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Final Report For Contract 9-XDH-3673N-1

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I. ABSTRACT

The principal objectives of the work effort were to reduce the surface-wave data obtained from the NTS event "Serena" (June, 1985), to invert these data to obtain one or more models of the earth, and to integrate these results with the results of other investigators (principally those at LANL), who were to use other geophysical data to obtain models of the same earth structure.

II. EFFORT AND ACCOMPLISHMENTS

A. Reduction of Data

The data from the nine intermediate-period stations have been reduced. Both group and phase velocities, for periods between 5 and 15 seconds, have been obtained.

B. Inversion of Surface Wave Data for Earth Models

The phase velocity data have been inverted to obtain models of the upper crust of the southern Colorado Plateau, and the Rio Grande rift.

C. Integration of Results

These results have not yet been integrated with those of other investigators.

III. PUBLICATIONS OR OTHER INFORMATION

The details concerning items II.A and II.B are to be found in the manuscript entitled "Upper-Crustal Structure From NTS To Carrizozo, N.M. From Rayleigh-Wave Data", copies of which are enclosed with this report. This manuscript has not been submitted for publication, nor has it been reviewed by anyone.

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"UPPER-CRUSTAL STRUCTURE FROM NTS TO CARRIZOZO, N.M. FROM RAYLEIGH-WAVE DATA"

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ABSTRACT

Seismic waves from the underground nuclear test "Serena" were recorded by a linear array of nine seismographs spaced more or less regularly from near the Nevada Test Site to Carrizozo, New Mexico. We have obtained Rayleigh wave group and phase velocity data from these stations, and have inverted the phase velocity data for models of the upper crust of the southern Colorado Plateau and the Rio Grande rift. The major difference between the two models is the thickness of their sedimentary sections, with the model for the rift having 2.65 km of sediments, and the model for the Colorado Plateau having 0.65 km. There is no substantial difference between the two models below 2.65 km, which have upper-crustal shear-wave velocities of 3.66 km/sec (Colorado Plateau) and 3.60 km/sec (Rio Grande rift) to a depth of 23.65 km.

UPPER-CRUSTAL STRUCTURE FROM NTS TO CARRIZOZO, N.M. FROM RAYLEIGH-WAVE DATA

I. INTRODUCTION

During the summer of 1985, personnel from several institutions collaborated in an effort to obtain a reversed seismic refraction line between White Sands Missile Range, New Mexico, and the Nevada Test Site (NTS). The source at the eastern end of the line was the above-ground chemical explosion "Minor Scale", detonated on 27 June. Nearly a month later, the underground nuclear event "Serena" served as the reverse shot (Table 1). Refraction stations for both shots were spaced at approximately 10 km intervals along the great-circle path between the two explosions. In conjunction with the refraction stations, nine intermediate-period ($T_0 = 5$ sec) vertical seismometers with digital recorders were deployed for the NTS event; the primary purpose of these stations was to record the surface waves generated by the explosion. The stations were irregularly spaced at intervals of 85-150 km between NTS to just beyond the eastern boundary of the Rio Grande rift (Figure 1; Table 2). This report details the procedures used in recording and analyzing the surface-wave data, and presents models of the upper crust obtained by inverting these surface-wave data.

II. RECORDING PROCEDURES

Each intermediate-period station consisted of at least one each of a Kinometrics SV-1 seismometer, a Sun-Teq amplifier, and a Kinometrics PDR-2 digital recorder. The output of the SV-1 was fed to the amplifier; the amplified signal was then sent to the PDR-2 where it was filtered by a 0.25 Hz (4 sec) filter before being recorded digitally on cassette tape at 10 samples per second.

Figure 1: Location map showing the nine intermediate-period seismic stations (x) and the NTS event "Serena" relative to the Basin and Range, the Colorado Plateau, and the Rio Grande rift. The dark features show late Cenozoic (≤ 11 Ma) volcanic fields. The event location is given in Table 1; station locations, azimuths, and distances are given in Table 2. [Map from Aldrich and Laughlin (1984)].

Table 1: NTS Event SERENA^a

Date	Time	Lat (°N)	Long (°W)
25 July 1985	14:00:00.0	37.297	116.438

^a from Preliminary Determination of Epicenters 30-85

Table 2: Station Parameters

Station Number	Latitude (°N)	Longitude (°W)	Distance (km) to		Azimuth (deg) to	
			NTS	Prev. Sta.	NTS	Prev. Sta.
WCC	36.807	114.854	151.0	-	291.6	-
STG	36.218	113.565	283.1	132.7	295.9	294.2
KNF	35.862	112.178	413.1	131.0	293.9	287.9
WPR	35.555	111.307	499.0	85.9	294.3	293.7
WSL	35.210	110.439	586.7	87.6	295.0	296.2
SJA	34.847	109.454	685.1	98.4	295.4	294.4
QAH	34.388	108.574	780.0	95.4	296.7	302.5
GRH	34.062	107.461	887.9	108.7	296.4	289.8
CZZ	33.483	106.055	1033.1	145.2	297.1	296.6

To obtain meaningful surface-wave velocities, precise relative timing is critical. For this experiment, timing was provided by the internal clocks of the recorders, which were synchronized to a standard time base either manually to time signals broadcast by WWV (Boulder, Colorado), or automatically to time signals from the GOES satellite. Despite the care taken by the individual operators of the various stations, analysis of the data from station STG lead us to believe that the clock was in error by at least 10 seconds; we have thus ignored the data from STG in our subsequent analyses and modelling.

Even if there are no timing errors, accurate surface-wave velocities cannot be obtained unless the effects of the instruments on the ground motion can be accounted for. In order to quantify these effects, we record the system response to a known acceleration applied to the seismometer; this calibration test results in a calibration pulse that is recorded in exactly the same manner as is a seismic signal from the seismometer. Analysis of this calibration pulse allows us to remove (numerically) the effects of the recording system on our data. A calibration test was done at all nine stations shortly before, or soon after, the signal from event Serena was recorded. All intermediate-period data were recorded on cassette tapes, which were taken to Los Alamos National Laboratories (LANL) so that the data could be played back, collected, and transferred onto a single standard 9-track computer tape for later playback and analyses.

III. DATA AND DATA REDUCTION

The nine-track tape produced by LANL personnel was transported to New Mexico Tech for data reduction and analyses. The data from each station was culled to obtain a time series 9001 points (900 sec) long, encompassing the entire seismic signal from P-wave through the coda. (Noise or recording spikes in the data from station WSL resulted in a time series only 7801 points

(780 sec) long.) The records containing the calibration pulses were similarly examined to obtain files 3001 points (300 sec) long. These labors produced files of manageable length containing either the seismic signal or the calibration pulse from each of the nine stations; these files were archived on floppy disk to provide both another back-up to the cassette and 9-track data as well as convenient access to the data.

III.A. Group Velocities

We began our data analysis by computing single-station (i.e., between NTS and the station in question), fundamental-mode group velocity curves for each of our nine stations. The group velocities were obtained by the multiple-filter technique described by Dziewonski and Hales (1972). Our results are displayed in Figure 2. Examination of the group velocities show that they are generally of the same character, with a maximum velocity near ~3 km/sec, decreasing to ~2.5 km/sec near a period of 4 seconds. However, two curves show substantially different behavior. In particular, the group velocities for both WCC (Figure 2a) and STG (Figure 2b) are substantially smaller than any of the others. Although the paths for both of these lie either wholly or substantially within the Basin and Range province (Figure 1), and thus could be expected to be lower than those with paths substantially within the Colorado Plateau, the velocities at STG, when compared with those of the stations adjacent to it (WCC and KNF), would require a structure with abnormally low velocities to exist between WCC and STG, and a structure with abnormally high velocities to exist between STG and KNF. We reject this hypothesis, and instead conclude that an unrectifiable timing error exists in our STG data. Rough calculations suggest that the magnitude of the error is probably somewhere between 10 and 15 seconds.

Figure 2: Single-station group velocities obtained using the multiple-filter technique [Dziewonski and Hales (1972)].

Initial attempts at computing interstation group velocities directly from the single-station group velocities produced disappointing results. The noisy data, together with the relatively short interstation distances, caused the two-station group velocity curves to have little form or comeliness. To improve the picture, we introduced a smoothing procedure by fitting each of our single-station group-velocity curves (Figure 2) with a fifth-order polynomial (Table 3) and then using the group velocities predicted by the polynomials to produce interstation group velocities. To further smooth the data, we have elected to compute interstation velocities between every second station. In part this is because we believe station STG has an uncorrectable timing error, and in part is because we found that the velocities for the station pairs WCC-KNF, KNF-WSL, and WSL-QAH were all similar, and thus calculations for shorter paths would gain little. These interstation velocities are shown in Figure 3.

III.B. Phase Velocities

Our method of obtaining interstation phase velocities is described in detail in Schlue et al. (1986). In brief, we begin by filtering each time series with a narrow band-pass filter of width $T_0/4$, where T_0 is the central period of the filter (Herrmann, 1973), and then windowing the filtered records in the time domain to remove energy arriving at times significantly different from that of the fundamental mode. We then cross correlate the two windowed records and, finally, perform a harmonic analysis on the cross correlogram to obtain the phase differences necessary for the phase velocity calculations. These phase differences are corrected for the phase response of the instruments before the phase velocities are calculated. Owing to the narrowness of our band-pass filters, each sequence of filtering, windowing, cross-correlation and harmonic analysis yields acceptable phase velocities for

Figure 3: Interstation group velocities from 5th-order polynomial fits (Table 3) to the single-station group velocities (Figure 2).

Table 3
Coefficients for 5th-Order Group Velocity (U) Polynomials*

Path	a_0	a_1	a_2	a_3	a_4
NTS - WCC	$0.1385 \times 10^{+1}$	0.3270×10^0	-0.2406×10^{-1}	0.2646×10^{-3}	0.1758×10^{-4}
NTS - STG	0.8091×10^0	0.4919×10^0	-0.5661×10^{-1}	0.2993×10^{-2}	-0.5893×10^{-4}
NTS - KNF	$0.1269 \times 10^{+1}$	0.5028×10^0	-0.6190×10^{-1}	0.3541×10^{-2}	-0.7626×10^{-4}
NTS - WPR	$0.2594 \times 10^{+1}$	-0.5760×10^{-1}	0.2537×10^{-1}	-0.2254×10^{-2}	0.6152×10^{-4}
NTS - WSL	$0.2819 \times 10^{+1}$	-0.1605×10^0	0.4438×10^{-1}	-0.3689×10^{-2}	0.9946×10^{-4}
NTS - SJA	$0.1892 \times 10^{+1}$	0.2624×10^0	-0.2141×10^{-1}	0.6117×10^{-3}	-0.1800×10^{-5}
NTS - QAH	$0.2354 \times 10^{+1}$	0.6788×10^{-1}	0.9225×10^{-2}	-0.1437×10^{-2}	0.4680×10^{-4}
NTS - GRH	0.1267×10^{-1}	$0.1021 \times 10^{+1}$	-0.1320×10^0	0.7488×10^{-2}	-0.1567×10^{-3}
NTS - CZZ	0.1437×10^{-1}	0.4046×10^0	-0.3927×10^{-1}	0.1618×10^{-2}	-0.2364×10^{-4}

*U = $a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5$, 5.0 sec $\leq$ T $\leq$ 15.0 sec

a small band of periods that is always smaller than the pass band of the filter. Thus, to obtain a complete suite of phase velocities for a particular station pair, we must repeat the sequence described above using several overlapping pass-band filters and subsequent operations. As a result of these labors we have obtained phase velocity data for the four station pairs for which we displayed group velocity data, namely WCC-KNF, KNF-WSL, WSL-QAH, and QAH-CZZ (Figure 4). Once again, we see that the velocities for the first three pairs are quite similar, with those for QAH-CZZ differing significantly from the first three.

IV. MODELLING OF THE DATA

Because of the similarity of the phase velocities for the path segments between WCC and QAH (Figures 4 and 5), we averaged the phase velocities from paths WCC-KNF, KNF-WSL, and WSL-QAH at each period to obtain an average phase velocity curve (Figure 6); these data will be used to obtain a one-dimensional model for the upper crust between WCC and QAH. The phase velocities for the path segment QAH-CZZ (Figures 4 and 5) are significantly different from those of the first three segments; these data will be inverted separately from the data of the other segments to obtain a one-dimensional model of the upper crust between QAH and CZZ.

Our initial models for the inversion process were obtained by making small changes to the models found by Schlue et al. (1987) until the phase velocities were "in the neighborhood" of one or the other of our observed phase velocity curves (Figure 6). All of our models were perfectly elastic one-dimensional structures; the phase velocities and their derivatives were obtained by standard Thompson-Haskell techniques (Schwab and Knopoff, 1972). We then inverted our data for the shear-wave velocities using linear inverse techniques (Jackson, 1972). During our initial inversion attempts, we learned

Figure 4: Interstation phase velocities.

Figure 5: Composite phase velocity plot showing similarity of Colorado Plateau paths WCC-KNF (+), KNF-WSL (□), and WSL-QAH (o) together with the Rio Grande rift path QAH-CZZ (x).

Figure 6: Average phase velocity for the Colorado Plateau paths (Δ) with one-standard deviation envelope (dashed line), together with Rio Grande rift phase velocities (x).

that our data had, at most, only three or four degrees of freedom. For this reason, and because we knew that our data had little or no control over the structure below mid-crustal depths, we held constant all parameters below 23.65 km, divided the upper crust into a two- or three-layered sediment section plus a 21 km-thick "basement", and inverted for the shear-wave velocities in this three-layer or four-layer "upper crust". Our results are given in Table 4, with the shear-wave profiles displayed in Figure 7.

The validity of our final models depends on how well their phase velocities match the observations. Figure 8 displays the observed data with the phase velocities generated from these models. In general, the fit is quite good, given the uncertainties in the data. In Figure 9, we show the group velocities obtained from our two models, together with the average of the interstation group velocities calculated from the fifth-order polynomials ("observed"). Although the group velocities were not used in the inversion process, the correspondence between the "observed" and calculated values are at least as good as for the phase velocities.

V. DISCUSSION AND CONCLUSIONS

A surprising result of our inversions is that the shear-wave profiles (Figure 7) differ significantly from each other only to a depth of 2.65 km. Given that our phase velocity data extend to a maximum wavelength (λ) of ~50 km, we should have excellent control over the resultant structures to depths of at least 17 km ($\sim 1/3 \lambda$) and good control to 25 km ($\sim 1/2 \lambda$). We thus conclude that the similarities below ~3 km are real, and above mid-crustal depths at least, the structures differ significantly only in the thickness of their sediments (0.65 km for "Plateau" versus 2.65 km for "Rift"). We have little or no information on lower-crustal or upper-mantle velocities.

Table 4
Models from Inversion of Phase Velocities

Thickness (km)	S velocity (km/sec)	P velocity (km/sec)	Density (gm/cm ³)
Southern Colorado Plateau			
0.65	1.34*	2.33	2.20
2.00	3.00*	5.20	2.67
21.00	3.66*	6.21	2.80
16.35	3.70	6.80	3.00
∞	4.26	7.85	3.36
Rift (QAH - CZZ)			
0.65	1.50*	2.60	2.20
1.00	1.90*	3.29	2.20
1.00	2.50*	4.33	2.67
21.00	3.60*	6.24	2.80
16.35	3.70	6.80	3.00
∞	4.26	7.85	3.36

* Variables in inversion process

Figure 7: Shear-wave (β) velocity profiles for upper 30 km obtained from inversion of phase velocity data. The solid line shows the "Plateau" model, while the broken line displays the "Rift" model.

Figure 8: Fit of phase velocities obtained from the models (solid lines) with the Colorado Plateau (Δ) and Rio Grande rift ($\times$) data.

Figure 9: Fit of group velocities obtained from the models (solid lines) with the average Colorado Plateau (Δ) and Rio Grande rift (x) data. Dashed lines show one-standard deviation envelope about the Colorado Plateau data (Δ). Note that the group velocities were not used in the inversion process.

These sediment thicknesses and upper-crustal shear velocities can be compared to models found by other investigators using similar techniques. Keller et al. (1976) obtained single-station group velocities for the eastern Basin and Range (BR) and northern Colorado Plateau (CP). Simple inspection shows that our group velocities, which are from paths that are dominately in the southern CP, are significantly higher than those from the northern CP, but comparable to those obtained from the eastern BR (Keller et al., 1976). Similarly, group velocities from paths in the central CP (Keller et al., 1979) are also higher than ours, although their phase velocities are comparable to ours. In fact, the CP group velocities of Keller et al. (1976, 1979) are closer to the group velocities of our QAH-CZZ "Rift" path than they are to our CP paths. The resultant models, taken at face value, show sediment thicknesses decreasing systematically from north to south (Table 5).

Similar comparisons can be made with the results of Bache et al. (1978), who obtained single-station phase and group velocities for paths between NTS and Tucson (TUC), and NTS and Albuquerque (ALQ). Once again, our "Rift" group velocities (QAH-CZZ) are similar to their velocities for the NTS-ALQ path (dominately Colorado Plateau), while our CP velocities are similar to those for their NTS-TUC path (dominately Basin and Range). It is difficult to compare our models with theirs in detail, as they have not tabulated their results. The most noticeable difference between their two models is in the thickness of the sediments, with a thickness of 2.5 km for NTS-ALQ, and 1.0 km for NTS-TUC.

Our model for the Rio Grande rift is similar in broad detail to that found by Schlue et al. (1987). Both have 2.65 km of low velocity sediments, although the shear-wave velocities for both the sediments and upper crust in

Table 5
Upper-Crustal Shear-Wave Models of the Colorado Plateau (CP)

Northern CP ^a		Central CP ^b		Southern CP ^c	
Thk (km)	β (km/s)	Thk (km)	β (km/s)	Thk (km)	β (km/s)
2.0	1.81	1.3	1.70	0.65	1.34
7.0	3.52	14.9	3.60	2.00	3.00
15.0	3.69	29.4	3.70	21.0	3.66

a Keller et al. (1976)

b Keller et al. (1979)

c This study.

their model (RGR) are substantially lower than those found here for "Rift". There are several obvious possibilities for the differences in velocities. One is that data for the "Rift" are from an area that is substantially to the south of where data for RGR were obtained; the velocity differences may reflect real differences in the Rift between these two locations. Another possible explanation is that our path QAH-CZZ includes a portion that is probably more Colorado Plateau than Rio Grande rift, and thus the higher velocities are a natural result of averaging Colorado Plateau structure with rift structure.

Because we have data only to a period of 15 sec, we do not have good structural control below mid-crustal depths. We therefore have little or no information on lower-crustal and upper-mantle velocities, and cannot speculate on how the thickness of the crust, or the upper-mantle velocities, vary over the extent of our line. We are surprised by the lack of variation in the upper crust between NTS and the western edge of the Rio Grande rift; whether that constancy continues into the lower crust and upper mantle cannot be determined from these data.

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