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THE ORIGIN OF FINE SCALE ACOUSTIC STRATIGRAPHY IN DEEP-SEA CARBONATES

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Abstract. In this paper we investigate the origin and geologic significance of the closely spaced high-frequency subbottom acoustic reflectors characteristic of pelagic carbonates. A detailed survey was conducted of a small area in the equatorial Pacific with the Marine Physical Laboratory's Deep-Tow instrument package, providing high-resolution 4-kHz profiles and precise positioning of core samples. The cores were sampled at closely spaced intervals for sound velocity and saturated bulk density. Acoustic impedances were calculated, and a reflection coefficient log determined for the upper 10 m of the sediment column. The reflection coefficient log revealed no interfaces with large reflection coefficients that correlated with the reflectors seen on the Deep-Tow 4-kHz seismic profile. The calculated reflection coefficients were very low (typically 10^{-3} - 10^{-5}) and varied about a wavelength that was on the order of the wavelength of the 4-kHz pulse, implying that interference plays a role in the composition of the seismic record. Convolving the outgoing 4-kHz pulse with the reflection coefficient log generated a synthetic seismogram that very closely resembled the 4-kHz reflection profile. Varying the frequency of the outgoing pulse changed the amplitude and position of the reflectors seen on the synthetic seismograms. Thus we conclude that the reflectors seen on the 4-kHz seismic profile were not caused by discrete geologic horizons but rather are the result of the interference of many small layers.

Introduction

Since the inception of seismic reflection profiling, the geologic significance of reflecting horizons has been an issue of key importance. These profiles have served as an invaluable tool for understanding geologic structure, but their close resemblance to a geologic cross section has prompted numerous investigators to assume a direct correlation between the acoustic and stratigraphic record. The validity of this assumption, however, is questionable. As Sheriff [1977] points out, stratigraphic interpretation of seismic sections must be constrained by knowledge of geophysical limitations, for, as '... most reflections are interference composites, there is no one-to-one correspondence between seismic events and interfaces in the earth.'

This is not to say, however, that it is impossible, directly, to correlate an acoustic horizon with a lithologic one. Indeed, in one of the earliest applications of subbottom profiling, Worzel [1959], using a 12-kHz echo sounder, acoustically identified a widespread ash layer in the eastern Pacific. Hersey [1965] and Ryan et al. [1965], also working at high frequencies, correlated reflectors in the Tyrrhenian Abyssal Plain with turbidite sands and ash layers.

The decreased resolution of low-frequency (air gun, sparker) reflection profiles makes stratigraphic correlation even more difficult. Before the Deep Sea Drilling Project, deep horizons could only be sampled where they appeared to outcrop [Ewing et al., 1966; Saito et al., 1966; Windisch et al., 1968]. This approach is plagued by uncertainty caused by the poor resolution of the seismic system and the lack of control on the position of the sample. The results of the drilling program proved to be of tremendous value in determining the relationship between the seismic and the geologic record. During the first two legs of the Deep Sea Drilling Project, Ewing et al. [1970] established that horizons A and A", prominent reflective zones in the North Atlantic and Caribbean, respectively, were caused by layers of chert. Subsequently, at many of the Deep Sea Drilling Project sites, correlations have been drawn between reflective zones and cored materials, but as was also true with the high-frequency work, those correlations established have been with major lithologic boundaries (e.g., sediment-basement, carbonate-chert, turbidites, and ash). It is certainly not surprising that the impedance contrasts associated with these types of interfaces would reflect a substantial amount of energy. What requires further examination, however, is the significance of the numerous reflectors that cannot be directly tied to such lithologic contrasts. This problem is particularly acute in pure pelagic carbonate sections which, in a coarse sense, appear homogenous in cores and, yet, typically show a large number of closely spaced reflectors. Schlanger and Douglas [1974] discuss a diagenetic model for the origin of these reflectors. They emphasize the possible relationship between the reflectors and paleoceanographic events such as glacioeustatic sea level changes and shifts of the calcite compensation depth. If the relationship between the acoustic record and such events can be more precisely established, then seismic profiling could become an important paleoceanographic tool. On a finer scale (at higher frequencies) the carbonates continue to show this characteristic acoustic stratigraphy. Many of these higher-frequency reflectors are shallow enough in the sediment column to be reached with standard piston cores; thus they can be studied without the expense and complications of deep sea drilling. With this in mind a study was

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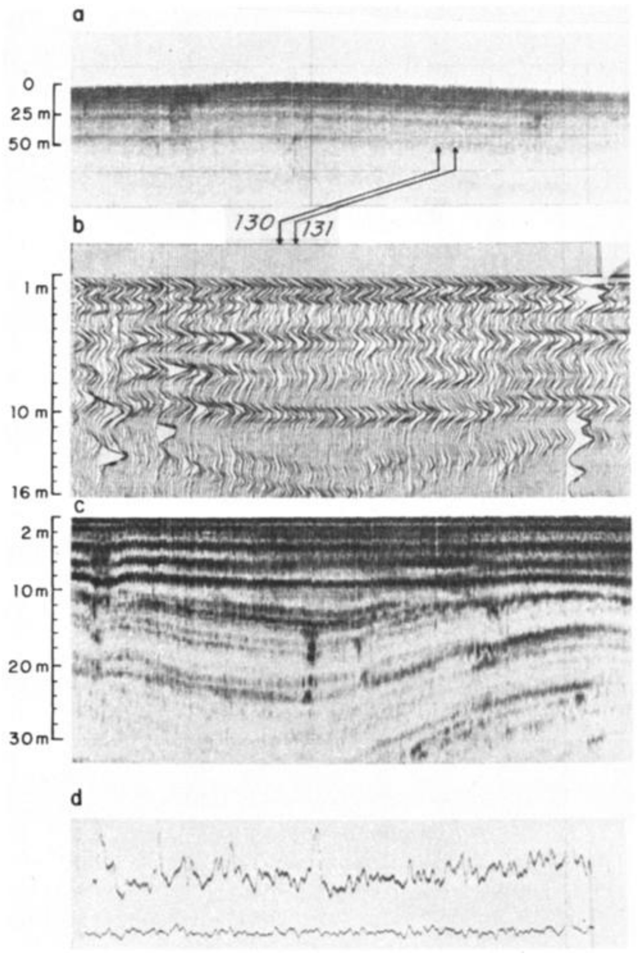

Fig. 1. (a) Unprocessed Deep-Tow 4-kHz record at core site. Arrows mark approximate core locations. Assumed velocity of 1524 m/s. (b) Computer-processed 4-kHz record. Assumed velocity 1524 m/s. Three-dimensional display of equivalent plane wave intensity. (c) Equivalent plane wave pressure. (d) Integrated equivalent energy: - - lower trace, - - 0-5 m: upper trace, 5-55 m (see Tyce [1977] for details).

undertaken to investigate the geologic significance of the high-frequency reflecting horizons common to pelagic carbonate sequences.

Methods of Study

The obvious approach to this problem is to profile a section, sample it, and see what correlations can be drawn between the geologic and acoustic record. To minimize the uncertainties normally associated with this approach (poor resolution, poor control of sample location, and disturbance), a survey was conducted with the Deep-Tow instrument of the Marine Physical Laboratory. The Deep-Tow is a submersible geophysical instrument package with a wide range of sensing systems, typically towed 50-100 m off the bottom (see Spiess and Tyce [1973] for a full description). Of particular interest to this study is a quantitative 4-kHz subbottom profiling system [Tyce, 1976, 1977]. The high frequency and short pulse length (0.5-1 ms) of the outgoing signal result in a theoretical vertical resolution of 20-40 cm. Computer processing of the received signal provides a real-time display in several forms (Figures 1a-1d) and attains the theoretical limit of resolution [Tyce, 1977]. The near-bottom position of the source also reduces many of the ambiguities that might result from lateral inhomogeneities in the acoustic structure and permits substantial penetration (typically 100 m) into the sediment column. Thus the problem of poor resolution is minimized.

The Deep-Tow system also greatly reduces the uncertainty of sample location. In the course of a survey the position of the instrument is accurately (±5 m laterally) and continuously determined with respect to an array of acoustic transponders. When a sample is to be taken, a relay transponder [Boegeman et al., 1972] is attached to the corer. This navigation device permits the positioning of the corer and the accurate location of the core site with respect to the subbottom profiles and the transponder network. For this study, two 9-m-long piston cores were taken in close proximity (±4 m) to Deep-Tow 4-kHz subbottom profiles that showed a large number of closely spaced and laterally continuous reflectors (Figure 1). The cores, separated horizontally by approximately 250 m, sampled sections that were acoustically identical. They were designed to examine the lateral continuity of the geologic stratigraphy as well as to provide redundant samples, should the section prove to be geologically continuous.

The problem of disturbance can be a serious one, and all efforts were made to minimize it. The piston cores were large-diameter (8.3 cm) linered cores. Upon retrieval the cores were cut into 75-cm sections, placed under seawater in sonobuoy cases, and stored upright at 3°C. This method of storage proved quite acceptable, as there was no evidence of dewatering or resuspension when the cores were examined in the lab. As will become apparent, the coring process itself caused some slight disturbance, but it proved not to be a serious problem. In the lab the cores were sampled every 8-9 cm for a wide range of geologic and physical properties.

Results

Among the many physical properties measured were the sound velocity and saturated bulk density of the sediments (Figure 2). Velocities were measured over 8- to 9-cm intervals by means of a Hamilton frame [Hamilton, 1970], and densities were determined with the weight-volume method [Bachman and Hamilton, 1976]. A remarkable correlation between cores 130 and 131 can be seen if the profiles of core 130 are shifted down approximately 125 cm, which implies that the top 1.25 m of the section is missing in either the core or the sediment column. Examination of the profiles from the gravity cores that tripped the piston cores (Figure 2b) reveals an excellent correlation between the uppermost sections at each core site and a close resemblance to the top 1.5 m of core 131. Thus the sedimentary structure is fairly continuous between the core sites, but core 130 has lost the uppermost 1.25 m of sediment, a phenomenon

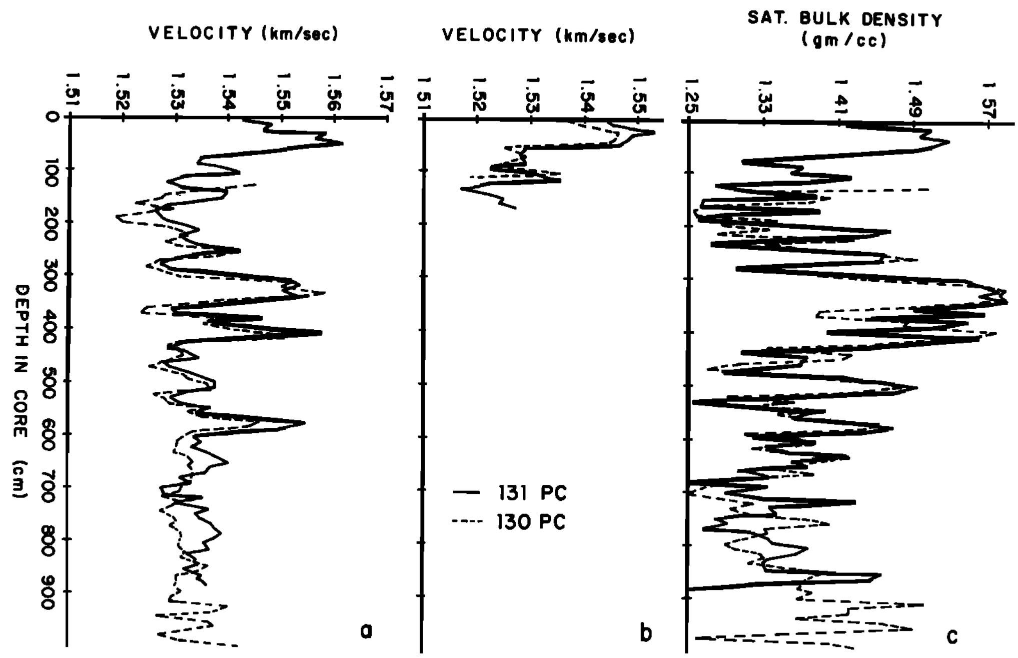

Fig. 2. (a) Sound velocity versus depth for piston cores 130 and 131. (b) Sound velocity versus depth for gravity cores that triggered piston cores 130 and 131. (c) Saturated bulk density versus depth for piston cores 130 and 131.

not uncommon in piston cores. The numerous other physical and stratigraphic properties measured provide further substantiation for this shift. By combining these data sets a composite profile representing the downcore velocity and density distribution for the top 10 m of the sedimentary section can be constructed (Figures 3a and 3b). The geologic setting of the core sites and the correlation and relationships between the physical properties will be discussed in more detail elsewhere (L. Mayer, manuscript in preparation, 1979).

The parameter of key importance to seismic profiling is the reflection coefficient: the ratio of the amplitude of the reflected wave to the amplitude of the incident wave. For normal incidence (the situation with which we are concerned) this quantity can be expressed strictly in terms of the density-velocity products (acoustic impedance) of the media involved. Given the impedance profile for the section (Figure 3c) and assuming homogeneity only on a scale many times finer than a wavelength, reflection coefficients can be

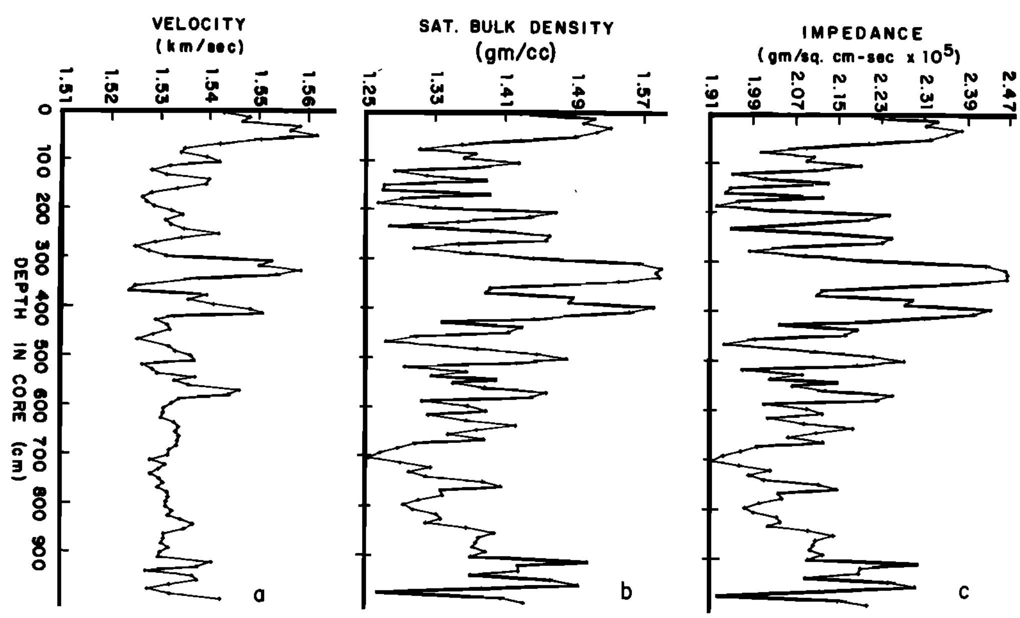

Fig. 3. Combined data sets representing top 10 m of sediment column. (a) Sound velocity, (b) saturated bulk density, and (c) calculated acoustic impedance.

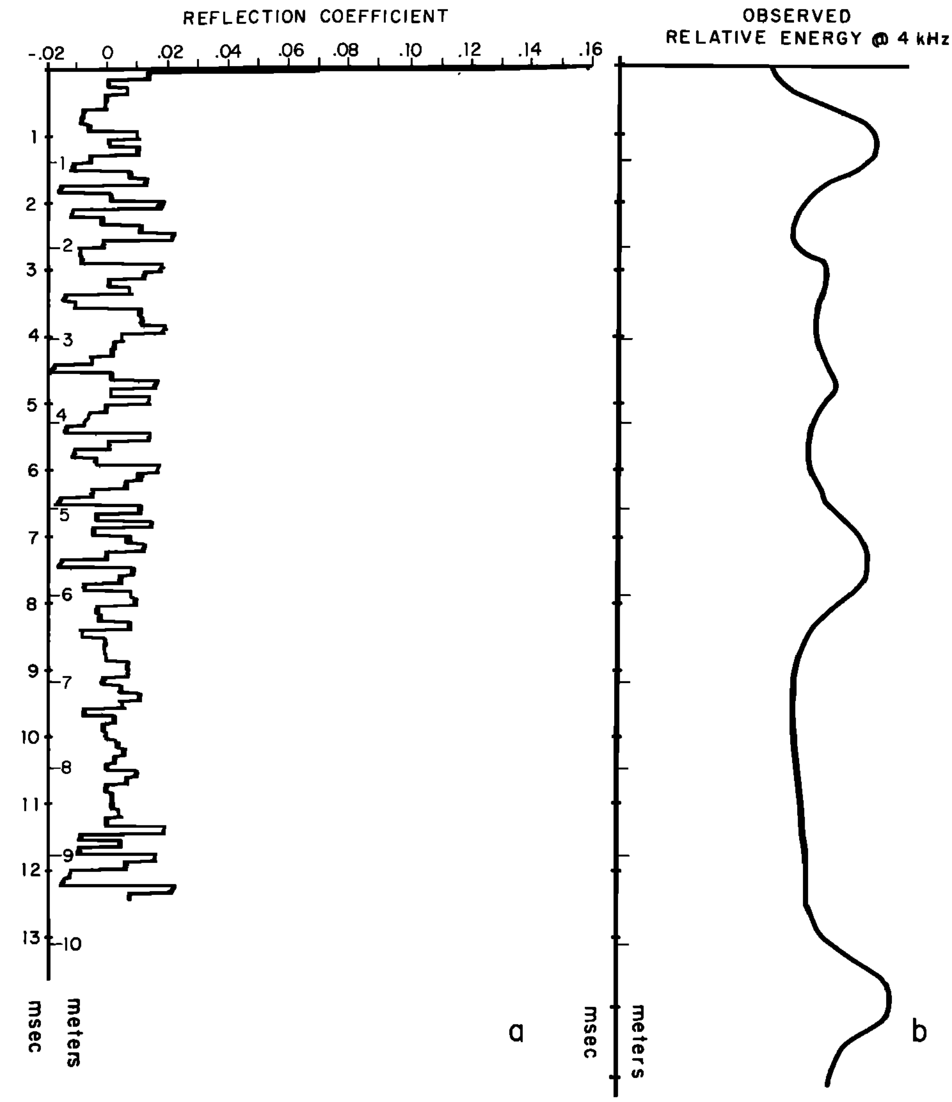

Fig. 4. (a) Reflection coefficient log calculated from impedance profiles for 10-µs-thick layers. Represents 1246 reflection coefficients. (b) Deep-Tow 4-kHz reflection profile at core site, - - from computer-processed equivalent intensity display.

calculated for very thin (10 µs thick) layers (Figure 4a).

Several lines of reasoning suggest that this reflection coefficient structure closely approaches the impulse response of the sedimentary section. First, the excellent correlation between the two cores (Figures 2a, 2b, and 2c) implies that aliasing is not a severe problem with the density and velocity data sets. For such a correlation to exist between the cores — especially since there is an arbitrary (≈125 cm) offset in data points -- indicates that the samples are spaced closely enough to be a true representation of the downcore physical property variation. This is further supported by a close look at the data themselves. For both the density and velocity data sets, high values are supported by other high values, and lows are supported by other lows (Figures 3a and 3b). Geologically, the 8-cm sample interval is a reasonable estimate for the vertical mixing depth, often the limiting factor in the vertical resolution possible for any property in a pelagic sedimentary sequence [Berger and Heath, 1968]. Thus the close spacing of our samples combined with the resolution limitations of vertical mixing have resulted in a data set that accurately represents the physical properties of the sediment column. Sampling at a closer interval would not substantially change the shape of the velocity and density (and thus impedance) curves.

Finally, to claim that the calculated reflection coefficient structure represents the impulse response of the sedimentary section, we must assume that we are dealing with plane waves and that interbed multiples have no significance. The source is far enough from the bottom (50-100 m) that we need only consider plane waves, and the reflection coefficients are so low (typically 10^{-3}-10^{-5}) that the role of multiples must be negligible.

Examination of the reflection coefficient

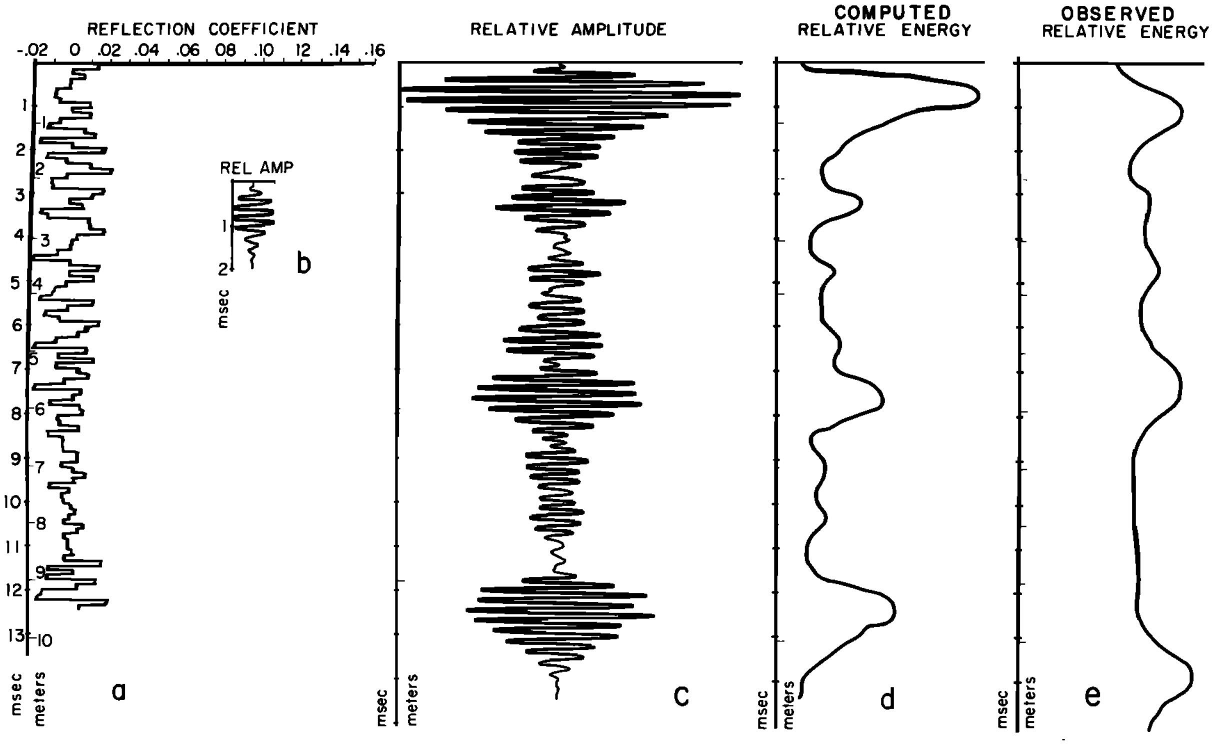

Fig. 5. (a) Reflection coefficient log. (b) Digitized outgoing 4-kHz pulse of Deep-Tow. (c) Output of convolution of Figures 5a and 5b (amplitude). (d) Output of convolution of Figures 5a and 5b (energy). (e) Deep-Tow 4-kHz reflection profile.

profile (Figure 4a) reveals an extremely complicated structure with no large values except at the sediment-water interface. The complicated reflectivity structure is not surprising in view of the relationship between reflection coefficient and the basic velocity and density data. The reflection coefficient depends on the differences in velocity-density products (impedance); thus small variations in either property can be magnified in the calculation of reflectivity. The lack of several interfaces with large reflection coefficients is surprising, however, in light of the distinct and laterally continuous reflectors observed with the Deep-Tow 4-kHz seismic profiler (Figure 4b).

It is obvious that the reflectors observed do not directly correspond to interfaces with large reflection coefficients and that there is certainly not a one-to-one correlation between the reflectivity and the seismic profile. What then does cause the reflectors? One clue is that the wavelength of variation of the reflection coefficient structure is often of the same order as the wavelength of the 4-kHz profiling system (≈0.4 m). Thus it is impossible to resolve many of the more closely spaced interfaces, and it is likely that interference plays a part in determining the content of the seismic profile.

To investigate the role of interference in the seismic record, the shape of the outgoing pulse must be well documented. This has been done for the Deep-Tow 4-kHz profiling system [Tyce, 1977]. A 1.0-ms input pulse results in a 2.0-ms transmit pulse that is broadband and well defined (Figure 5b). We must concern ourselves with how this outgoing pulse interacts with the physical property structure of the sediment column to form the reflection profile. This problem can be approached by treating the outgoing pulse as a source function and the reflectivity as the impulse response and convolving the two to generate a synthetic seismogram. In doing so we sum the effects of each interface in appropriate time relations and construct the resulting interference composite. The output of the convolution (Figures 5c and 5d) bears a striking resemblence to the reflection profile collected with the Deep-Tow 4-kHz seismic profiler (Figure 5c). The match is nearly perfect except for the deepest reflector, which is at 14 ms on the Deep-Tow profile and 12.5 ms on the synthetic seismogram. A possible explanation for this discrepancy lies in the fact that the Deep-Tow profile represents in situ physical properties, while the seismogram was generated from cored material. A paleontological analysis of the cores suggests that the bottom 2 m are compressed (D. Johnson, personal communication, 1978).

Thus Sheriff's [1977] assertion is substantiated; the reflections we have observed were not caused by discrete geologic horizons but rather are interference composites caused by many small interfaces. The large reflectors at 0.7, 7.5, and 12.5 ms in the synthetic seismogram (Figure 5c) occur where the spacing of the interfaces results in constructive interference. Tyce [1977], using the Deep-Tow 4-kHz profiler quantitatively, calls upon a similar phenomenon to explain the anomalously large reflection coefficients he calculated for deeper reflectors.

We may deduce that given a uniformly continuous sediment column, the position and

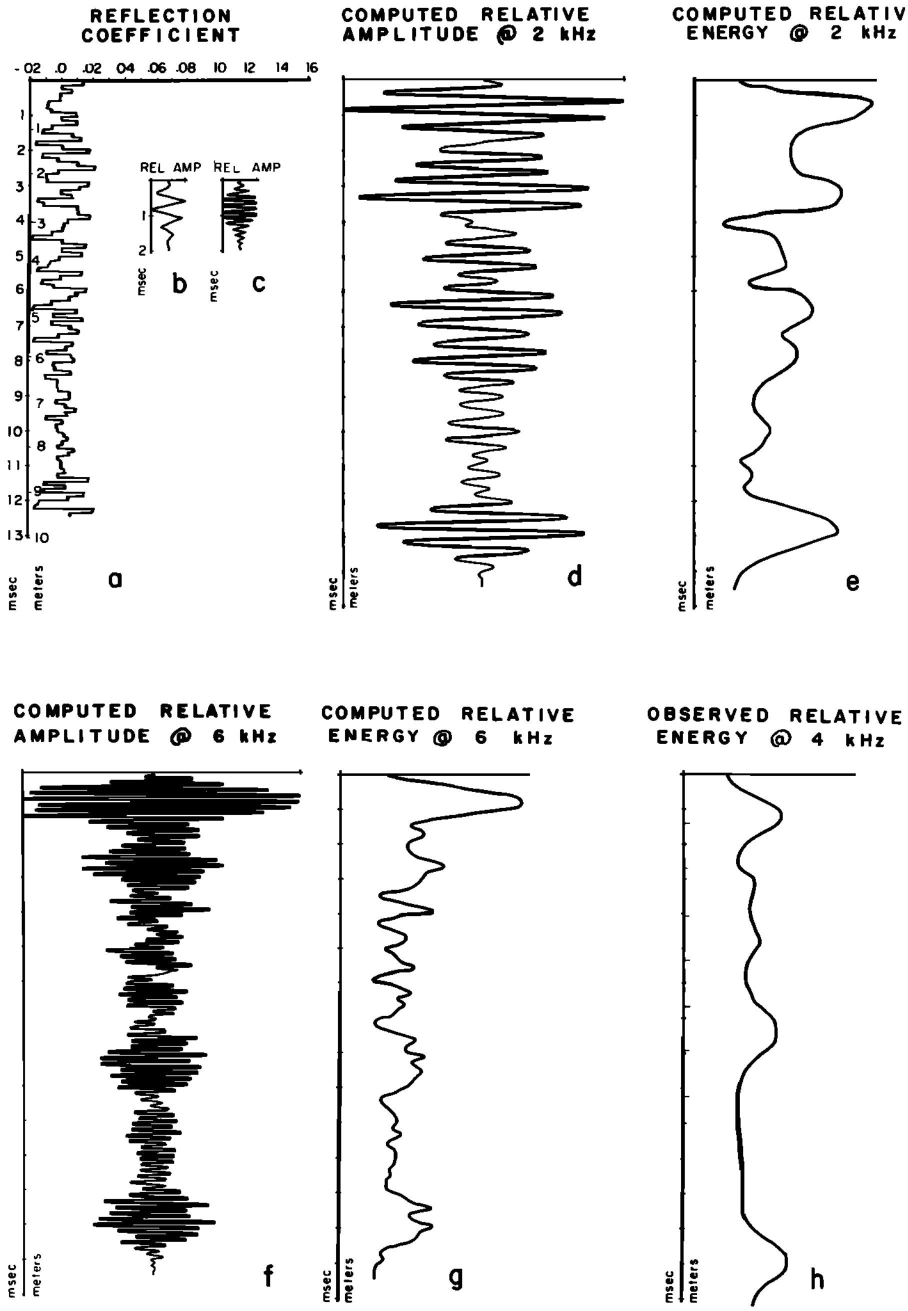

Fig. 6. (a) Reflection coefficient log, (b) 2-kHz pulse, (c) 6-kHz pulse, (d) output of convolution of Figures 6a and 6b (amplitude), (e) output of convolution of Figures 6a and 6b (energy), (f) output of convolution Figures 6a and 6c (amplitude), (g) output of convolution of Figures 6a and 6c (energy), and (h) Deep-Tow 4-kHz reflection profile.

amplitude of the reflectors should be dependent upon the frequency and shape of the outgoing pulse. To test this hypothesis, the same reflection coefficient structure was convolved with a 6-kHz and 2-kHz pulse. The resulting synthetic seismograms are dissimilar from each other and from the original 4-kHz reflection profile (Figure 6). The Deep-Tow system now has the capability to collect reflection profiles at both 4 and 6 kHz. In the first test of this system, records collected at the two frequencies over the same sediment pile showed distinctly different reflections.

Discussion of Future Developments

The lack of a one-to-one correlation between geologic horizons and acoustic reflectors does limit the stratigraphic information that can be read directly from the seismic record, but if the interference phenomenon is understood, it may well be possible to use it to retrieve a wide range of geologic data. The lateral continuity of the reflection profiles in the survey area implies uniform interference, but this in turn can be attributed to a continuity in the reflection coefficient structure. From this information we may draw inferences about the nature of sedimentation and the structure of the sediment column in the survey area. Changes in the composition of reflection profiles present a more perplexing problem; such changes may directly represent stratigraphic events or may be the result of slight variations in interface spacing that cause differing interference patterns. A solution to this problem may lie in the use of several discrete profiling frequencies or a tunable broadband profiling system. A tunable profiling system would permit the determination of those frequencies at which resonance occurs and would provide detailed interface-spacing data. It may also be possible to directly trace slight variations in interface spacing and thus obtain a record that more closely approximates the stratigraphy.

A multiple-frequency capability would be particularly useful in discriminating between reflectors that are interference composites and those that are geologic interfaces. In this study we have examined the top 10 m of an equatorial pelagic carbonate sediment column. Equatorial carbonates are extremely sensitive to changes in environmental conditions that produce small but closely spaced downcore variations in physical properties [Berger and Mayer, 1978]. Thus the interference problem is particularly severe in carbonates, and the composition of reflection profiles will be strongly frequency dependent. However, in those areas where there are major lithologic boundaries (and therefore significantly large reflection coefficients) the reflectors should persist over a wide range of frequencies. Turbidite sequences may also lend themselves to this type of analysis. One would expect that the sand-mud boundary defining separate events would have a large reflection coefficient and therefore would be a persistent reflector. The graded bedding within the turbidite, however, should create reflectors that are very frequency dependent. A sequence of turbidites would then appear as groups of variable reflections separated by reflectors that remain constant when viewed over a broad frequency range. Observing the behavior of a reflection profile as a function of frequency becomes a simple method of determining the nature of the reflectors (interference composites or discrete horizons) and may also provide a basis for the remote classification of sediment type.

Finally, a broadband, quantitative profiling system may allow the determination of the physical properties of sediments from acoustic records. With high-resolution profiling, careful and closely spaced sampling, and consideration of the nature of the outgoing pulse, we have been able to generate a synthetic seismogram that closely matches the acoustic record. If, however, we could generate the reflection coefficient structure from the acoustic record, we would have a truly powerful geologic tool. The deconvolution of the seismic record requires a detailed knowledge of the shape of the outgoing pulse and the collection of quantitative reflection data over a wide range of frequencies. The successful deconvolution of the seismic record should result in the reflection coefficient structure of the sediment column from which we may begin to derive physical properties.

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