NEOGENE GRABENS IN SOUTHERNMOST ILLINOIS

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ABSTRACT

High-resolution seismic-reflection and ground-penetrating radar (GPR) surveys were carried out at seven sites in southernmost Illinois in this Year 1 of a two-year project. Geophysical surveys were designed to detect tectonic faults that displace Neogene and Quaternary sediments. The GPR surveys were unsuccessful because loess, which mantles nearly all upland surfaces in the study area, apparently acts as a barrier to radar waves. Among the seismic surveys, all but one (Post Creek) achieved good resolution of subsurface reflectors and imaged tectonic faulting. The faults interpreted from seismic are steeply dipping normal and reverse faults that commonly outline narrow grabens and less commonly outline horsts. Some grabens and horsts appear to be flower structures, indicative of strike-slip faulting. They displace Paleozoic bedrock and, in many cases, offset Cretaceous and Tertiary strata as well. Using the seismic data, we have identified many promising targets for drilling in Year 2 of this project.

INTRODUCTION

This report covers Year 1 of a 2-year program to investigate tectonic faults that displace Neogene and Quaternary sediments in southernmost Illinois. Year 1 was devoted to geophysical surveys designed to characterize known or suspected fault zones that had been identified from field mapping. These surveys consisted of high-resolution seismic reflection surveys carried out by two different contractors, and ground-penetrating radar surveys conducted by a third contractor. Data derived from these geophysical studies are being used to select targets for drilling, which will be carried out during Year 2 of this project.

Tectonic deformation of Neogene strata in Massac County was suspected by previous workers (Ross, 1963 and 1964; Kolata et al., 1981) and confirmed during detailed geologic mapping in the early 1990s (Devera and Nelson, 1997; Nelson, 1996). Further field mapping, drilling, and trenching were carried out under NEHRP grants, results of which are presented in previous reports (Nelson et al., 1996 and 1998) and journal articles (Nelson et al., 1997 and Nelson et al., in press). As these papers state, Neogene and Quaternary faults in southern Illinois typically outline narrow grabens, most of which strike northeast and are part of the Fluorspar Area Fault Complex (Fig. 1). Grabens are in line with the New Madrid Seismic Zone which, together with the Fluorspar Area Fault Complex, shares ancestry in a Cambrian-age failed rift (the Reelfoot Rift). Thus southern Illinois provides an opportunity to view, at or near the ground surface, structures that are closely tied to seismically active faults in the New Madrid area. Understanding the timing, recurrence intervals, structural style, and other factors of faulting in Illinois may lead to improved understanding of seismic mechanisms and earthquake risks throughout the central Mississippi Valley.

Geophysical surveys were carried out at seven sites under this year's NEHRP grant (Fig. 2). The ground-penetrating radar failed to provide data useful for interpreting geologic structure, and will be discussed in brief fashion. Seismic reflection surveys provided significant and valuable new insights on faulting in the region; the bulk of this report focuses on the seismic profiles and their interpretation.

GROUND-PENETRATING RADAR SURVEYS

Ground-penetrating radar (GPR) is a technique for imaging underground features at shallow depth by means of radio waves. A transceiver or antenna is used to transmit radio waves into the ground; reflected signals are recorded and processed. The image produced by GPR resembles a seismic-reflection profile, but has much higher resolution and much lesser depth of penetration (typically 5 to 30 meters, depending on ground conditions). GPR potentially can be used to show small-scale faulting and deformation of Quaternary sediments near the surface.

A GPR survey carried out by Sexton et al. (1996) along the valley bottom of Barnes Creek in Massac County (Fig. 2) produced clear imaging of sediments to depths of 10 to 20 m. Sexton's GPR profile indicated numerous faults, some of which were confirmed by outcrops in the bed of Barnes Creek and by a seismic reflection survey run along the same line of traverse. Encouraged by these results, we included GPR surveys in this year's investigation.

GPR surveys were carried out at 5 sites in Massac County by Mark Howell of Xenon Geosciences from Dayton, Ohio. The sites surveyed by GPR were Massac Creek, New Columbia, Reineking Hill, Choat, and Maple Grove (Fig. 2). All surveys were conducted using an 80-megahertz(MHz) antenna. Data were recorded continuously, then processed in Dayton by Ernie Hauser of Xenon. Following preliminary processing, Xenon re-surveyed (at no additional cost) portions of the New Columbia traverse using antennas of 300- and 500-MHz. These additional surveys were intended to enhance subsurface features imaged by the initial 80-MHz survey.

Results of the GPR surveys were highly disappointing. At three of the five sites surveyed, the GPR failed to penetrate the ground to any significant depth and therefore yielded essentially no reflections. An example of a GPR profile from Choat (Fig. 3) illustrates the lack of penetration as shown by absence of coherent reflectors. Significant ground penetration and well-defined reflectors were achieved only along portions of the Massac Creek and New Columbia lines. At these sites, discontinuous reflectors were imaged only in valley bottoms. No reflectors were imaged on the loess-covered valley walls at either site.

The best quality results from GPR were achieved along the valley bottom at the New Columbia site. Sets of broken, tilted reflectors are evident on images produced by 80-, 300-, and 500- MHz antennas. Lower frequencies produced better penetration, while the higher frequencies produced higher resolution. The 300-MHz antenna produced the best results (Fig. 4), but even this profile is difficult to interpret. Tilted reflectors might represent faulted and tilted layers of sediments in the shallow subsurface. However, the lack of continuity and context for these broken reflectors precludes any definitive geologic interpretation.

Evidently, GPR is generally unable to penetrate the loess that mantles nearly all upland surfaces in the central Mississippi Valley. Loess is dominantly silt, but some loess (particularly the Loveland Silt, which contains the Sangamon Geosol) has a high clay content; clay is impervious to GPR. Good penetration is achieved only in valley-bottom settings (as in the GPR survey of Sexton et al. at Barnes Creek) where sediments consist of silt, sand, and gravel with little or no clay content.

SEISMIC REFLECTION SURVEYS

Acquisition and Processing

High-resolution seismic reflection surveys were carried out at five sites during this year's program. Two different contractors were employed to acquire and process seismic data; the two operators used substantially different equipment and techniques for acquisition and processing.

Seismic surveys at Choat and Maple Grove (Fig. 2) were conducted by a team from the U.S. Geological Survey of Golden, Colorado. Bill Stephenson was the crew chief. The USGS survey ran a Mini-Sosie survey, using three modified earth-tamping machines as the source. Sixty groups of three geophones each were laid out at a spacing of 3.0 meters. Data were recorded in SEG 2 format on a 60-channel seismograph.

The USGS processed seismic data according to the following procedure:

1. Reformat data from SEG 2 to ProMax internal format.
2. Install elevation data into trace headers.
3. Remove bad traces and fix polarity reversals.
4. Resample data to 2 ms.
5. Apply a brute velocity function in preparation for applying a normal move-out correction. .
6. Using a frequency-wave number (FK) filter, remove ground roll and other dipping coherent noise. Apply polygonal accept region after normal move-out.
7. Apply inverse normal move-out correction.
8. Apply elevation statics using 1000 m/sec reduction velocity.
9. Apply adaptive spiking deconvolution, using L2 norm, 200 ms operator length.
10. Use time variant-bandpass filter and sort to receiver domain.
11. Make the normal move-out corrections.
12. Use the FK filter to remove coherent noise specific to each station. Sort to common midpoint domain.
13. Apply residual statics and dip move-out.
14. Conduct final stack.
15. Apply migration, using reverse-time time-wave number alogrithm, 80% of mean stacking velocity function used. Apply Eigenvector filtering to attenuate migration artifacts.
16. Carry out the time-to-depth conversion.

A team from the University of Missouri at Rolla (UMR), led by Neil Anderson, acquired seismic data at Massac Creek, Kelley, and Post Creek. This team used a truck-mounted multiple-impact wave generator (Bison Model EWG-1) as the source. Shot-point spacing was 10 feet (3.0 m), and 6 to 10 impacts were made at each station. An end-on array consisting of twenty-four 40-Hz geophones, spaced at 10-foot intervals, was employed. Data were recorded on a 24-channel Bison Model 9024A engineering seismograph with roll-along capabilities. Two records were generated at each shot point, using near offsets of 30 and 70 feet (9.1 and 21.3 m).

The UMR team processed their data using Winseis, a PC-based commercial software package (Kansas Geological Survey, 1996). The processing routine included:

1. Downloading reflection data from the seismograph to the PC and reformatting to Winseis,

2. Application of automatic gain control.
3. Muting of "dead" or excessively noisy traces.
4. Muting of first breaks and ground roll.
5. Design and application of the time-domain bandpass filter.
6. Resorting of data into common midpoint gathers.
7. Application of constant velocity stacks. Elevation statics were calculated using a replacement velocity of 4500 feet/second (1370 m/sec); zero time on each profile represents the point of highest elevation along that line.
8. Analysis of constant velocity stacks.
9. Determination of normal move-out velocities.
10. Generation of brute stack.
11. Residual statics correction.
12. Final stack.
13. Design and application of frequency-domain bandpass filter.

Choat

Surface mapping and drilling indicated a fault zone displacing the late Miocene to early Pleistocene Mounds Gravel and possibly younger units near the former village of Choat, located 5 km northwest of Metropolis, Illinois (Fig. 2). At the Metropolis City Landfill (Fig. 5), borehole data and exposures in borrow pits indicate the Mounds Gravel is downdropped into a northeast-trending graben. North of the landfill, the Melferd Krueger water well and a cored ISGS test hole also encountered Mounds Gravel(?) that appears to be dropped into a graben (Fig. 5). These faults, and others mapped in the vicinity, strike northeast and are part of the Raum Fault Zone in the Fluorspar Area Fault Complex.

The USGS carried out a seismic reflection survey 1.5 km long on county roads, passing within 100 m of the Krueger boreholes (Fig. 5). The seismic profile (Fig. 6a) contains two distinct sets of reflectors along its entire length. The upper set consists of relatively high-frequency reflectors down to about 150 to 180 milliseconds two-way travel time. These are interpreted (Fig. 6b) to represent the McNairy Formation (Cretaceous) and overlying Tertiary and Quaternary units. Individual reflectors in the upper set lack lateral continuity and cannot be identified with specific stratigraphic horizons. The lower set of reflectors, stronger and lower in frequency than the upper set, represent Paleozoic bedrock. The Paleozoic reflectors exhibit good lateral continuity. Maximum depth of coherent reflectors was 250 to 300 ms.

Several faults are indicated by interruption or offset of reflectors on the Choat seismic profile. The most prominent, labeled Fault A on the map (Fig. 5) and interpreted seismic profile (Fig. 6b), is at shot point (SP) 415, where strong, horizontal Paleozoic reflectors on the west terminate abruptly against a zone of weak, disrupted reflectors on the east. The uppermost Paleozoic reflector east of Fault A declines gradually toward the west from SP 250 to 380. Comparing the position of this reflector from SP 380 to SP 415, the reflector appears to be downthrown about 30 ms to the east. The upper, Cretaceous and younger package of reflectors seems to be displaced a like amount. Notice in particular how the set of high-amplitude reflectors, which is at 50 to 110 ms at SP 430, drops abruptly to 80-130 ms at SP 410.

Fault B, which is exposed in a borrow pit at the Metropolis city landfill (Fig. 5), outlines a graben with Fault A. However, Fault B cannot be identified on the seismic profile; the structure east of Fault A appears to be a half-graben (Fig. 6b).

Two steeply-dipping small faults outline Graben C at SP 225 and 250 (Fig. 6b). Displacements are modest, only 5 to 10 ms in the Paleozoic section. The effect on the Cretaceous and younger package is ambiguous, except that displacement of the uppermost strong Paleozoic reflector implies post-Cretaceous movement. A shallow stratigraphic test hole that the ISGS drilled before the seismic survey was run happens to lie within Graben C, only 35 m north of SP 240 on the seismic line (Fig. 5). The drill penetrated 3.3 m of silty Holocene alluvium, overlying 13 m of the Pleistocene Metropolis Formation. Drilling was halted in a gravelly phase of the Metropolis without reaching the base of the unit. The Metropolis Formation was much thicker than we expected, and at the time of drilling we interpreted it as filling a deep paleovalley. In light of the seismic data, Quaternary-age faulting must be considered as explanation for the thick Metropolis Formation. Additional drilling is needed to test this possibility.

We anticipated that the seismic profile might indicate a graben near SP 500, because two boreholes on the Krueger property just north of the seismic line indicated a downdropped fault block. No such graben is evident on the seismic profile; the large graben outlined by Faults A and B passes east of the Krueger boreholes (Fig. 5). We do not know whether the Krueger boreholes penetrated a small northeast-trending graben, or possibly a graben having a different orientation.

Other faults interpreted on the Choat seismic profile are high-angle normal faults that displace Paleozoic reflectors less than 10 ms. These small faults have no discernable effect on Cretaceous and younger reflectors. However, the Krueger boreholes may lie on the downthrown side of one of these stair-stepping faults (Fig. 5).

Taken together, the faults interpreted on the Choat profile fit the regional pattern of dominantly high-angle normal faulting in the Fluorspar Area Fault Complex.

Maple Grove

Borehole data indicate that the Lusk Creek Fault Zone, one of the major elements of the Fluorspar Area Fault Complex, passes beneath Maple Grove School near Joppa, Illinois (Figs. 2 and 7). A water well drilled at the school penetrated 55 m of gravelly sand that may be Pleistocene, overlying 35 m of the Cretaceous McNairy Formation, which in turn rests on limestone bedrock. The abnormally great thickness of Pleistocene(?) sediments in this upland setting suggests a Quaternary-age graben. The ISGS drilled a shallow cored test hole near the school water well in October, 1997. The core encountered a succession of Pleistocene loesses that are somewhat thicker than normal, overlying 5 m of the Metropolis Formation, a Pleistocene fluvial unit. The Metropolis in turn overlies nearly 12 m of an unidentified silt-sand unit. Presence of the unidentified unit strengthened the neotectonic hypothesis, which we seek to test via geophysics and additional drilling.

The USGS ran an east-west seismic profile 0.9 km long and 0.8 km north of Maple Grove School (Fig. 7). A seismic line closer to the school would have been preferred; however, the Panhandle Eastern gas-compressor plant, southwest of the school (Fig. 7) generates steady, strong low-frequency vibrations that severely interfere with recording of seismic data. Vibrations from the compressor plant were quite evident during seismic acquisition on the line selected 1.5 km from the compressor station. Interference from this source was partially alleviated by use of FK filtering.

The Maple Grove seismic profile (Fig. 8) presents reflections similar in character to those at Choat. Shallow reflectors, above about 100 ms, are of high frequency and generally discontinuous. Reflectors from 100 to 220 ms are of lower frequency and more continuous. These reflectors probably represent Cretaceous and younger, and Paleozoic strata, respectively (Fig. 8b).

Several faults are interpreted on the Maple Grove seismic profile (Fig. 8b). Three narrow grabens are inferred, at SP 115-130, 190-210, and 280-305. These grabens displace Cretaceous as well as Paleozoic reflectors. A small fault that displaces only Paleozoic reflectors is at SP 240. Near the east end of the line at SP 400, a fault appears to offset the top of Paleozoic bedrock about 20 ms down to the east. Cretaceous reflectors on the eastern part of the profile are folded into a broad anticline.

Together with the limited outcrop and borehole data, the Maple Grove seismic profile indicates a broad fault zone composed of near-vertical horsts and grabens. Whether the faults inferred from drilling at the school intersect the seismic line is not clear. Our preferred interpretation (Fig. 7) suggests the graben near SP 300 most likely is correlative with the one at the school. The seismic profile presents several targets for drilling to test the possibility of Quaternary tectonism here.

Massac Creek

The Massac Creek site is located within the Hobbs Creek Fault Zone of the Fluorspar Area Fault Complex (Figs. 1 and 2). Outcrop and borehole data indicate a complex graben that strikes north-northeast and displaces sediments as young as Pleistocene. The key borehole is a core-drilled test hole on James Weaver's property (Fig. 9), which indicates the Metropolis Formation (Pleistocene) is downdropped 30 m relative to nearby outcrops. In the core the Metropolis Formation overlies at least 60 m of Neogene sediments previously unknown in the northern Mississippi Embayment (Nelson et al., 1997 and in press).

The UMR team ran two seismic reflection profiles at Massac Creek (Fig. 9). The Massac Creek North line 1 passes within 30 m south of the cored test hole that encountered the graben. The Massac Creek South seismic line follows an east-west county road approximately 0.8 km south of Line 1 (Fig. 9).

Cretaceous and younger strata are essentially transparent on the UMR seismic lines (Figs. 10 and 11). Well-defined reflectors, which appear at depths of 50 to 250 ms, are interpreted as Paleozoic bedrock.

Reflectors on the Massac Creek North line (Fig. 10b) are greatly broken, tilted, and arched, suggesting a fault zone of considerable complexity. Inferred faults dip steeply and commonly merge at depth, outlining narrow wedge-shaped horsts and grabens. The most prominent feature on this profile is the large graben structure between SP 90 and 125. This feature contains near-horizontal reflectors down to 220 ms, and is bordered by well-defined faults that dip steeply inward. This graben is directly on line with the one penetrated by core-drilling on the Weaver property. Other faults show both normal and reverse offsets. Given the structural complexity and lack of deep drilling data the identity of reflectors on this profile is uncertain. The prominent doublet highlighted on the interpreted section (Fig. 10b) probably is within Paleozoic bedrock.

The Massac Creek South line (Fig. 11b) also portrays a complexly faulted section. Near the middle of the profile (SP 160 to 205) is a zone of strongly disrupted reflectors that may represent the Weaver graben. This is flanked on both sides by many high-angle normal and reverse faults that have apparent offsets of 5 to 20 ms. In particular, reverse faults are evident near both ends of the seismic profile. Several sets of closely-spaced nearly vertical faults outline small horsts and grabens.

Correlating faults between the two seismic profiles is rather problematic. On the map (Fig. 9) we have assumed that all faults run parallel with the Weaver graben, which is well defined. Note that on the northern seismic profile (Fig. 10b), there are three east-dipping normal faults west of the Weaver graben. On the southern profile (Fig. 11b) several east-dipping reverse faults are interpreted. If these faults connect, they are "scissors faults", which are commonly produced in strike-slip fault zones. Possible scissors faults also occur east of the Weaver graben.

Kelley

The Kelley site is a railroad cut about 5 km northeast of Joppa (Figs. 2, 12). Trenching in the cut revealed a graben-like structure in which the Mounds Gravel (late Miocene to early Pleistocene) occurs at least 30 m below its elevation in a gravel pit south of the railroad (Fig. 12). Overlying the Mounds is reworked gravel of probable Pleistocene age, overlain by Pleistocene loesses. The Loveland Silt (late Illinoian) is confined to the lowest point of the structure; the Roxana Silt (mid-Wisconsinan) thickens into the structure. Possibly, the Loveland Silt was dropped down into a graben and protected by erosion; continued subsidence of the structure during Wisconsinan time resulted in thickening of the Roxana Silt. .

Because trenching did not conclusively demonstrate whether the feature is of tectonic origin, we ran two seismic profiles at Kelley. The Kelley North line is about 100 m south of and parallel with the railroad; the Kelley South line is about 300 m south of Kelley North (Fig. 12). The lines are 342 and 730 m long, respectively.

The two seismic lines provide dramatic evidence for tectonic faults at Kelley. The Kelley North profile (Fig. 13b) depicts a faulted anticline or arched horst that is nearly symmetrical. Faults converge at depth and include both normal and reverse faults. The Kelley South profile (Fig. 14b) also shows a faulted anticline or arched horst that is broader and gentler than the one on Kelley North. Bedrock reflectors are sharply resolved to depths of approximately 200 ms. As at Massac Creek, Cretaceous and younger sediments are virtually transparent on these profiles.

The seismic lines present an enigma. They clearly indicate an anticline or horst, but the feature observed at the surface is a graben or syncline. Although small grabens are visible on Kelley North (at SP 30 and 53) these are much narrower than the 80-m-wide graben exposed in the railroad cut only 100 m north.

Evidently, the structure at Kelley underwent at least two episodes of movement. Early compressional movements formed a faulted arch in Paleozoic bedrock. The structure shown on the Kelley North line may represent a positive flower structure, such as typically forms in strike-slip faults having a component of compression. The compressional episode was post-Mississippian and no younger than Miocene, or pre- Mounds Gravel. The later episode of movement was extensional and took place during the Quaternary Period, producing the structure observed in the railroad cut. The extensional movement presumably was of lesser magnitude than the earlier compressional one, as the anticlinal structure remained intact at depth.

Post Creek

A graben-like structure in Mounds Gravel (Miocene to early Pleistocene) adjacent to Post Creek Cutoff in Pulaski County (Fig 2) was investigated by Kolata et al. (1981) and interpreted as a product of solution-collapse in Mississippian limestone. Our re-study of the field exposures and borehole records raised the possibility that this is a neotectonic structure.

In order to determine whether faults or sinkholes are present at depth, we ran a seismic survey along a county road about 0.8 km north of, and in line with the graben-like feature (Fig. 15). The seismic profile (Fig. 16) has poorly defined reflectors and is difficult to interpret. The only reflectors worthy of mention are found in the depth range of 70 to 120 ms. Along most of the length of the profile, two adjacent weak, intermittent reflectors can be traced. These undoubtedly represent Mississippian limestone, which is exposed in the bottom of Post Creek Cutoff only 15 to 20 m below the gently rolling upland surface.

What may be a large fault is imaged near SP 80 (Fig. 16b), where the pair of reflectors rise sharply above their general level and are tilted strongly toward the west. Between SP 15 and 80 these same reflectors are offset and broken into a series of short, west-dipping segments. East of SP 80 the pair of reflectors is horizontal or gently undulating, with possible small offsets in several places.

The pattern shown on the seismic profile is more readily attributed to tectonic faulting than to solution collapse. Karst activity should produce either "transparent" (no coherent reflectors) spots on the profile or, if large enough in scale, might produce locally downdropped and tilted segments of reflectors. Karst action would be unlikely to rotate a large block of rock and raise it above its normal level, as indicated on the seismic line at SP 80.

CONCLUSIONS

High-resolution seismic reflection profiles acquired during this project provide information on Neogene and Quaternary tectonic faulting at five sites in Massac and Pulaski Counties, Illinois. The faults are part of the Fluorspar Area Fault Complex and are in line with the linear zone of intense seismicity near New Madrid, Missouri. Most of the faults imaged on our seismic profiles are nearly vertical to steeply dipping normal faults, which commonly outline narrow grabens. High-angle reverse faults also are present, and at Kelley they outline an arched horst or faulted anticline that fits the definition of a positive flower structure. At Kelley and Massac Creek some faults appear to reverse dip direction along strike and/or change from normal to reverse faults along strike. Such behavior is characteristic of faults that have a component of strike-slip motion. In the case of Kelley, there is evidence for two distinct episodes of faulting: the first compressional/strike slip involving Paleozoic bedrock, and the second extensional, producing a graben that affects units as young as Wisconsinan (late Pleistocene).

In addition to providing information on structural style, the seismic program accomplished a second key objective of this year's project. That objective is to identify targets for drilling, specifically, grabens that may contain down-dropped Neogene and Quaternary sediments. A few such grabens were known to exist before the seismic program, but the seismic data reveal several apparent grabens that have no surface expression. Also, the seismic profiles provide evidence that two enigmatic structures, Kelley and Post Creek, probably are of tectonic origin rather than being products of channel-cutting or solution-collapse.

Following the promising results of Sexton et al. (1996) using GPR along Barnes Creek, this year's GPR results were a major disappointment. Apparently this technique (as currently practiced) is not applicable to loess-covered uplands because the radar will not penetrate loess. GPR may still be a valuable tool for imaging details of shallow Quaternary-age faulting in valley-bottom settings where the soils are moist and sandy.

In spite of the setback with GPR, we view this season as a success. The drilling program in Year 2 of this program, combined with selective trenching, should provide a comprehensive picture of neotectonic activity in southernmost Illinois.

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LIST OF FIGURES

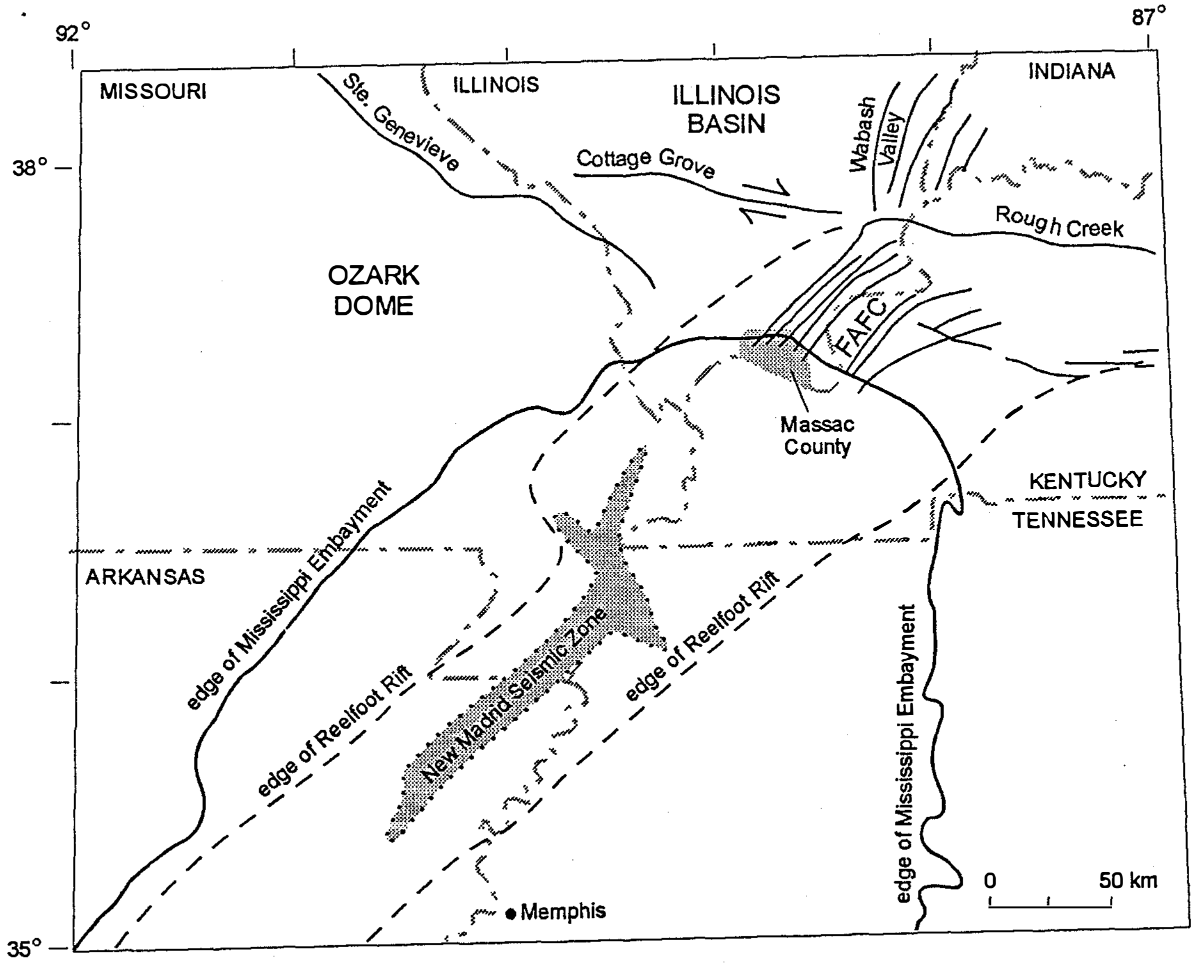


Figure 1. Map of northern Mississippi Embayment showing study area in Massac County, Illinois, the New Madrid Seismic Zone, and selected structural features. FAFC= Fluorspar Area Fault Complex.

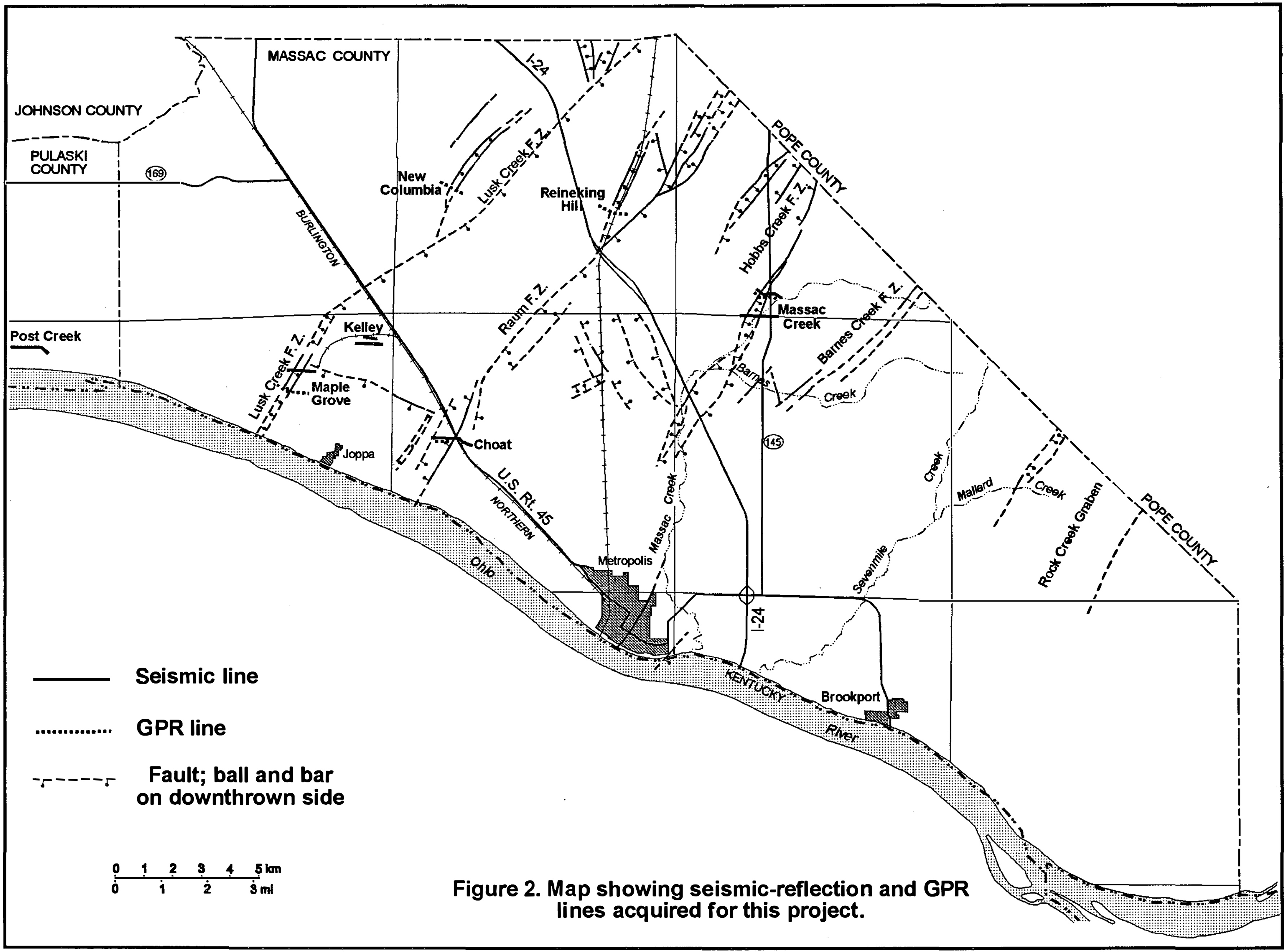
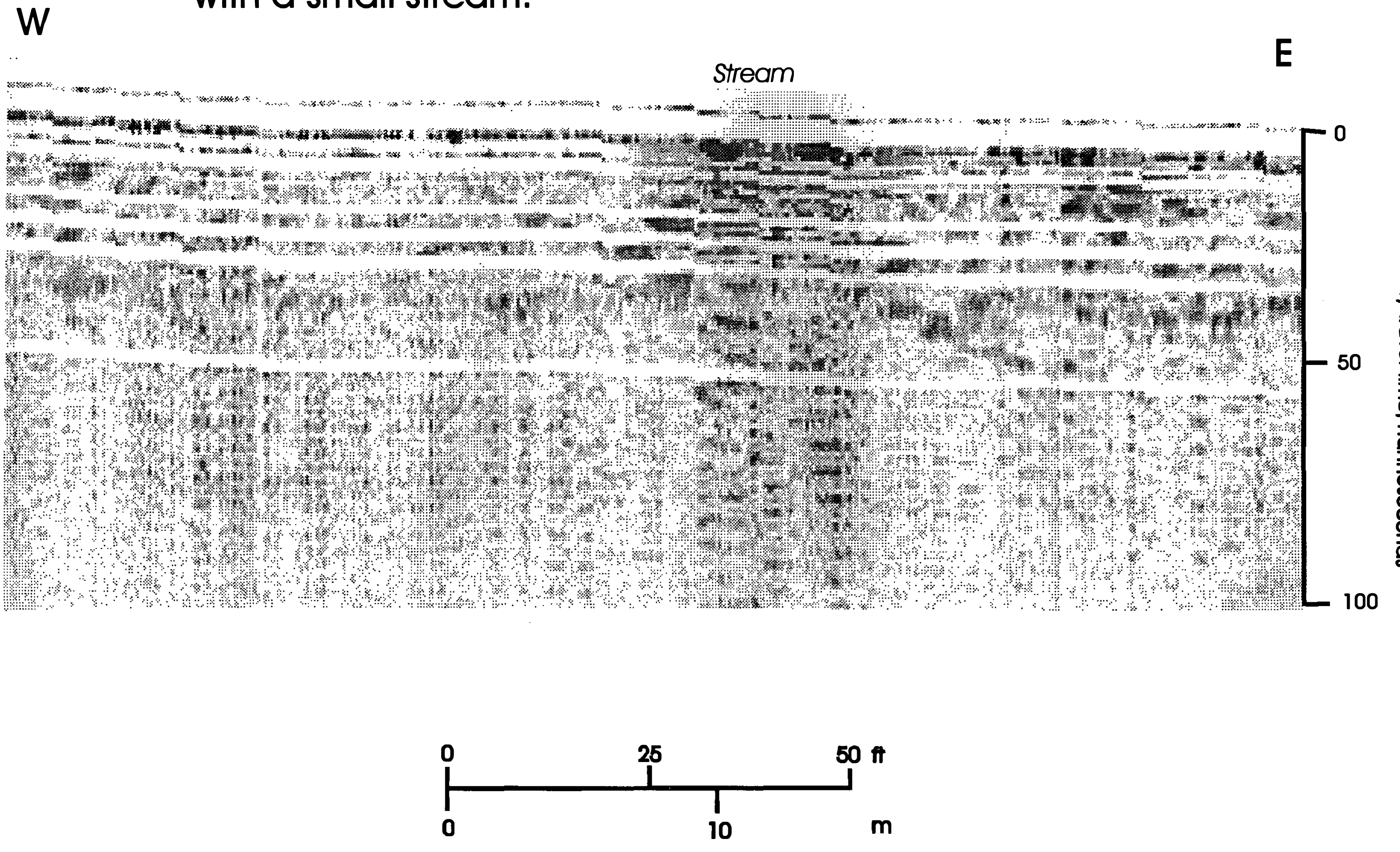


Figure 2. Map showing seismic-reflection and GPR lines acquired for this project.

Figure 3. Portion of GPR profile from Choat, illustrating lack of radar penetration in loess. The "bright" zone corresponds with a small stream.



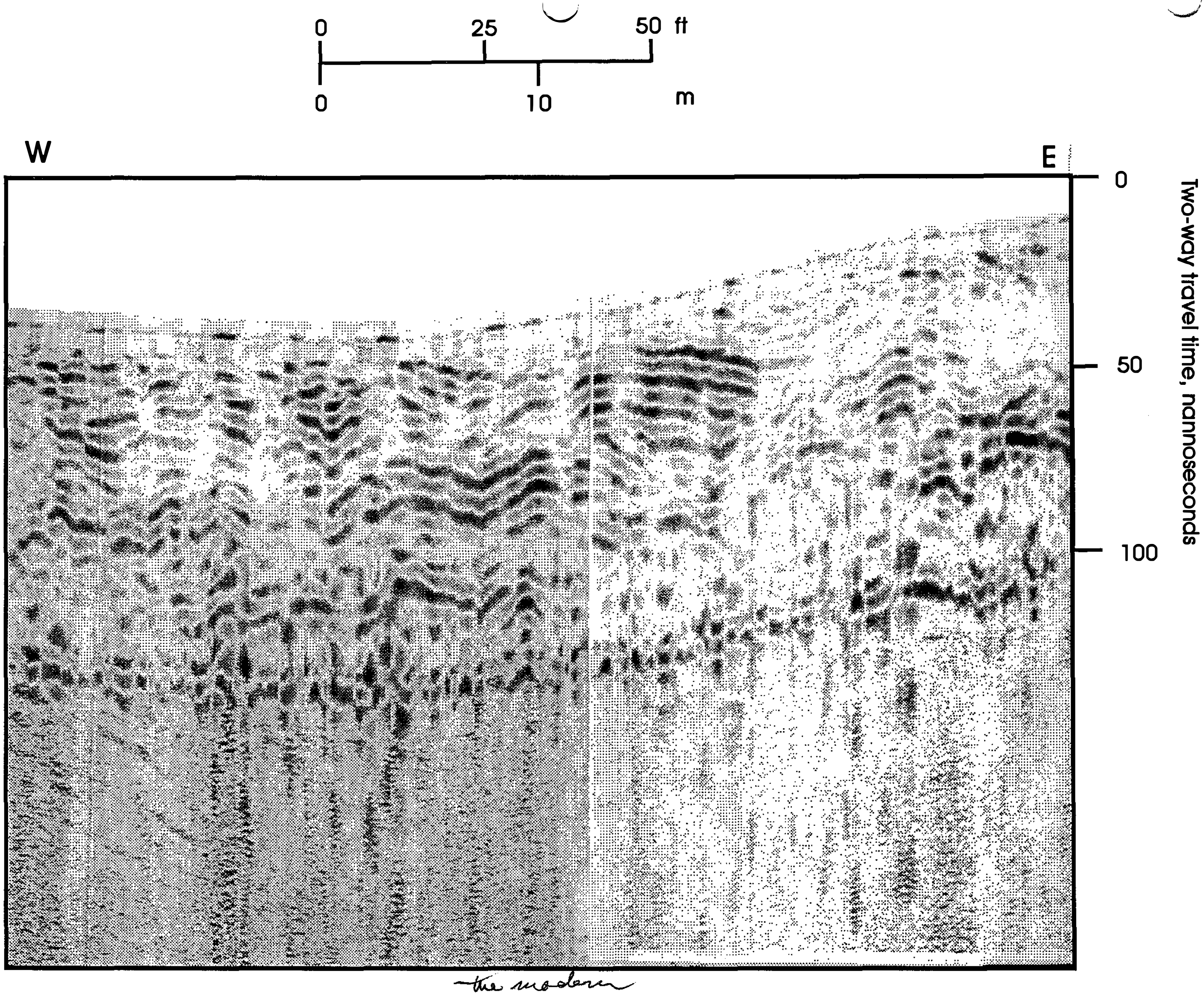


Figure 4. Portion of GPR profile from the modern valley bottom at New Columbia, acquired with 300 Mhz antenna. This was the best quality GPR profile obtained during this project. The tilted, discontinuous reflectors may represent faulted sediments.

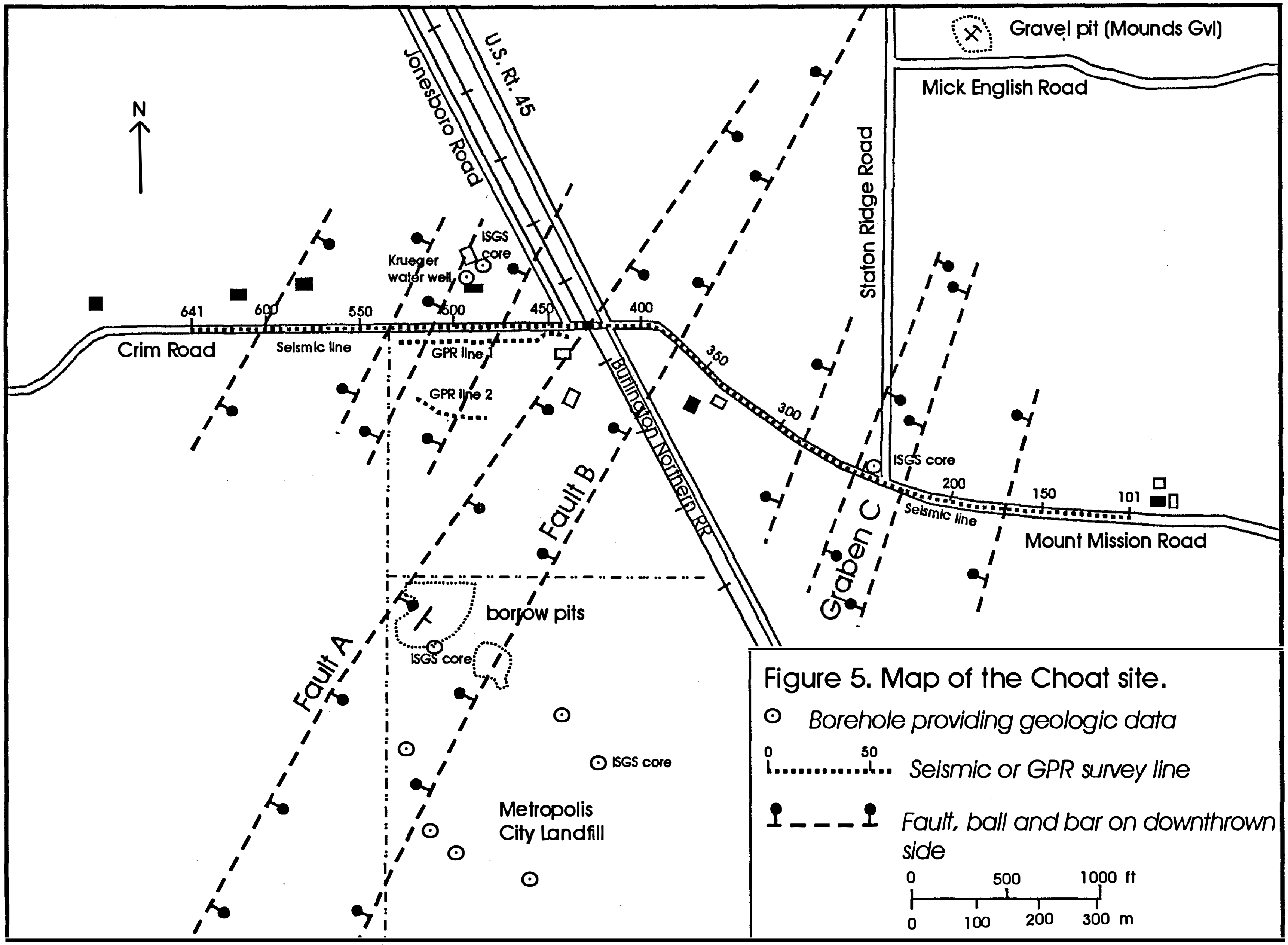


Figure 5. Map of the Choat site.

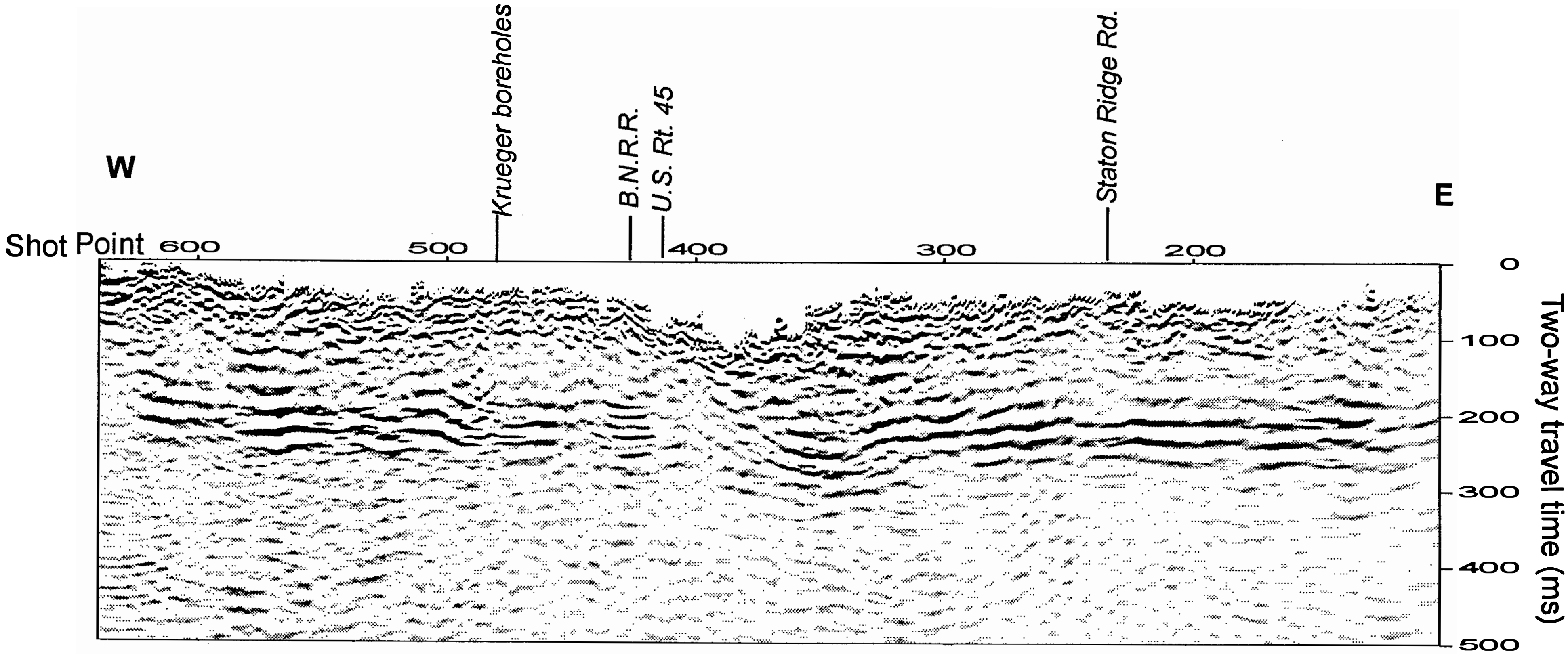


Figure 6a. Migrated seismic profile (uninterpreted) from Choat site.

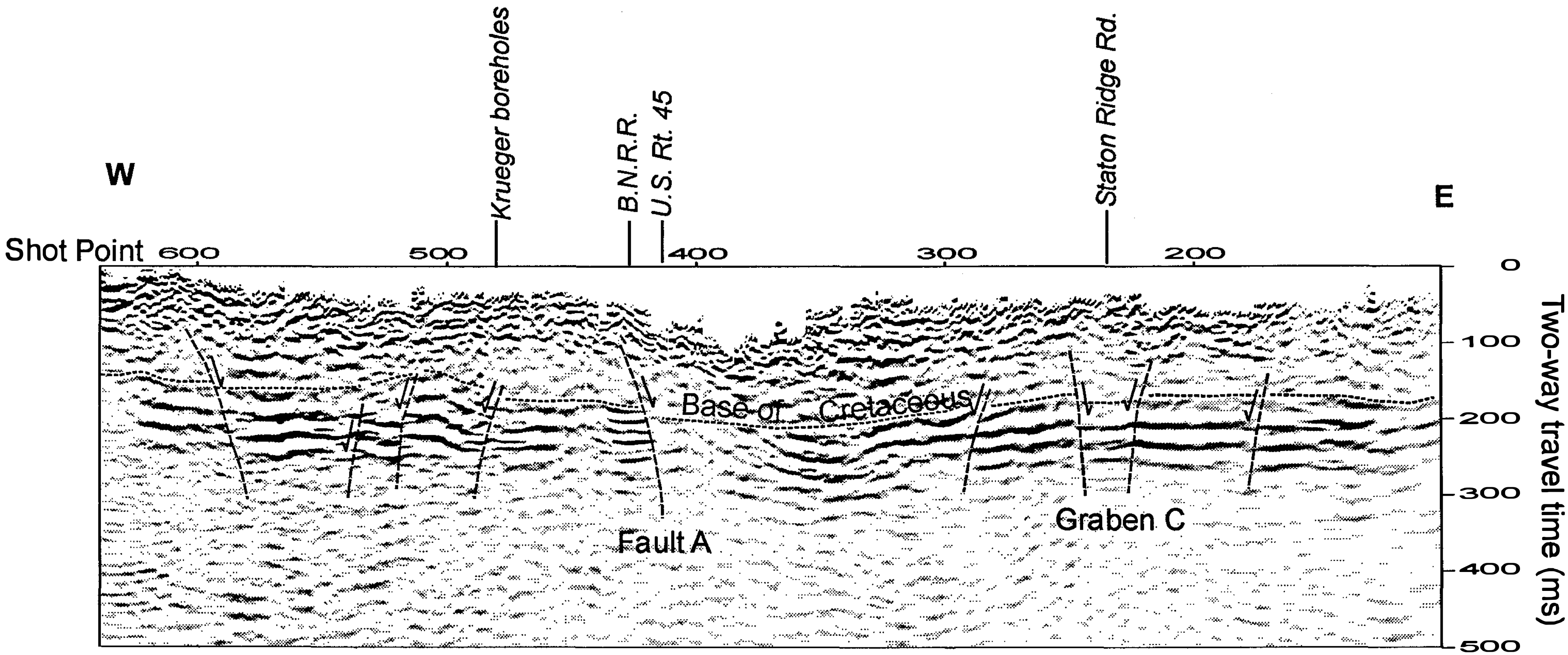
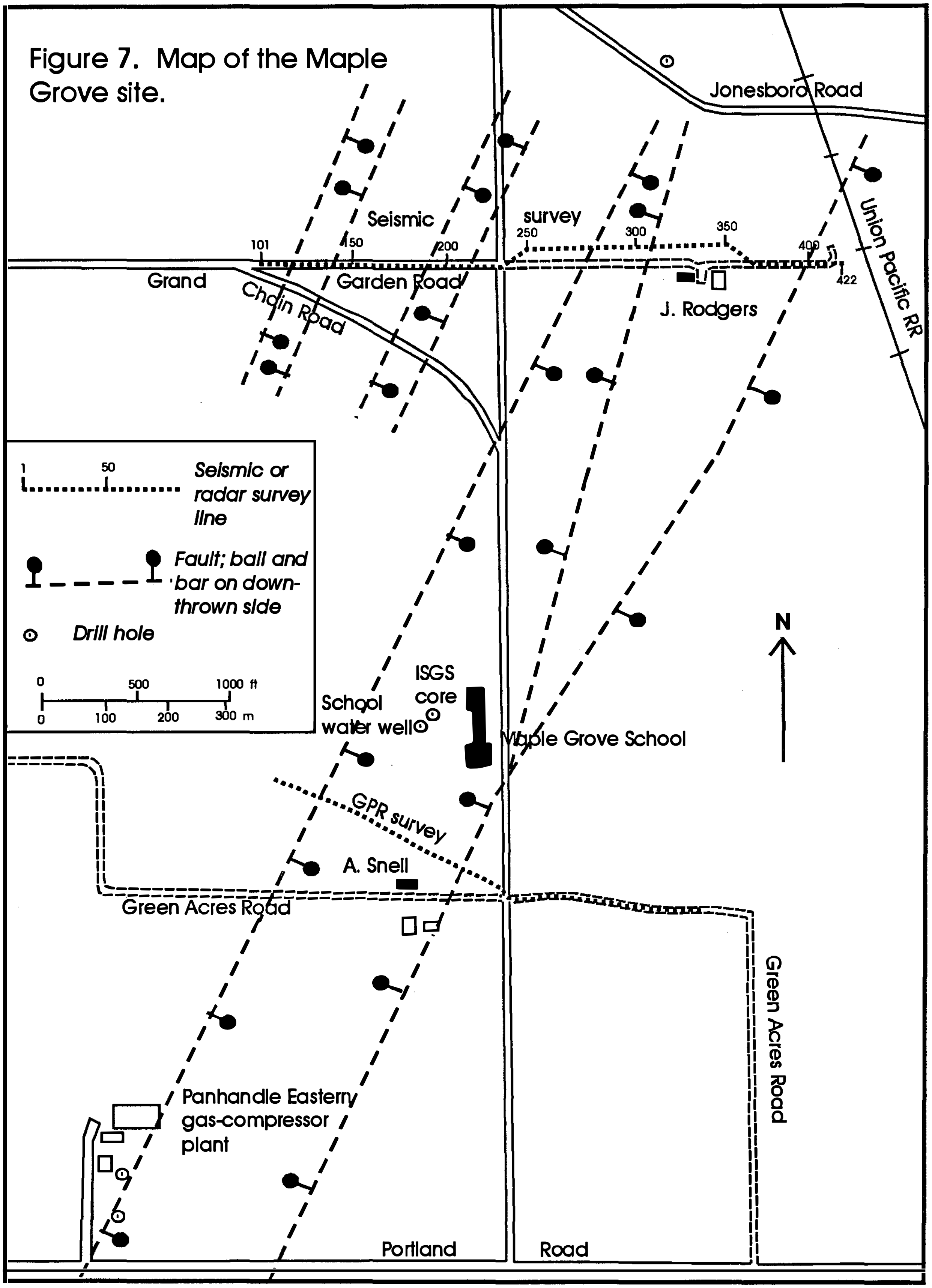


Figure 6b. Migrated seismic profile (interpreted) from Choat site .

Figure 7. Map of the Maple Grove site.



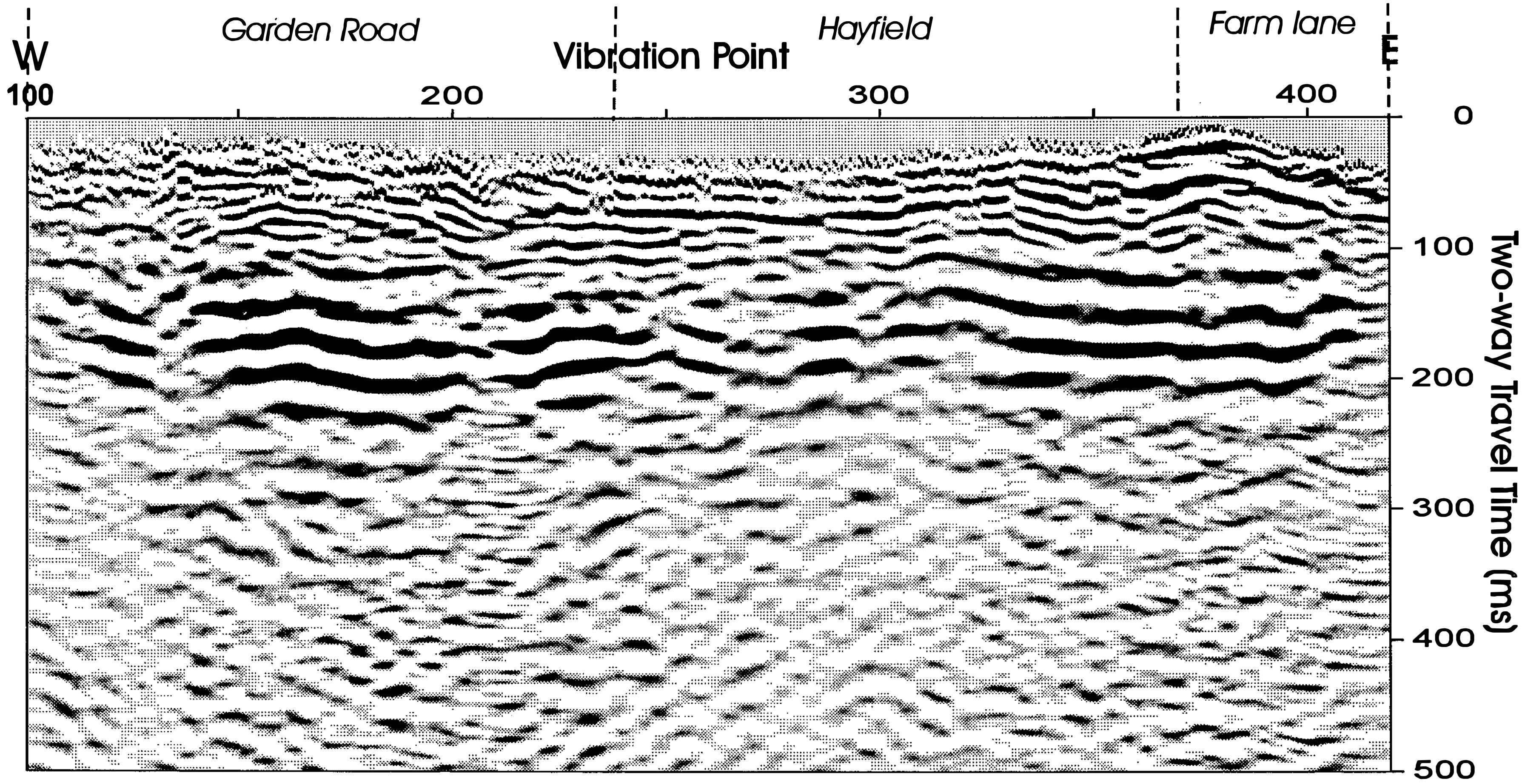


Figure 8a. Migrated seismic profile (uninterpreted) from the Maple Grove site. Vibration points are 3.0 meters apart.

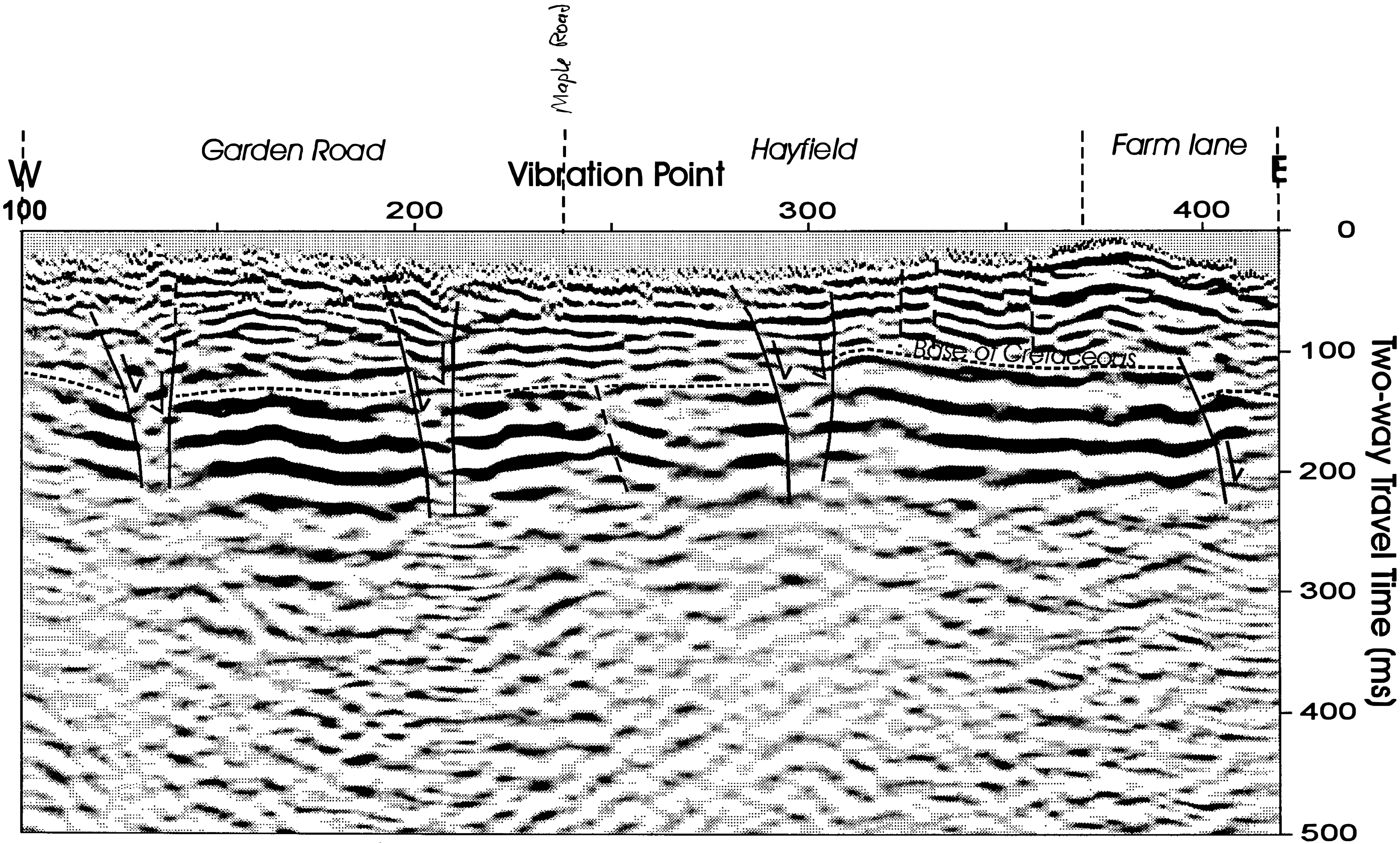


Figure 8b. Migrated seismic profile (interpreted) from the Maple Grove site. Vibration points are 3.0 meters apart.

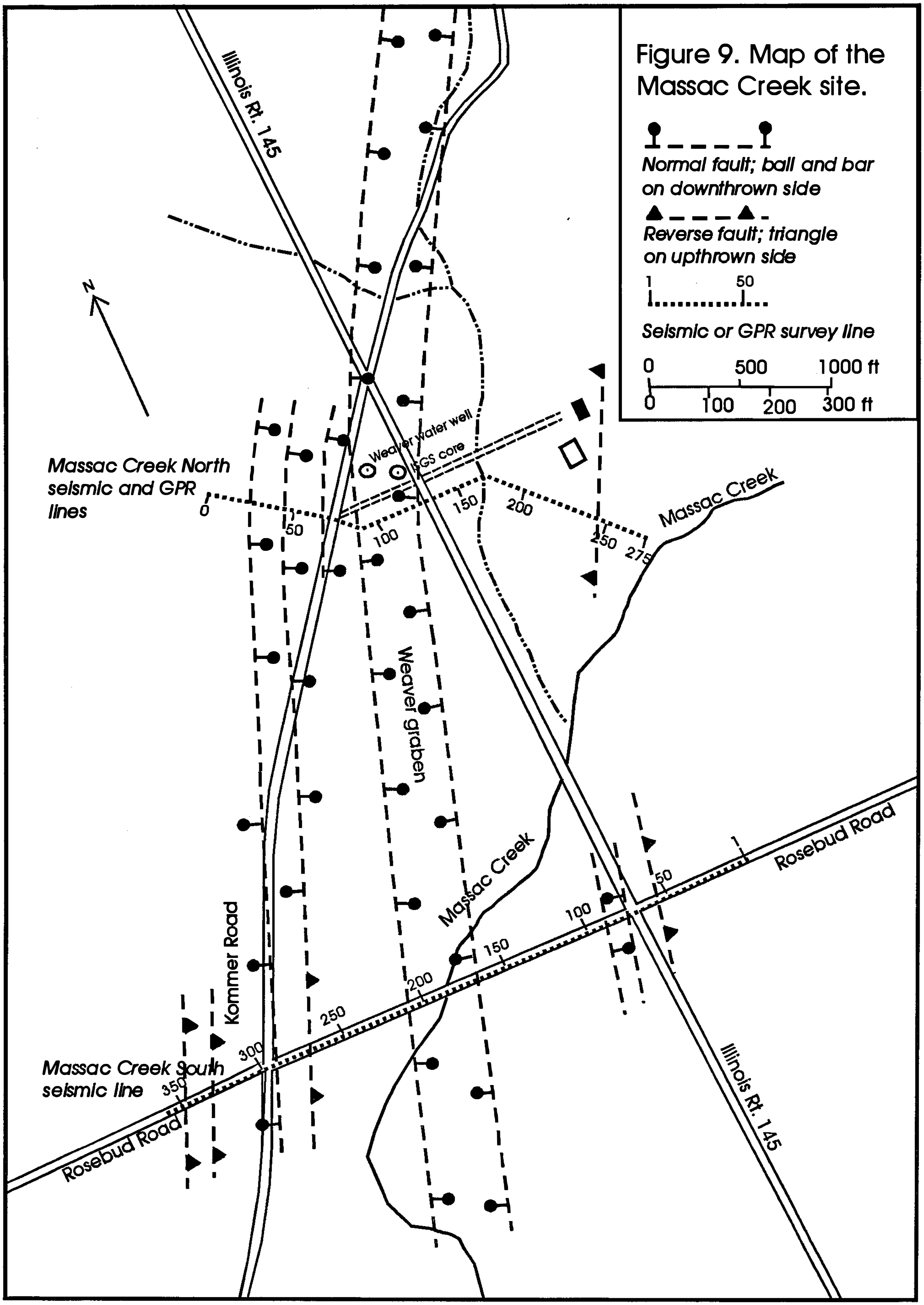


Figure 9. Map of the Massac Creek site.

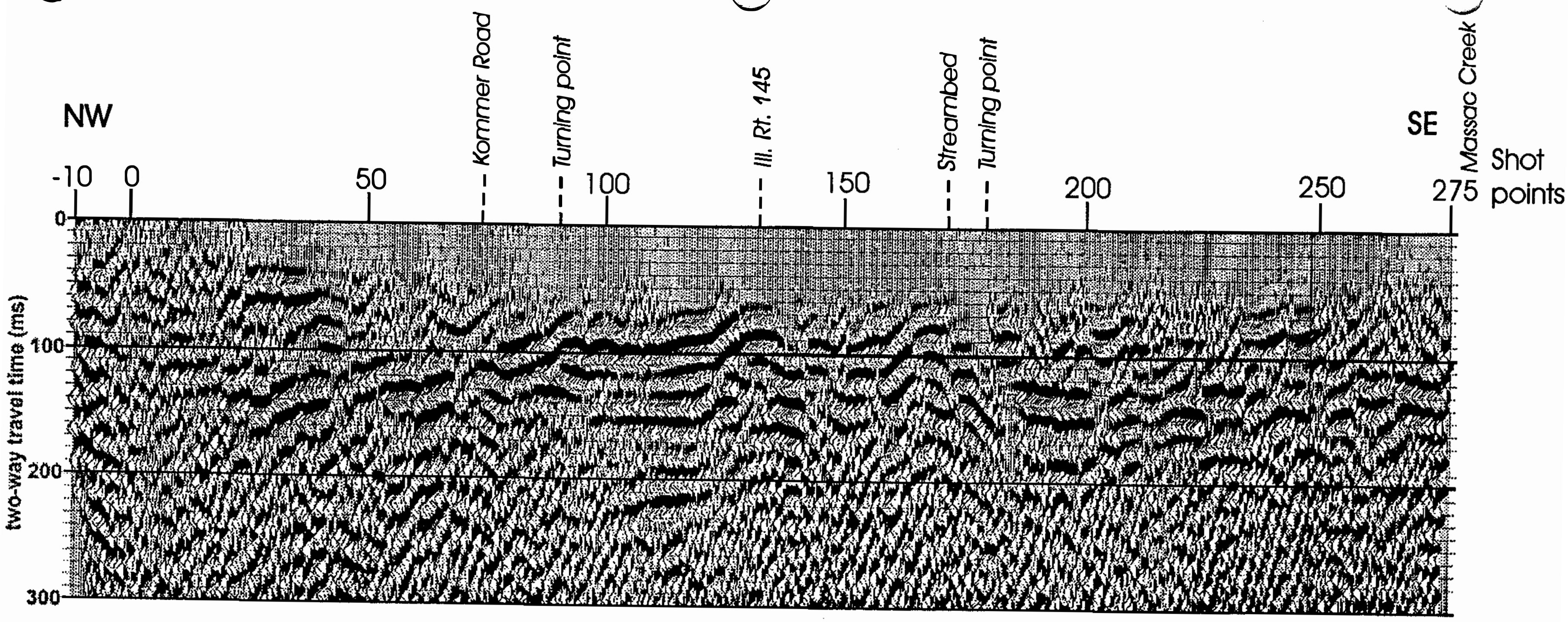


Figure 10a. Uninterpreted seismic profile, Massac Creek North. Shot points are 10.0 feet apart.

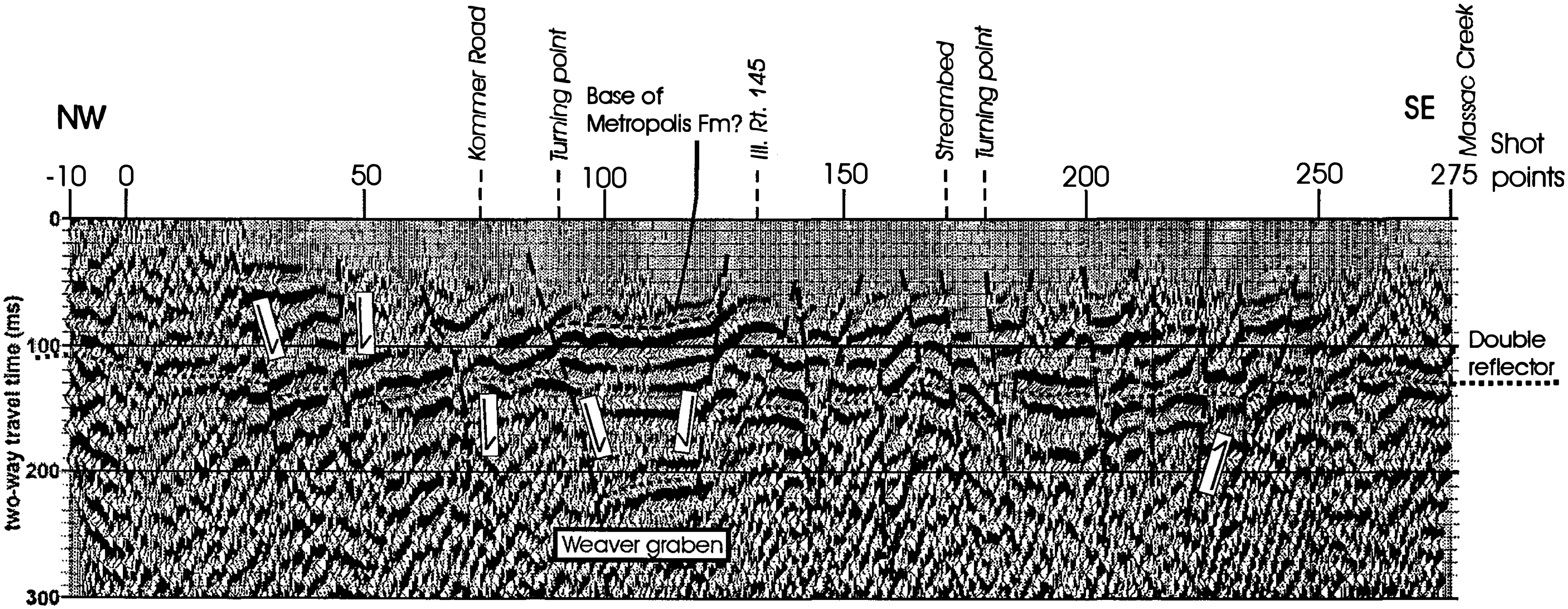


Figure 10b. Interpreted seismic profile, Massac Creek North. Shot points are 10.0 feet apart.

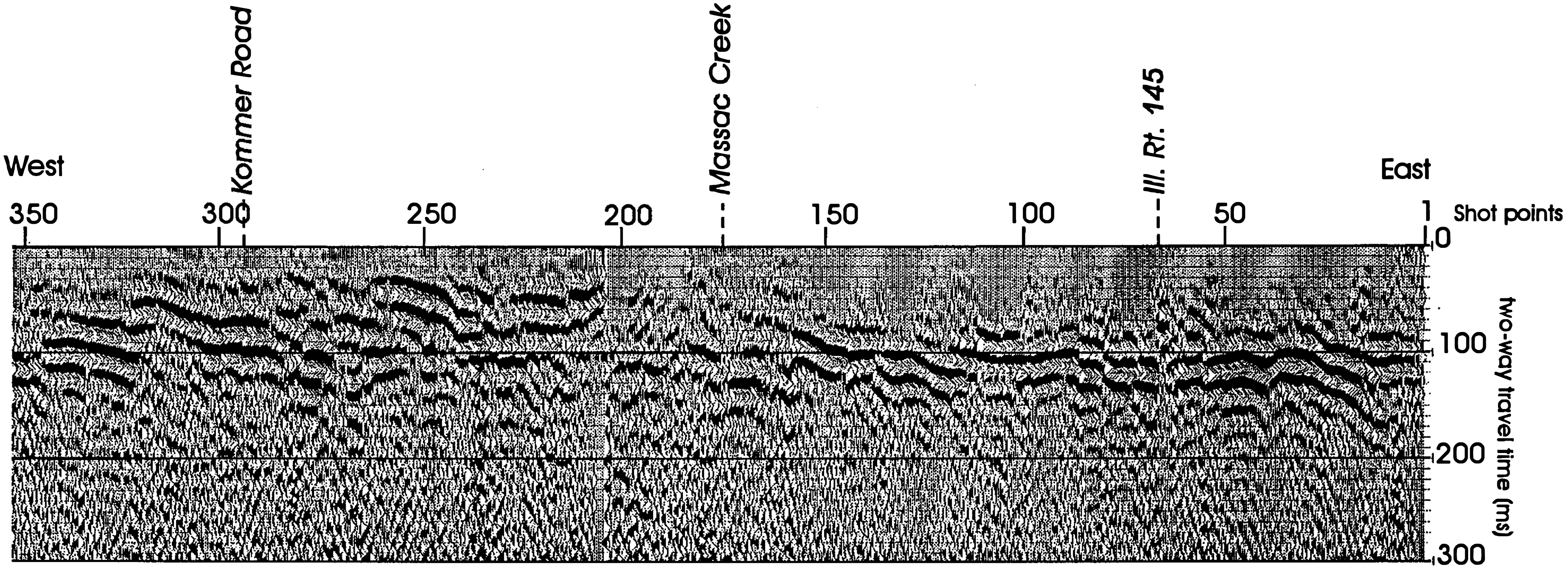


Figure 11a. Uninterpreted seismic profile, Massac Creek South. Shot points are 10.0 feet apart.

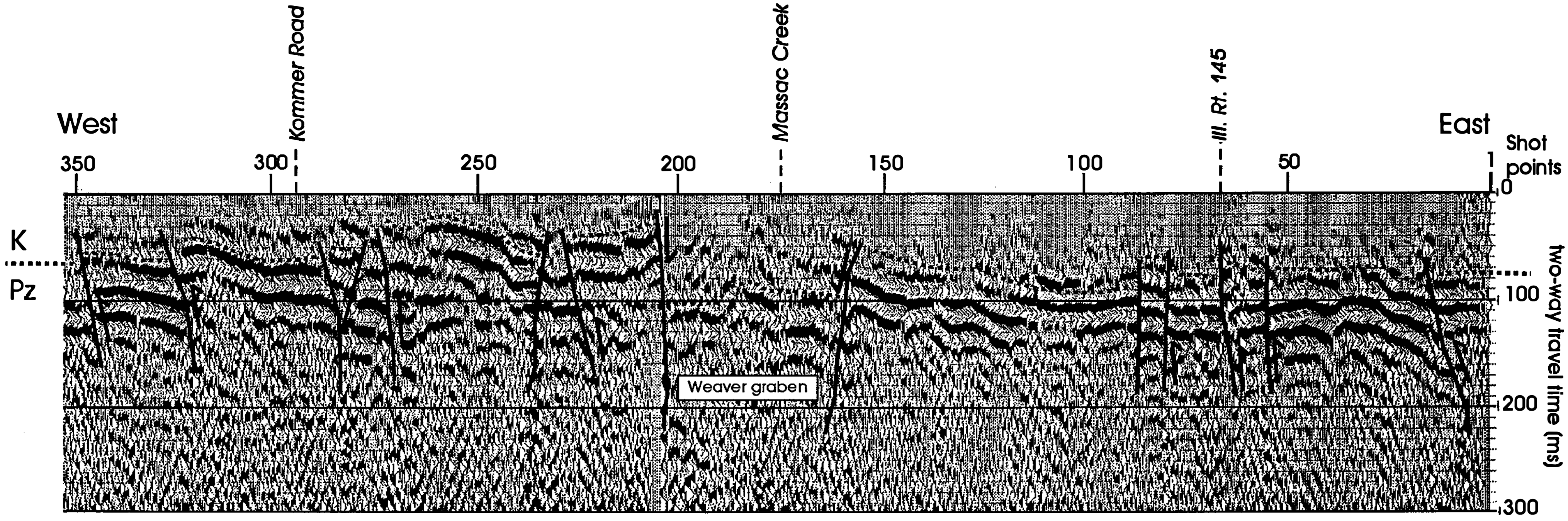


Figure 11b. Interpreted seismic profile, Massac Creek South. Shot points are 10.0 feet apart.

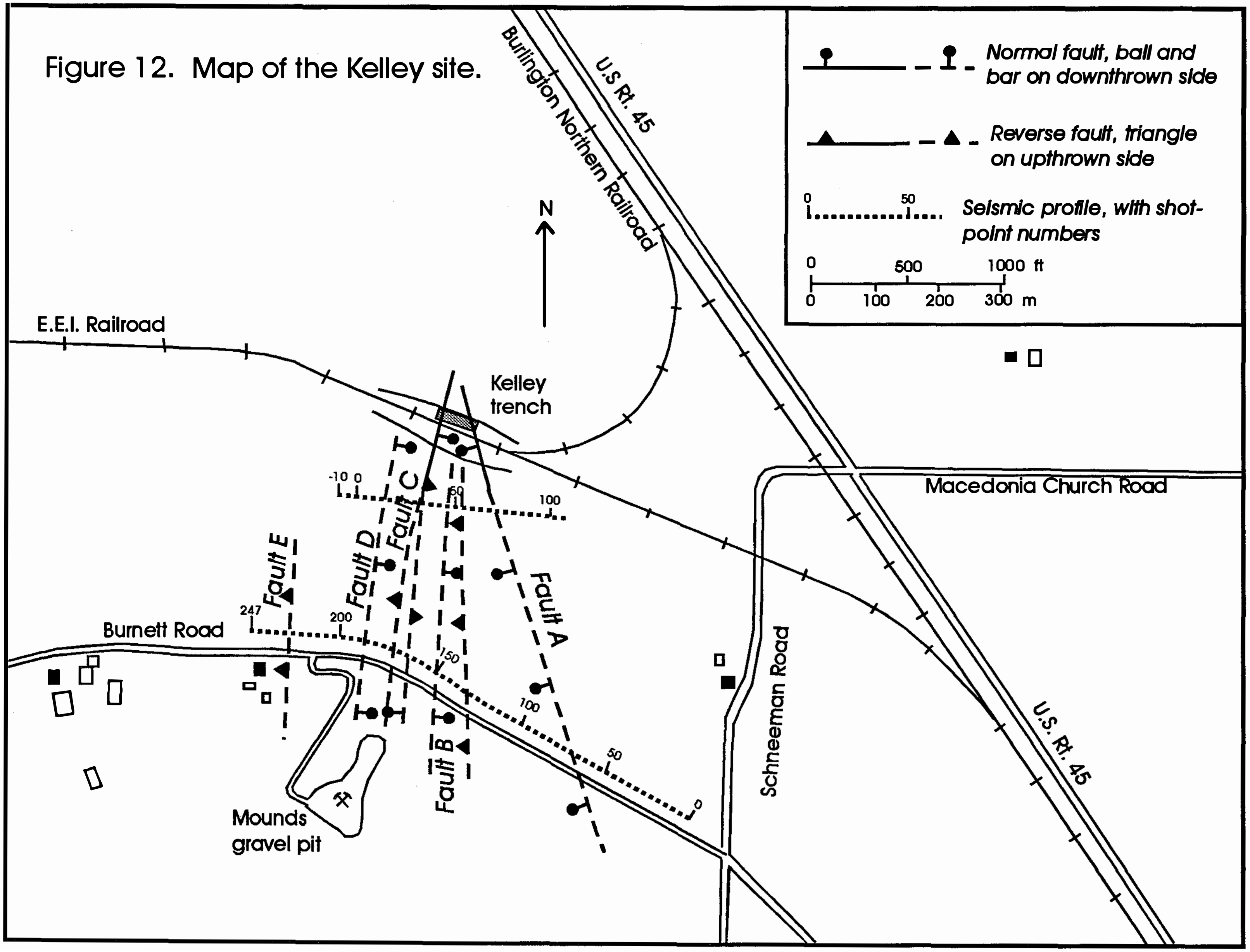


Figure 12. Map of the Kelley site.

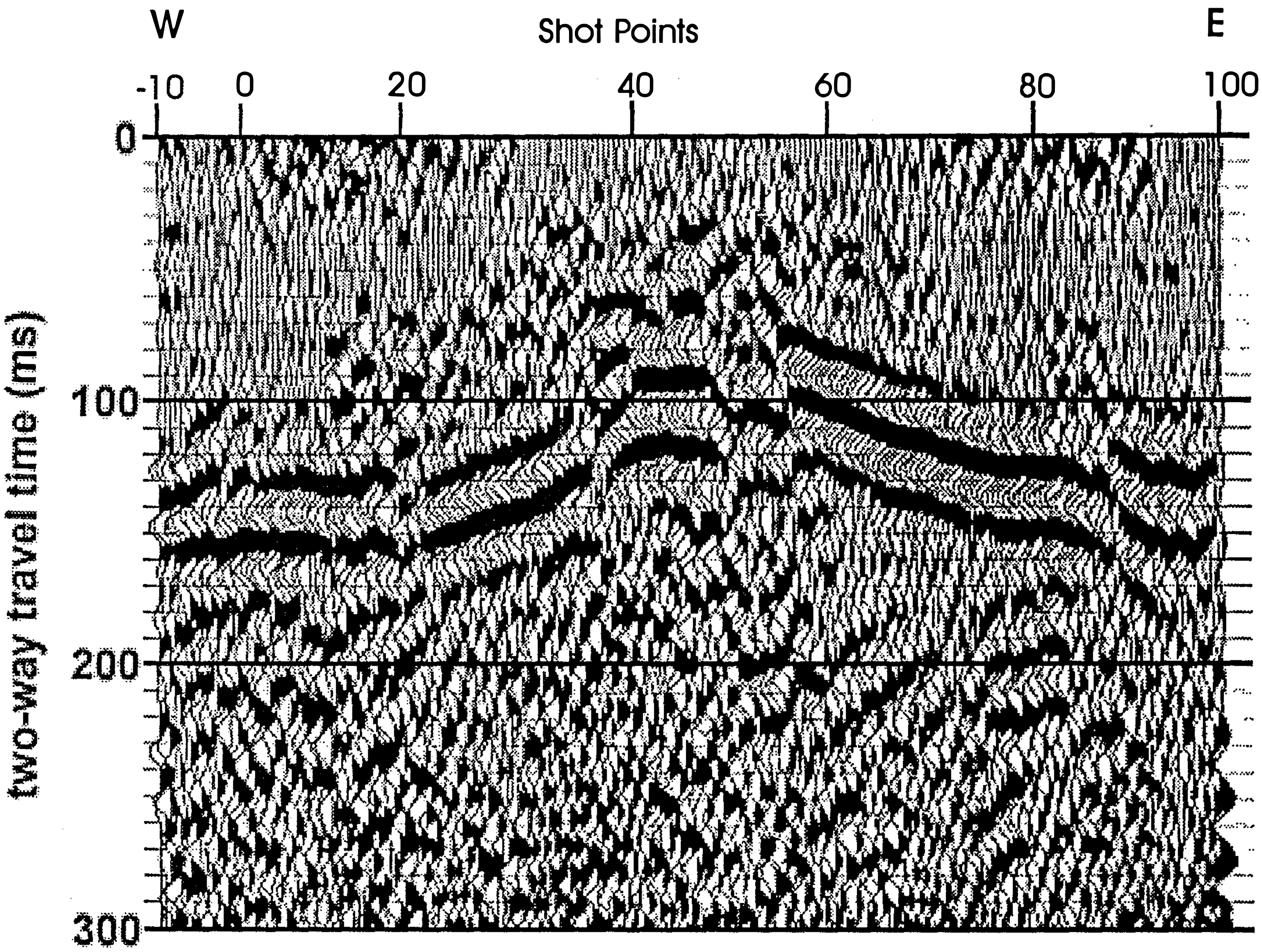


Figure 13a. Uninterpreted seismic profile, Kelley North. Shot points are 10 feet apart.

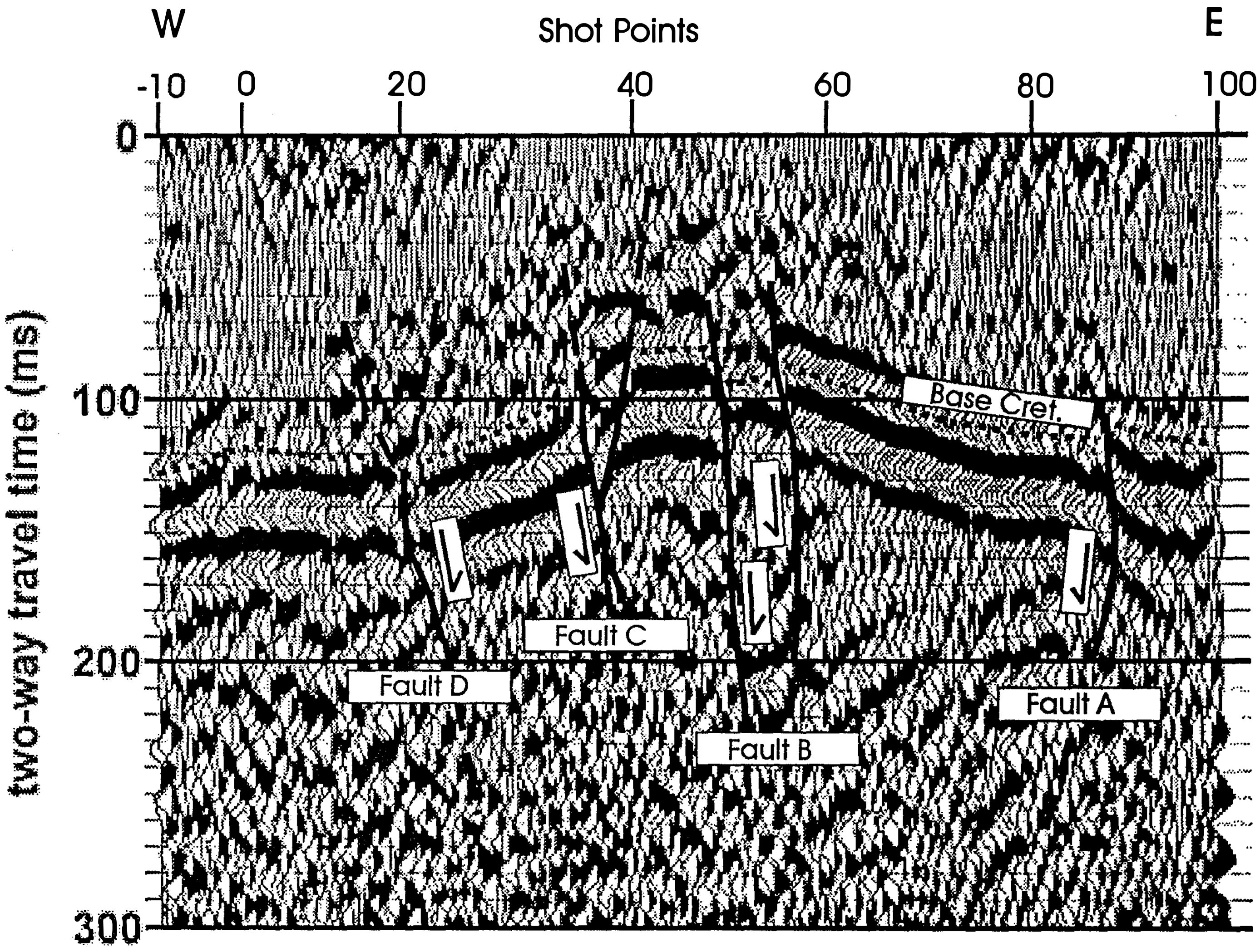


Figure 13b. Interpreted seismic profile, Kelley North. Shot points are 10 feet apart.

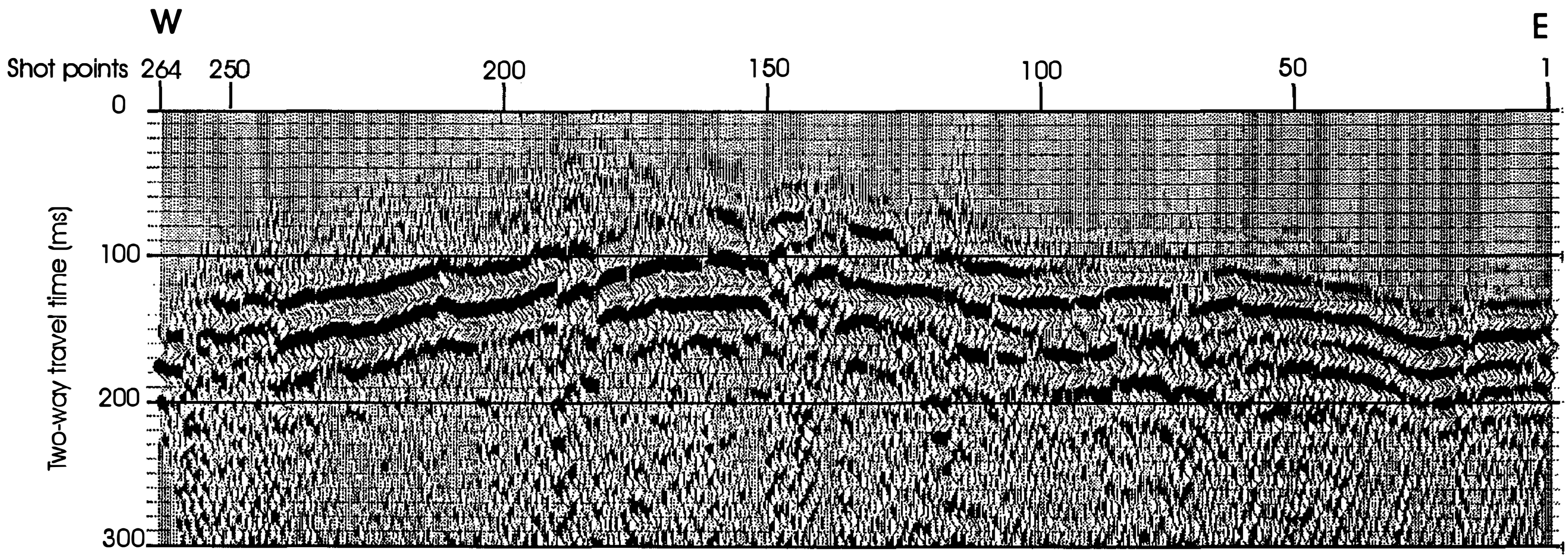


Figure 14a. Uninterpreted seismic profile, Kelley South. Shot points are 10 feet apart.

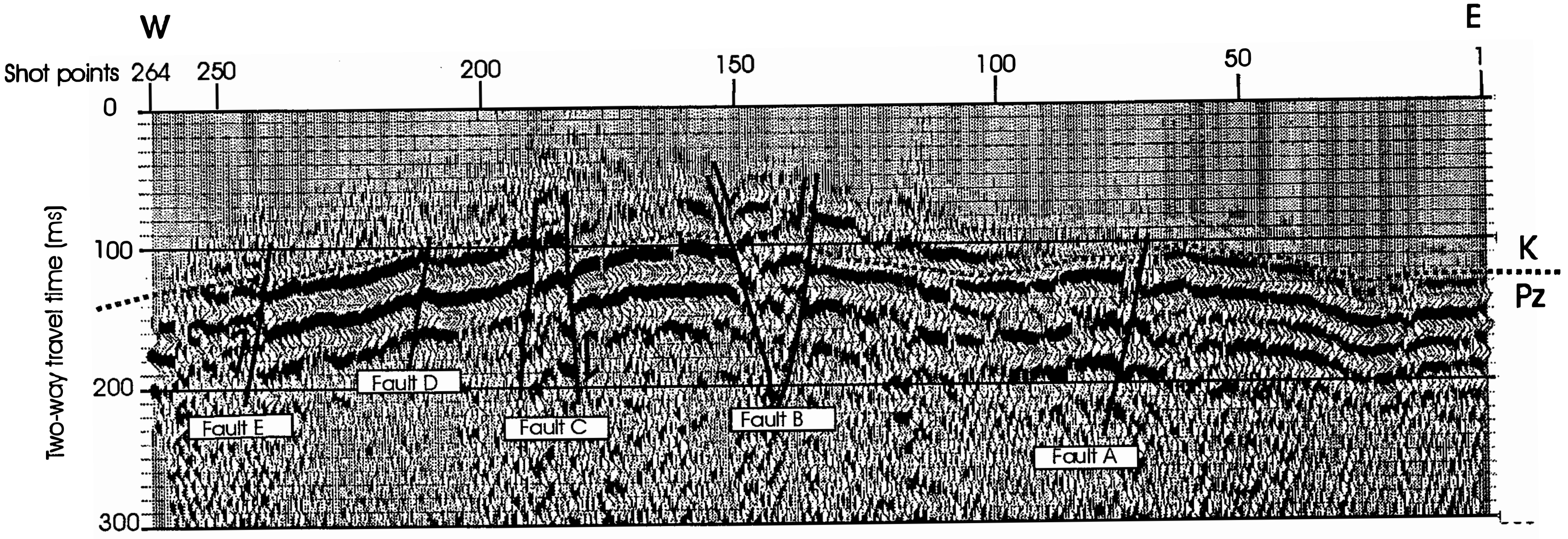
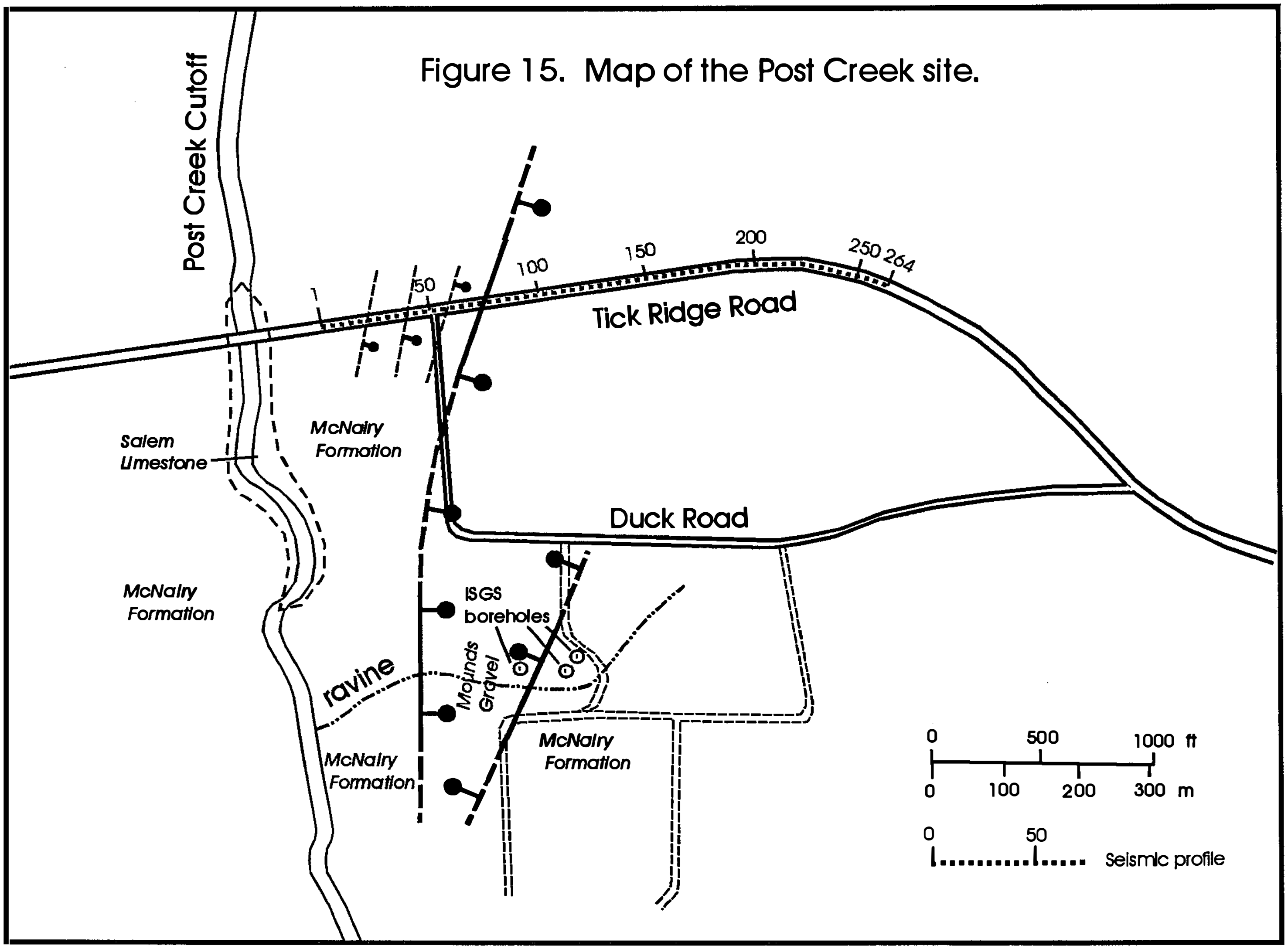


Figure 14b. Interpreted seismic profile, Kelley South. Shot points are 10 feet apart.

Figure 15. Map of the Post Creek site.



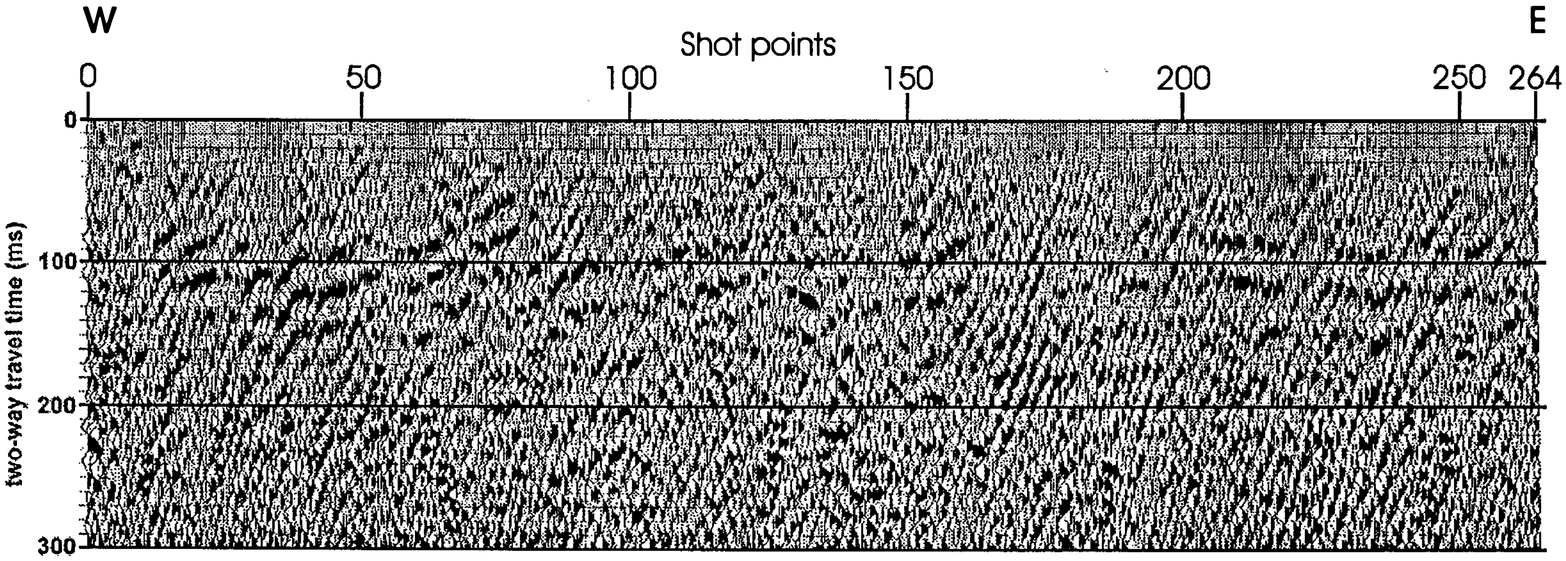


Figure 16a. Uninterpreted seismic profile, Post Creek. Shot points are 10 feet apart.

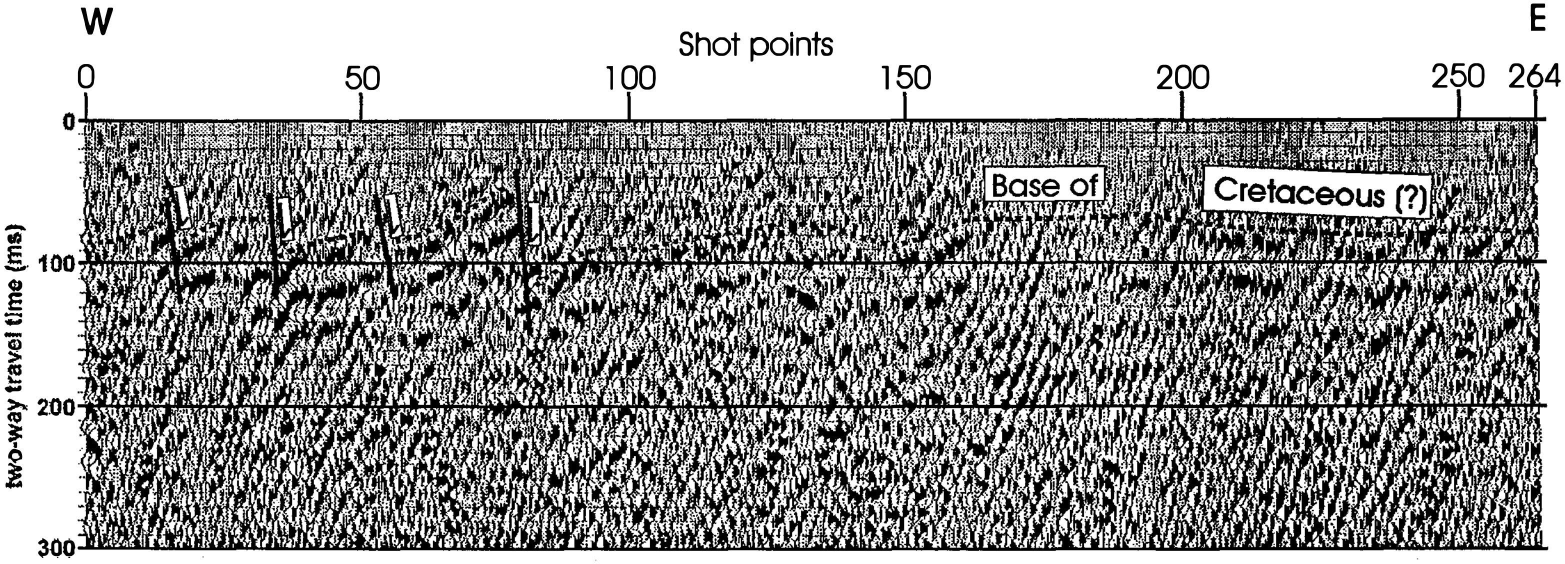


Figure 16b. Interpreted seismic profile, Post Creek. Shot points are 10 feet apart.