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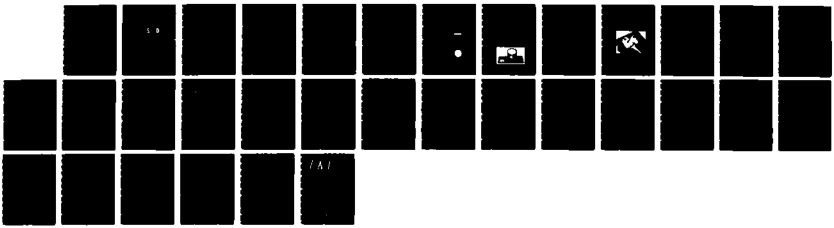

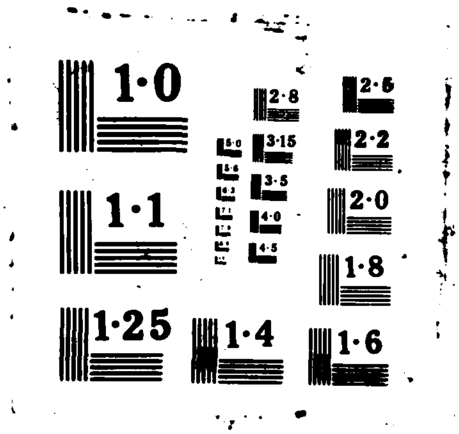
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ULTRASONIC PHYSICAL MODELING OF SEISMIC WAVE PROPAGATION FROM A GRABEN-LIKE STRUCTURE: A PRELIMINARY REPORT

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OCTOBER 1986

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We have performed ultrasonic experiments intended to help clarify the problem of seismic wave propagation in cases where sources are excited in a region with significantly different properties from those of the surrounding propagation medium. Such a case exists, for example, when nuclear explosions are detonated at Yucca Flat. We produced ultrasonic waves using a breaking pencil lead as a source (step unloading of the surface), and a true-displacement conical transducer as a receiver. We have made measurements setting the source off on the half space (made of fine grained gabbro, with Vp = 6.2 km/s), and with a cylindrical "graben" of 13mm diameter and 2mm depth. The graben was filled with either crystal wax (Vp = 2.407) or HPAL3 (an aluminum-filled resin with Vp = 3.287). Rayleigh waves of frequency 100 KHz in the model are roughly analogous to 20 s in the Earth. The presence of a source region with significantly slower velocities than the surrounding region appears to lead to a more complex signal, with more "ringing" than would be apparent if there were no such source region. The presence of such a source region appears to result in a relative amplification of the high frequency part of the signal. The frequencies analogous to 3 or 4 s in the Earth appear to be amplified relative to lower frequencies. Although the pencil-lead source used in this study is not exactly similar to an explosion, this

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result may still be significant. When the source is set off in the graben in an off-center position, a radiation pattern is established, with amplitude varying by a factor of 2 or more. Material effects appear to be accentuated when the source is excited off-center.

1. Introduction

The overall purpose of the Ultrasonic Physical Modeling Program at the Rockwell International Science Center is to model seismic wave propagation in the Earth using ultrasonic wave propagation in scale laboratory models. By using well calibrated sources and receivers our hope is to shed light on the effects of complex structure and geology on the propagation of seismic waves, and thus aid the national research effort in seismic monitoring of nuclear explosions. The intent is to complement numerical modeling, providing insight and guidance in complex situations where such modeling may not yet be feasible, owing to limitations in computer power.

In this report, we address the general problem of a nuclear explosion source region which has material properties significantly different from those of the surrounding seismic wave propagation medium. Such a situation exists, for example, in the case of explosions set off in Yucca Flat, at the Nevada Test Site. The existence of an irregularly shaped source region with differing material properties from the surrounding medium can have considerable effects on recorded surface wave amplitudes, as has been shown by some numerical studies (e.g., Regan and Glover, 1985). This in turn has implications for yield estimation, and possibly for discrimination.

2. The Model

As a first step towards studying this problem, we have studied a cylindrical low velocity "graben," or plug, embedded in a high velocity medium (Fig. 1). The high velocity medium is a fine grained gabbro with V_p = 6.2 km/s, V_s = 3.6 km/s, and V_R = 3.3 km/s. The plug is filled with lower velocity materials, whose properties are shown in Table 1.

Table 1

Properties of Modeling Materials

Material	Longitudunal Velocity V_p, km/s	Shear Velocity V_s, km/s	Rayleigh Velocity V_R, km/s	Poisson's Ratio ν	Density ρ, g/cc
Crystal Wax	2.407	1.096	1.01	0.369	1.32
HPAL3	3.287	1.742	1.61	0.305	2.01
Gabbro	6.200	3.623	3.33	0.240	2.97

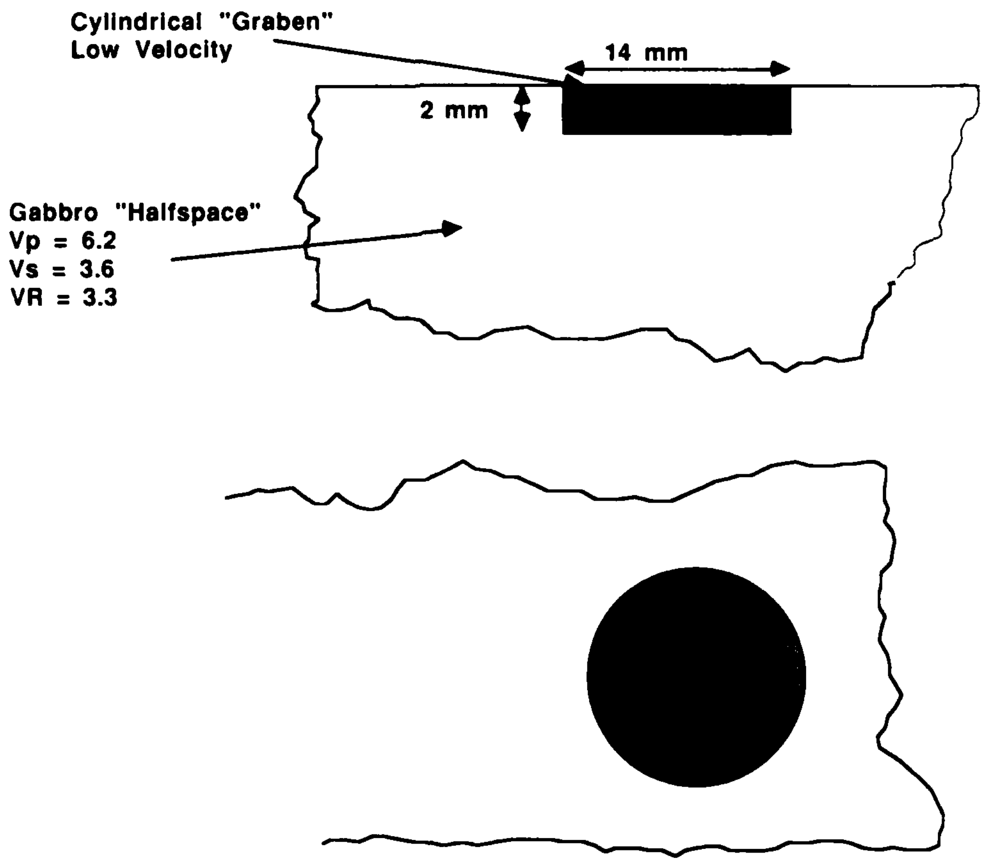

Fig. 1 The model of a cylindrical graben filled with low velocity material, embedded in a fine grained gabbro "halfspace."

It is important to have a good idea of the scale factors involved. Taking Yucca Flat as a rough guideline, we may say that a graben of interest in the Earth is roughly $L^e \approx 20$ km in diameter. If the source material in the Earth has a Rayleigh wave velocity $V_R{}^e \approx 1.2$ km/s, then a 20 s Rayleigh wave in the Earth has a wavelength $\lambda_R{}^e \approx 24$ km $\approx L^e$. Now, the model graben has a diameter L^m of 13 mm. We would like to know the frequency in the model of the Rayleigh wave analogous to a 20 s Rayleigh wave in the Earth. The wavelength of this analogous wave in the model graben must be roughly equal to the graben diameter, i.e., $\lambda_R{}^m \approx L^m$. Since $V_R{}^m$ ranges from roughly 1 to 1.6 km/s, this means that the frequency ranges from roughly 80 to 120 KHz, depending on the material in the graben. Hence, Rayleigh waves of 80 to 120 KHz in the model are analogous to 20 s Rayleigh waves in the Earth.

3. The Receiver

It is absolutely imperative in a study of this kind to have a receiver with a well known response. We use an NBS-type conical transducer (Proctor 1980, 1982a,b) manufactured by Industrial Quality, Inc.; it is shown in Fig. 2. This transducer is a vertical component displacement sensor with a 1 mm contact area, and a very flat response. The element is piezoceramic, and it is coupled to a large brass backing which effectively eliminates resonances, as well as minimizing coherent reflections back into the element. Figure 3 shows typical response curves for this type of transducer, sent to us by NBS. The response is flat enough that when we look at a signal from this transducer, we can consider that we are looking essentially at raw vertical component displacement.

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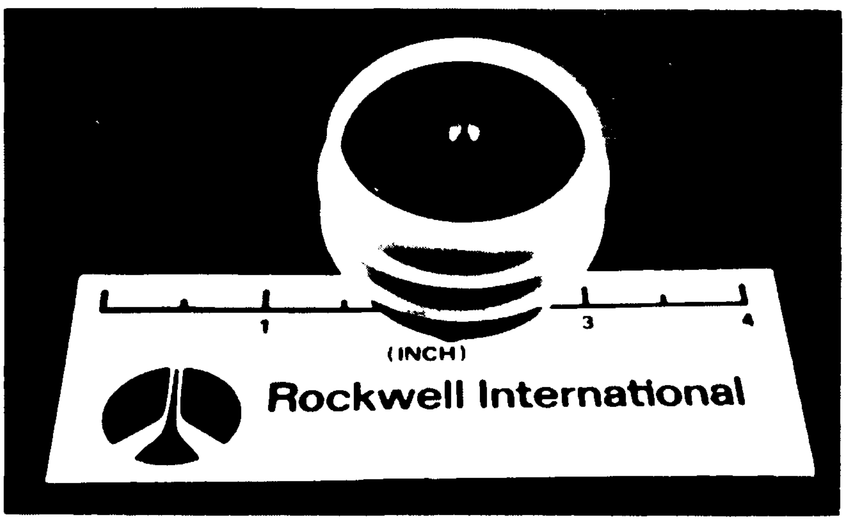
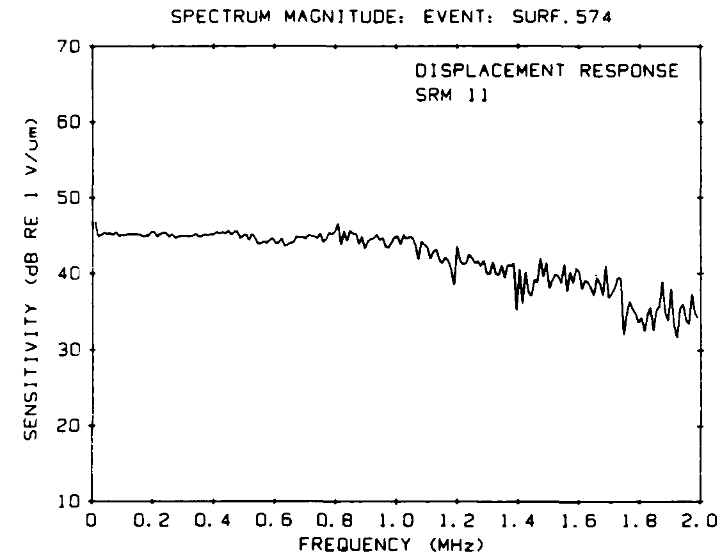


Fig. 2 The NBS-type conical transducer used in this study, showing the point-like probe.



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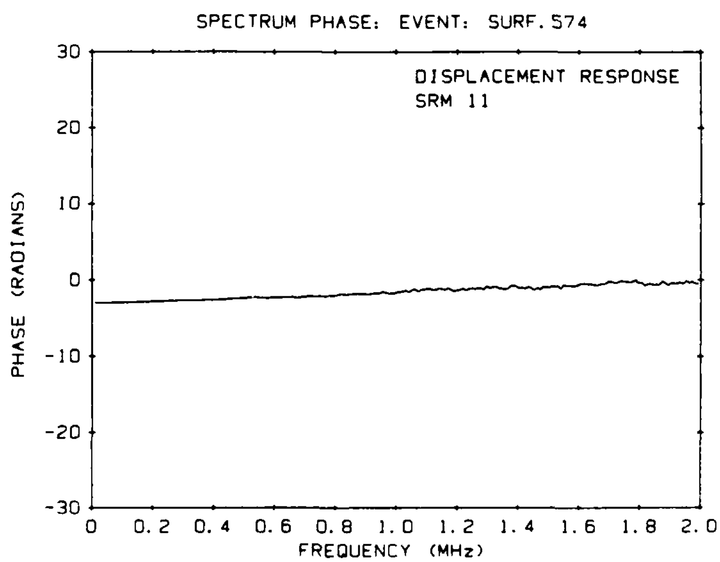

(b)

Fig. 3 Typical displacement response curves for the NBS-type conical transducer. a) Amplitude. (b) Phase. The receiver is close to a true displacement sensor.

4. The Source

Just as important as having a well characterized receiver is having a well characterized source. The source we use is a simple one, but it is quite effective. Basically, we achieve a step-function point unloading of the surface by breaking a pencil lead on it. This is a variant of the well known breaking-glass-capillary source used by the NBS, and is discussed in detail by Hsu and Hardy (1978). Figure 4 shows a picture of the source assembly, and Fig. 5 shows the source time function of the breaking pencil lead, obtained via deconvolution by Hsu and Hardy. The apparent noisiness in the response is due to the deconvolution process. The source approximates a step function; actually it is a ramp, but the rise time of the ramp is less than one microsecond.

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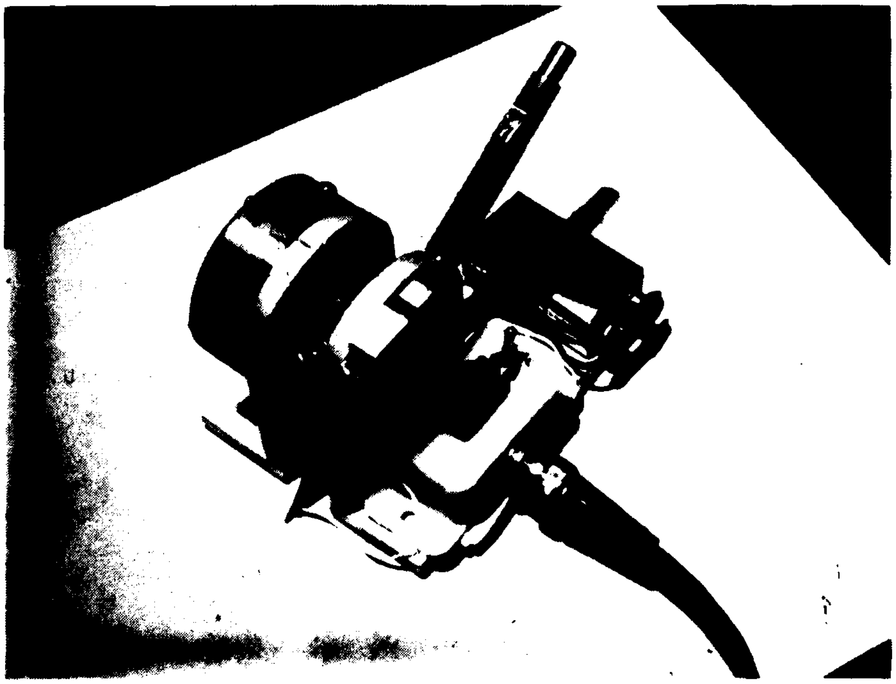


Fig. 4 The pencil-lead source used in this study. Electrical contact is broken when the pencil lead breaks, triggering the recording system. The pencil-lead source corresponds to step function unloading of the surface.

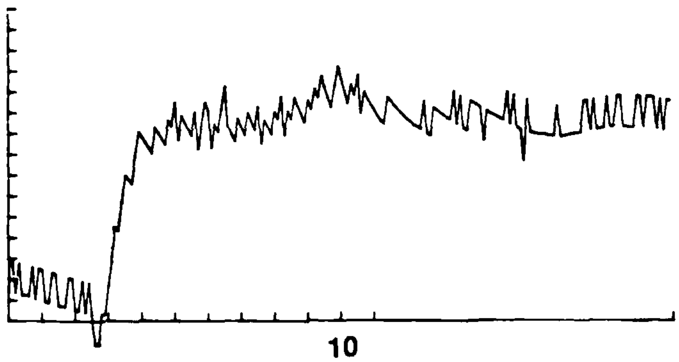


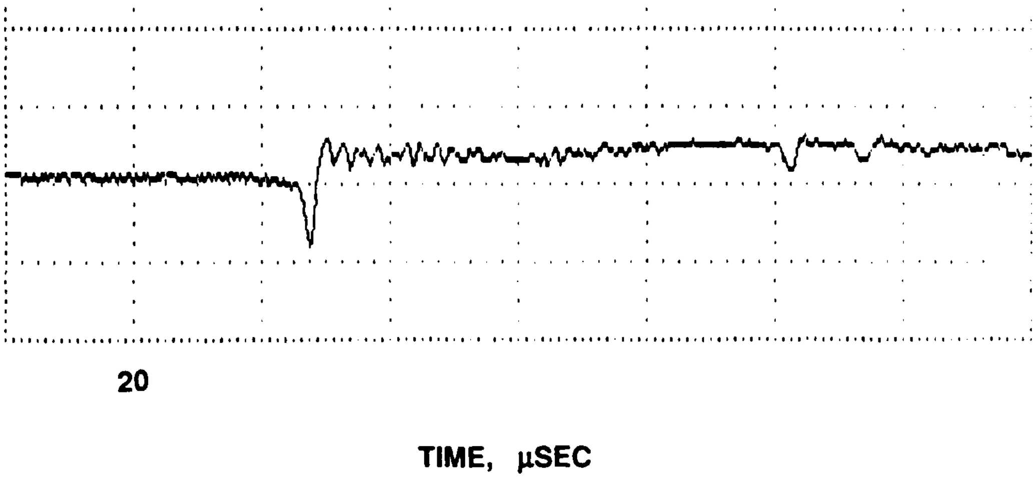
Fig. 5 Source-time function of a pencil lead source, obtained by Hsu and Hardy (1978) by deconvolution. Some spurious structure has been introduced by the deconvolution.

5. Lamb's Problem

Figure 6 shows the result of a measurement made by setting off the source on the gabbro "halfspace", and recording the signal received by the transducer 200 mm away (the standard distance for all the measurements presented in this report). The displacement record is essentially a solution of the classic Lamb's problem (see e.g., Miklowitz, 1978; Mooney, 1974; Breckenridge et al., 1975) for a point force on a surface. Figure 6 shows, for comparison, the result of Boler et al., (1984) for a similar setup, using a breaking glass capillary source and a true displacement transducer. The results are very similar in appearance to ours. Boler et al., include the theoretical response computed from Lamb's solution. The first arrival P wave is very small in the theoretical solution, and is very small in Boler et al.'s measurements. In our results there is only a hint of it, as a minor inflection before the onset of the large signal. The large signal observed in both our record and in Boler et al.'s is, ot course, the S wave followed by the Rayleigh wave.

6. Source in Graben, Centered

Figure 7 compares the halfspace response discussed above to the displacement signal obtained when the source is set off at the surface of the cylindrical graben, in the center. The graben is filled with crystal wax, a material with significantly slower velocities than gabbro (see Table 1). The signal is quite complex, with a large amount of ringing.



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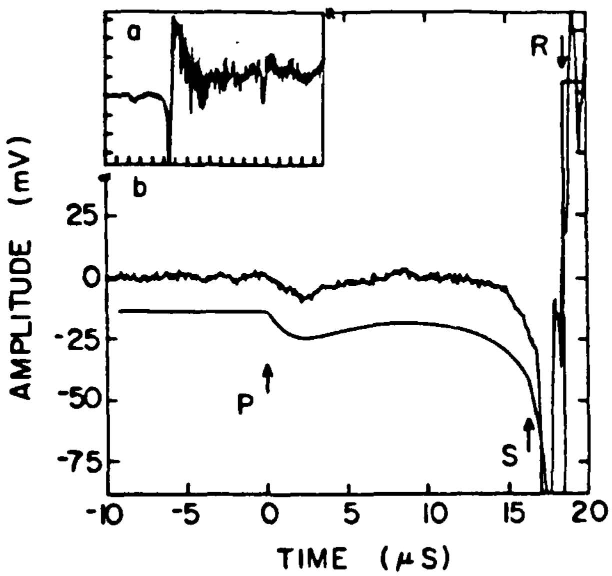
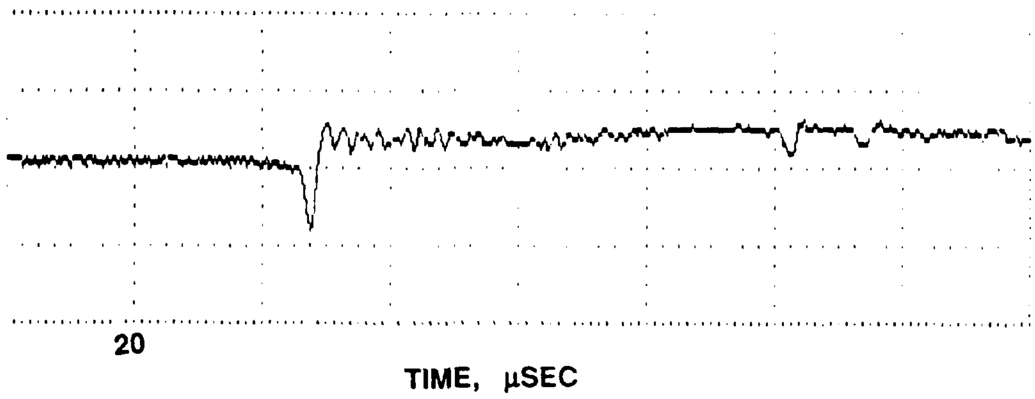


Fig. 6 Signal observed by actuating the source on the gabbro "halfspace." Similar signals obtained by Boler et al. (1984) are shown for comparison.



SOURCE AT GRABEN CENTER
GRABEN FILL = CRYSTAL WAX

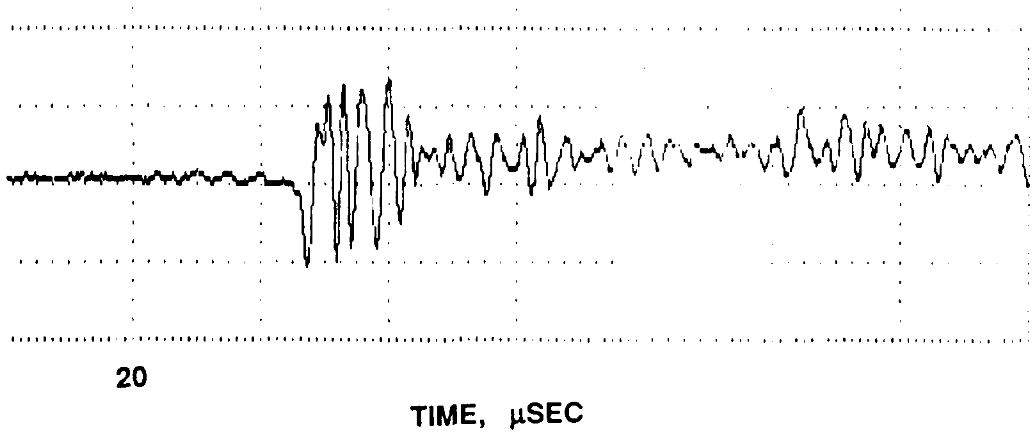
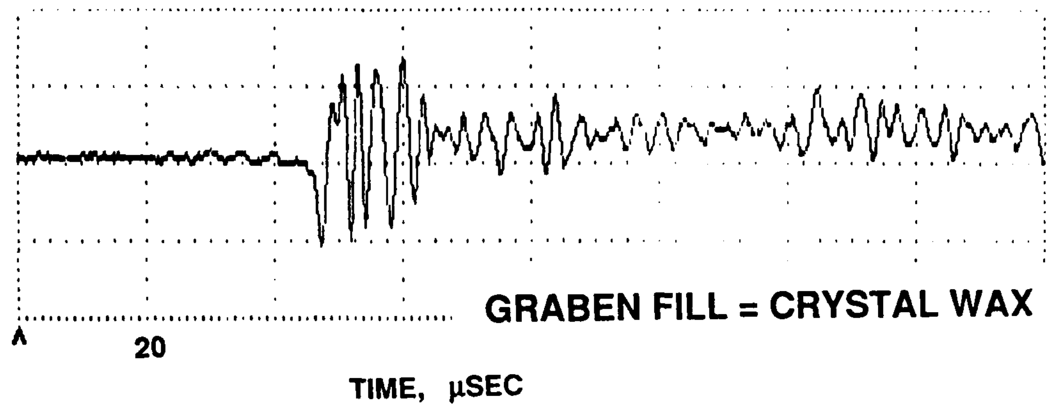


Fig. 7 Comparing the halfspace signal (also shown in Fig. 6), with the signal observed when the source is actuated at the center of the surface of the cylindrical plug ("graben") filled with crystal wax. Source-receiver distance is 200 mm.

Energy which, when the source is set off on the halfspace, goes downward and is not recorded at the surface, is now trapped and redirected by the graben structure.

Figure 8 compares the results from a centered source in the graben, for two different fill materials. The top trace is a copy of the signal discussed immediately above, where the graben is filled with crystal wax. The bottom trace is for a graben filled with



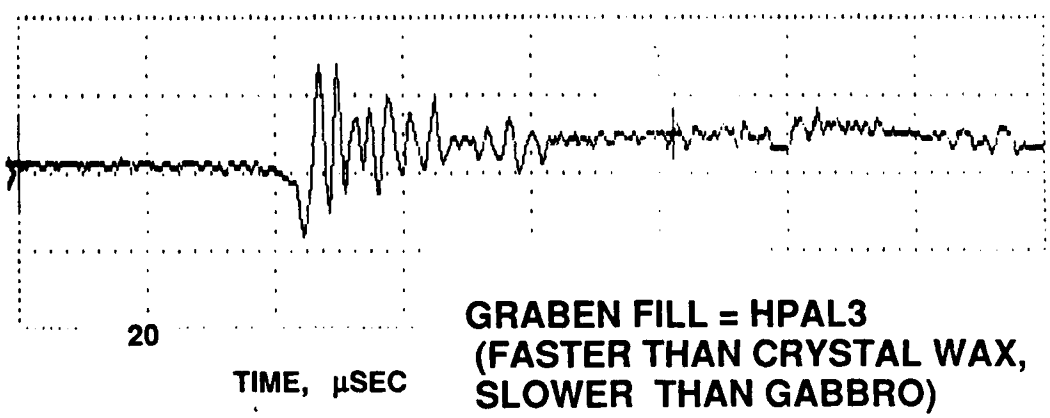


Fig. 8 Comparing signals from a source at the graben center. Top trace is for a graben filled with crystal wax (same as Fig. 6); bottom trace is for a graben filled with HPAL3. HPAL3 is faster than crystal wax, but slower than gabbro. Source-receiver distance is 200 mm.

HPAL3, an aluminum-filled resin with faster velocities than crystal wax, but slower velocities than gabbro. As might be expected, the amplitude of the ringing is smaller than in the case of crystal wax. As the material property contrast increases between the graben and the surrounding medium, the observable effects of ringing appear to increase.

7. Source in Graben, Off-Center

Figure 9 shows signals obtained when the source is actuated in the graben in various off-center positions. The relative position of source and receiver is shown schematically in plan view beside each trace. In each case, the source is actuated along a diameter, halfway between the center and the rim of the graben. (It is easy to see that this is as if the source were kept in one of the three positions, and the receiver were moved around.) Clearly, an off-center source produces a radiation pattern. Both the shape and amplitude of the signal depend on the relative position of source and receiver. The trace with the largest amplitude has a maximum peak-to-peak amplitude about twice as large as that with the smallest amplitude. These results are fairly easy to rationalize in terms of simple focusing. When the source is excited in the off-center position furthest from the receiver (Fig. 9, top trace), a larger portion of the boundary between the graben and the rest of the medium is illuminated in the direction of the receiver.

Figures 10 through 12 show the off-center signals in each of the three positions just discussed, for different fill materials (again, crystal wax and HPAL3). The effect on amplitude of the different fill materials appears to be accentuated in the off-center cases.

8. Voiceprints

Figures 13 and 14 show an interesting presentation of the data. What is shown is a "voiceprint" of the data for the source on a halfspace (Fig. 13), and the data for the source in the graben center when the graben is filled with crystal wax (Fig. 14).

The voiceprint is obtained by filtering the traces with different bandpass filters, and plotting the results in order of increasing center frequency of the bandpass filter. In this case, the filters have a passband of 200 KHz, and the increment in center frequency between traces is 40 KHz. Thus, the bottom trace shows the data filtered from 0 - 200 KHz (center frequency 100 KHz), the next trace up shows the data filtered from 40 - 240 KHz (center frequency 140 KHz), the next trace after that shows the data filtered from 80 - 280 KHz (center frequency 180 KHz), etc. What results is essentially a frequency-time plot. (Note that the traces are also rectified and low pass filtered, to avoid spurious wiggles resulting from the increasing center frequency of the bandpass filter.)

Examination of the voiceprints shows that although the low frequency levels are quite similar between the two cases, the case with the source in the graben has considerably

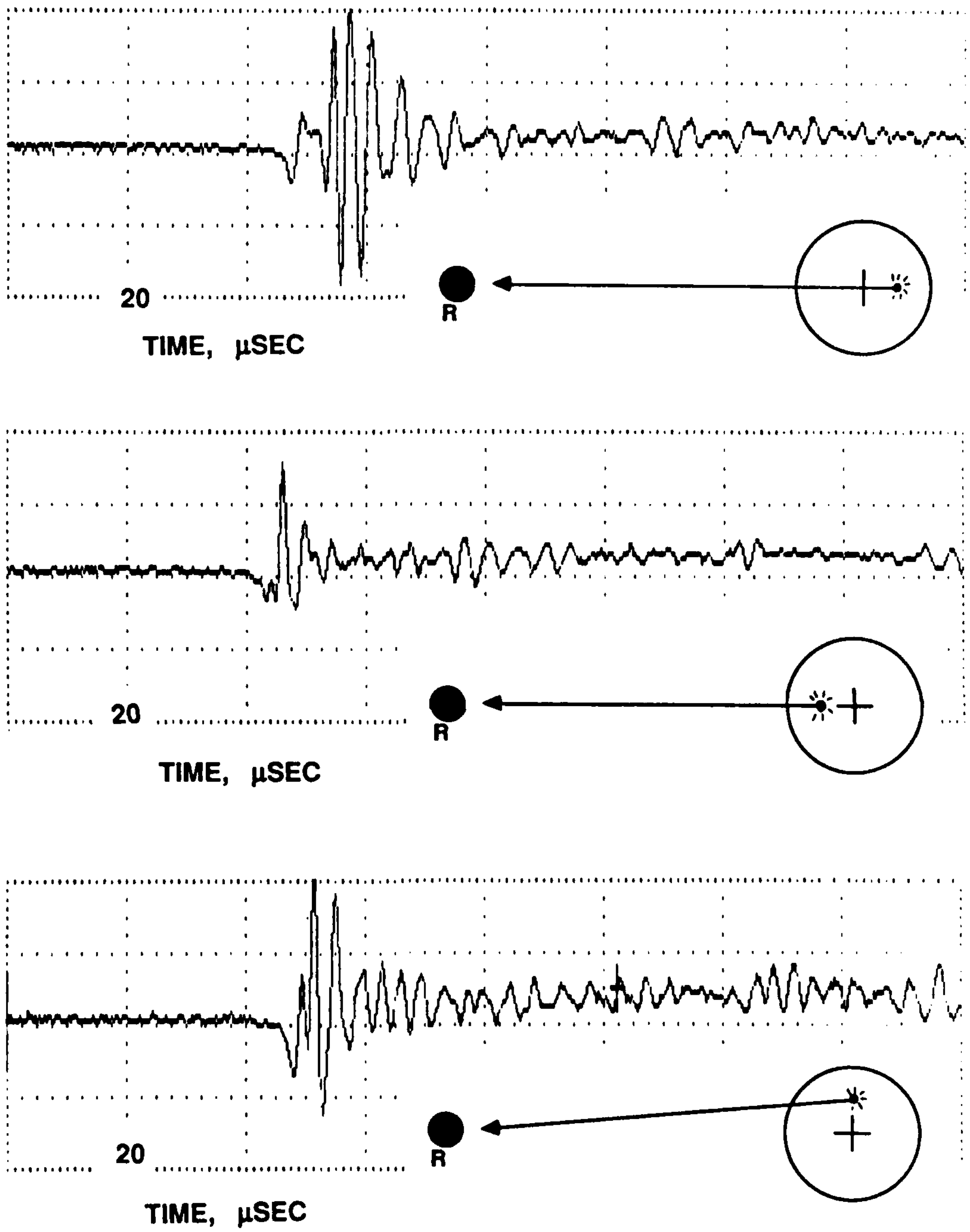


Fig. 9 Signals from sources actuated off-center in a graben filled with crystal wax. Each trace is accompanied by a plan view showing the relative positions of source and receiver. Distance from graben center to receiver is 200 mm.

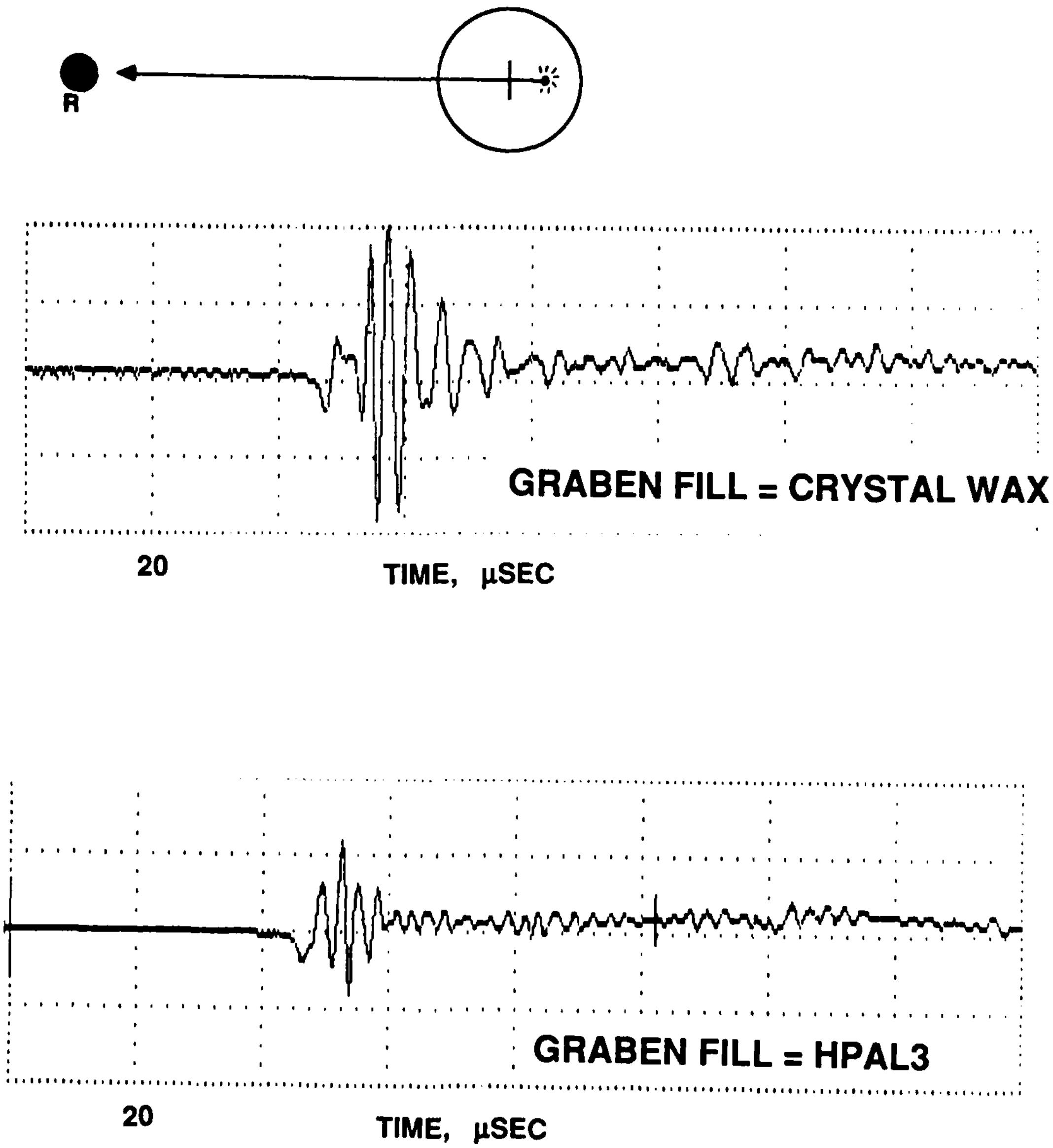


Fig. 10 Signals for one of the off-center positions in Fig. 9, for a graben filled with crystal wax and a gaben filled HPAL3. Distance from graben center to receiver is 200 mm.

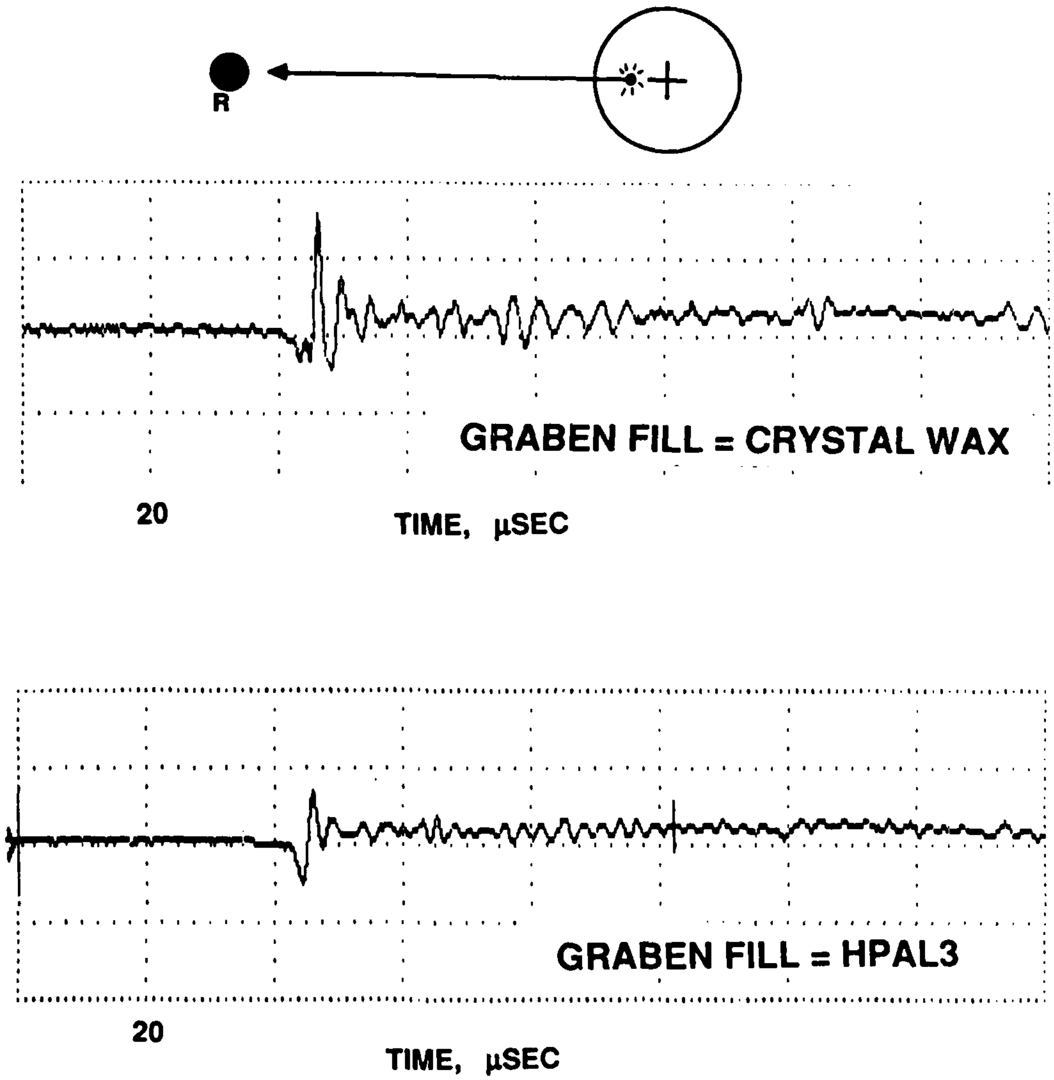


Fig. 11 Signals for one of the off-center positions in Fig. 9, for a graben filled with crystal wax and a graben filled with HPAL3. Distance from graben center to receiver is 200 mm.

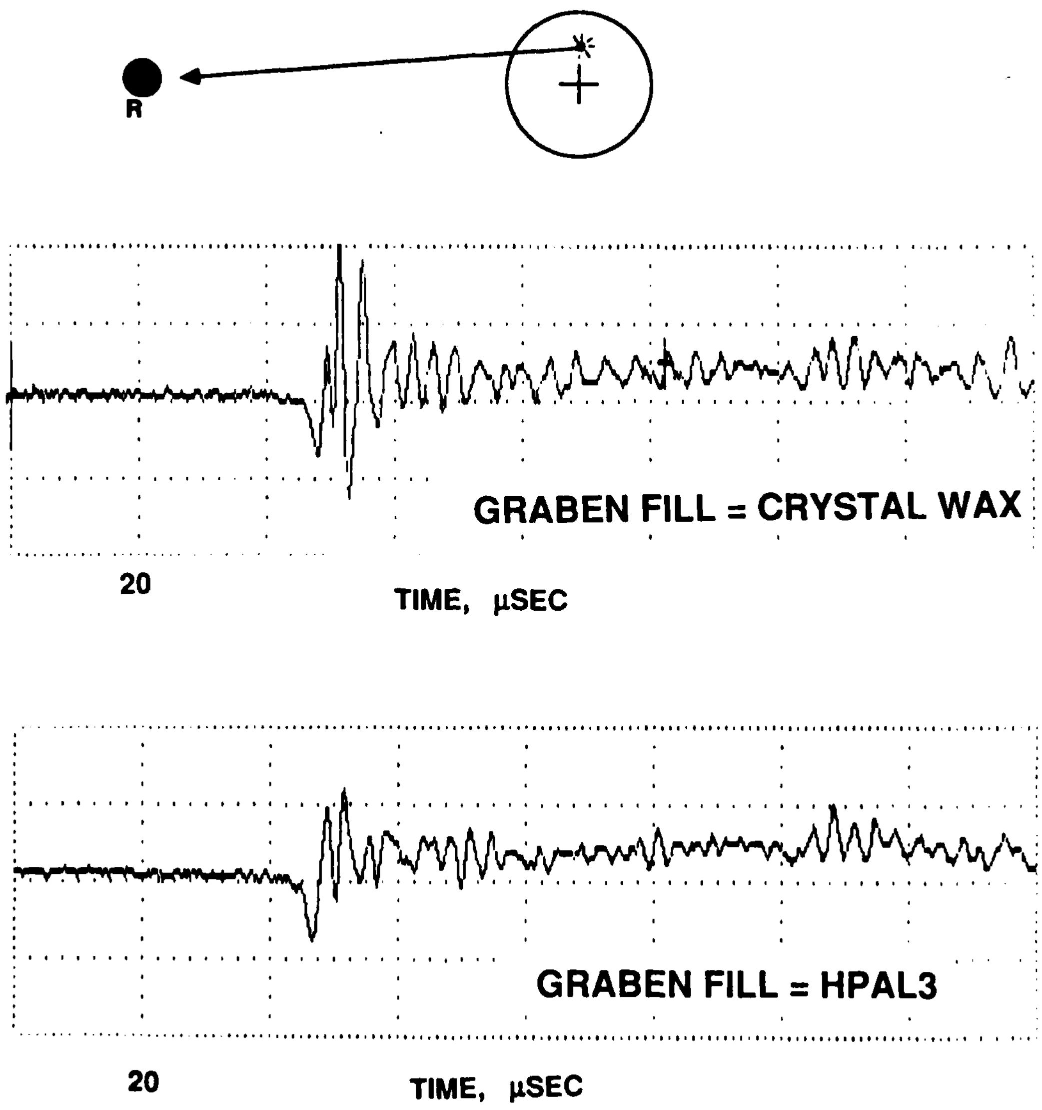


Fig. 12 Signals for one of the off-center positions in Fig. 9, for a graben filled with crystal wax and a graben filled with HPAL3. Distance from graben center to receiver is 200 mm.

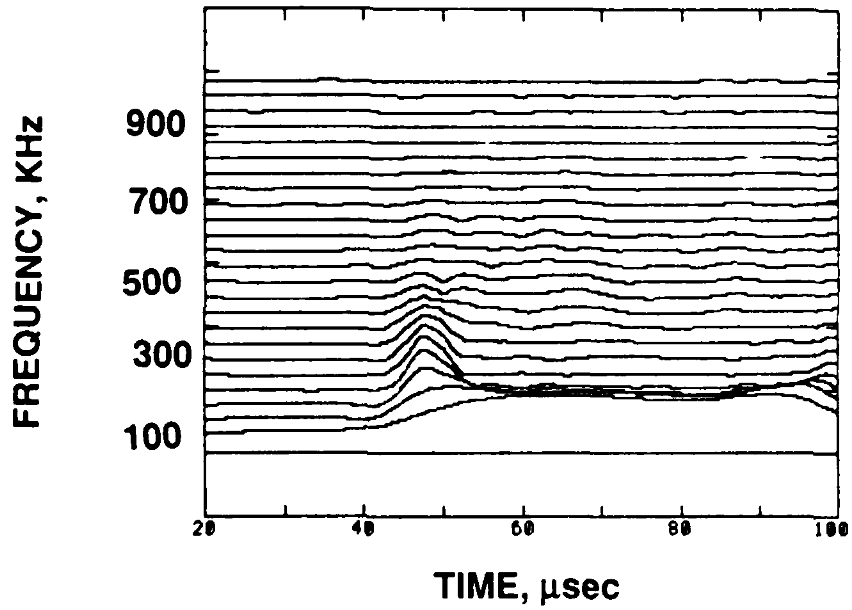


Fig. 13 "Voiceprint" of the halfspace signal shown in Fig. 6. Each trace in the voiceprint represents the signal filtered by a bandpass filter with a bandwidth of 200 KHz. The increment in center frequency of the filter is 40 KHz as we move from the bottom trace upwards. Thus, this is a time-frequency diagram.

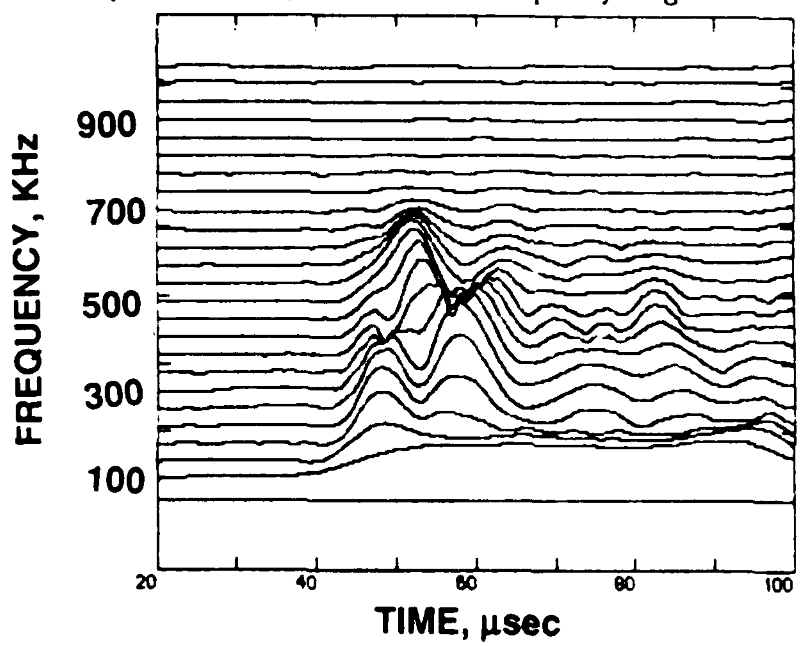


Fig. 14 Voiceprint similar to that in Fig. 13, but this time for the signal of Fig. 7, the signal from the source actuated in the graben center when the graben is filled with crystal wax.

more energy in the higher frequency range, from 500 to 700 KHz center frequency. Considering that 100 KHz in the model is roughly analogous to 20 s in the Earth (see Sect. 2), this 500 to 700 KHz range corresponds roughly to 3 or 4 s in the Earth.

9. Comments on the Pencil Lead Source as Related to a Bomb

Clearly, a breaking pencil lead is a different source from a nuclear explosion, and although it is well characterized and useful in experiments such as these, it is not an exact model of a bomb. The pencil lead source is a constant-force source, not a constant - (seismic) moment one. Thus one would expect to see wave amplification when the pencil lead source is set off in weaker materials, because for a given force, a weaker material will experience more displacement. However, it should be noted (see Sect. 8 above) that there appears to be a preferential amplification of waves in the 500 - 700 KHz range, corresponding to 3 or 4 s in the Earth, and that this is likely to be unchanged by corrections applied to obtain constant-moment results. This issue will be addressed in more detail in future work.

10. Conclusions

We have described experiments wherein ultrasonic waves have been excited using a breaking pencil lead as a source, and a true-displacement conical transducer as a receiver. We have made measurements setting the source off on the half space (made of gabbro, with V_p = 6.2 km/s), and within a cylindrical "graben" of 13 mm diameter and 2 mm depth. The graben was filled with either crystal wax (V_p = 2.407) or HPAL3 (V_p = 3.287). Rayleigh waves of frequency 100 KHz in the model are roughly analogous to 20 s in the Earth.

1. The presence of a source region with significantly slower velocities than the surrounding region appears to lead to a more complex signal, with more "ringing" than would be apparent if there were no such source region.

2. The presence of such a source region appears to result in a relative amplification of the high frequency part of the signal. The frequencies analogous to 3 or 4 s in the Earth appear to be amplified relative to lower frequencies. Although the pencil-lead source used in this study is not exactly similar to a bomb, this result may still be significant (see Sect. 9).

3. When the source is set off in the graben in an off-center position, a radiation pattern is established, with amplitude varying by a factor of 2 or more. Material effects appear to be accentuated when the source is excited off-center.

These results bear further examination, with additional off-center measurements desirable. After completing these, we will begin measurements on a realistic scale model of Yucca Flat, using a map similar to that shown in Fig. 15 as a guide, exciting the source in various positions within the graben with different fill materials.

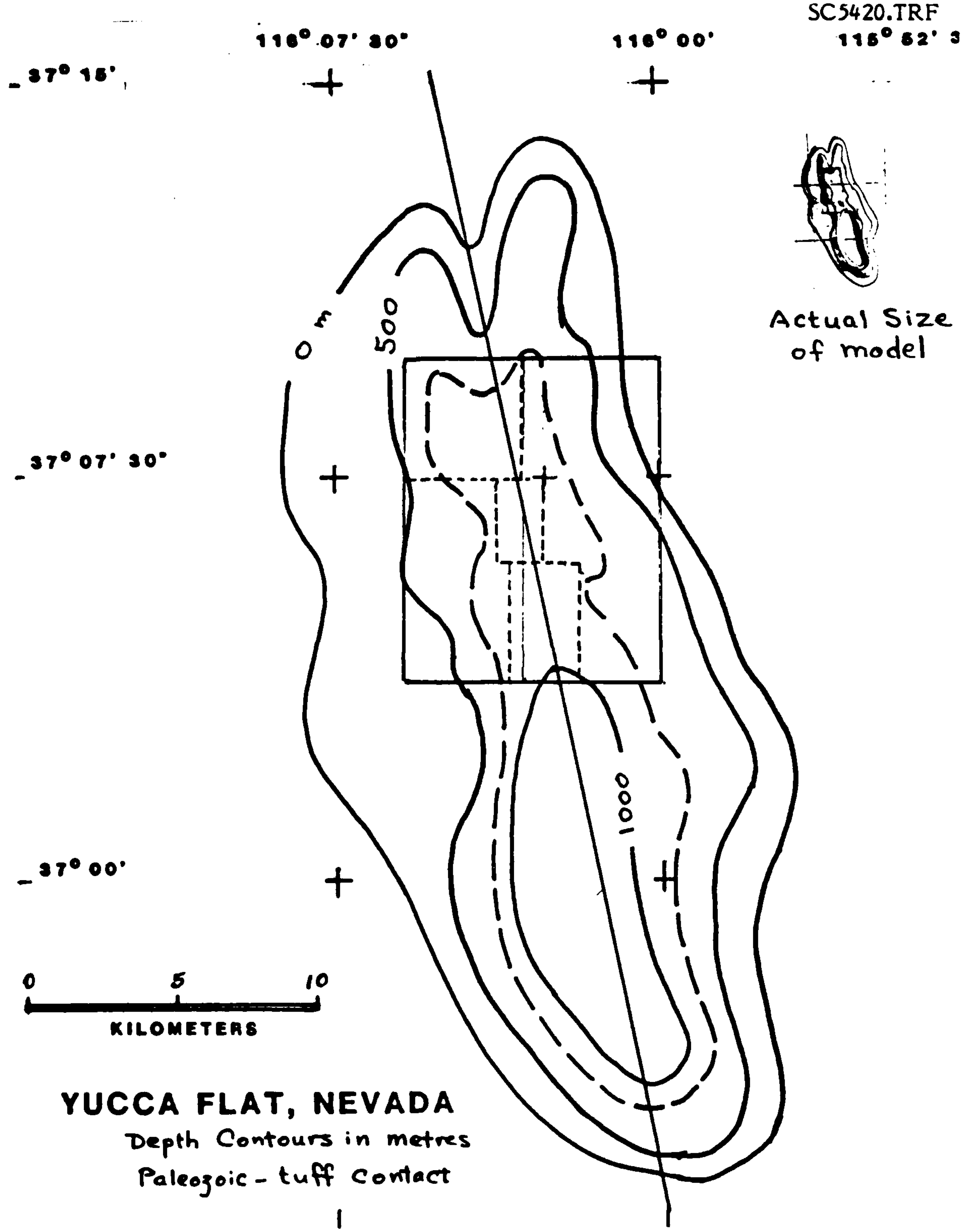


Fig. 15 Generalized map of Yucca Flat, Nevada, showing the actual size of the model which we are in the process of studying.

11. Acknowledgements

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NOTE ON THE FIGURES: Although ultrasonic waveforms were recorded with varying gains, they are plotted here on the same scale, both time and amplitude, and may be directly compared.

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