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Shallow-Water, High-Resolution, Marine Multichannel Seismic-Reflection Techniques

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ABSTRACT

Acquisition of shallow-water, marine multichannel seismic reflection data provides a method for mapping shallow structures in rivers, bays, lagoons, and the shallow part of the continental shelf, but presents operational difficulties for conventional-sized ships and marine seismic recording systems. Over the past five years, the U.S. Geological Survey has experimented with several high-resolution marine multichannel recording systems in estuaries, rivers and near-shore areas along the U.S. east coast with the objective of obtaining 1 to 2 km of penetration in Tertiary and Mesozoic sediments with a frequency resolution of at least 250 hertz. Surveys have also been conducted in a lake, the Mississippi River, and a Pacific coral atoll, and reliable operational systems and processing techniques have now been achieved.

This paper focuses on the details of a high-resolution seismic experiment conducted at Enewetak Atoll in the Marshall Islands. One system using a 15-in^3 watergun, a 24-channel, 150-meter streamer (6.25-meter groups), and a 1-ms sample rate produced good quality penetration of 1/2 to 1 km depth. A larger system using an 80-in^3 watergun, a 24-channel, 300-meter streamer (12.5 meter groups), and a 1 ms sample rate obtained reflections from as deep as 1,400 meters. On-board digital processing proved to be advantageous in selecting the optimum field procedure. Signature deconvolution and careful timing adjustments during detailed processing provided resolution of beds as thin as 2-5 meters or faults with similar offsets. Average interval velocities in the upper 300 meters are accurate to within $\pm 5\%$.

INTRODUCTION

In 1980, the U.S. Geological Survey began an effort to develop high-resolution, marine multichannel reflection techniques for shallow-water areas such as the Inner Continental Shelf, estuaries, bays, lakes, and rivers where 1 to 2 km of penetration into Tertiary and Mesozoic sediments was desired with frequency resolution up to 250 hertz. A 38-foot, trailerable vessel, the Research Vessel NEECHO was equipped with a 12-channel DFS V digital recording system, a 12-channel 120-m streamer composed of 10-meter groups, and two possible sound sources--a 15-in^3 watergun and a 40-in^3 airgun with a wave shaper.

The first cruise for the RV NEECHO was in December 1980 at Rend Lake, Illinois, where the U.S. Bureau of Mines wanted to test for detection of coal mine shafts and faults which could cause mine flooding hazards. Rend Lake is an artificial lake underlain by high-velocity ($\approx$4 km/s), Paleozoic sedimentary rock and a thin layer of gassy lake sediments behind a manmade dam. Extremely severe water-bottom multiple reflections were encountered and results were very discouraging (Miller and others, 1984). Figure 1 shows an example of shot gathers at Rend Lake after automatic gain control (AGC) and reveals an almost constant frequency ($\approx$110 Hz) train of waves. All attempts to suppress these strong water-bottom multiples were unsuccessful.

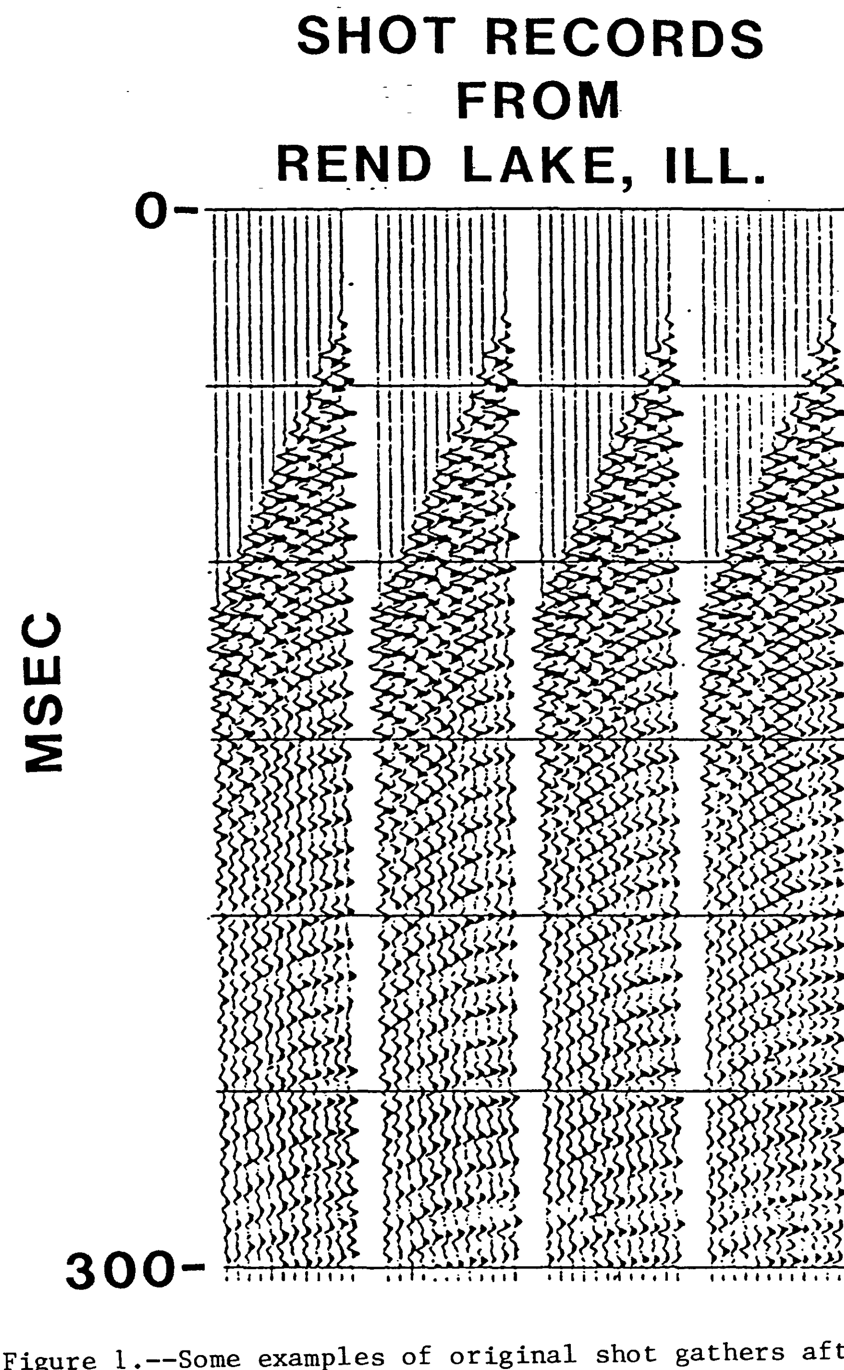

Figure 1.--Some examples of original shot gathers after gain application showing strong water-bottom multiples. These data were acquired by a 15-in^3 watergun at Rend Lake, Ill.

In January 1981, the RV NEECHO ran some lines in the Mississippi River near St. Louis where high-velocity, Paleozoic sedimentary rocks also occur. Weak reflections could be seen to a time of 200 ms, but the results were also not especially encouraging. Later that same month, the RV NEECHO moved down the Mississippi River near the New Madrid earthquake zone where 800 meters of Mesozoic and Tertiary sediments overlie the Paleozoic sedimentary rocks and good penetration was obtained down to the top of the Paleozoic rocks. An example of the New Madrid data from Shedlock and Harding (1982) is shown in figure 2. Near freezing water conditions at New Madrid prevented the use of the watergun, but the 40-in^3 airgun still produced valuable data. Our initial experience at Rend Lake and in the Mississippi River suggested that poor results may be expected in areas underlain by high-velocity Paleozoic sedimentary rocks, but that usable data could be obtained in areas underlain by Tertiary and Mesozoic sediments with less lithification.

During 1981 and 1982, the USGS conducted several cruises along the inner shelf off the east coast, Long Island Sound, and Chesapeake Bay using the 15-in^3 watergun with both single-channel and multichannel streamers. One new fault system was discovered in the New York Bight Area (Hutchinson and Grow, 1985). Because of congested shipping lanes near New York harbor and streamer problems, many of the New York Bight lines were shot with an 80-in^3 watergun and a single-channel streamer. This single-channel digital line across the New York Bight fault shows a near vertical growth fault with 109-m offset on the basement (fig. 3). Drill holes in the area and seismic tie lines suggest that this fault was active in the early Tertiary, but may not have been active in the late Tertiary and Holocene.

Another survey was conducted over the Helena Banks Fault off South Carolina in 1981 using twin 80-in^3 waterguns and a 12-channel, 240-m streamer (Behrendt and Yuan, 1987). In spite of some gun synchronization problems and intermittent streamer problems, good resolution can be observed on the Helena Banks Fault to a time of 1 second (about 1 km).

In 1984, the USGS conducted an extensive high-resolution, marine multichannel seismic reflection survey of Enewetak Atoll (fig. 4) for the Defense Nuclear Agency, including lines over nuclear craters (Grow et al, 1986). While neither the evolution of atolls nor details of the nuclear craters will be discussed in this paper, examples of Enewetak data which demonstrate seismic techniques, penetration capability, and resolution will be shown because of their relevance to seismic exploration. A total of 382 km of seismic lines were collected at Enewetak using either 15- or 80-in^3 watergun sources and 24-channel streamers of either 150- or 300-m total length, depending on the penetration or resolution required in different areas.

PURPOSE AND DATA ACQUISITION

The main purpose of the Enewetak survey (fig. 4) was to acquire better information on the subsurface geometry of the nuclear craters for a drilling program which commenced about 6 months after the completion of the seismic survey. The multichannel seismic survey was to provide acoustic stratigraphic profiles with penetration to a depth of at least 500 m (1,640 ft) to assist in the selection of drilling sites and, thereby, maximize the amount of scientific benefit derived from each hole. The processing of the key seismic lines was completed at almost exactly the time that they were needed for the drilling program.

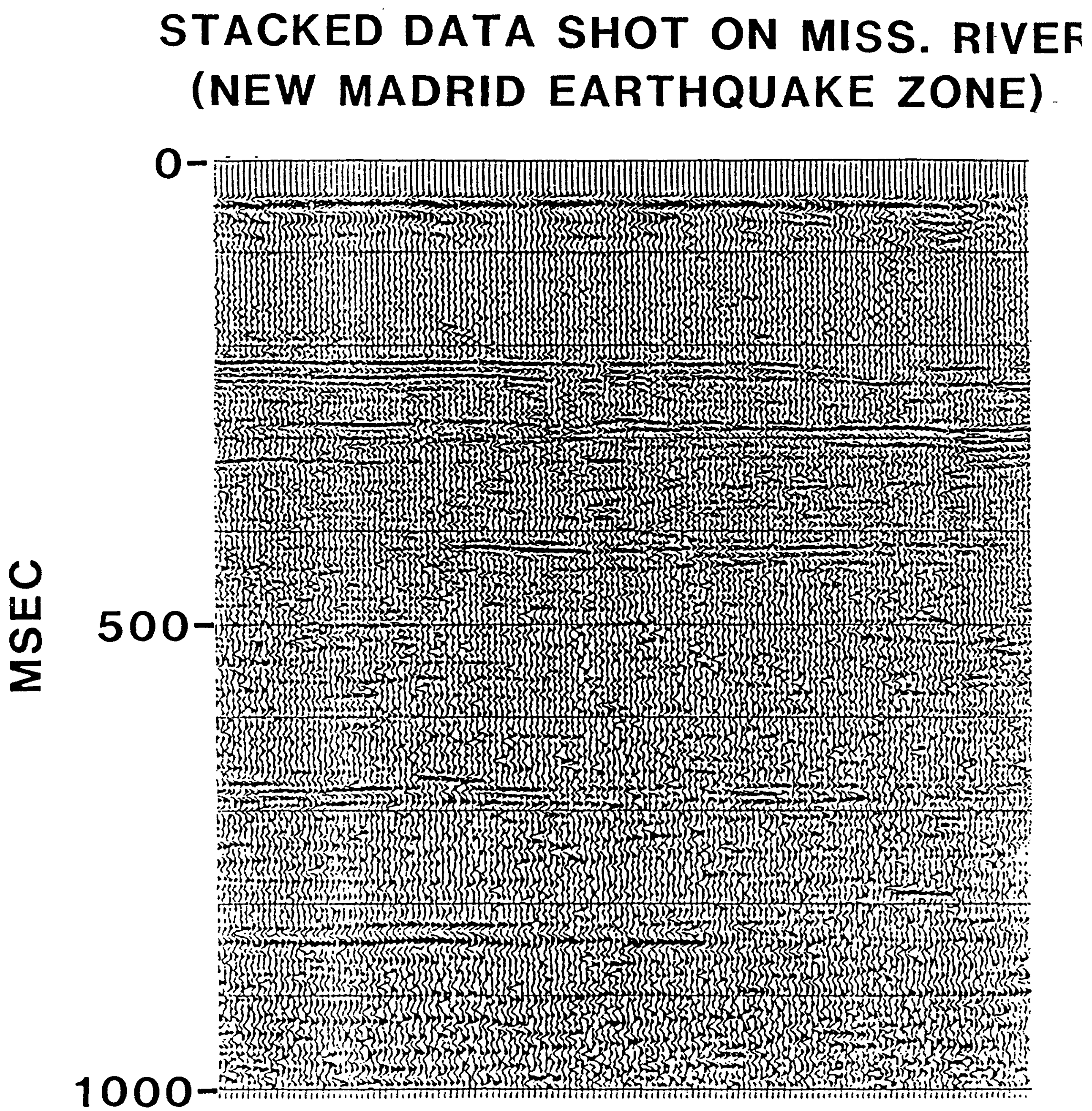

Figure 2.--Stacked cross-section shot on Mississippi River (New Madrid earthquake zone) by a 40-in^3 airgun from Shedlock and Harding (1982).

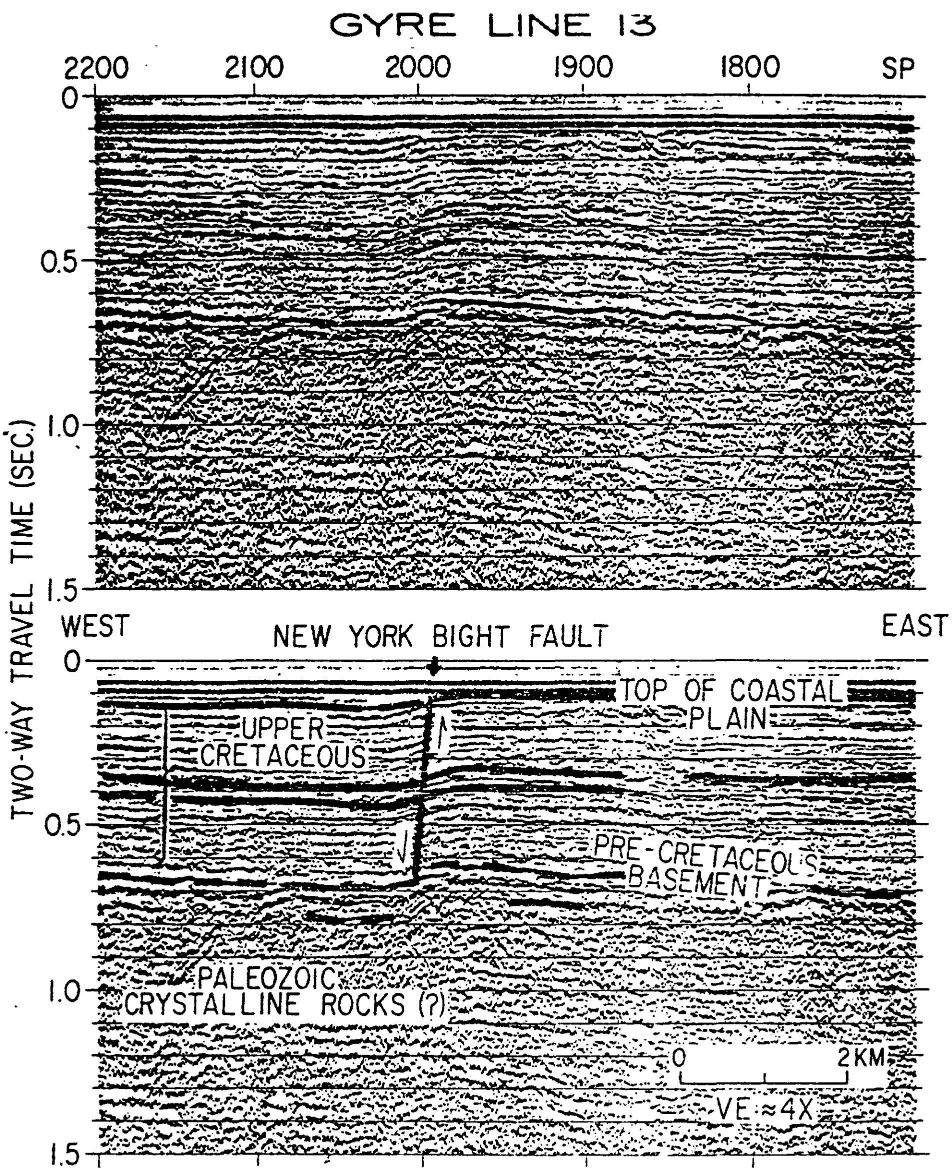

Figure 3.--Single-channel seismic reflection profile by an 80-in^3 watergun showing the New York Bight fault near Long Island, New York, from Hutchinson and Grow (1985).

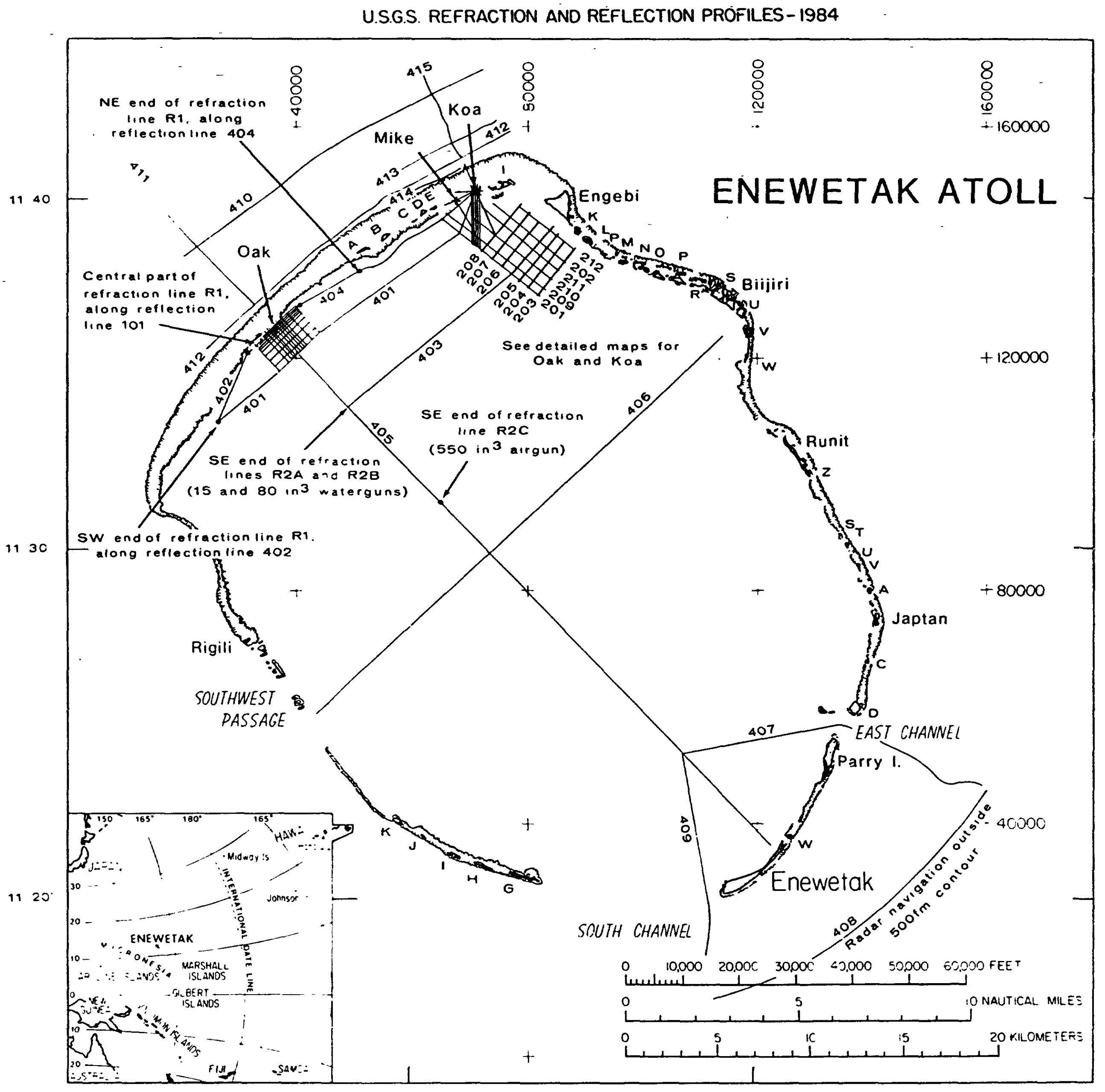

Figure 4.--Seismic lines at Enewetak Atoll. The inset at the lower left corner shows the geographical location of the Enewetak Atoll.

Previously, this area was surveyed twice by single-channel and multichannel systems using an 8-kilojoule sparker system (Ristvet and others, 1978; Tremba and others, 1982). Owing to the very complex source signature and short streamer (75 m), the previous survey did not provide sufficient information to resolve the velocity structure under the craters accurately. However, the previous seismic data were highly useful for developing the design of the USGS multichannel program.

The Enewetak seismic lines were acquired aboard a 120-ft vessel, the RV EGABRAG. The lagoon provided an almost perfect meteorologic and oceanographic setting to carry out the multichannel survey. Winds were light and sea state was low (<2 ft waves) during the entire period of the data acquisition. The physiographic and geologic settings, however, were far from ideal. Handling a long seismic streamer close to the reef in shallow water at OAK crater (fig. 4) was difficult and precluded acquisition of data in some areas. At KOA crater (fig. 4), the area was even more confining because of the shoal on the lagoonward side of the crater. The number of lines that could be run were limited because of the EGABRAG's size and the length of the seismic streamer needed to acquire the penetration and resolution desired. In the open lagoon, great care had to be exercised to avoid the many reef pinnacles, some of which rise to within a few meters of the sea surface.

Albeit the previous seismic survey provided useful information for the design of the multichannel system, we mobilized our Phoenix I seismic data processing system onboard the EGABRAG in order to optimize the new recording parameters (streamer length, sample interval, source type, etc.). We considered on-site processing to be an essential ingredient for providing the required information.

We experimented with four different streamer configurations and acoustic sources to determine the system that would give us optimum penetration and resolution of the complex atoll strata. These included: (1) a 75-m streamer cable with 12 channels in 6.25-m groups, (2) a 150-m cable with 24 channels in 6.25-m group, (3) a 300-m cable with 24 channels in 12.5-m groups, and (4) a 300-m cable with 12 channels in 25-m groups. The acoustic sources included 15- and 80-in^3 waterguns, and 1-, 20-, 40-, and 540-in^3 airguns. The USGS' digital recording system had the option of recording either 12 channels at 0.5-ms (millisecond) sampling rate or 24 channels at 1.0-ms sampling rate.

After 4 days of testing and processing the data aboard ship, we found that one combination of sound and receiving systems gave us best results in the craters, and another combination gave us best results for regional work. For the detailed crater work, we used a 15-in^3 watergun and a 150-m streamer cable with 24 channels in 6.25-m groups at a sampling rate of 1.0 ms and a recording time of 1.0 seconds. For regional lines across and outside the atoll, we used an 80-in^3 watergun, a 300-m cable with 24 channels in 12.5-m groups at a sampling rate of 1 ms and a recording time of 2.0 seconds.

DATA PROCESSING

The preliminary processing was done onboard using a conventional marine processing sequence. The detailed processing was performed later at the USGS processing center in Denver on a VAX 11/780 computer using mainly Digicon Inc., DISCO software.

Detailed processing of the Enewetak data included signature deconvolution in order to increase vertical resolution and static time shift to estimate interval velocity consistently. While the 15- and 80-in^3

waterguns were considerably cleaner sources than the 8-kiljoule minisparker used in the previous multichannel seismic survey, source signature deconvolution before stack was desirable to remove a low-frequency precursor and small oscillations following the main pulse. It is well known that seismic resolution depends not only on the frequency bandwidth of the source wavelet but also on the phase of the wavelet. Within the same frequency content, the zero-phase wavelet provides the optimum resolution power. Spiking deconvolution is the most conventional and robust technique used to increase resolution and works well when the source signature is minimum phase or close to it. However, the source signature from the watergun is a highly mixed phase and the precursor of the watergun signature is very difficult to remove by the conventional technique.

When the source signature is known either by direct measurement or by estimation from the seismic data, deconvolution can be carried out without any assumptions about phase and amplitude of the wavelet.

In Enewetak, the source signature was measured by a single hydrophone in deep water. However, the signature deconvolution applied to this data used the estimated signature from the shot gather rather than the measured one. The main reason for this is that the measured signature does not have the effect of the receiver array and the receiver ghost effect.

Variable norm deconvolution by Gray (1978) was applied to estimate source signature. Figure 5 shows an example of the estimated source signature for the 15-in^3 watergun and its amplitude spectrum. Notice the precursor appeared about 18 ms earlier than the main energy burst. The usable frequency content extends up to 250 Hz where the field anti-aliasing filter started. Under the assumption that quarter wavelength criteria is applicable to the seismic resolution and the interval velocity of the rock is in the range of 2,000 m/s, the average bed thickness we can resolve from this source is in the range of 4 m. A single source signature for each seismic line was extracted from a CDP gather. On the basis of the extracted wavelet, a deconvolution operator was derived and applied to the corresponding seismic line.

An accurate interval velocity estimation was one of the important factors to be considered for the data processing because of its relevance to the subsequent drilling program. An interval velocity can be derived from the stacking velocity using the Dix equation.

Stacking velocity of the seismic data is a function of T_o, which is the zero-offset, two-way arrival time. If there is an error in T_o, either by the data acquisition or the processing, the interval velocity estimation by the Dix equation is erroneous. One of the T_o errors induced by the processing is shown in the top of figure 6. The variable norm deconvolution operator put the peak of the zero-phase wavelet at the highest amplitude point of the input data. The time of the peak of the zero-phase wavelet is not identical to the onset time of the seismic arrival. In order to estimate accurate interval velocity, the seismic section after variable norm deconvolution should be static-shifted to fit the onset time.

Using the normal moveout (NMO) equation, the error in the stacking velocity due to errors in T_o can be estimated, which is given by:

$$\frac{\Delta V_s}{V_s} = -\frac{\Delta T_o}{2T_o}$$

where V_s is the stacking velocity. Errors in the stacking velocity with respect to the T_o error are shown in the bottom of figure 6. For example,

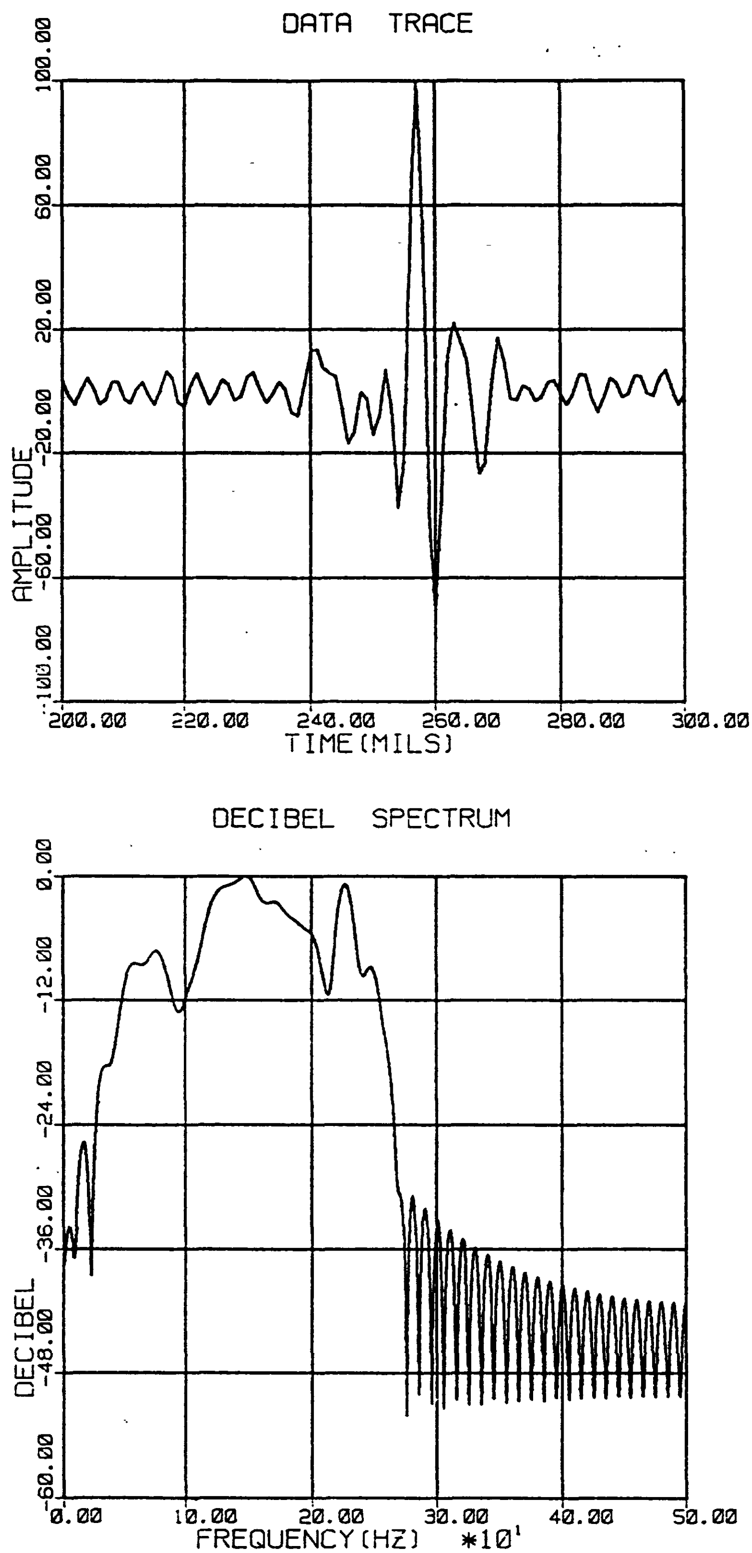

Figure 5.--Extracted 15-in^3 watergun source signature and its amplitude spectrum.

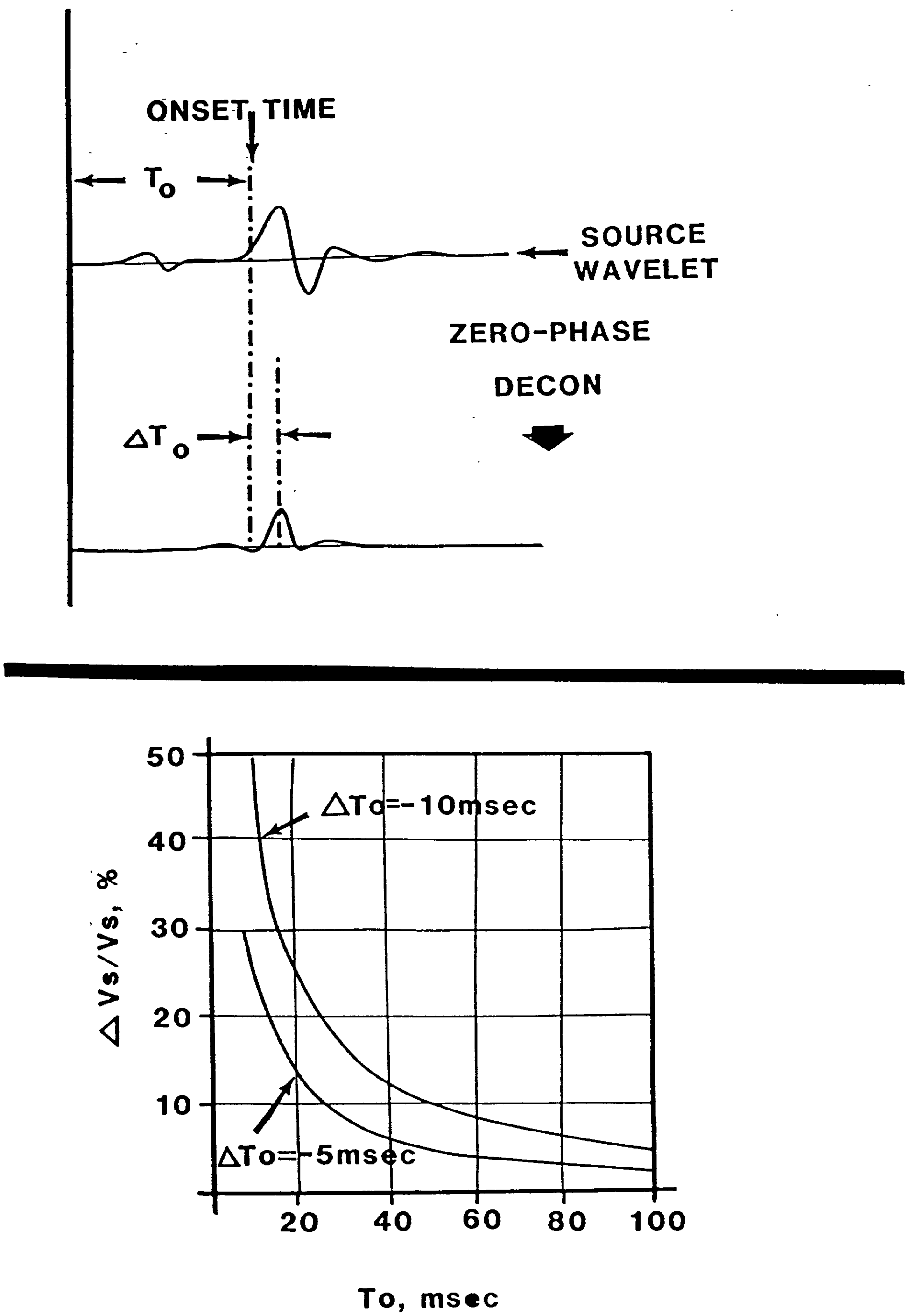

Figure 6.--Errors in the stacking velocity (ΔV_s) with respect to the errors in the two-way traveltime (ΔT_o). Top part of figure shows one of the T_o errors induced by the processing.

when the T_o error is -5 ms, the estimated stacking velocity is about 12% higher than the true stacking velocity when the true T_o time is 20 ms. For a shallow, high-resolution seismic investigation, this small amount of error in T_o (processing and acquisition) should be corrected before velocity analysis.

Before static time-shifting, the water velocity in this study area averaged about 1,450 m/s, which is about 6% lower than the other measurements would indicate. Interval velocities between the shallow reflectors showed a substantial scattering. After a 6-ms static-shift of the data, which included the cumulative effect of processing and acquisition, the water velocity was estimated consistently at 1,540 m/s, and subsequent interval velocity estimation was reliable.

Sediments between the seafloor and 100 ms had an average interval velocity of 1,752 m/s in KOA crater and 1,687 m/s in OAK crater (fig. 4). Sediments between 100 and 300 ms had an average interval velocity of 2,095 m/s at KOA crater and 1,995 m/s at OAK crater. Scatter within the data suggested that the accuracy was within ±5%. No consistent velocity anomaly was detected within either crater. Check shots from subsequent drilling within and outside KOA crater did discover a 5% velocity decrease between 100- and 200-m depth, but the average velocities were within the range predicted by the multichannel analyses. Check shots from subsequent drilling at OAK crater showed good agreement with the multichannel velocities outside the crater, but a large velocity decrease observed in the check shots between 100- and 300-m depth within the crater was not detected by the multichannel velocities. A complete analysis of this discrepancy is beyond the scope of this report, but the diffraction effects of fractured discontinuous reflectors and side echoes from the slopes around the crater are probably major factors.

After the source signature deconvolution and 6-ms time-shift corrections were applied, a conventional processing sequence was effective. Water-bottom multiples were not severe, but a post-stack predictive deconvolution was applied and improved the data in many cases.

EXAMPLES

An example of Enewetak data collected with the 15-in^3 watergun and 150-m streamer is shown in figure 7. Strong reflection events can be seen at 350 ms, 520 ms, 720 ms, and 980 ms. The 350-ms reflection group shows a strong increase of reflectivity from left to right, that is from the lagoon toward the reef. This pattern and other lines in the northwest side of the atoll suggest a prograding of the reef. A close-up of this line (fig. 8) in the upper 400 ms near the reef illustrates resolution capability of the system. The strong band of reflections between 300 and 350 ms was sampled by drilling in 1985 and was confirmed to be a denser "reef-plate" facies.

Examination of the seafloor return shows a single, clean, positive pulse with a period of approximately 4 ms, and this gave us a strong degree of confidence that the signature deconvolution worked extremely well. Drilling in the vicinity of this line shows that the Holocene-Pleistocene boundary is frequently a good reflector, and it can be seen downwarped beneath the flanks of the crater on this line. Although the Holocene-Pleistocene boundary shows a broad depression, a shallow fault with approximately 2-m offset can be resolved. The truncation of this reflector can also be clearly observed further into the crater.

Figure 9 shows the 12-fold CDP stacked section acquired by an 80-in^3 watergun with a 300-m streamer (24 channels). Notice the prograding reef

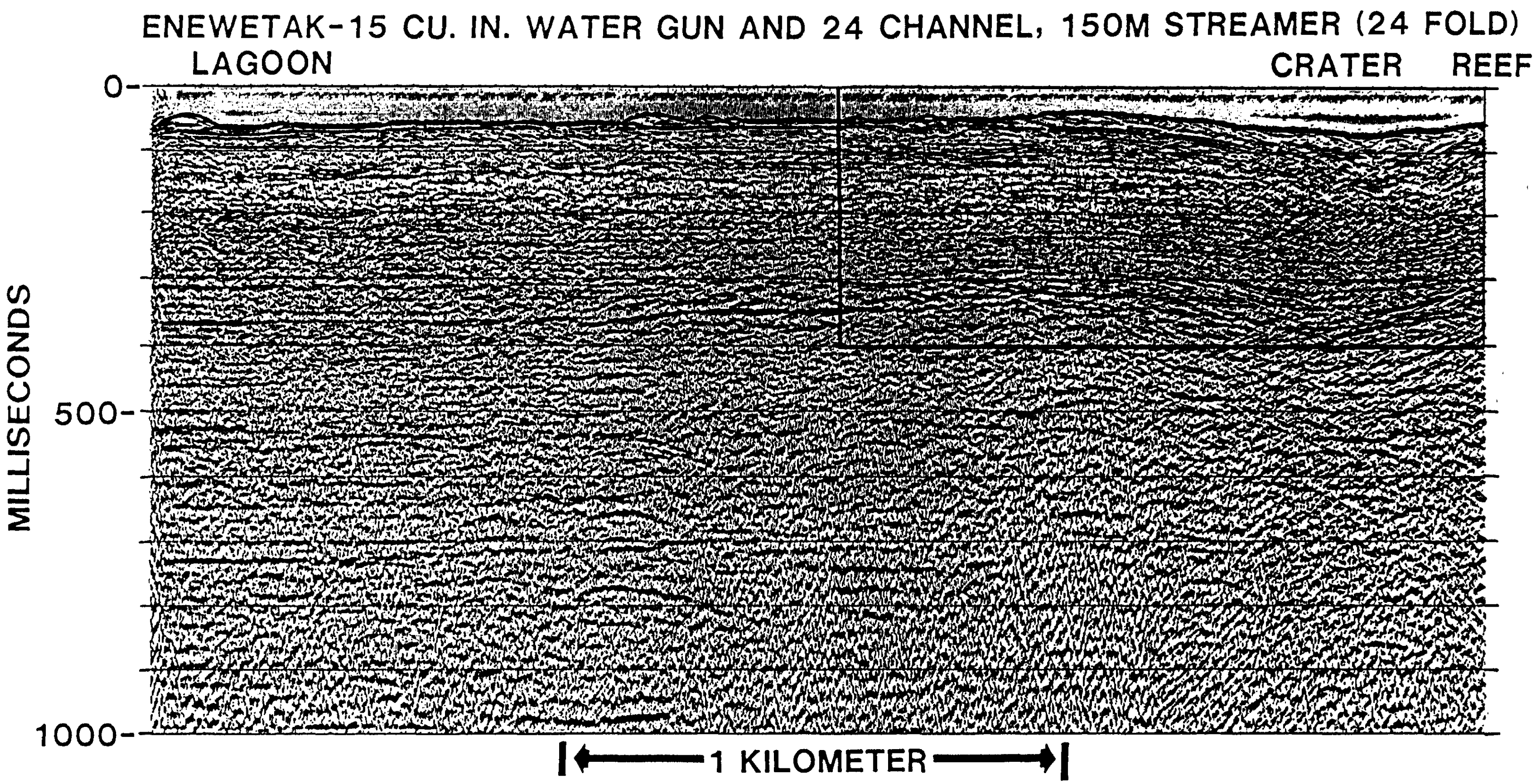

Figure 7.--An example of 24-fold stacked section with a 15-in^3 watergun with 150-m streamer at Enewetak Atoll. See enlargement of the top right corner in figure 8.

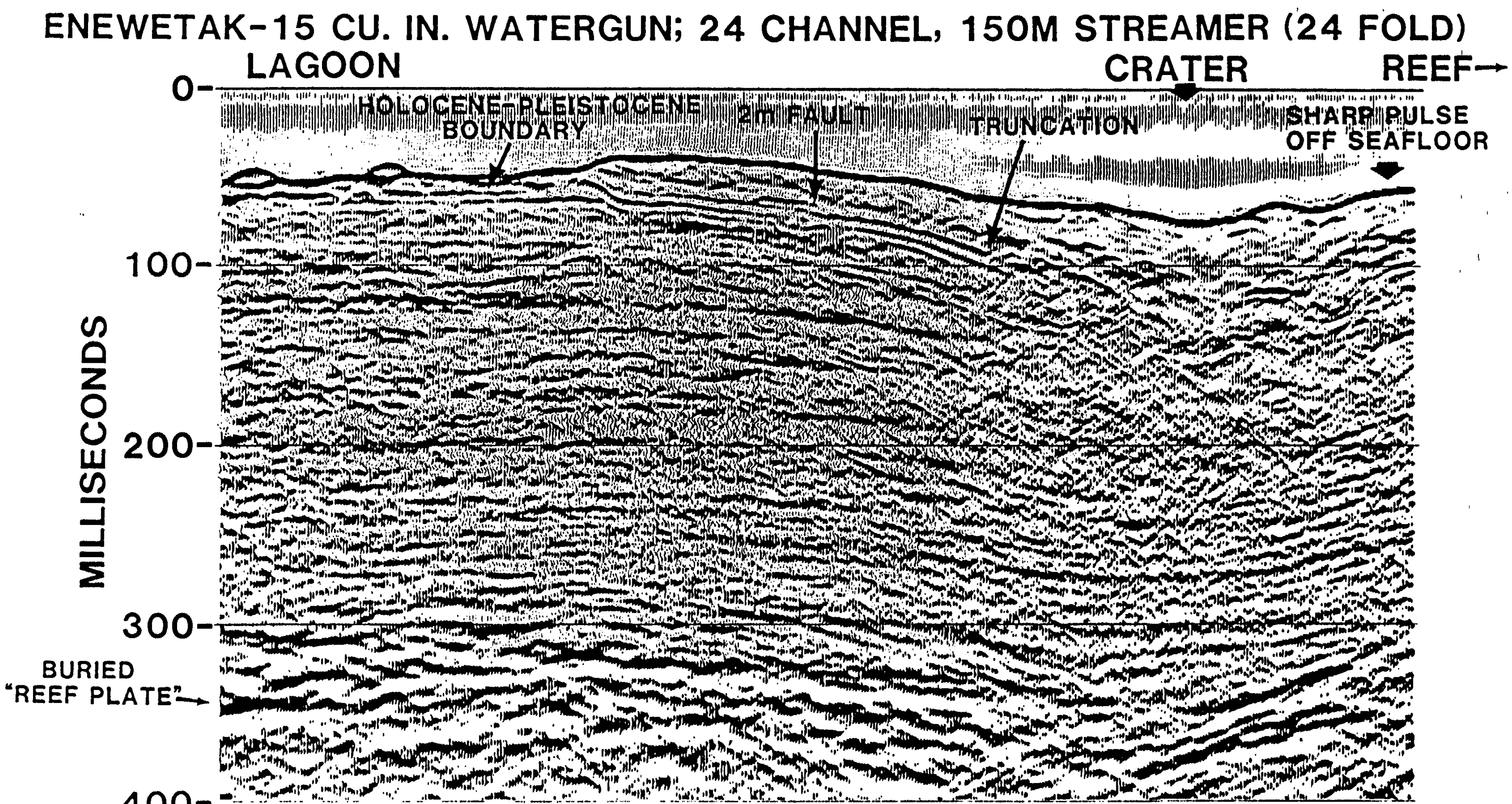

Figure 8.--Blow-up of the top right corner of figure 7 showing detailed shallow subsurface.

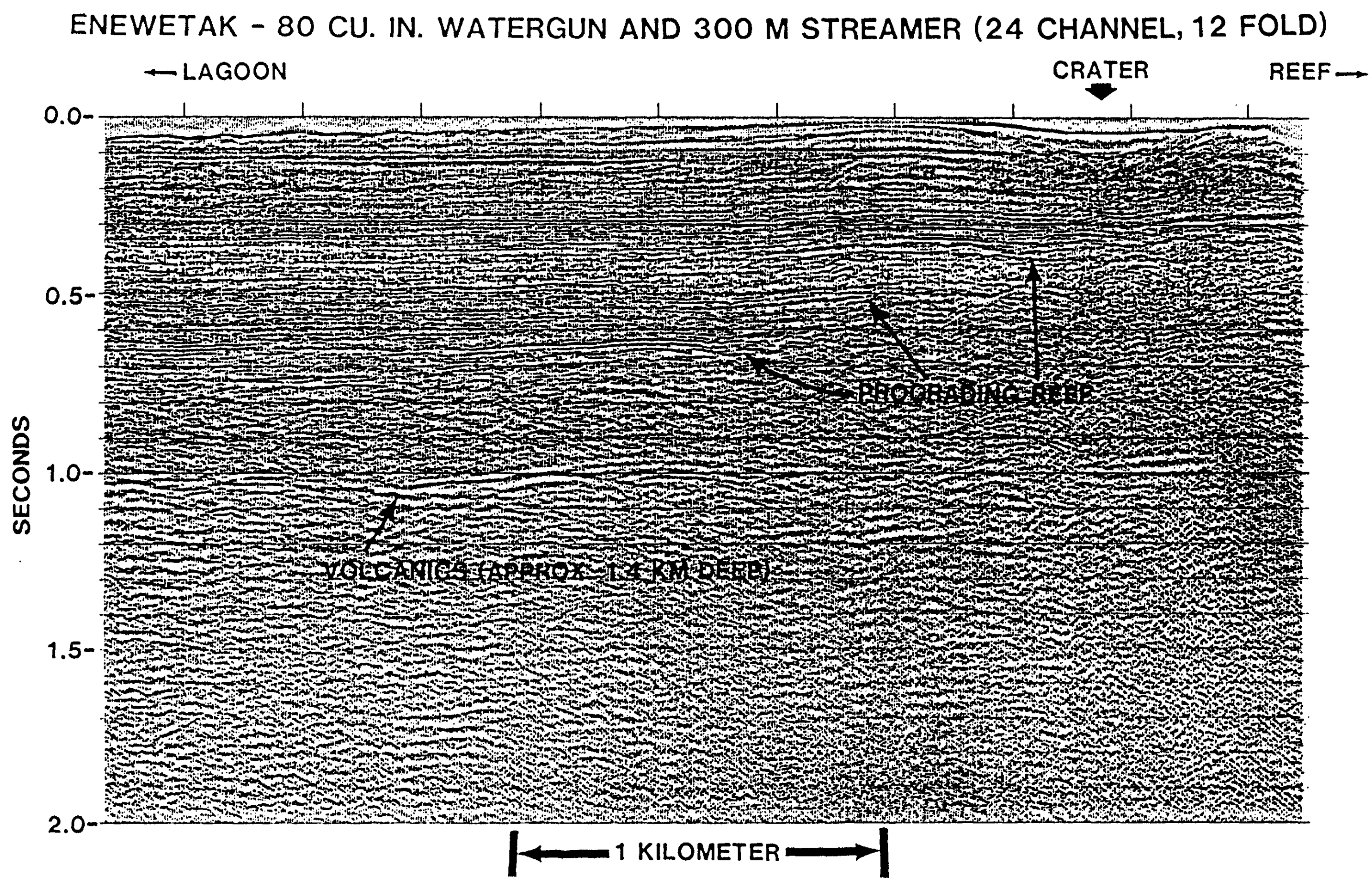

Figure 9.--An example of 12-fold stacked section using an 80-in^3 watergun with 300-m streamer at Enewetak Atoll.

and the volcanic surface around 1.0 s. Lack of coherent reflections below 1.0 s does not indicate the weak penetration of an 80-in^3 watergun. In this area, the volcanic surface is acoustic basement. Other lines outside the lagoon clearly show a volcanic surface as deep as a two-way reflection time of 2 s. Comprehensive analyses of the multichannel seismic data at Enewetak Atoll may be found in Grow and others (1986).

CONCLUSIONS

1. The two seismic systems used in Enewetak culminate a 4-year effort to develop a shallow-water, high-resolution multichannel seismic reflection capability which we believe will have valuable application for subsurface mapping in many geologic environments. Although survey areas underlain by high-velocity Paleozoic sedimentary rocks and/or gassy sediments will remain difficult, in general, areas underlain by Mesozoic and Cenozoic sediments have a good probability of obtaining useful reflection data.

2. One acquisition system using a 15-in^3 watergun and a 150-m streamer provided very accurate shallow subsurface mapping with vertical resolution in the range of 2-5 m and penetration of 1/2 to 1.0 s. The other acquisition systems using an 80-in^3 watergun and 300-m streamer provided strong reflections to the two-way travel times of over 1 s in Enewetak and penetration up to 2 s might be expected in weakly consolidated Tertiary and Late Cretaceous sediments.

3. Improved acquisition and processing techniques for marine high-resolution multichannel data could detect previously unmapped small features such as faults in the Inner Continental Shelf, estuaries over the coastal plain, and navigable rivers.

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