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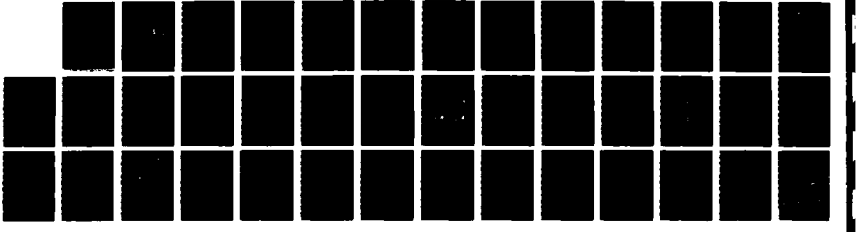

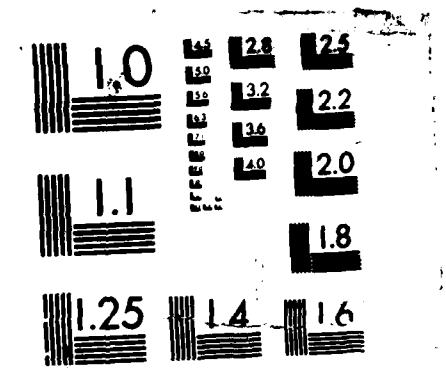

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AFGL-TR-87-0106

FINITE-DIFFERENCE MODELING OF SEISMOLOGICAL PROBLEMS IN MAGNITUDE ESTIMATION USING BODY WAVES, SURFACE WAVES AND SEISMIC SOURCE IMAGING

Keith L. McLaughlin
Zoltan A. Der
Rong-Song Jih
Alison C. Lees
Lisa M. Anderson

Teledyne Geotech Alexandria Laboratories
314 Montgomery Street
Alexandria, VA 22314-1581

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

We briefly summarize in this final report the results from the three scientific reports delivered under this contract. Our work has focused on the effects of near-source heterogeneity upon seismic magnitude-yield determination. The basic tool in this work has been a developing 2-dimensional linear finite-difference code which computes the dynamic elastic response of an Earth model to specified initial conditions. By use of various initial conditions and the reciprocity theorem, we can generate the linear response of the Earth model to a general seismic source. Current work is limited to 2-D models and line sources. This FORTRAN-77 code has been run under the UNIX operating system on VAX, Cray, SUN, and Celerity. Major modifications on the code during this project include the addition of general free-surface boundary conditions capable of handling topography with slopes of any angle, as well as the fundamental mode Rayleigh wave packet adequate for numerical studies. Work on this program continues to increase it's performance, versatility, and portability.

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Finite-difference simulations of P wave propagation through models of extreme topographic profiles of the southern Sahara test site were used to investigate the effect of topography on the variation of short-period m_b estimate of contained nuclear explosions. We have shown, as much as the 2-D assumption is valid, that the topography above the explosions RUBIS and SAPHIR could be responsible for suppressing the elastic pP. As part of the data analysis to support these calculations we have refined the attenuation estimate (spectral $\overline{t^*}$ estimate) for the southern Sahara test site and confirm that the attenuation bias between this test site and NTS should be minimal. Furthermore, we have used both spectral and deconvolution techniques to estimate far-field P-wave source time functions and explosion moments for SAPHIR, RUBIS, EMERAUDE, and GRENAT.

Synthetic teleseismic P-wave seismograms were also produced for a two dimensional, laterally heterogeneous model of Yucca Flats, NTS. This work shows that the geologic structure of Yucca Flats could be responsible for generation of the reverberant P coda and for teleseismic magnitude variations as large as 0.3 magnitude units. This structure would also make difficult the identification of elastic P+pP interference in the frequency domain. Indications are that m_b magnitude variations should be reduced by averaging over many azimuths and takeoff angles at teleseismic distance.

Finite-difference simulations were used to investigate the scattering of incident Rayleigh waves. Shallow explosions in layered media generate considerable more short-period Rayleigh wave energy than is observed, so the Rayleigh waves must be either attenuated by absorption or scattering. We find that reflection of Rayleigh waves by topographic features is an inefficient process and the bulk of the energy that is not transmitted as Rayleigh waves is converted to bodywaves. The scattering of these short-period Rayleigh waves into SV trapped in the crust as Lg or as P waves scattered into teleseismic P coda serve as possible models for the generation of Lg by explosions and the generation of teleseismic P coda near the source. Future work along this line is to compare the scattering from topography to that produced by shallow heterogeneity.

Recommendations for further work include:

(1) Extensions of the current finite difference code from 2-D to 3-D to study the attenuation of body waves by 3-D heterogeneity in the crust, test hypotheses about the generation of P coda and anisotropic P wave generation, and generation of transverse Lg by explosions.

(2) Introduction of other numerical methods to explore the coupling (scattering) of modes of wave-guide regional phases such as Pg and Lg, as well as the scattering of Pn and Sn. These methods include 2-D and 3-D scattering from localized heterogeneity as well as from rough boundaries.

(3) Coupling of efficient reflectivity methods to finite difference calculations to propagate the scattered field to regional distances and to drive the finite difference responses with realistic in-coming regional phases.

(4) Investigation of scattering of fundamental and higher mode short-period Rayleigh waves by 2-D topography and shallow heterogeneity with more realistic velocity gradients near the surface.

(5) Extension of the general topographic boundary condition to include the general fluid-solid interface for the modeling of scattering at rough fluid-solid boundaries.

SUMMARY

We briefly summarize in this final report the results from the three scientific reports delivered under this contract. Our work has focused on the effects of near-source heterogeneity upon seismic magnitude-yield determination. The basic tool in this work has been a developing 2-dimensional linear finite-difference code which computes the dynamic elastic response of an Earth model to specified initial conditions. By use of various initial conditions and the reciprocity theorem, we can generate the linear response of the Earth model to a general seismic source. Current work is limited to 2-D models and line sources. This FORTRAN-77 code has been run under the UNIX operating system on VAX, Cray, SUN, and Celerity. Major modifications on the code during this project include the addition of general free-surface boundary conditions capable of handling topography with slopes of any angle, as well as the fundamental mode Rayleigh wave packet adequate for numerical studies. Work on this program continues to increase it's performance, versatility, and portability.

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BOUNDARY CONDITIONS FOR ARBITRARY POLYGONAL TOPOGRAPHY IN A 2-D ELASTIC FINITE-DIFFERENCE SCHEME FOR SEISMOGRAM GENERATION

Rong-Song Jih, Keith L. McLaughlin, and Zoltan A. Der
Teledyne Geotech Alexandria Laboratories
314 Montgomery Street
Alexandria, Virginia 22314-1581

ABSTRACT

A simple method to implement the free-surface topography of polygonal shape in 2-D explicit finite-difference simulations of the elastic wave equation is presented that includes an empirically stable treatment of various slopes and transition points between the sloping segments.

On the inclined free surface, the vanishing stress conditions are implemented to a rotated coordinate system parallel to the inclined boundary as previous works did. While for each transition point on the topography where the slope changes, we propose to use the first-order approximation of boundary conditions in a locally rotated coordinate system in which the normal axis always coincides with the bisector of the corner. This mixed algorithm is stable for Poisson ratios of practical interest and thus enables us to study a wide range of problems where the topography plays a significant role in shaping the wavefield. Examples are shown simulating the propagation of P and Rayleigh waves traveling through a model with a 45^o ramp and a mountain shape as the free surface. By using reciprocity principle and appropriate deconvolutions on the seismograms generated in this scheme, the effect of complicated near-source topography on the far-field teleseismic waveforms can be characterized.

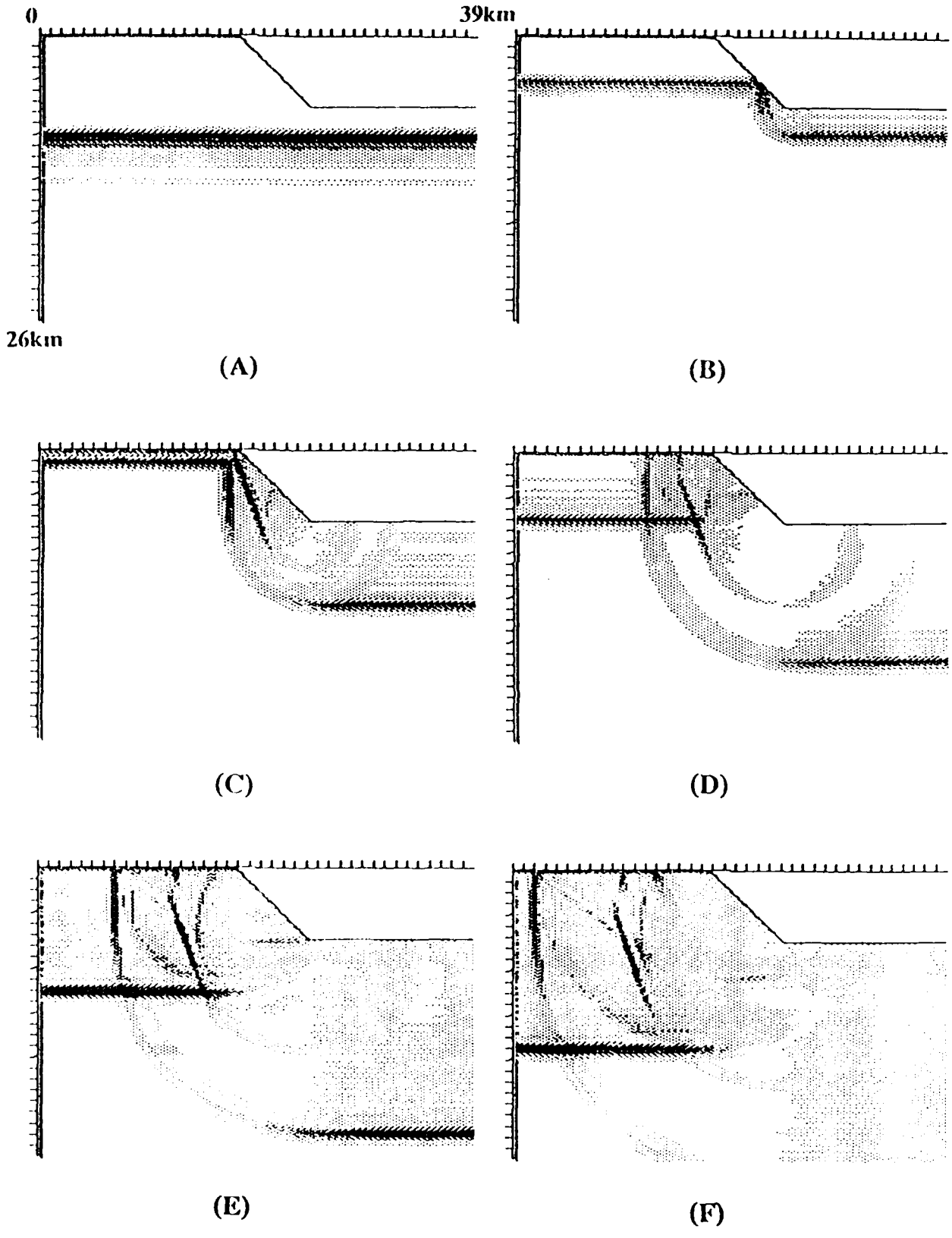

Figure 1.1 The propagation of a normally incident broadband plane P wave through a model with a 45° ramp on the top of grid and symmetric boundary condition used on both sides. Shading is proportional to displacement amplitude. The appropriate P-S conversions and reflections, diffractions satisfying Snell's law and Huygen's principle are clearly visible in these successive snapshots taken every second.

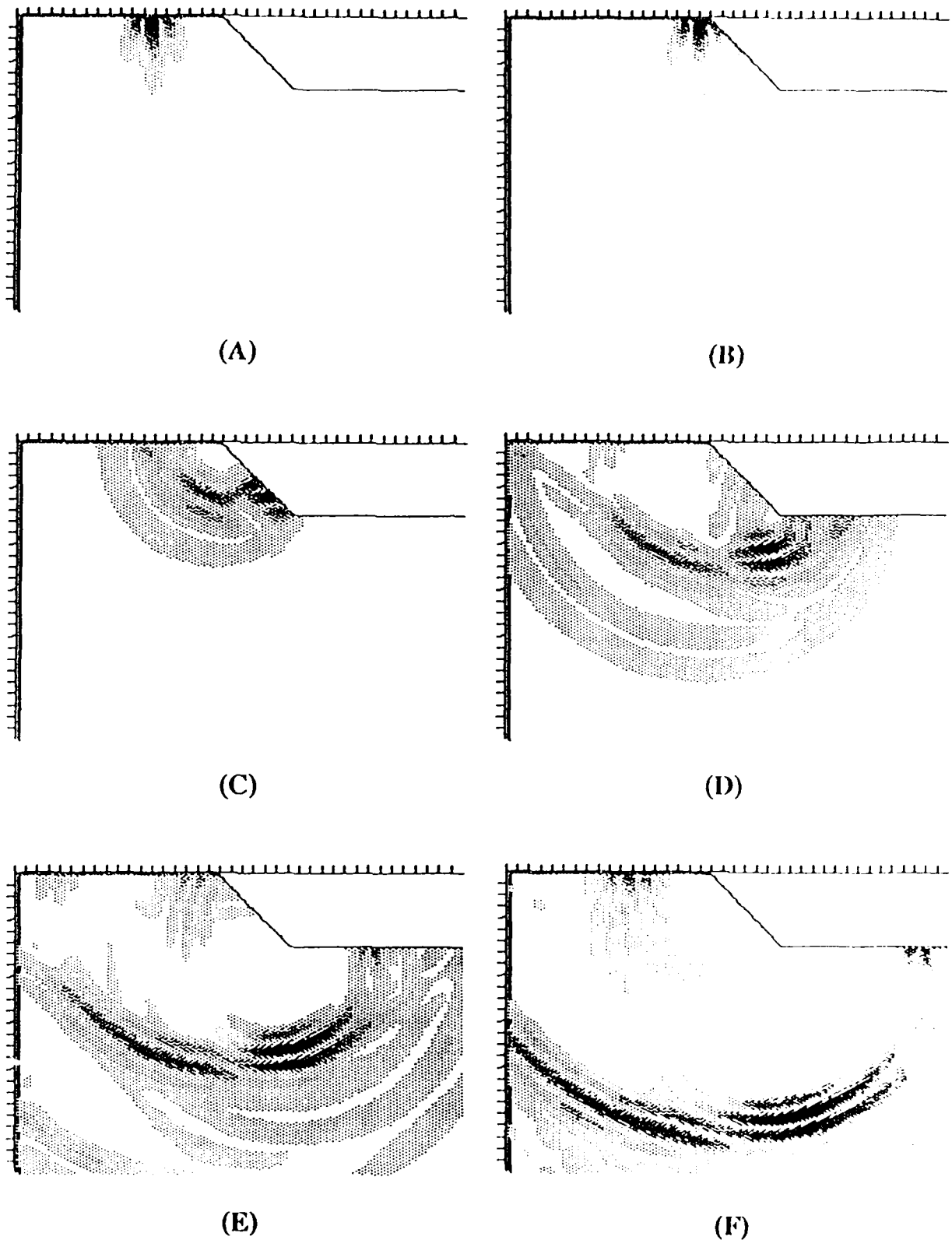

Figure 1.2 Same topographic configuration as in Figure 1.1 with Ricker wavelet-shaped Rayleigh wave of fundamental mode propagating from left side of the grid. When the incident wave packet encounters the corner points of the ramp, the diffraction patterns look like radiation due to point source at corners. Most energy of the incident Rayleigh wave is scattered as body waves and absorbed by the quasi-transparent boundary conditions used in this simulation.

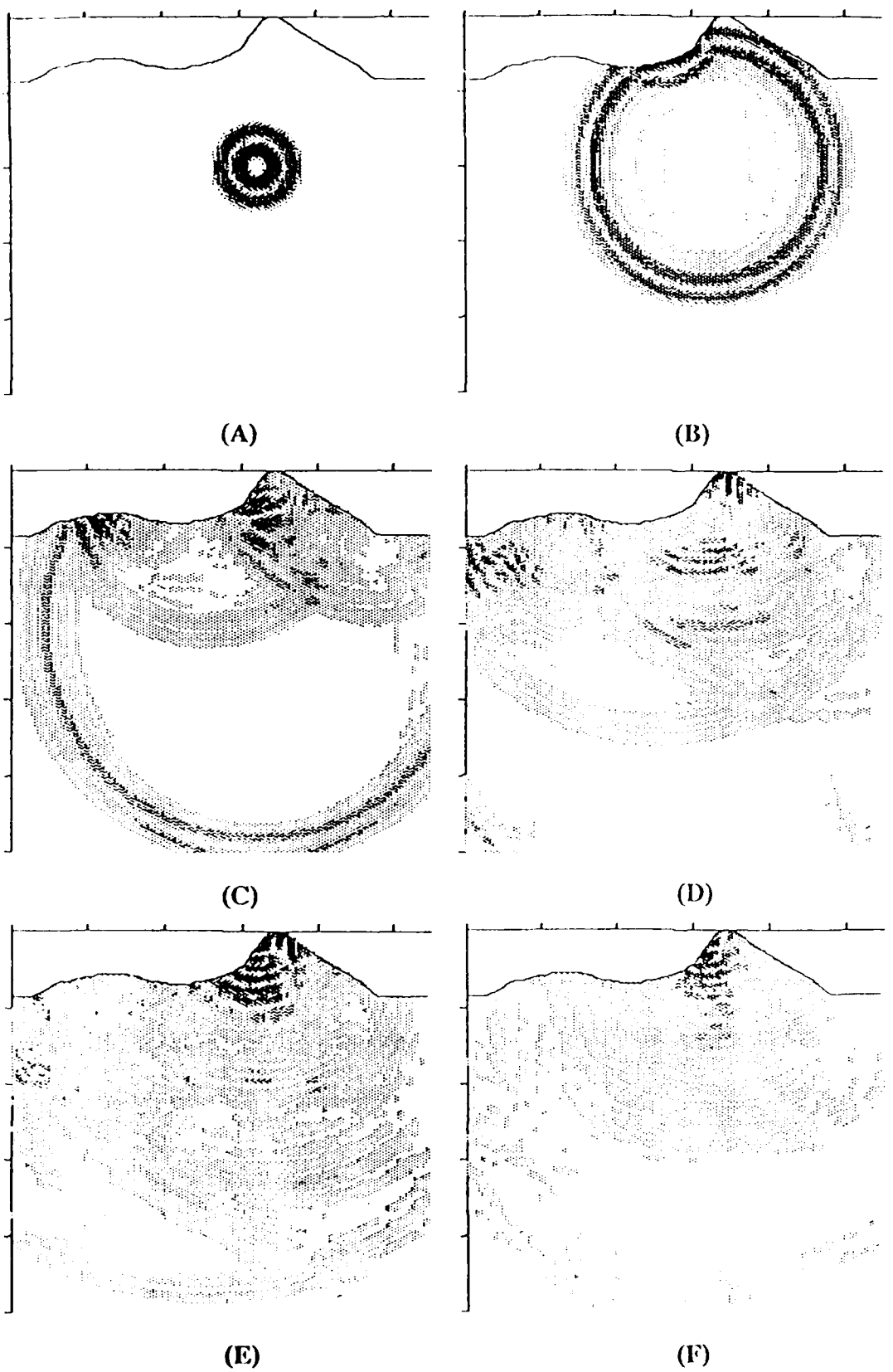

Figure 1.3 shows the propagation of a compressional point (line) source located beneath a steep topographic profile. Note that the quasi-transparent boundary conditions allow the wave to disappear into the sides and bottom of the grid. Snapshots are separated by 0.25 second.

TELESEISMIC SPECTRAL AND TEMPORAL M_o AND Ψ_∞ ESTIMATES FOR FOUR FRENCH EXPLOSIONS IN SOUTHERN SAHARA

Keith L. McLaughlin, Alison C. Lees, and Zoltan A. Der
Teledyne Geotech Alexandria Laboratories
314 Montgomery Street
Alexandria, Virginia 22314-1581

ABSTRACT

Estimates for explosion moment, M_o, and reduced displacement potential, Ψ_∞, are made for four French explosions at Taourirt Tan Afella Massif in southern French Sahara using data from the LRSM network and the arrays EKA and YKA. Preparatory to determining moments, $\overline{t^*}$ estimates are made for each station and the source region $\overline{t^*}$ values of 0.30 to 0.35 seconds are found for the southern Sahara test site. This source region attenuation level is consistent with the "hot spot" hypothesis for the Ahaggar plateau in northern Africa. Consequently, the attenuation bias between Ahaggar and the Nevada Test Site should be small.

Both spectral estimation and broadband temporal deconvolution methods are used for estimation of the explosion moments. The deconvolution estimates of static moment are found to be consistent with the spectral estimation methods. Deconvolved seismograms for the explosions EMERAUDE, RUBIS, SAPHIR, and GRENAT show evidence of strong anisotropic free surface interaction that may be due to scattering from the steep topography of the Taourirt Tan Affela Massif test site.

LRSM SPECTRAL MOMENT ESTIMATES 10^{24} dyne-cm				
EVENT	MEAN	RMS	GEOMETRIC MEAN	MEDIAN
RUBIS	0.064(0.01)	0.072	0.056	0.059
SAPHIR	0.30(0.10)	0.42	0.19	0.16

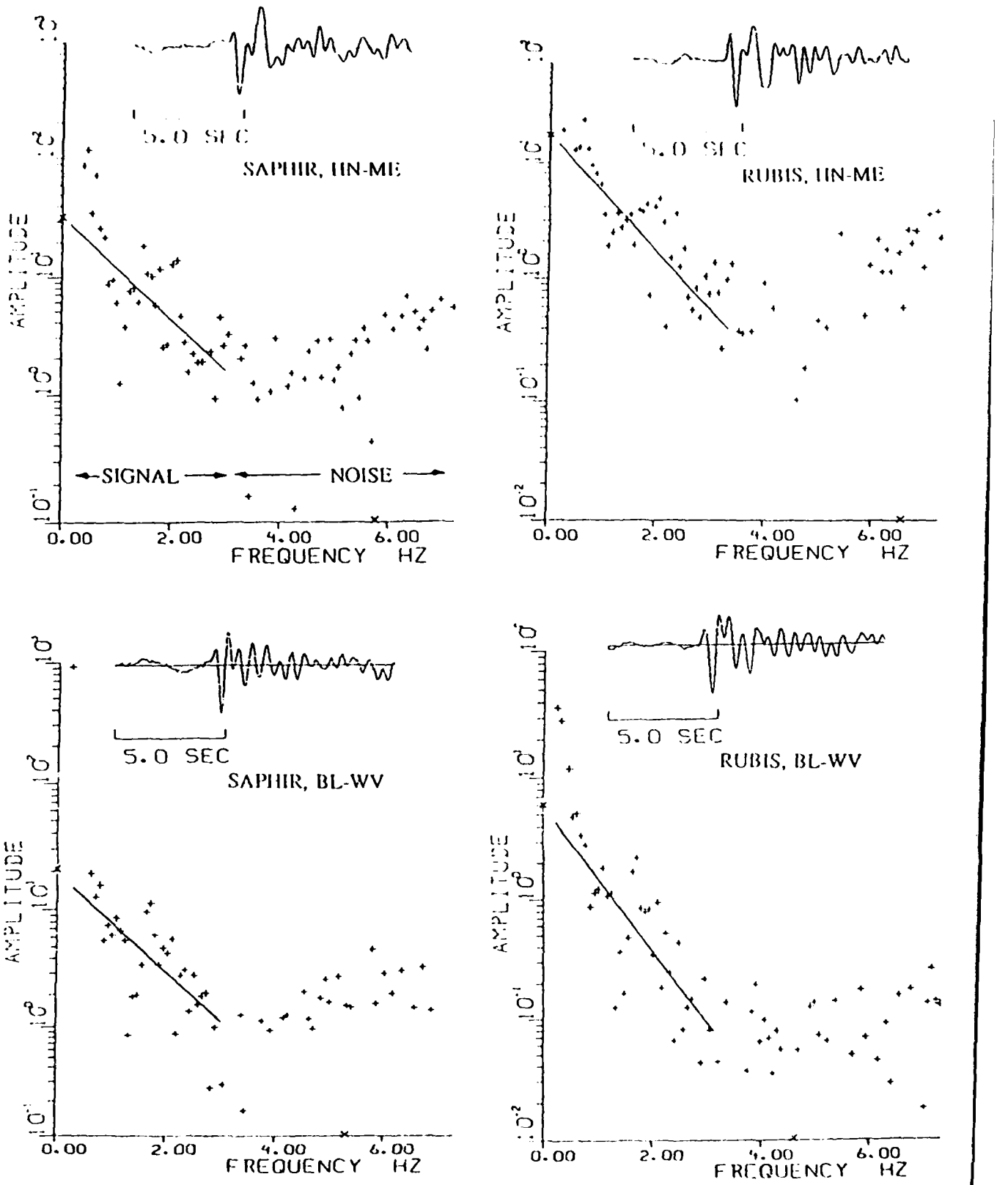

Figure 2.1 Spectra corrected for instrument and RDP. Slopes between 0.5 and 3.0 Hz are estimates of t^*, intercepts are estimates of Ω_o. Only spectral levels with an estimated signal-to-noise power ratio greater than 2 were used.

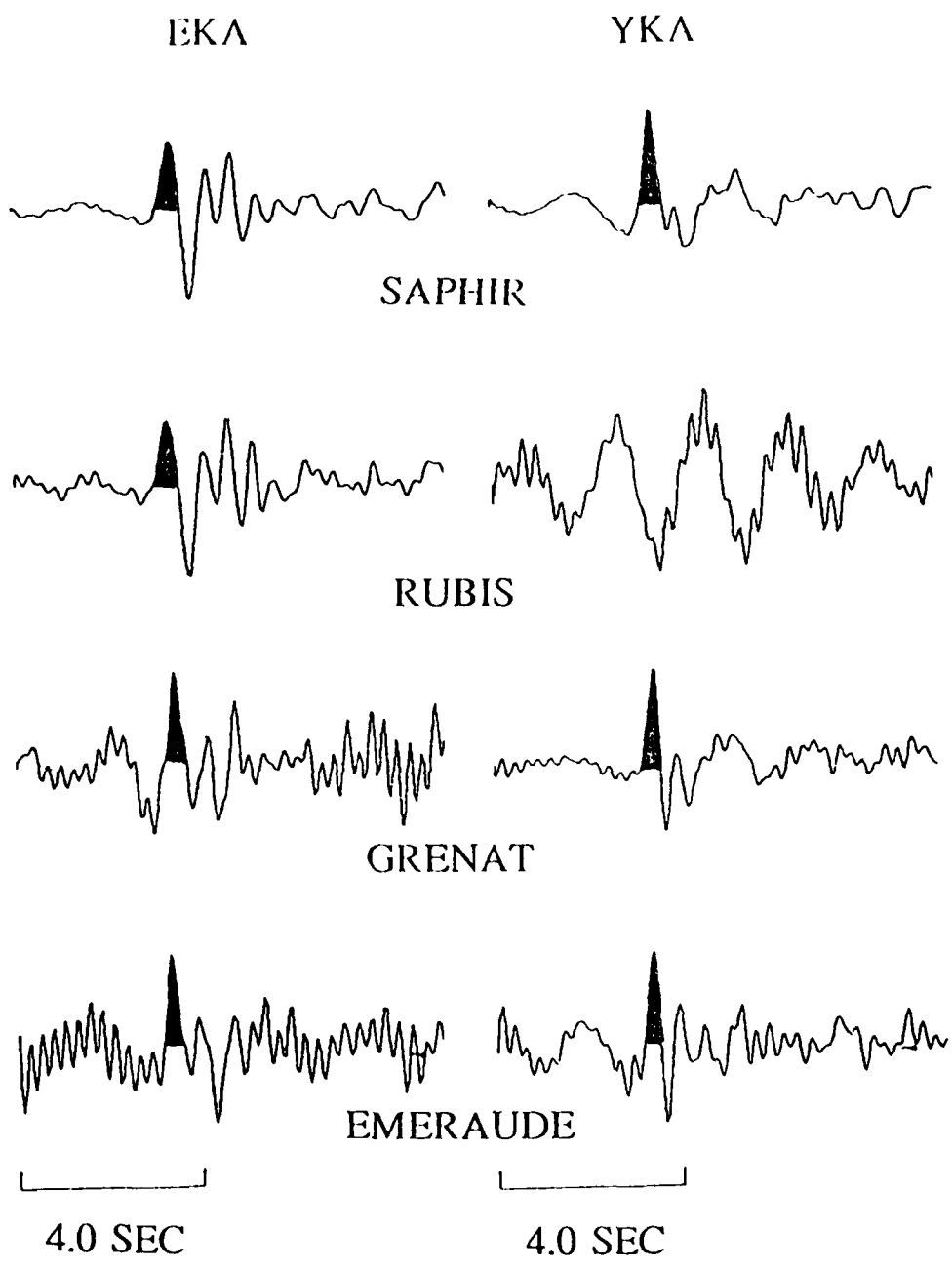

Figure 2.2 Deconvolved source time functions at the EKA and YKA arrays for SAPHIR, RUBIS, GRENAT and EMERAUDE. RUBIS was poorly recorded across YKA.

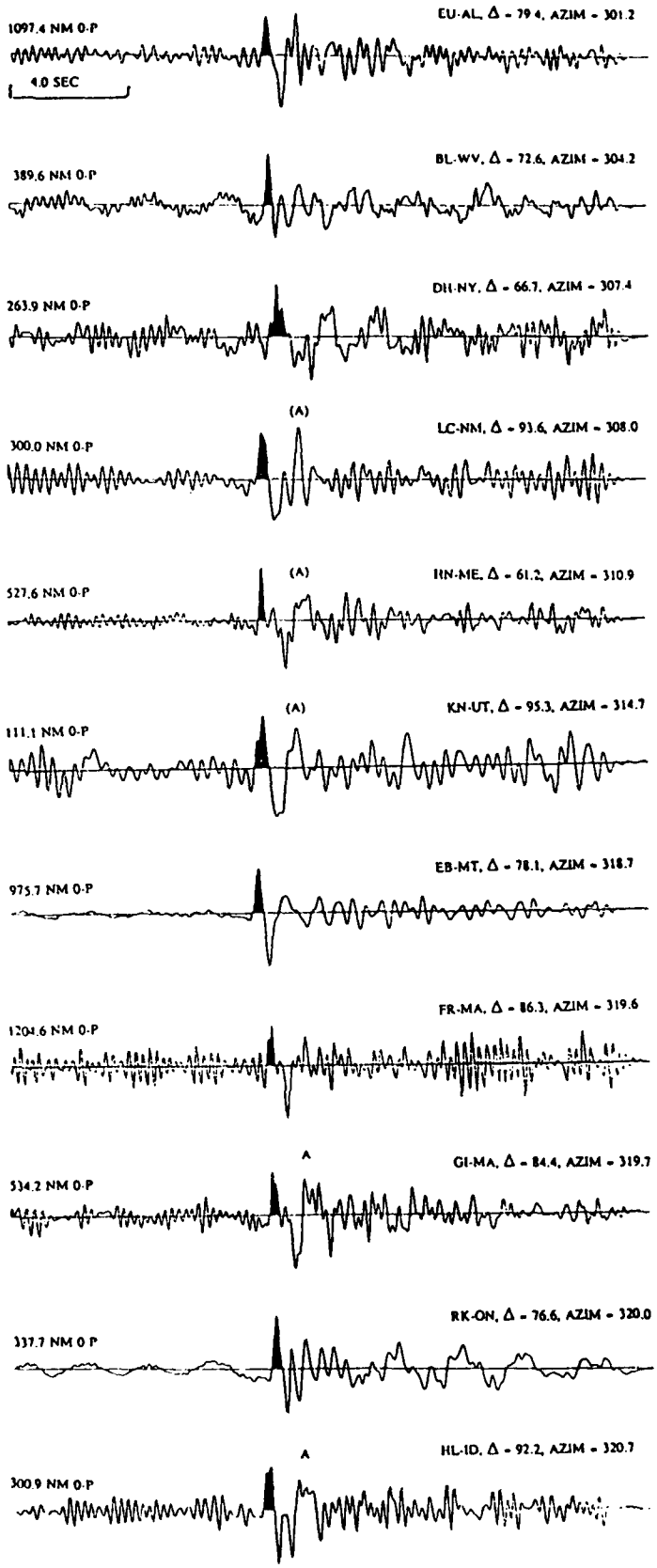

Figure 2.3 Deconvolved waveforms for RUBIS at LRSM stations. The causal P-wave pulse area is indicated for each trace. Traces are ordered in decreasing azimuth from the top. Late positive arrivals that may be correlated between stations are indicated by labels "A" and "(A)".

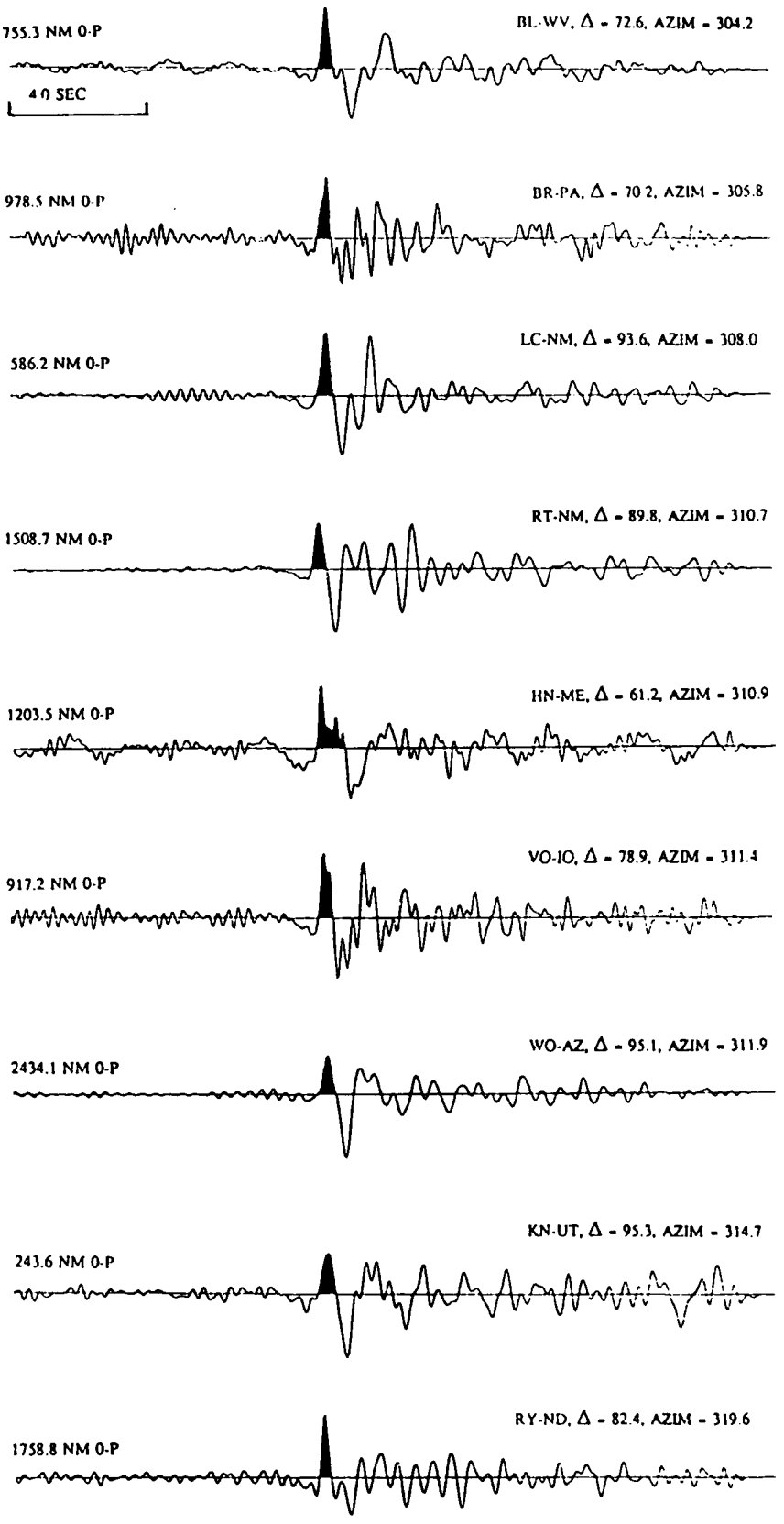

Figure 2.4 Deconvolved waveforms for SAPHIR at LRSM stations. The causal P-wave pulse area is indicated for each trace. Traces are ordered in decreasing azimuth from the top. The HN-ME waveform shows considerable broadening that may be due to a positive secondary arrival unique to the HN-ME station.

SCATTERING FROM NEAR-SOURCE TOPOGRAPHY: TELESEISMIC OBSERVATIONS AND NUMERICAL 2-D EXPLOSIVE LINE SOURCE SIMULATIONS

Keith Lynn McLaughlin and Rong-Song Jih
Teledyne Geotech Alexandria Labs
314 Montgomery Street
Alexandria, Virginia 22314-1581

ABSTRACT

2-D linear elastic finite-difference simulations of teleseismic P waveforms from line sources have been used to explore the variations that may be induced in event magnitude-yield determination by the emplacement of explosive sources under mountainous topographic features. The southern Sahara French test site in Algeria, at Taourirt Tan Afella Massif on the Ahaggar plateau has been used as a case study. The topography of this test site is extreme and the event locations permit a test of the hypothesis that topography influences short-period event magnitudes of contained nuclear explosions. The maximum variation that is expected is plus or minus 0.15 magnitude units from the network mean. The magnitude variations are expected to change rapidly with takeoff angle and azimuth.

Teleseismic observations of the explosions at the southern Sahara test site are compared to predictions made from 2-D simulations. Waveform data from the arrays EKA, and YKA as well as LRSM data have been deconvolved to broadband displacement for inspection of the apparent far-field P-wave source. Qualitative comparisons are favorable that the topography above the explosions RUBIS and SAPHIR defocused teleseismic pP at certain takeoff angles and azimuths. Long-period positive-polarity pulses can be seen at several sites that may indicate Rayleigh-to-P scattering from topography near the source.

WWSSN maximum likelihood magnitude data for the "a", "ab", and "max" P phases have been used to estimate that the magnitude variation due to topographic scattering is no more than 0.15 rms magnitude units across the WWSSN.

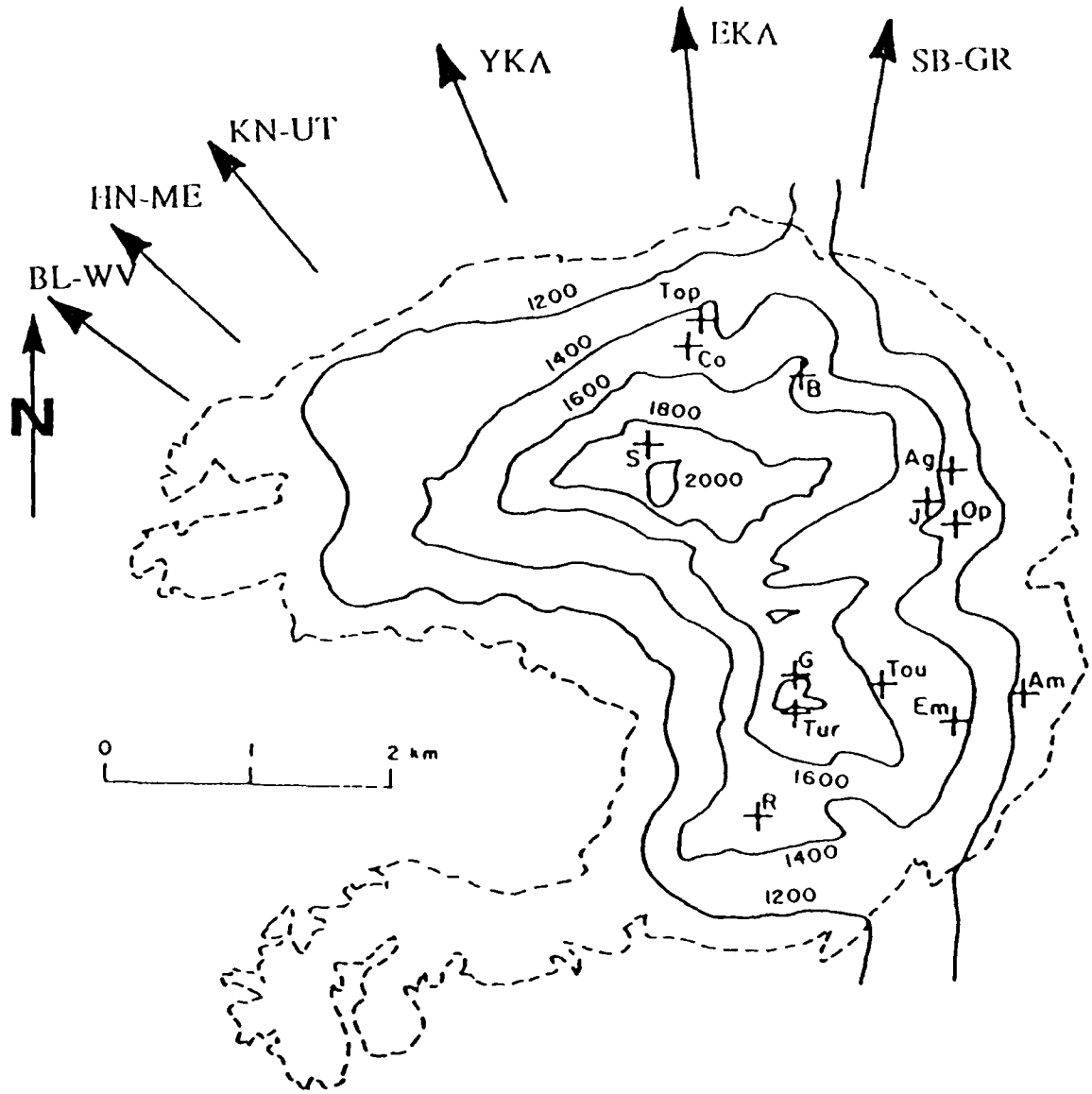

Figure 3.1 Topographic map Taourirt Tan Afella Massif from Duclaux and Michaud (1970) with event locations from Faure (1972) for SAPHIR (S), RUBIS (R), EMERAUDE (E), and GRENAT (G). Contours are 100 meters. The dashed line is the outcrop of the Taourirt Tan Afella Massif granite. Azimuths to several stations and arrays are indicated.

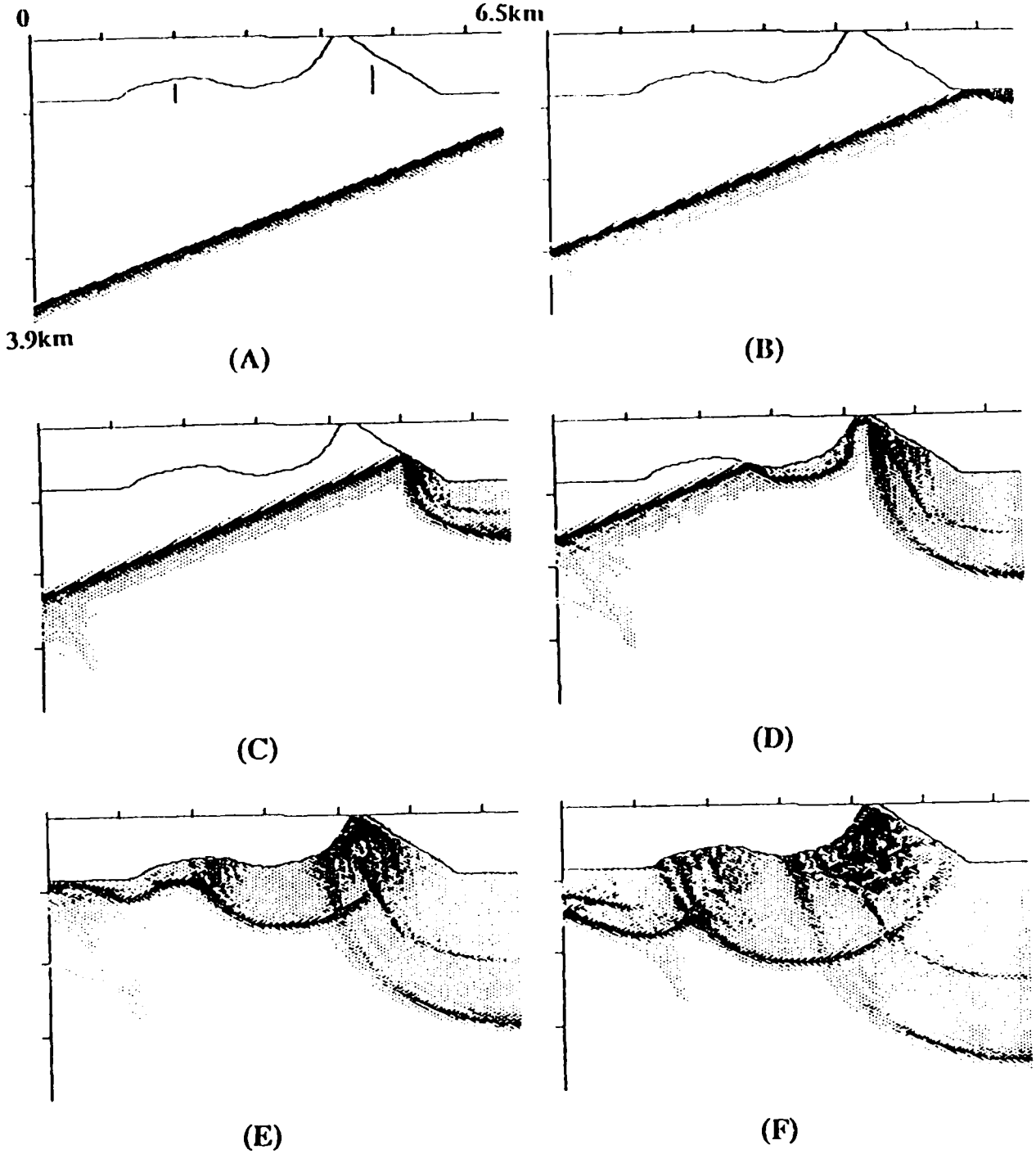

Figure 3.2 The displacement fields generated by a broadband plane P wave (*i.e.* source at infinity) of incidence angle 20° in a grid with steep topographic configuration. The topography is a (due north 344°) cross section of Taourirt Tan Afella Massif in southern Algeria. The successive frames separated by 0.125 sec show the initialization of the wave (A), P-reflection followed by S wave starting at right (B,C), completely developed reflections from all parts of the topography (E) and complex wavefields containing reflections, diffractions and possibly excited surface waves (E,F). It can be observed that the free-surface reflection is severely altered due to scattering from the free-surface. Far-field seismograms with compressional sources at locations beneath this topographic profile (black spots in (A)) can be derived by reciprocity.

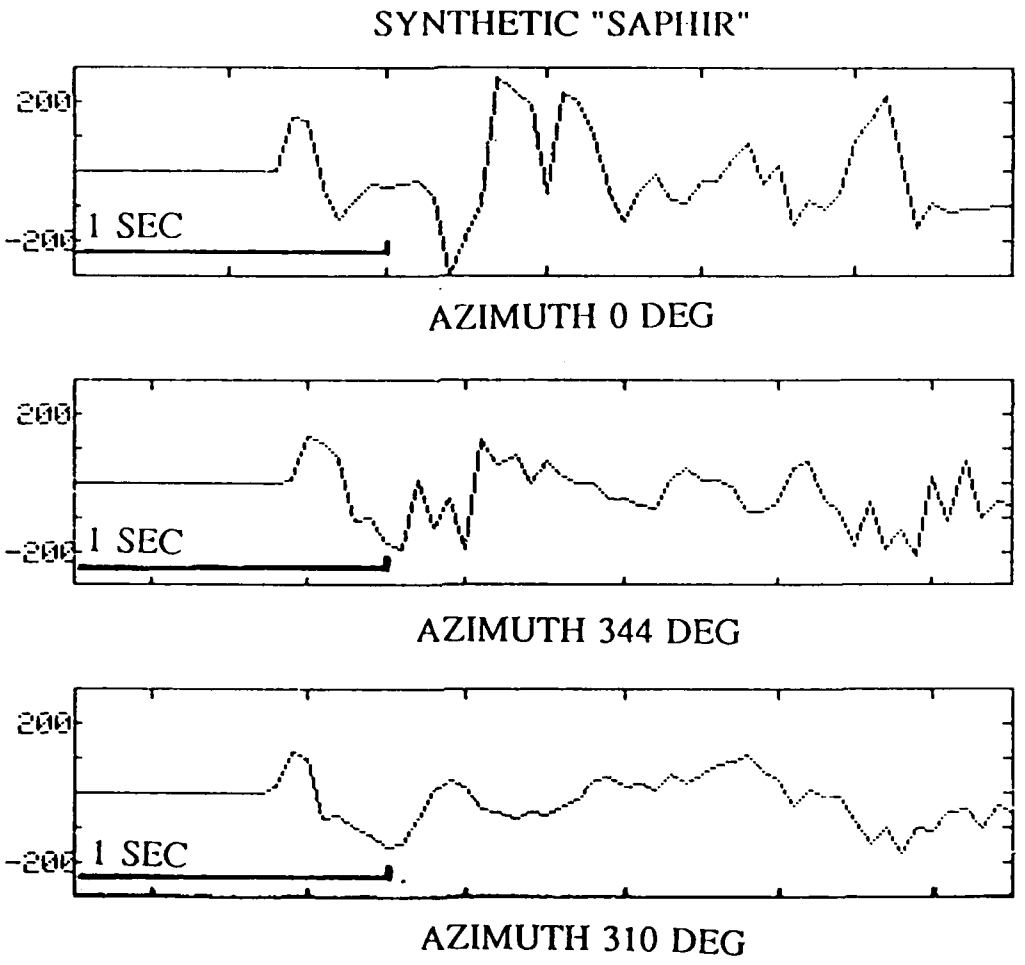

Figure 3.3 Synthetic teleseismic P waves (takeoff angle of 20 degrees) for the 2-D "SAPHIR" models at azimuths of 310, 344, and 0 degrees. Synthetics have only been convolved with an explosion source time function. No distinct well defined elastic pP is apparent although, several long-period complicated negative pulses can be seen to follow the initial P wave. Large positive secondary arrivals can be seen 0.5 sec following the initial P wave at 0 degrees azimuth.

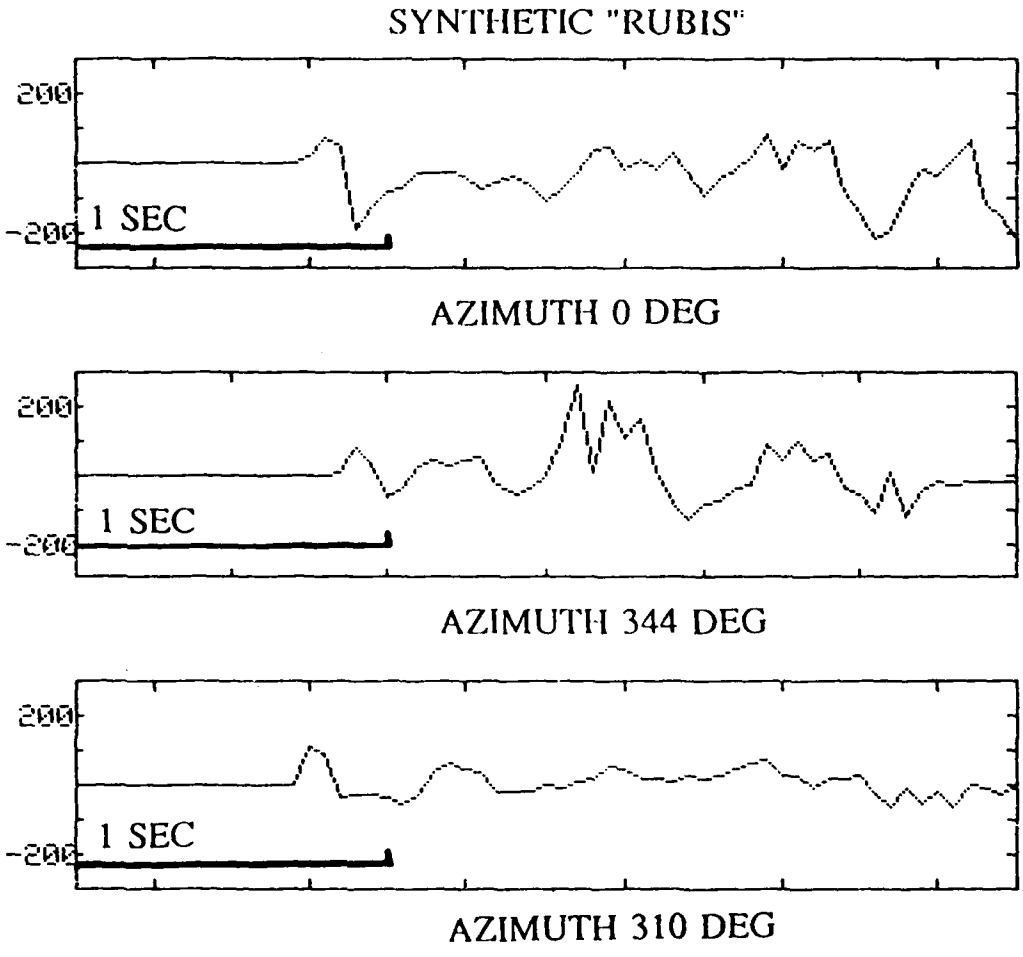

Figure 3.4 Synthetic teleseismic P waves (takeoff angle of 20 degrees) for the 2-D "RUBIS" models at azimuths of 310, 344, and 0 degrees. Synthetics have only been convolved with an explosion source time function. A distinct well defined elastic pP is only apparent for the azimuth of 0 degrees. Large positive pulses can be seen about 1 second after the P wave for the azimuth of 344 degrees.

EFFECTS OF LOCAL GEOLOGIC STRUCTURE ON YUCCA FLATS, NTS, EXPLOSION WAVEFORMS: 2-DIMENSIONAL LINEAR FINITE-DIFFERENCE SIMULATIONS

Keith L. McLaughlin, Lisa M. Anderson, and Alison C. Lees
Teledyne Geotech Alexandria Laboratories
314 Montgomery Street
Alexandria, Virginia 22314-1581

ABSTRACT

Two-dimensional linear elastic finite-difference calculations were performed for a two-dimensional geologic model of Yucca Flats, Nevada Test Site, Nevada. The calculations were used to produce synthetic teleseismic P-wave seismograms for explosive line sources in Yucca Flats. P-wave coda (first 5 seconds) is observed to be highly dependent on takeoff angle for the teleseismic synthetics. P-wave coda also varies with the position of the source in the valley structure and may produce variations in the individual station teleseismic P-wave m_b magnitude of up to 0.3 magnitude units. However these magnitude variations should be substantially reduced by averaging over stations at multiple azimuths.

The reverberant coda appears to arise from scattered modal waves that are initially excited in the low velocity near-surface structures of the Yucca Flats deposits of alluvium and tuff. Scattering of the waves occurs at offsets in the basement structure and the at the sides of the valley.

The combined effects of scattering, source function, intrinsic attenuation, and instrument response serve to obscure the P+pP spectral scalloping that is expected from a linear model. This loss of spectral resolution is the product of P coda filling in the P+pP interference notches and the lengthening of the initial P wave source time function by the convolution of the source time function, intrinsic attenuation operator and instrument response. Therefore, short time windows that do not include P coda energy do not have sufficient resolution to reliably detect the P+pP interference notches.

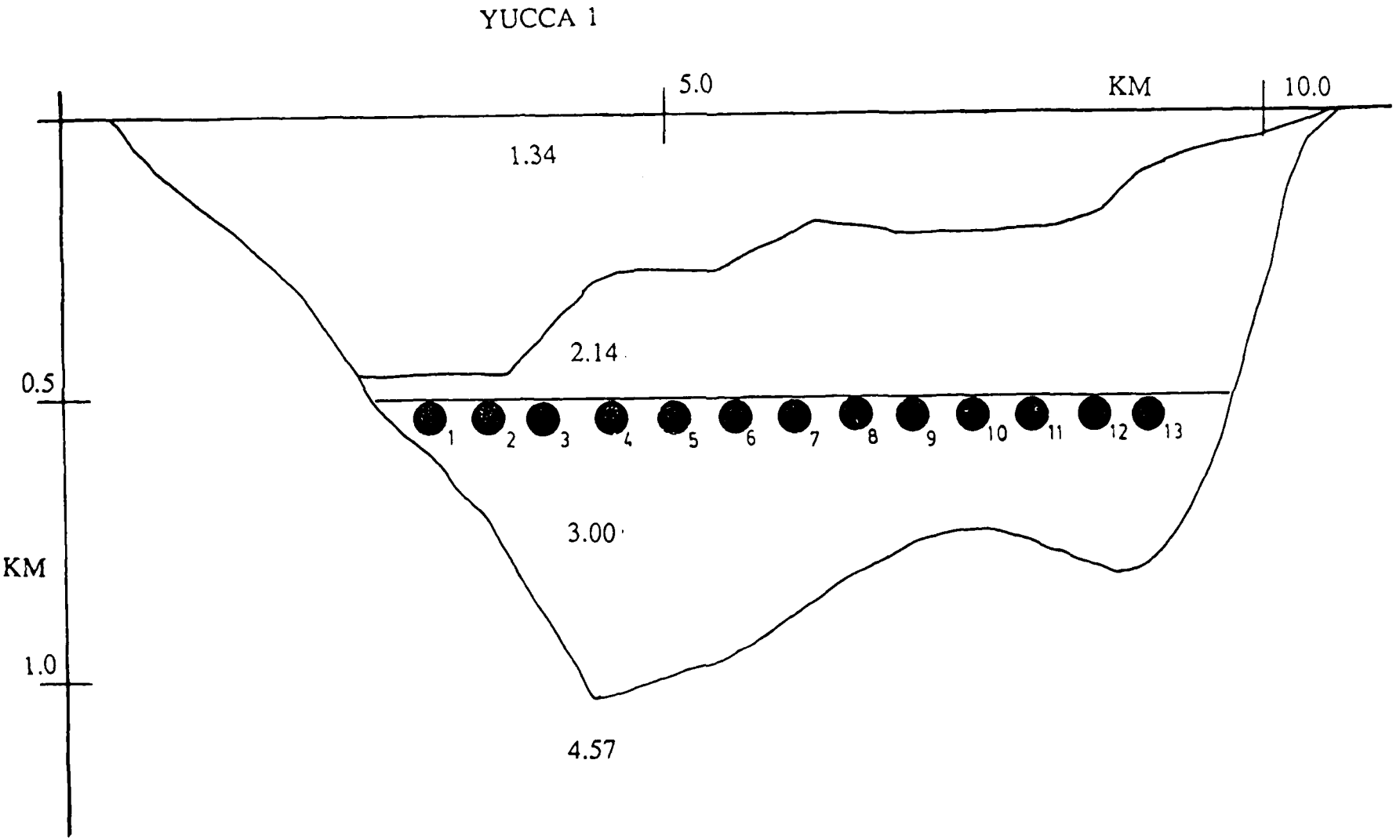

Figure 4.1 West-to-East model for geologic structure across Yucca Flats from Ferguson (1983). Model shown with 5-to-1 vertical exaggeration. Numbered source locations referred to in the text are indicated by solid dots at a depth of 550 meters below the surface. P-wave velocities of 1.34, 2.14, 3.00, and 4.57 km/sec are indicated for the geologic units of alluvium, unsaturated tuff, saturated tuff, and Paleozoic carbonates respectively.

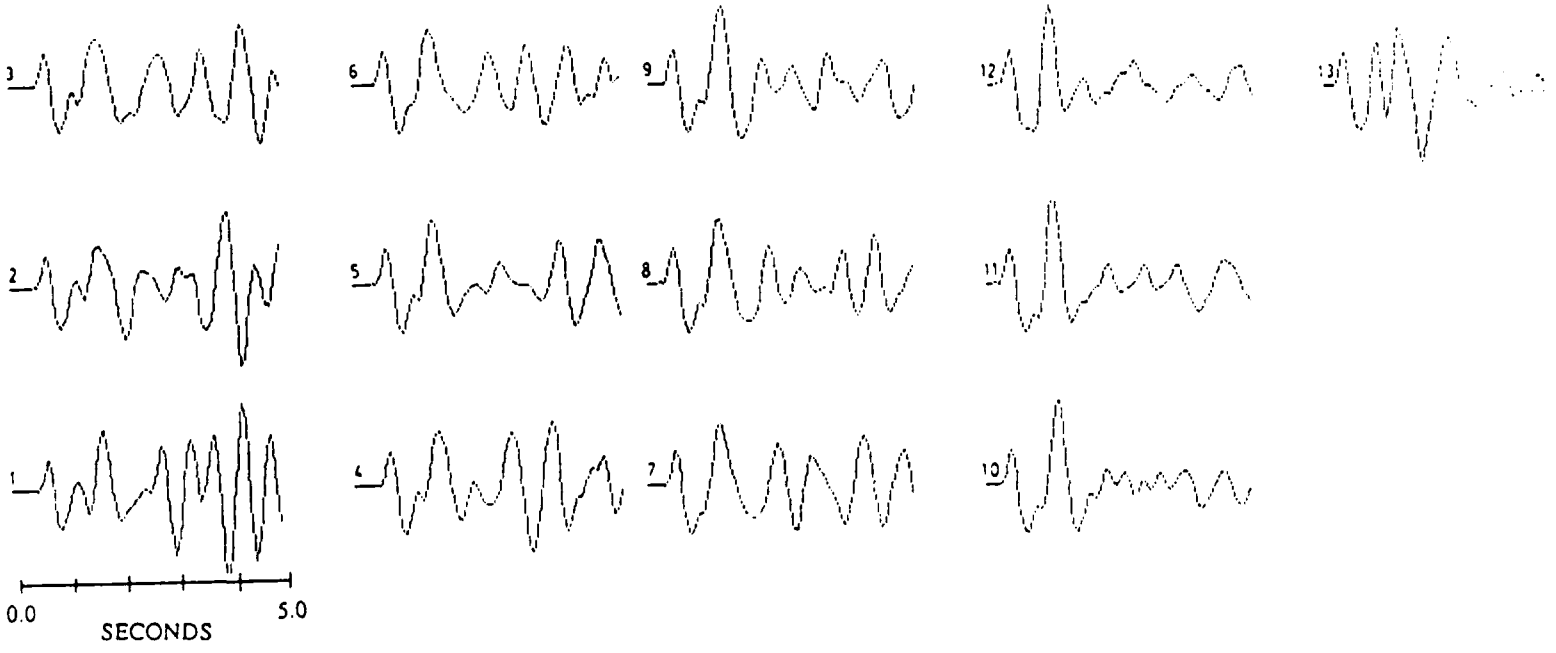

Figure 4.2 Teleseismic P-wave synthetics appropriate for a takeoff angle of 15 degrees for model in Figure 1. Numbers correspond to numbered source locations in Figure 1. 5 seconds of record are shown in each case. All synthetics are plotted at the same scale. Synthetics are calculated for a von Seggern Blandford (1972) hard rock 100 Kt RDP convolved with an instrument response and an attenuation operator as in FIGURE 2.

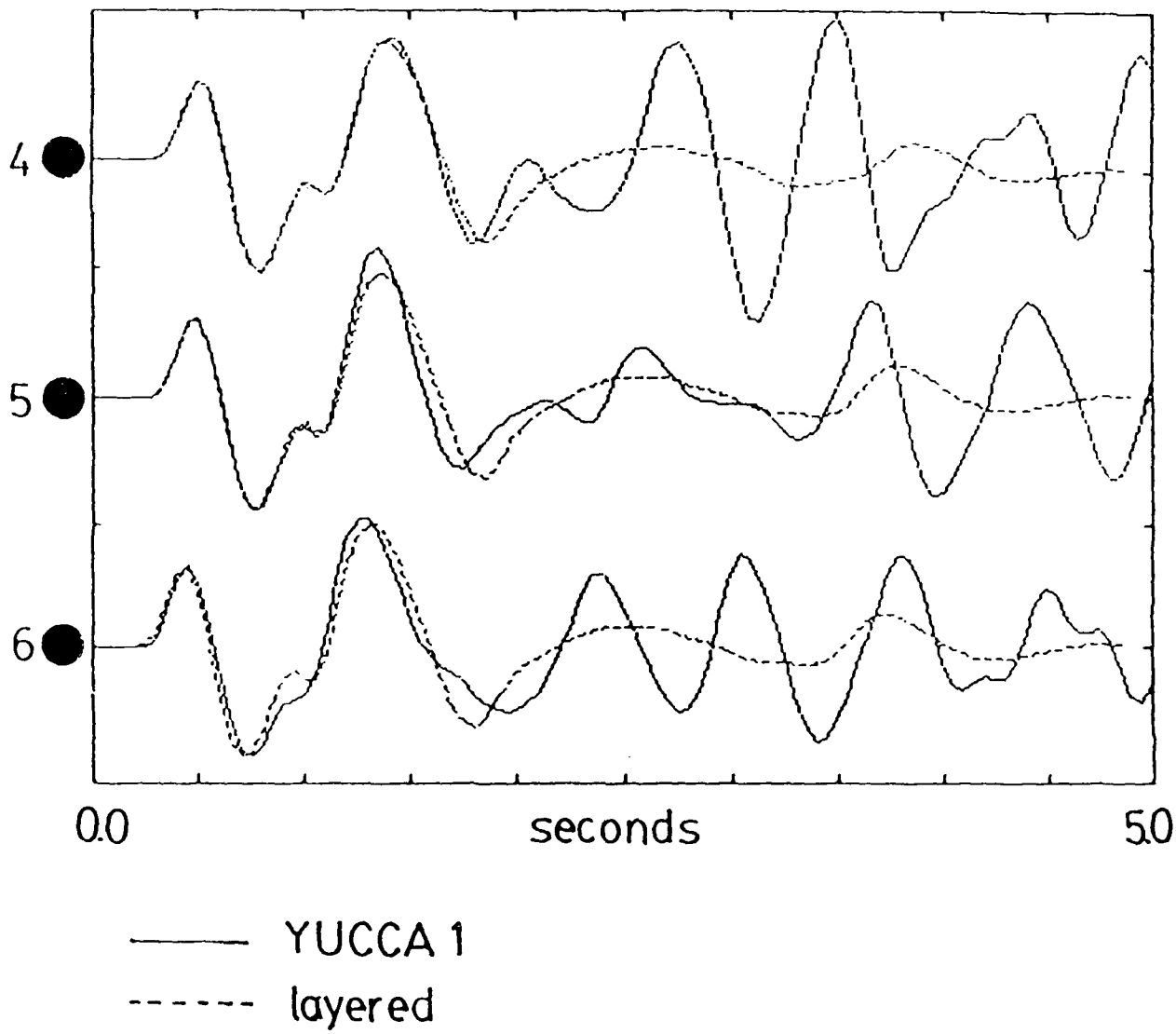

Figure 4.3 Synthetics for source locations 4, 5, and 6 at takeoff angle of 15 degrees compared to the layered model.

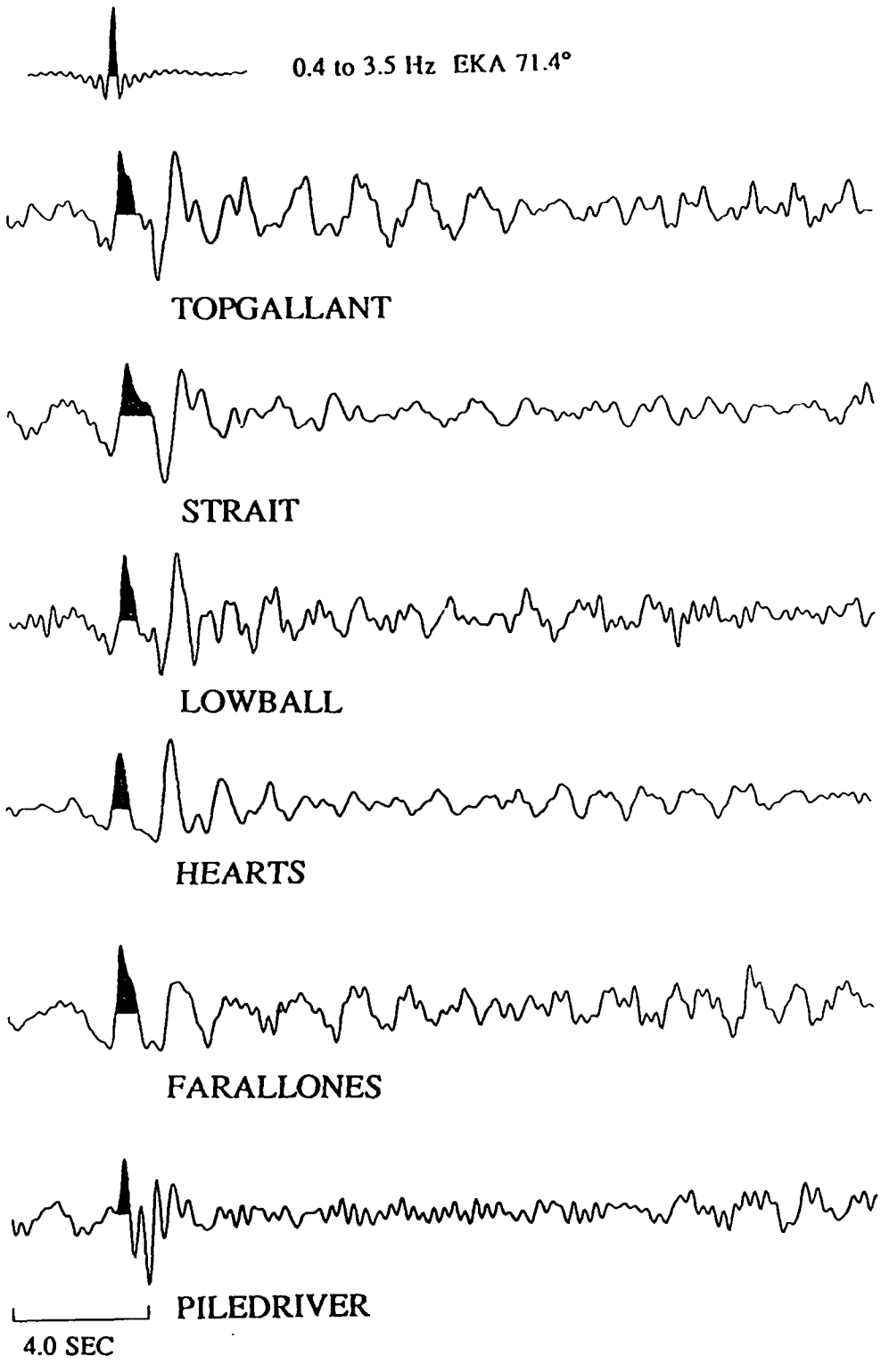

Figure 4.4 Deconvolved source time functions (far-field displacement) of Yucca Flats events and Piledriver at EKA array (Δ=71.4°). The effects of a constant t^*=0.45 sec attenuation operator have been removed. A resolution kernel is shown at the top representing the limited bandwidth of the deconvolutions, 0.4 to 3.5 Hz. The initial causal P wave has been been shaded for clarity. Note the higher frequency and shorter duration source time function of Piledriver with respect to the Yucca Flats events. Topgallant, Lowball, and Farallones have considerable reverberation in the first 5 seconds of record. The Yucca Flats events do not show a clear pP within 1 second of the initial P wave, although several events do show a negative phase about 1 second following the P wave and a positive pulse about 1.5 seconds following the P wave. Piledriver shows a negative pulse about 0.25 seconds following the P wave (pP?) and another negative polarity pulse about 0.8 seconds following the P wave.

FINITE-DIFFERENCE SIMULATIONS OF RAYLEIGH WAVE SCATTERING BY 2-D ROUGH TOPOGRAPHY

Keith Lynn McLaughlin and Rong-Song Jih
Teledyne Geotech Alexandria Labs
314 Montgomery Street
Alexandria, Virginia 22314-1581

ABSTRACT

Rayleigh waves normally incident upon 2-D simple or rough topographic structures are simulated by the linear finite-difference method to study the attenuation, transmission, and reflection of Rayleigh waves and to measure the Rayleigh-to-P and -SV bodywave conversion. For simple ramp structures, transmission, reflection, and scattering depend on the sign of change of slope of the topographic feature, as well as the ratio of the ramp height to the wavelength, h/λ. Simple ramp structures produce back-scattered bodywaves for $h>\lambda$, and forward-scattered bodywaves for $h<\lambda$. The radiation patterns of P and S bodywaves are roughly consistent with the model of equivalent point forces along the free surface. More complicated topographic features generated by random Markov sequences have been characterized by the Rayleigh-wave spatial Q(f). As expected, rougher topography attenuates Rayleigh waves more than smooth topography. P and S ampiitudes ratios are consistent with radiation from equivalent point forces near the surface, but the distribution of slownesses generated is greater than from the simple ramp structures. Reflection of Rayleigh waves by topographic slopes and by random topography is an inefficient process and the bulk of the energy that is not transmitted as Rayleigh waves is converted to bodywaves. Fundamental Rayleigh-to-Lg scattering and generation of teleseismic P coda by short period Rayleigh should be observable.

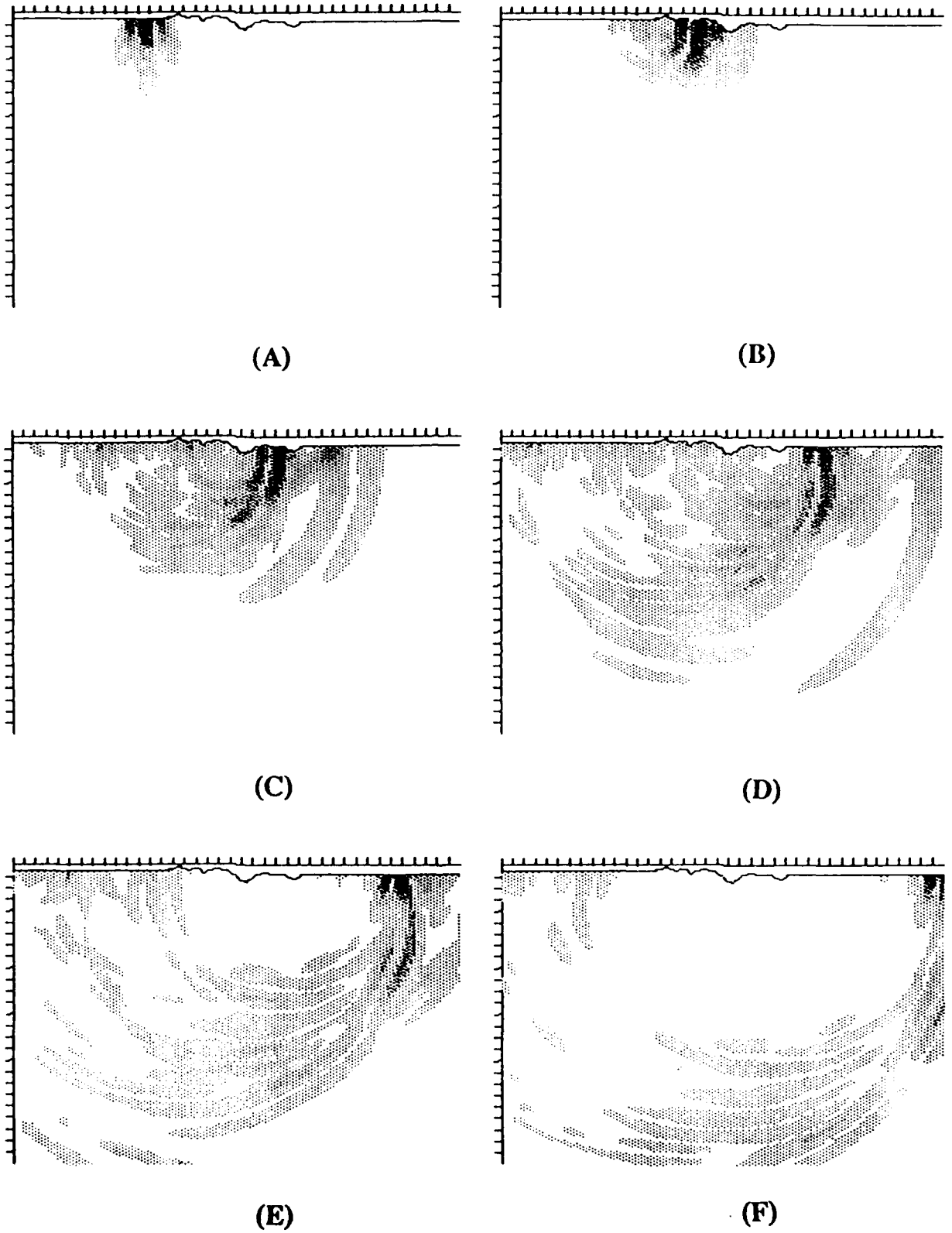

Figure 5.1 Rayleigh wave incident on a rough topographic profile superimposed on a grid with absorbing boundary conditions for the sides and the bottom. Figures (A) through (F) correspond to displacement wavefields at distinct times with a temporal spacing of 2 sec. Note that the high frequency scattering of Rayleigh wave is *forward*.

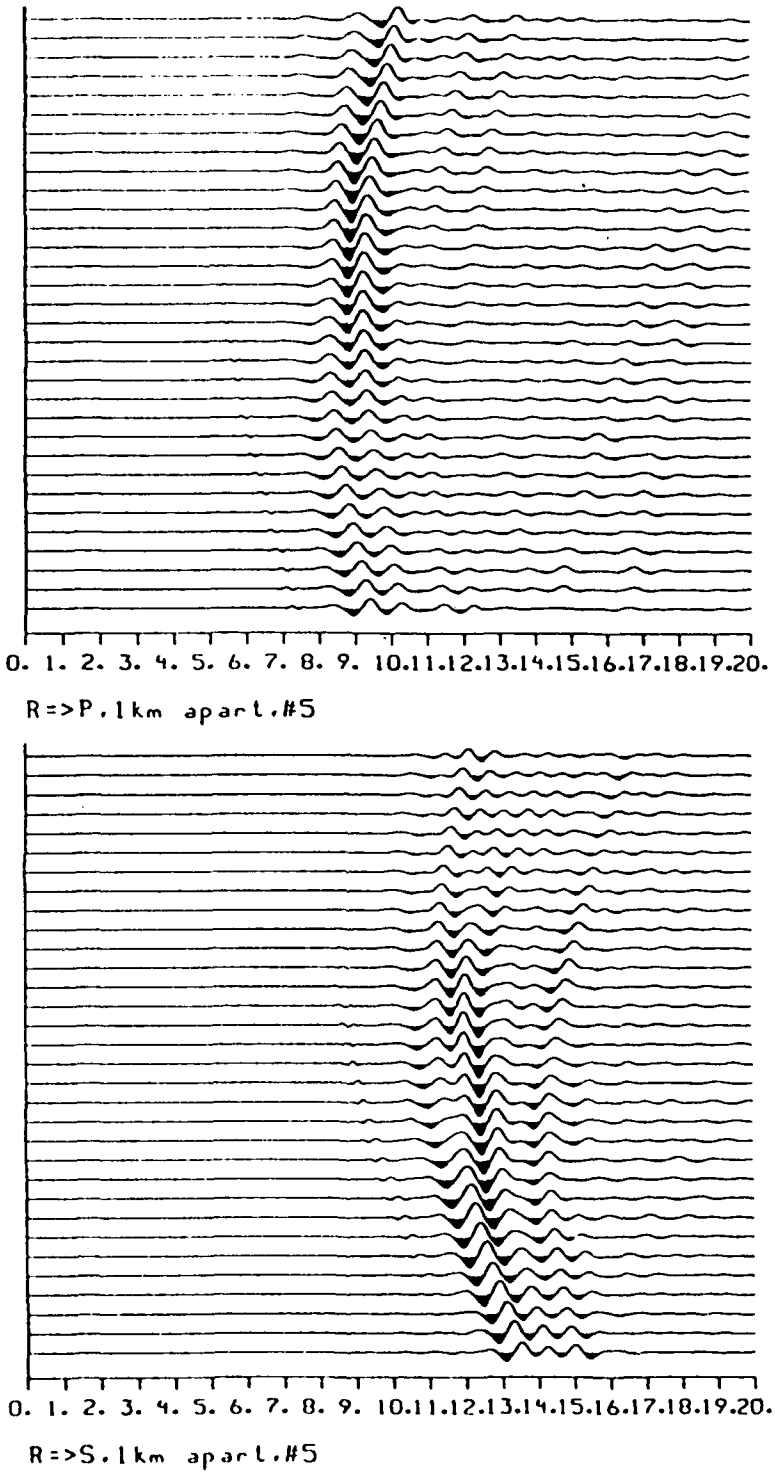

Figure 5.2 Seismic sections recording the converted P wave (dilatational strain, upper) and S wave (rotational strain, below) at a line of 32 sensors located near the bottom of the grid spaced 1 km apart for the same rough topography (#5)as in previous figure. Complicated interference patterns are evident for both P and S wavefields.

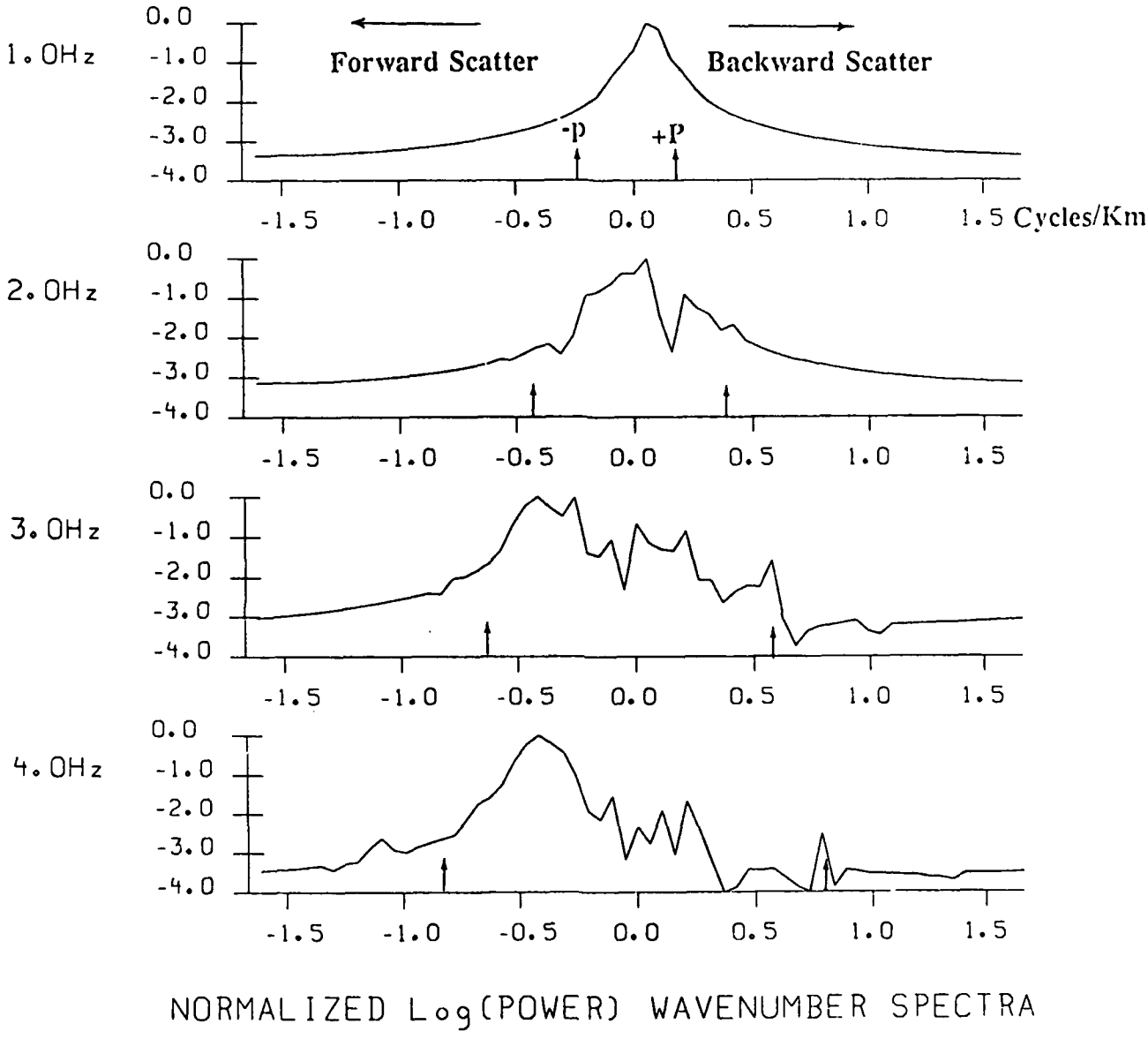

Figure 5.3 Frequency wavenumber spectra for the dilatational strain field (P-wave) recorded near the bottom of the grid with topography #5 on the top of the grid. The dilatational strain energy is largely confined to P wave slowness across the array. P wave energy shifts from back-scattered to forward-scattered from 1 to 4 Hz.

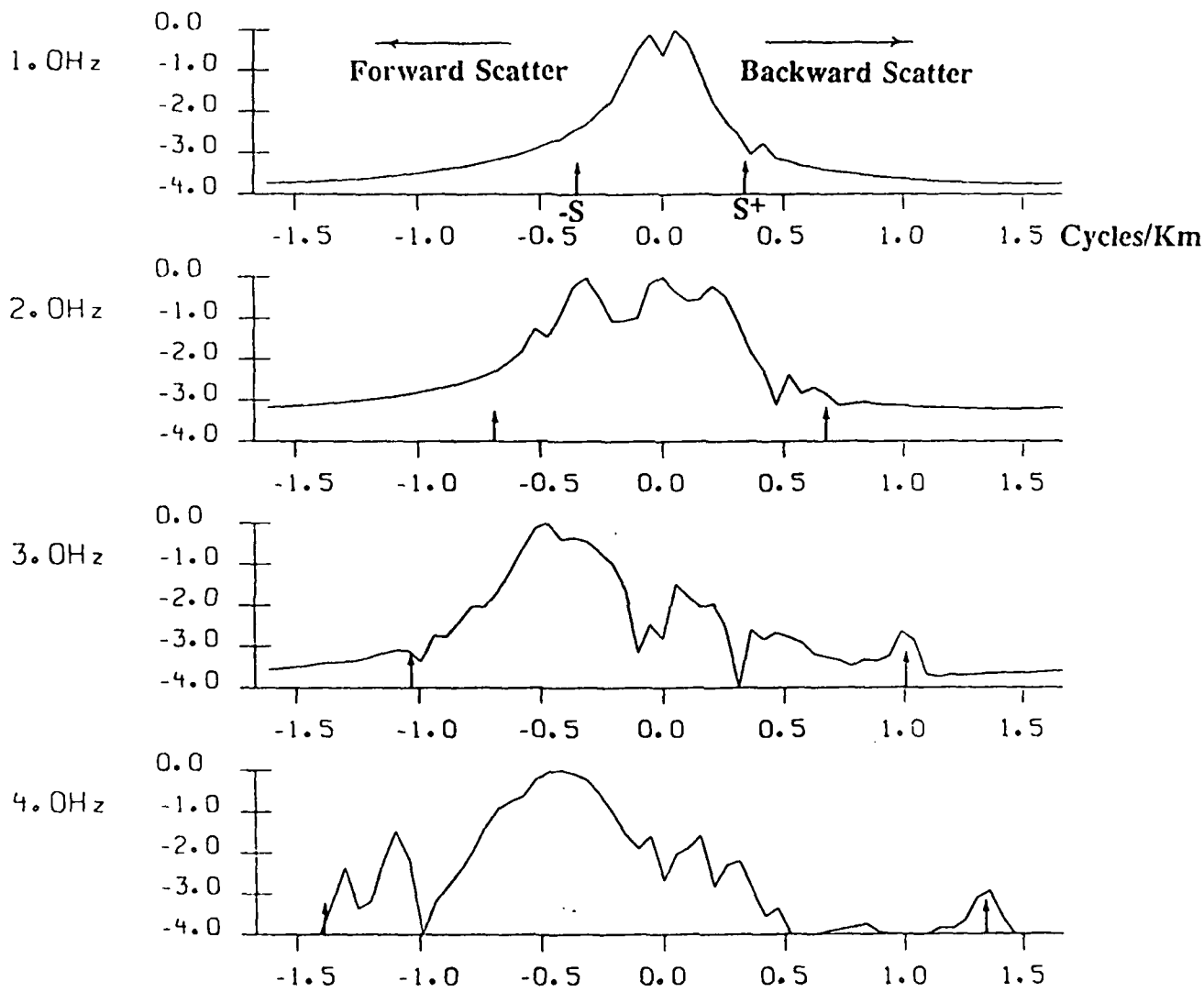

Figure 5.4 Frequency wavenumber spectra for the rotational strain field (S-wave) recorded near the bottom of the grid with topography #5 on the top. The rotational strain energy is largely confined to S wave slowness across the array. S wave energy shifts from back-scattered to forward-scattered from 1 to 4 Hz.

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Earth Resources Laboratory
Department of Earth, Atmospheric and
Planetary Sciences
Massachusetts Institute of Technology
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Dr. Zoltan A. Der
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314 Montgomery Street
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20 Oxford St.
Cambridge, MA 02138

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Sierra Geophysics
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Kirkland, WA 98033

Prof. Roy Greenfield
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California Institute of Technology
Pasadena, CA 91125

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Seismological Laboratory
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California Institute of Technology
Pasadena, CA 91125

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Saint Louis University
Saint Louis, MO 63156

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Seismographic Station
University of California
Berkeley, CA 94720

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Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Alan Kafka
Department of Geology & Geophysics
Boston College
Chestnut Hill, MA 02167

Professor Charles A. Langston
Geosciences Department
403 Deike Building
The Pennsylvania State University
University Park, PA 16802

Professor Thorne Lay
Department of Geological Sciences
1006 C.C. Little Building
University of Michigan
Ann Arbor, MI 48109-1063

Dr. George R. Mellman
Sierra Geophysics
11255 Kirkland Way
Kirkland, WA 98033

Professor Brian J. Mitchell
Department of Earth and Atmospheric Sciences
Saint Louis University
Saint Louis, MO 63156

Professor Thomas V. McEvilly
Seismographic Station
University of California
Berkeley, CA 94720

Dr. Keith L. McLaughlin
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

Professor Otto W. Nuttli
Department of Earth and Atmospheric Sciences
Saint Louis University
Saint Louis, MO 63156

Professor Paul G. Richards
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. Norton Rimer
S-Cubed
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Professor Larry J. Ruff
Department of Geological Sciences
1006 C.C. Little Building
University of Michigan
Ann Arbor, MI 48109-1063

Professor Charles G. Sammis
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Dr. David G. Simpson
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. Jeffrey L. Stevens
S-CUBED,
A Division of Maxwell Laboratory
P.O. Box 1620
La Jolla, CA 92038-1620

Professor Brian Stump
Institute for the Study of Earth
and Man
Geophysical Laboratory
Southern Methodist University
Dallas, TX 75275

Professor Ta-liang Teng
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Dr. R. B. Tittmann
Rockwell International Science Center
1049 Camino Dos Rios
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Earth Resources Laboratory
Department of Earth, Atmospheric and
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Massachusetts Institute of Technology
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Department of Geosciences
Building #11
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Dr. Carl Newton
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Dr. Alan S. Ryall, Jr.
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