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New Mexico Bureau of Mines and Mineral Resources

Completion Report

USE OF SEISMIC REFLECTION PROFILES TO CHARACTERIZE SOIL DEFORMATION ASSOCIATED WITH EARTH FISSURES AND GROUNDWATER WITHDRAWAL NEAR DEMING, NEW MEXICO

funded in part by

New Mexico Institute of Mining and Technology Research Council

submitted by

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INTRODUCTION

The formation of earth fissures due to groundwater withdrawal is a common occurrence in the American Southwest, where high water demand and low recharge cause aquifer depletion and subsidence (Holzer, 1984). Consequences of fissuring include damage to civil structures such as roads and canals, decreased property values, and danger of injury to humans and animals. Fissures associated with groundwater withdrawal in New Mexico have so far been limited to the Deming area, where groundwater is pumped heavily for irrigation. It is likely, however, that subsidence and fissuring will spread to other areas of the state as population and water demand both continue to grow.

It commonly believed that many fissures, including some near Deming, are the result of stresses developed during differential compaction of strata over irregularities such as bedrock structures or slowly-consolidating clay lenses. The cost of drilling on a scale detailed enough to document soil deformation around small, isolated irregularities is generally prohibitive, and existing water wells are typically spaced too far apart for information from driller's logs to be of much use. Geophysical methods such as gravity surveys, although affordable, provide only information on large-scale bedrock structures. Thus, using conventional methods the significance of differential compaction can only be inferred from surface and bedrock topography. Seismic reflection profiling has the potential to fill this void by providing a relatively inexpensive, reliable method of characterizing soil deformation associated with earth fissures and other geotechnical problems.

Funds from the NMIMT Research Council grant were used for collection and processing of 1.5 km of high-resolution, shallow seismic reflection lines across an area of known earth fissures south of Deming, New Mexico. Additional funding from the New Mexico Bureau of Mines and Mineral Resources was used for 1) collection and processing of seismic data, 2) collection of gravimetric and topographic data, and 3) formulation of mechanical models for stress and displacement fields in compressible elastic layers draped over irregularities.

RELATED STUDIES

A review of field studies by Holzer (1984) shows that detailed measurement of ground subsidence and separation across fissures, and passive geophysical methods such as gravity and magnetic surveys, are the conventional methods of characterizing soil deformation associated with earth fissures. Detailed gravity and magnetic surveys (e.g., Jachens and Holzer, 1979, 1982) provide only limited data on bedrock topography, from which the existence of differential compaction can only be inferred by comparing geophysical anomalies with measured subsidence and fissure locations. Surface subsidence measurements have also been used to partially constrain finite element models of soil deformation, which suggest that some fissures may be located in areas of high tensile strain at the ground surface (Jachens and Holzer, 1982; Larson and Pewe, 1986). Finally, in situations where geophysical data were not available, geomorphology and regional geology suggest that neotectonic uplift may also have played a role in the development of earth fissures in Nevada (Bell *et al.*, 1989) and west Texas (Keaton and Shlemon, in press).

Profiles across geologically young fault scarps in Idaho (Miller and Steeples, 1986; Treadway *et al.*, 1988) and Oklahoma (Miller *et al.*, 1990) show that shallow seismic reflection methods can yield considerable information about soil deformation associated with near-surface structures. Current research on the San Marcial earth fissure, which crosses I-25 some 50 km south of Socorro, also shows that shallow reflection surveys can resolve shallow geologic structures that cannot be detected by detailed gravity surveys alone. Such information can be used to better constrain mechanical analyses of differential compaction and monoclinal flexure of soil layers (Haneberg and Reynolds, in press; Reynolds *et al.*, in review; Haneberg *et al.*, in preparation).

GEOLOGIC SETTING

Deming lies near the center of Luna County, in south-central New Mexico, which was first described and geologically mapped by Darton (1916, 1917). With the exception of small mountain blocks such as Cooke's Range, the Florida Mountains, and the Tres Hermanas Mountains, the Deming area is physiographycally characterized by flat, nearly featureless Quaternary deposits filling the Mimbres bolson. Oil and gas exploration well logs from four wildcat wells near Deming show about 700 to 1300 m of undifferentiated basin fill deposits overlying Oligocene and Miocene volcanic rocks, although lithologic similarities between the volcanic rocks and sediments derived from the former make it difficult to identify a sharp contact between basin fill and underlying volcanics (Clemons, 1986). In general, bolson fill deposits are composed of alternating gravel, sand, and clay with some interstratified volcanic rocks. Both Darton (1916) and Clemons (1986), however, report lithified deposits at depths of 250 to 300 m; Clemons believes these deposits to be Tertiary bolson fill.

Average annual precipitation at Deming has averaged 0.24 m between 1899 and 1986, with a low of 0.07 m in 1956 and a high of 0.56 m in 1986 (Mueller, 1988). Soils near the center of the bolson are of the Mimbres association, consisting of deep, well-drained, moderately fine-grained soils on very gentle slopes sparsely covered by mesquite, four-wing saltbush, grasses, and yucca (Neher and Buchanan, 1980). There is some lime accumulation near the surface, with additional buied calcic soil horizons at depth.

Darton (1916, 1917) first described early agricultural use of groundwater from shallow bolson-fill sands and gravels south of Deming. Although recharge rates are unknown, they must be only a fraction of the average annual precipitation; therefore, large-scale groundwater withdrawal from the Mimbres bolson is, in effect, groundwater mining. Over the years water levels have fallen up to 35 m, producing a large cone of depression centered some 12 km south of Deming, along with the attendant problems of land subsidence and earth fissuring (Contaldo and Mueller, 1988; Contaldo, 1989). This gives an average water level decline of nearly 0.5 m per year. It is impossible to accurately determine the amount of subsidence that has occurred, because level lines across the Mesilla bolson have not been re-surveyed. However, re-occupation of several isolated benchmarks near the center of the cone of depression suggests that approximately 0.33 m of subsidence occurred between 1953 and 1988. Earth fissures are likewise concentrated in the cone of depression, and can be grouped into two broad categories: curvilinear and polygonal. The fissures commonly appear as hairline cracks, and are subsequently widened by piping and erosion during storms. Contaldo (1989) believes that polygonal fissures form in finer, more plastic soils than do curvilinear features. However, beyond the general association with groundwater withdrawal, not enough geologic details are known to infer the origin or origins of individual fissures.

The fissure described in this report is located in NE/4, NE/4, Sec. 32, T25S, R9W of the USGS Midway Butte 7.5 minute quadrangle, on property owned by Ms. June Cox. It was chosen because of its accessibility, proximity to occupied dwellings, and the cooperation of Ms. Cox. This fissure, which appeared during a heavy October, 1984 rainstorm is about 360 m long, may be the continuation of a shorter fissure immediately to the south, which appeared in June, 1982. These two fissures will thus be referred to as the northern and southern Cox fissures. Both of these fissures have been significantly altered by erosion, piping, and human activity since they appeared. As such, it is difficult to say much about the details of original fissure morphology. A sketch map by Contaldo (1989, p. 34) does, however, show the norther Cox fissure to be a generally linear feature striking nearly north-south. Much of the northern Cox fissure has been naturally filled and healed in the five years since its origin; this stands in contrast to cavernous subsurface voids that exist along an earth fissure near San Marcial, New Mexico, which formed in 1981.

GEOPHYSICAL DATA

Seismic

Seismic data were collected and processed under contract by Charles B. Reynolds & Associates, Albuquerque. Energy source was a soft leather bag filled with 250 kg of lead shot and dropped from a height of 2 m. Data were collected for 1 s at 1 ms intervals, using a 12-channel EG&G digital system and 10 Hz Mark Products gimbal-mounted, self-orienting drag geophones. Drop point and geophone spacing was 5 m, with 1 to 3 drops per point, giving a total of 300 reflection traces. Data processing included reduction to 0.5 s record length; application of an F-K filter to remove refractions, ground roll, and air waves; deconvolution; 1200% CDP stacking; 2:1 horizontal stacking; application of datum corrections; and frequency filtering. Refraction breaks from the raw data were also used to infer near-surface P-wave velocities at every third drop point, giving a total of 100 shallow depth-velocity profiles.

Reflectors are fairly continuous above 0.20 s two-way time beneath the northern Cox fissure, but become discontinuous thereafter, suggesting a group of high-angle normal faults beneath an angular unconformity (Figure 1). The fissure intersects the seismic line at drop point 56. Although the reflectors above the unconformity do not show evidence of faulting, the arrival time for the uppermost reflector decreases by about 0.014 s to form a small structural high with about 1.5 m relief directly beneath the fissure. P-wave velocity contours reveal a surficial layer from about 0 to 5 m in depth, with velocities less than 400 m/s, and a second layer, from about 5 to 30 m in depth, with velocities between 400 and 700 m/s (Figure 2). This low velocity zone bifurcates to follow two west-dipping buried normal faults. Directly beneath the low velocity zone, however, is a zone of elevated velocities; this observation is opposite that described by Haneberg *et al.* (in preparation), who were concerned with the opposite situation of concave-up flexure of soil layers above a graben. Although the theoretical lower limit for P-wave velocities is the speed of sound, approximately 335 m/s, calculated velocities lower than 300 m/s are common at extremely shallow depths both the northern Cox and San Marcial (Haneberg and Reynolds, in press). Refraction depth-velocity solutions also allow a structure section to be constructed (Figure 3), again showing that the fissure is located along the eastern edge of a small structural high and density (from velocity and gravity data) low.

Gravity

Gravity readings were recorded at every tenth drop point (*i.e.*, 50 m intervals) using a LaCoste & Romberg Model G gravity meter on loan from the U.S. Geological Survey. Data were reduced using standard methods (*e.g.*, Dobrin, 1976), with a combined free-air and Bouguer correction of 0.1969 mgal/m. Elevation changes ware negligible, so terrain corrections were not applied.

Negative gravity anomalies are generally associated with topographic highs and positive gravity anomalies are generally associated with topographic lows (Figures 4 and 5), with no evidence of buried structures. The fissure, which crosses the gravity line at drop point 56, lies above a very small (≈ -0.25mgal) gravity anomaly. However, anomalies of similar magnitude are centered beneath drop points 140 and 220, above structural lows (*cf.* Figures 1,2, and 3) with no evidence of fissuring.

MECHANICAL INTERPRETATION

Although neither gravity nor shallow seismic methods provide an unambiguous explanation of the northern Cox earth fissure, results can be used to constrain a mechanical analysis of conditions that might have led to fissuring. The combination of topographic and structural highs along with gravity and near-surface velocity lows suggests that shallow bolson fill deposits were draped over a small structural high, centered around drop point 65, and possibly related to movement along a series of west-dipping normal faults. Details of the mechanical model, derived as part of a previous earth fissure investigation, are described elsewhere (Haneberg *et al.*, in preparation) and will not be elaborated upon.

As a first approximation, this analysis assumes that fissuring is restricted to unconsolidated bolson-fill deposits above the 0.2 s buried unconformity; this corresponds to Horizon "A" on the structure section (Figure 3). The structural high can be represented by specifying vertical displacement along the lower boundary as a simple consinusoidal function of distance, with an amplitude of 2 m and a wavelength of 500 m. The upper boundary, representing the earth's surface, is a free surface along which both shear and normal tractions must vanish. Thickness of the theoretical soil layer is assumed to be 35 m. The Young's modulus of soils typically ranges over an order of magnitude or less, so the solution presented here is not particularly sensitive to values of the elastic constants (*e.g.*, Das, 1984, p. 129). This analysis will use typical values of $E = 15$MPa and $\nu = 0.25$ for Young's modulus and Poisson's ratio as reasonable first guesses. Density of the layer is assumed to be $\rho = 2000 \text{kg/m}^3$.

Figure 6 shows a relatively uniform pattern of horizontal and and vertical displacements within the deformed layer, similar to the flexure of a simple elastic beam. The state of stress can be characterized by the values of two principal stresses, σ_1 and σ_3. Tensile stresses and strains are assumed to be positive throughout this analysis, so σ_1 represents the least compresssive or most tensile principal stress, whereas σ_3 represents the most compressive or least tensile principal stress. Figure 7, illustrating the most compressive principal stress, shows that the influence of a cosinusoidal displacement along the lower boundary are most pronounced along the upper free surface. There is a slight increase in compression along the lower boundary; however, the magnitude of this increase is small compared to the lithostatic compression of -700000Pa due to gravity loading. In contrast, the cosinusoidal flexure has a much more pronounced effect on the least compressive principal stress, particularly near the upper boundary. As above, however, the effects of the flexure are dominated by lithostatic compression at depth. Zones of reduced compression correspond to the low velocity zone in Figure 2, suggesting that low velocities are produced by stretching of shallow soil above a neutral surface, and that high velocities are produced by compression beneath a neutral surface. This is consistent with surface-stretching models of earth fissure origin (*e.g.*, Holzer, 1984; Larson and Péwé, 1986), in which fissures propagate downward from the earth's surface. Moreover, a fissure that propagated downward and died out with depth (*e.g.*, the northern Cox fissure) would tend to be filled much more rapidly than one which propagated upward from depth (*e.g.*, the San Marcial fissure).

SUMMARY AND FUTURE WORK

Seismic, gravity, and topographic surveys show that the northern Cox earth fissure is developed above a small, shallow structural high, perhaps associated with a series of buried normal faults. In particular, the velocity anomalies associated with the structural high can be understood using a simple mechanical model for flexure of a gravity-loaded elastic layer. As such, appropriately collected and processed seismic reflection data can provide invaluable yet affordable information with which to constrain mechanical models of soil deformation. These results are consistent with a previous geophysical and mechanical study of the San Marcial earth fissure. Future work on geophysical characterization of shallow soil deformation will be concentrated on mapping and mechanical interpretation of velocity anomalies, particularly the use of theoretical models to create synthetic velocity contour maps.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

FIGURE 1.– Seismic reflection record section across the northern Cox earth fissure, Luna County, New Mexico. Fissure is approximately perpendicular to the seismic line, which it intersects at drop point 56.

FIGURE 2.– P-wave velocity contours from refraction depth-velocity solutions at every third drop point. Contour interval is 100 m/s.

FIGURE 3.– Structure section prepared across the northern Cox earth fissure.

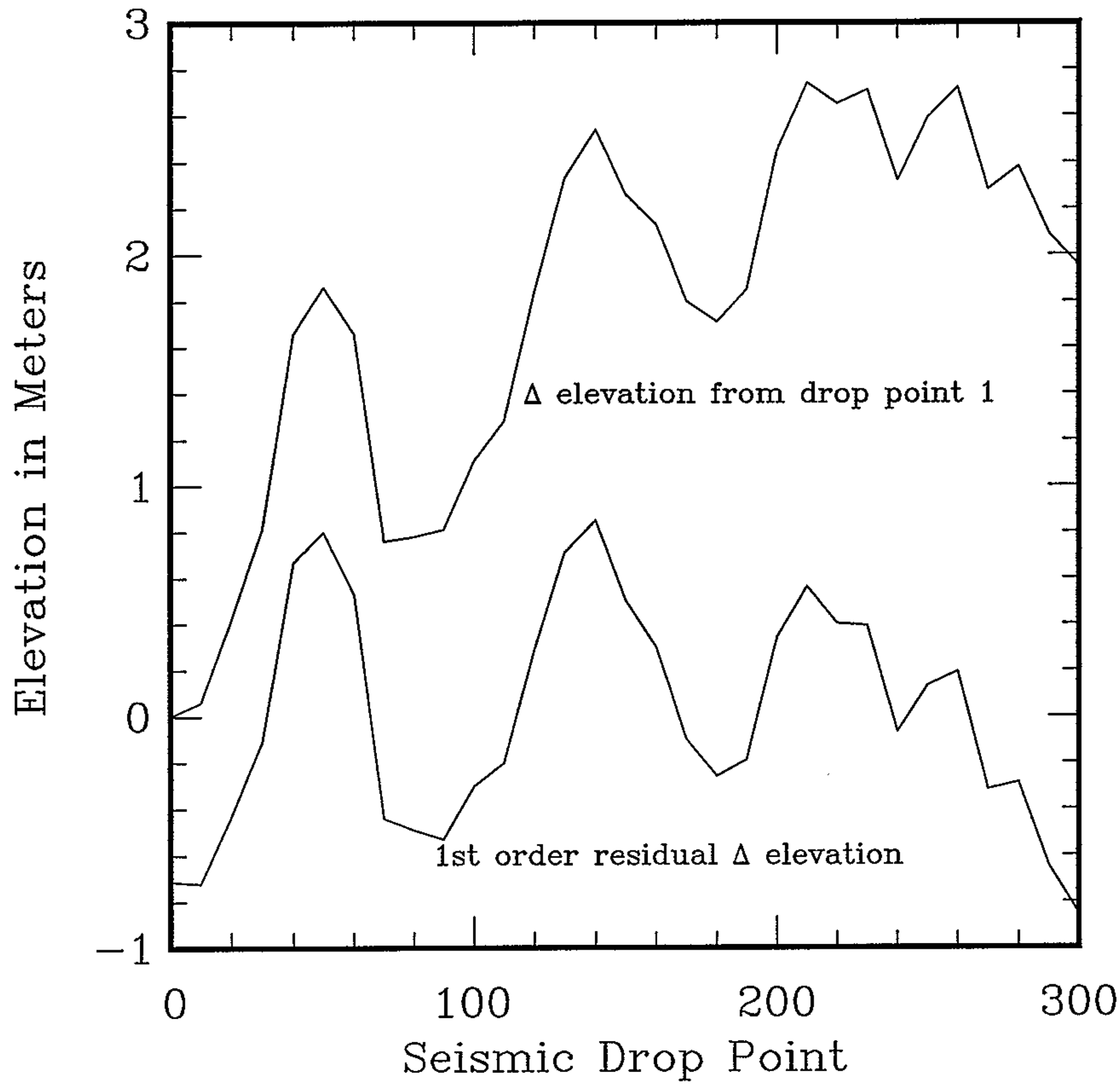
FIGURE 4.– Elevation changes relative to drop point 1 and 1st order residual elevation changes after subtraction of a best-fit linear trend.

FIGURE 5.– Combined Bouguer and free-air gravity anomaly and 1st order residual gravity anomaly, northern Cox earth fissure.

FIGURE 6.– Deformed mesh illustrating displacement fields induced by cosinusoidal flexure of a compressable elastic slab loaded by gravity. Horizontal and vertical components of displacement magnified by 10 $\times$.

FIGURE 7.– Least compressive/most tensile prinicple stresses for the slab illustrated in Figure 6. From top to bottom, curves are for dimensionless depths of 0, 0.25, 0.50, 0.75, and 1.00. Tension is positive.

FIGURE 8.– Most compressive/least tensile prinicple stresses for the slab illustrated in Figure 6. From top to bottom, curves are for dimensionless depths of 0, 0.25, 0.50, 0.75, and 1.00. Tension is positive.



3
2
1
0
−1
0
100
200
300
Elevation in Meters
Seismic Drop Point
Δ elevation from drop point 1
1st order residual Δ elevation

FIG. 4

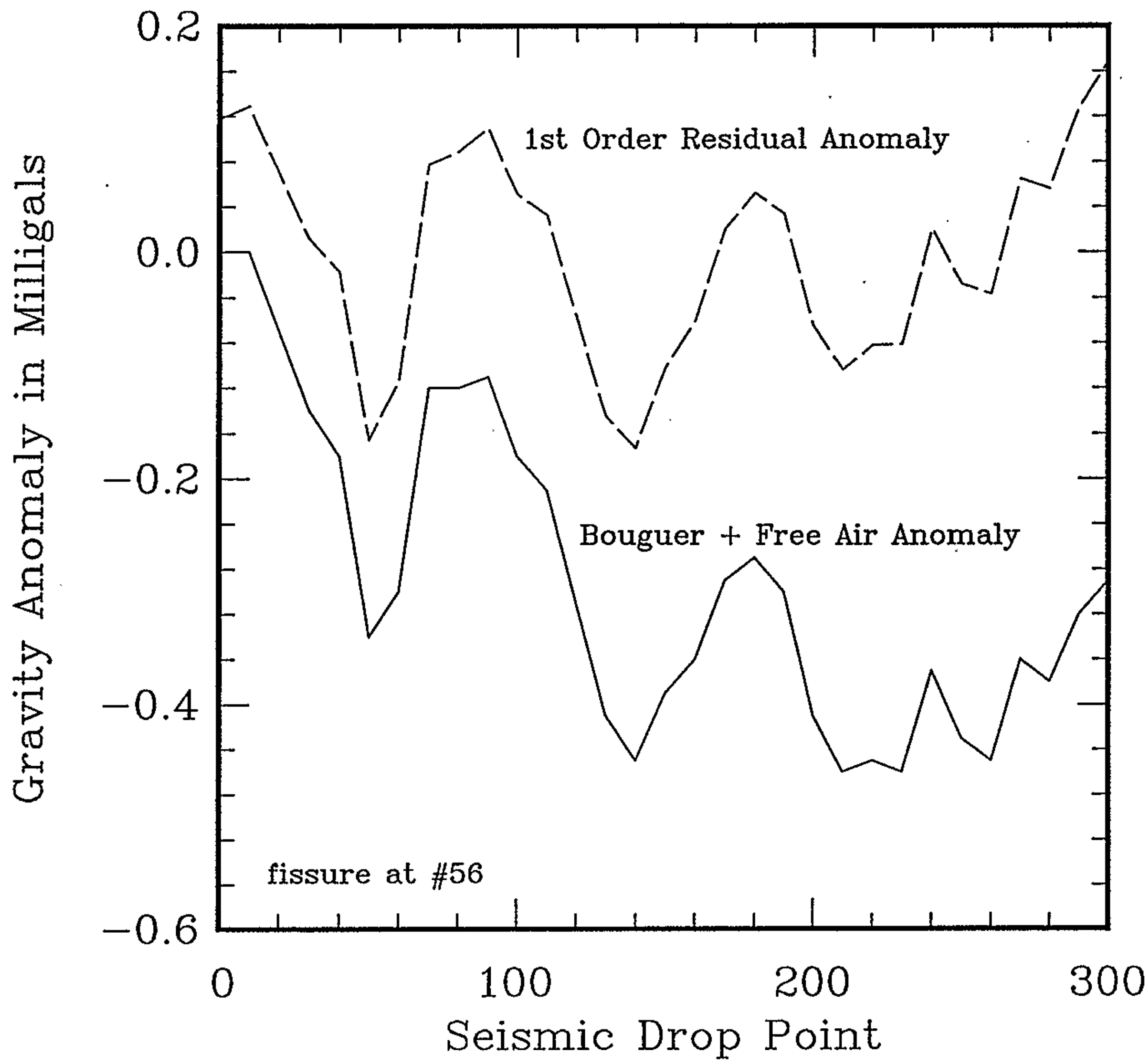
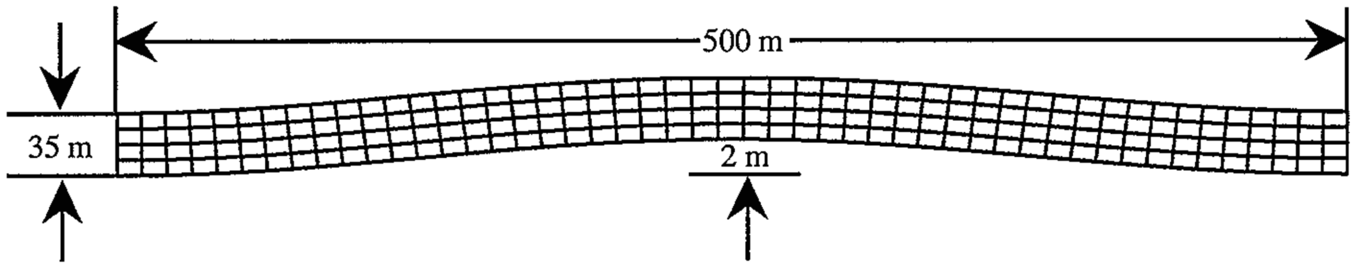
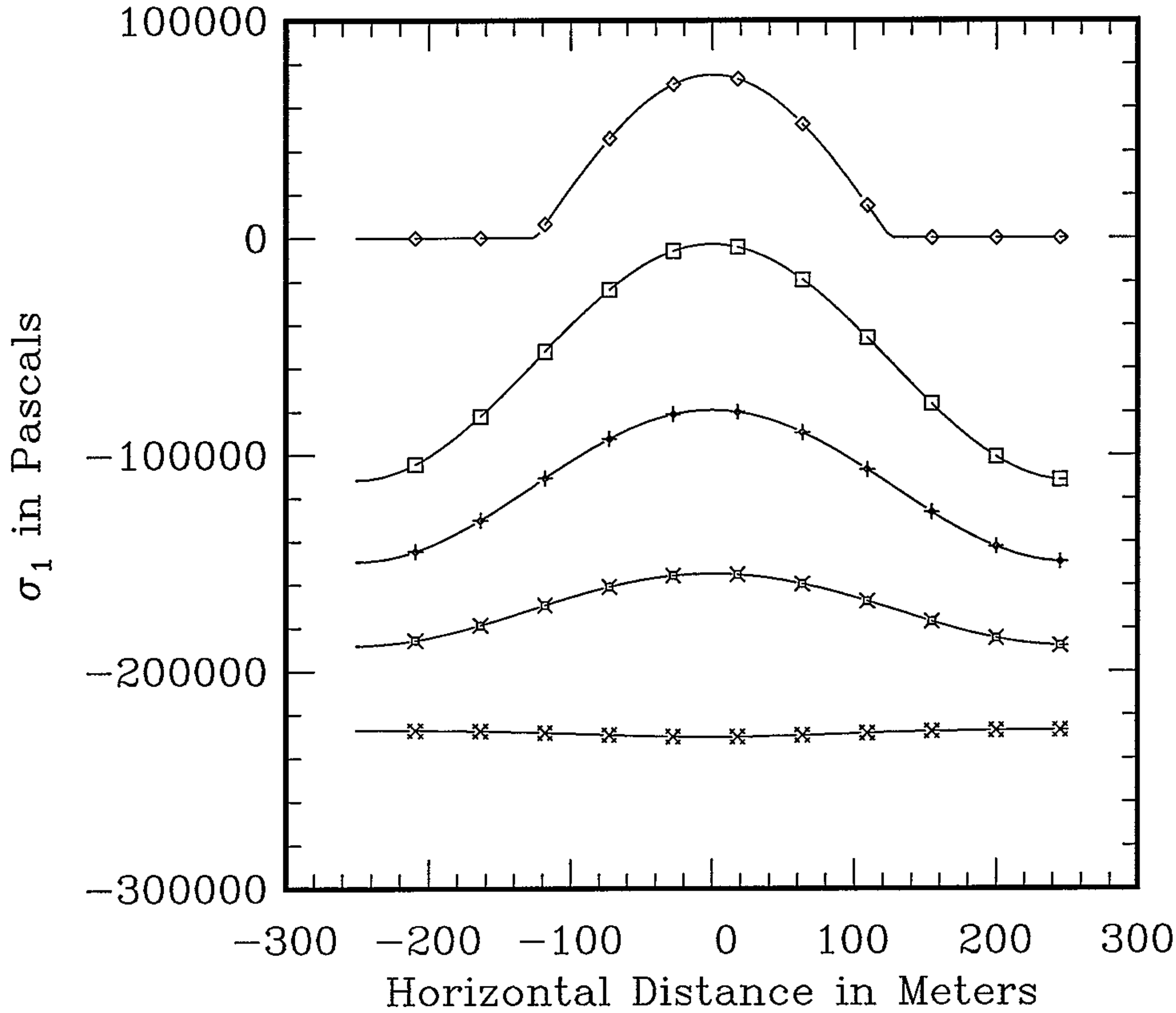

1st Order Residual Anomaly
Bouguer + Free Air Anomaly
fissure at #56
0.2
0.0
−0.2
−0.4
−0.6
0
100
200
300
Gravity Anomaly in Milligals
Seismic Drop Point

FIG. 5



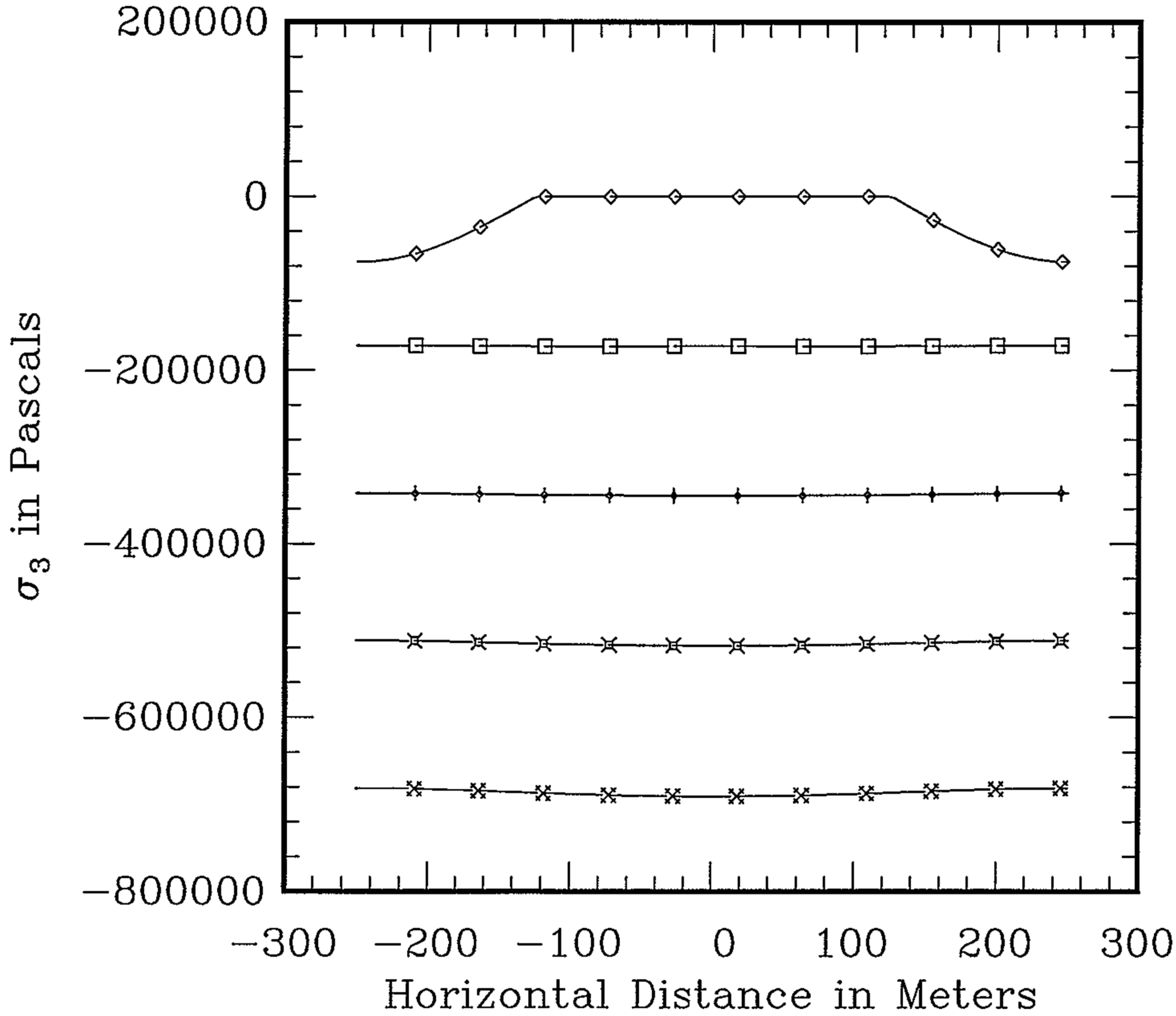
horizontal and vertical displacements magnified 10×

FIG. 6



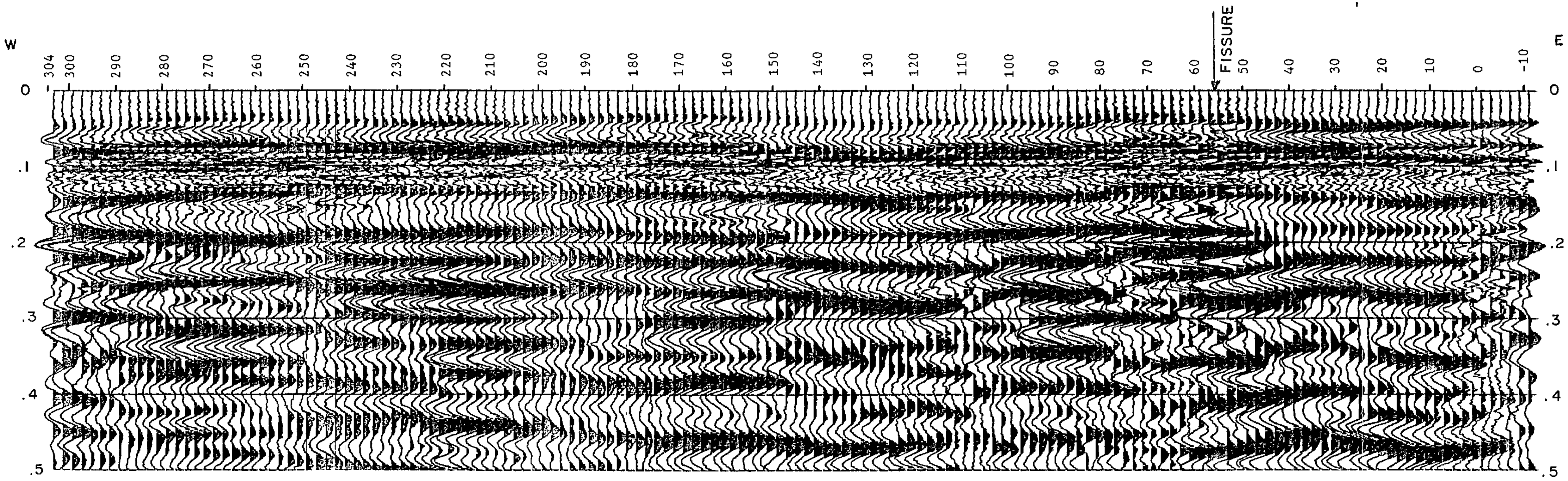
100000
0
−100000
−200000
−300000
σ_1 in Pascals
−300
−200
−100
0
100
200
300
Horizontal Distance in Meters

FIG. 7



200000
0
−200000
−400000
−600000
−800000
σ_3 in Pascals
−300
−200
−100
0
100
200
300
Horizontal Distance in Meters

FIG. 8



NM BUREAU OF MINES AND MINERAL RESOURCES

LINE JC-1 R1-R304

LUNA COUNTY NEW MEXICO
.5 SEC 2400% RECORD SECTION

RECORDING		
RECORDED BY: PRG	DATE RECORDED· 1/26/90	INSTRUMENTS: EG&G ES1210F
GAIN MODE: FIXED	FIELD FILTER: 0-200 HZ	60HZ NOTCH FILTER· IN
RECORD LENGTH: 1 SEC	SAMPLE RATE: 0.001 SEC	

SPREAD		
TYPE: END OVER	CDP FOLD: 12	NO OF GROUPS: 12
LINE DIR: E TO W	NEAR GRP CTR: 10 M	FAR GRP CTR: 120 M
SEISES/GRP: 1 @ 10 M INLINE	GROUP INTERVAL: 10 M	

ENERGY		
SOURCE· 250 KG WT DRP	SP ARRAY: POINT	SP INTERVAL· 5 M
SP OFFSET. 0	DROPS/SP: 1-3	

PROCESSING SEQUENCE		
(1) TRANSCR	(2) DATA EDIT	(3) REFRAN
(4) FANFIL	(5) DCON 20 MS	(6) STK 1200% CDP
(7) HZSTK 2:1	(8) DIPFIL	(9) TRC NORM
(10) PLOT VA/WT	(11)	(12)

PLOTTER DISPLAY		
HORIZ SCALE: 10 M/TRC	POLARITY: POS	VERT SCALE: 19 CM/SEC
WX VEL· 436 M/SEC	DATUM: NONE	SUBWX VEL· 744 M/SEC

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ENCLOSURE NO. 1

FIGURE 1

NEW MEXICO BUREAU OF MINES AND MINERAL RESOURCES

JUNE COX PROPERTY
Deming, Luna County, New Mexico

<u>VELOCITY DISTRIBUTION SECTION</u>
SEISMIC LINE JC-1

Horizontal scale: 1 cm = 20 m.
Vertical scale. 1 cm = 5 m.
Contour interval: 100 m/sec.

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ENCLOSURE NO. 4

FIGURE 2

FIGURE 3

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JUNE COX PROPERTY
Deming, Luna County, New Mexico

DEPTH SECTION
SEISMIC LINE JC-1

Scale: 1 cm = 20 m.

Deming Tertiary Velocity Function

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ENCLOSURE NO. 3