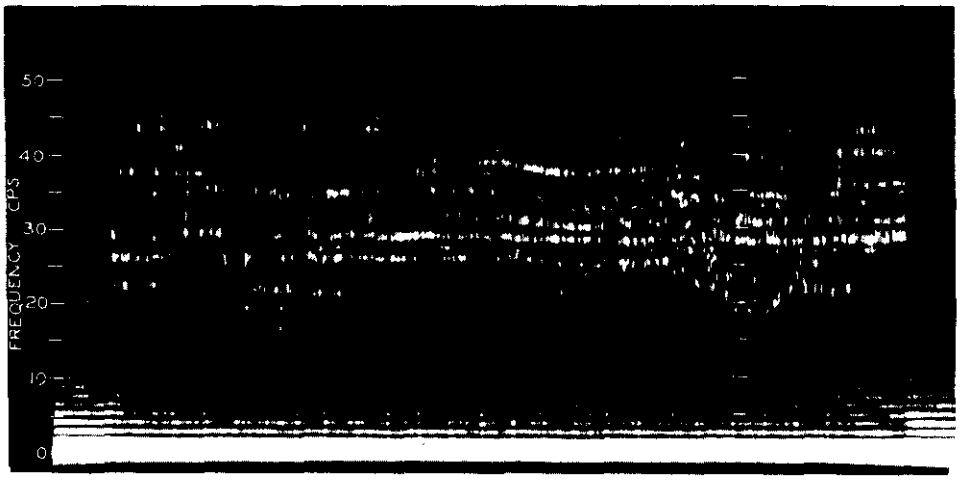

FIG. 12b.—Optical spectrum of zone "A" on Figure 11 showing a well-defined frequency increase above the reef level.

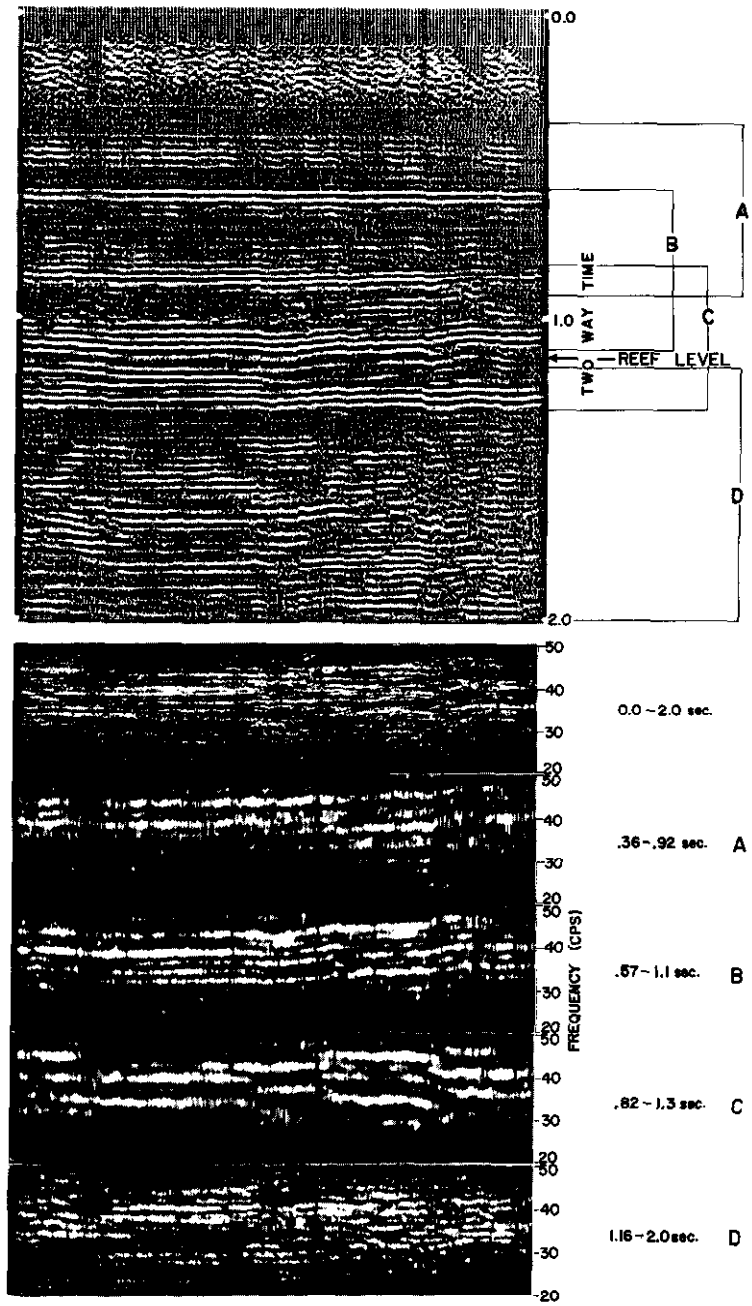

FIG. 13.—Seismic section across Rainbow Lake reef (above). Sequential spectrum display showing frequency increase above the reef level (below).

shows a definite increase in frequency approaching the right edge of the reef edge from off the reef. The left edge is less well-defined. At about 29 cps a frequency band is observed which shows very little anomalous increase. In interpreting this band we may tentatively ascribe it to multiple reflections or to energy returning from below the reef level. If we reject this frequency by an optical band stop filter of about 2 cps width, we immediately find its source on the time section to be the low frequency event near the lower extremity of window "A." We may thus interpret this event as energy from below the reef, noting that thinning would not be present at this level, and that the frequency of this reflection would not be influenced by the presence of the reef above. The spectrum of window "B" shows that the frequency anomaly extends well into the shallower sediments, penetrating a major unconformity. The differential in the shallow spectrum is only about one cycle per second, but it is enough to be potentially useful in interpretation where deeper diagnostic evidence is ambiguous or obscured by noise or multiples.

Figure 13 displays the section, made by common-depth-point techniques which led to the first discovery well at Rainbow Lake in Canada. At the reef level indicated on the section, the lithology grades from a normal sedimentary sequence to salt solution and finally to a large reef on the right side of the section. The upper halves of the frequency spectra at four different levels are compared with the spectrum of the full section in a sequential display. On the spectrum of the complete section there is no obvious anomaly. The spectrum of band "C," including the reef level and beds just above the reef, shows sharp frequency increases over the salt and again at the reef edge. This effect is non-existent below the reef, as is seen on spectrum "D." The anomaly diminishes in the shallow section, as indicated on spectra "A" and "B" but higher frequencies persist in the energy recorded over the reef body.

The next example (Figure 14a) is again from the Rainbow Lake area. The section consists of records shot with 100% coverage only. Reef

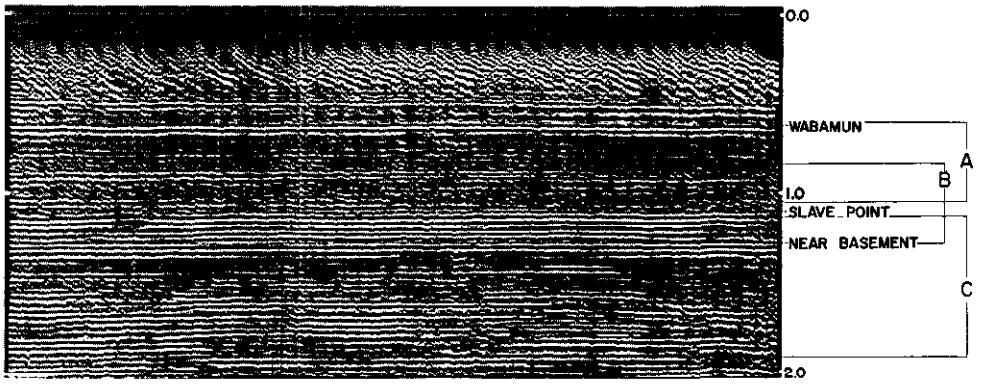

FIG. 14a.—Seismic section across a known reef at Rainbow Lake.

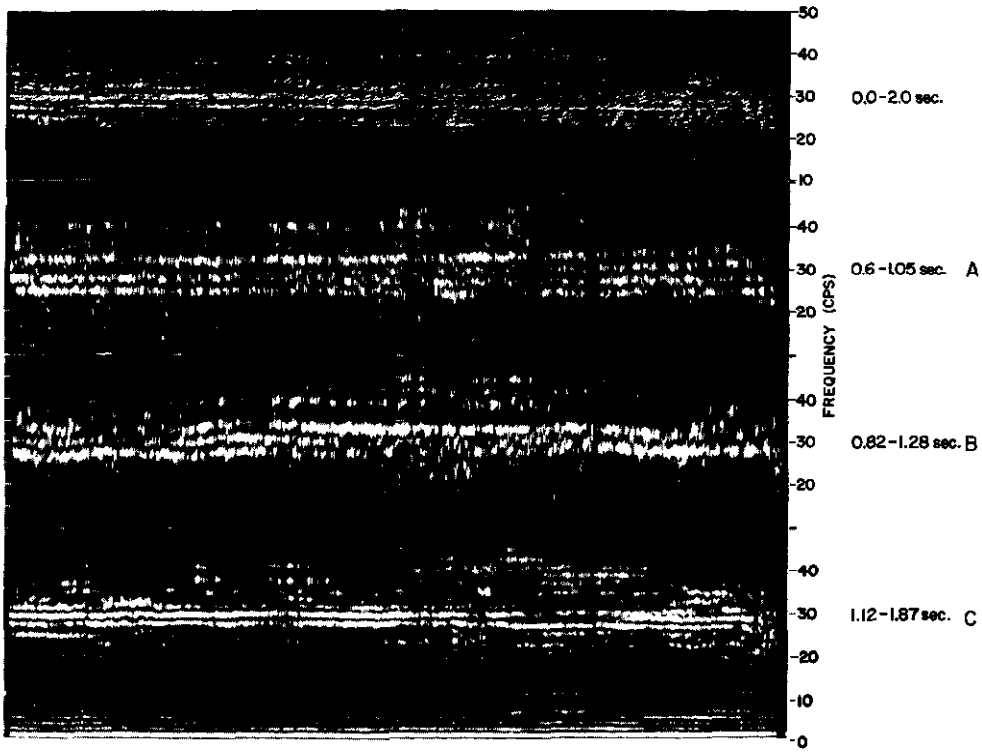

FIG. 14b.—Spectra showing a frequency increase just above the reef level and an absence of frequency effects in the shallower and deeper sections.

evidence at about 1.2 seconds is more subtle than on the previous example, probably because of interference on the 100% section that could be removed by common depth point processing. On Figure 14b the spectrum of the full section shows a slight tendency toward banding, possibly resulting from long-period multiples generated in the shallow section. Spectrum "A" of a time band selected well above the reef level shows a convergence of frequencies toward the left which suggests a general thinning of sediments toward the right. No indication of reefing is seen. Spectrum "B," emphasizing reflections returning from an interval just above the reef level, indicates a well-developed anomaly with clear indications of the reef edges. Wells have been drilled on either side of this structure, confirming the interpretation as shown by the frequency spectra. Spectrum "C," emphasizing the zone below the reef, gives no observable anomaly, as would be expected.

In the previous examples we have been concerned with reef structures which have been interpretable on the time sections, although the frequency anomaly adds significantly to the confidence level. We shall now consider two examples where the interpretation of reefing on the

record section itself is more difficult. In both of these examples it is uncertain whether apparent reef indications on the time section might not be due to the effects of multiple interference.

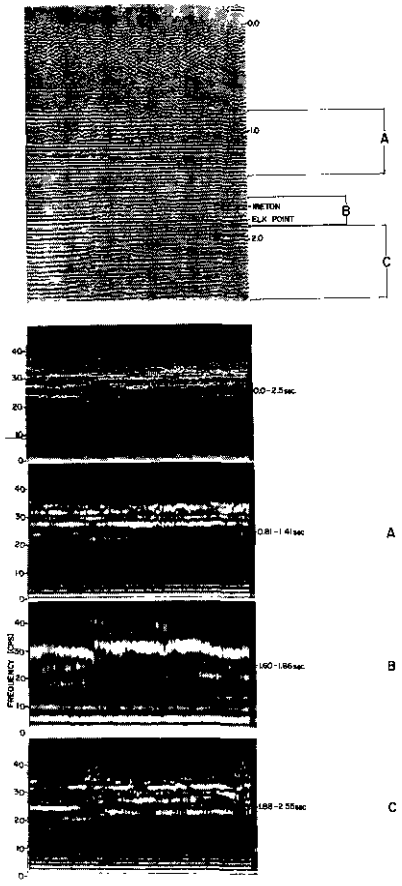

FIG. 15.—Seismic section across known Devonian Leduc-type reef with selected spectra.

Evidence for reefing on the record section shown in Figure 15 is quite weak due to interference by multiple reflections at the Ireton level. A reef edge, however, was interpreted from the time section near position 1, off reef to the right. This interpretation was confirmed by drilling. The sequential spectrum display in Figure 15 shows evidence confirming a reef edge interpretation: an anomalous frequency shift on spectrum "B" and uniform frequency relationships on spectra "A" and "C" above and below the reef levels respectively. These three spectra would certainly have increased the confidence level of the original interpretation.

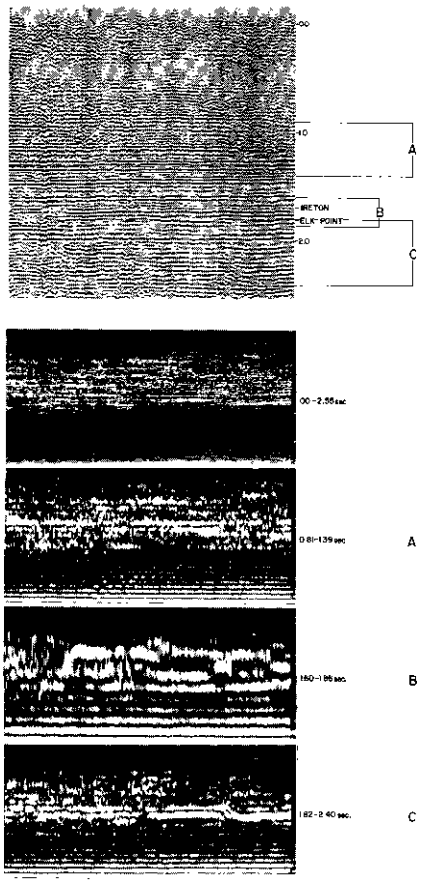

FIG. 16.—Seismic section across possible Devonian reef and selected spectra.

Subsequent drilling indicated a later stage of reefing on the left side of the section. From the well information the reef appeared to increase in thickness from 300 ft. near position 1 to about 800 ft. to the left of position 2. On the spectrum at the reef level we see an important frequency change at position 2 but it is doubtful whether this change could be correctly interpreted on the basis of a single frequency analysis. The interpretation of frequency spectra involving unusual reef forms, as well as irregular sedimentary conditions, not only requires considerable experience, but also as much seismic control as possible.

On the time section shown in Figure 16 reef indications might well be overlooked because of interference by multiple reflections. Spectrum "B" on Figure 16 shows well-defined reef indications: a frequency high in the main band of energy of about three cps magnitude and a definite sparsity of low frequency energy along with a concentration of quite

high frequencies in the vicinity of the interpreted reef body. The absence of such anomalous changes in the remaining spectra in this sequence reinforces the interpretation of a reef at the Ireton level. Due to inconclusive evidence on the original time section, this area has not yet been drilled.

CONCLUSIONS

Reef indications on seismic sections are often subtle and elusive. Our investigations and results suggest that much evidence for reefing lies undetected in the frequency domain. Record section spectra appear to have an important potential as an additional tool in the interpretation of reef structure. They can also contribute to a more convincing presentation of evidence during the final selection of locations for drilling.

In a larger sense the use of seismic spectra may constitute a new approach to many of the interpretational problems confronting the explorationist. Frequency analysis can provide a whole new way of looking at seismic data and perhaps one with far reaching significance.

ACKNOWLEDGMENTS

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