SHALLOW SEISMIC DATA ACQUISITION, PROCESSING, AND INTERPRETATION AT PLAYA 3, PANTEX PLANT, CARSON COUNTY, TEXAS

Jeffrey G. Paine

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713-7508

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ABSTRACT

Shallow seismic refraction and reflection data were collected in 1993 at Pantex Playa 3, a small (0.5-km diameter), nearly circular ephemeral lake near the northern boundary of the Pantex Plant, as part of a hydrogeological study of Pantex area playa and interplaya environments. These studies will be used to help understand the hydrogeological framework of the Pantex Plant and the paths of ground water and potential contaminants in the subsurface.

Seismic refraction data collected along two reversed spreads show that near-surface compressional velocities increase from less than 400 m/s at the surface to 700 to 1200 m/s a few meters below the surface. Two shallow seismic reflection lines across Playa 3, each 1.8 km long, reveal the presence of four major reflecting horizons beneath the playa basin. Horizon 0, the shallowest, is interpreted to be from the Ogallala caprock and appears to be absent directly beneath Playa 3. Horizon 1 is interpreted as a fine-grained zone within the upper Ogallala Formation that may perch ground water above the main Ogallala aquifer. Horizon 2, the strongest reflector on the seismic sections, is a lower Ogallala reflector that may be either a stratigraphic unit or a horizon related to past Ogallala water levels. Horizon 3, the deepest major reflector recognized, is interpreted to be the top of Permian or Triassic bedrock.

Each horizon visible on the reflection lines mimics surface topography. Relief increases with depth: the playa floor is 8 m below the upland, Horizon 0 (caprock) has 16 to 24 m of relief, Horizon 1 (upper Ogallala fine-grained zone) has 30 m of relief, Horizon 2 (lower Ogallala reflector) has 35 m of relief, and Horizon 3 (bedrock) has 75 m of relief. Increasing relief with age, coupled with the presence of internal bedrock reflectors that dip toward the basin center beneath the margins of Playa 3, indicate that subsidence has been important in the formation of the basin. Subsidence is probably caused by dissolution of underlying Permian evaporites.

INTRODUCTION

Work described in this report is part of a larger effort to use noninvasive geophysical methods (principally shallow seismic reflection profiling) to help understand the hydrogeological framework of the Pantex Plant and surrounding areas, including the City of Amarillo water supply field north of the Pantex Plant. Subsurface targets of interest include the top of the Ogallala Formation (the "caprock"), internal Ogallala stratigraphy (particularly units that may retard the flow of ground water from the surface to the main Ogallala aquifer), and the surface of the underlying Permian or Triassic bedrock. Specifically, the purpose of this study is to examine the stratigraphy beneath Pantex Playa 3, a relatively small playa basin near the northern boundary of the Pantex Plant (fig. 1), for comparison with results from a much larger basin (Sevenmile Basin) as well as with results from seismic data collected in interplaya areas. These studies will lead to a better understanding of stratigraphic differences between playa basins, which serve as preferential recharge points for the Ogallala aquifer, and between playa and interplaya areas, where little Ogallala recharge is thought to occur.

Between 1991 and 1993, the Bureau of Economic Geology (BEG) collected more than 46 km of shallow seismic reflection data in interplaya and playa basin settings (fig. 1 and table 1). Regional interplaya data (lines PRL1, 2, 3, 4, and 5) were collected in 1991 on the Pantex Plant, on the perimeter of the plant, and in the Amarillo well field north of the plant (Paine, 1992). These lines show that (a) major reflecting horizons include the top of bedrock, a lower Ogallala reflector, and a persistent upper Ogallala reflector that correlates with a perching horizon composed of a sequence of water-saturated interbedded clays and fine sands detected in well logs; and (b) elevation of the interpreted perching horizon remains relatively constant across the area, whereas the bedrock and lower Ogallala reflectors dip to the northeast.

In 1992, data collection in playa basin settings began with a reflection line across Sevenmile Basin, a large playa basin located just south of the Pantex Plant (Paine, 1993, 1994). Subsurface images across this basin showed that all major reflecting horizons dip into the basin and that relief on these surfaces increases with age, indicating a strong subsidence influence in

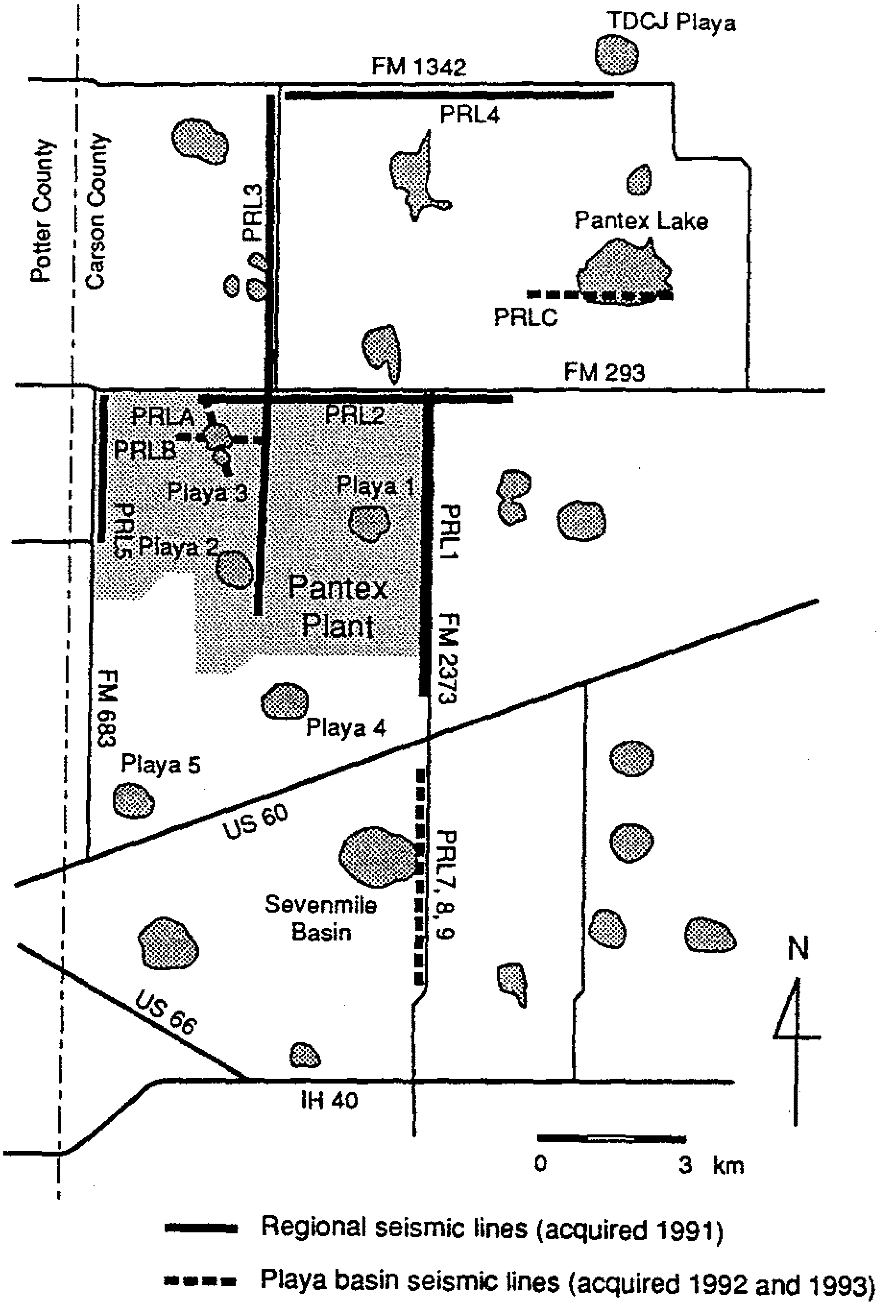

Figure 1. Locations of Bureau of Economic Geology playa and interplaya seismic lines in the vicinity of the Pantex Plant.

Table 1. Line lengths for shallow seismic reflection data collected in the vicinity of the Pantex Plant in 1991, 1992, and 1993. Line locations shown on fig. 1.

	Length (km)
Interplaya lines	
PRL1	6.5
PRL2	7.3
PRL3	11.3
PRL4	6.5
PRL5	3.2
Total interplaya lines	34.8
Playa basin lines	
PRL7 (Sevenmile Basin)	4.5
PRLA (Playa 3)	1.8
PRLB (Playa 3)	1.8
PRLC (Pantex Lake)	3.2
Total playa basin lines	11.3
Total interplaya and playa basin lines	46.1

the formation of the basin. Playa basin studies were expanded in 1993 with two lines across Playa 3 and one long line across Pantex Lake (fig. 1). The last playa basin to be studied in this phase of our investigation will be Playa 5 (fig. 1), located on the Texas Tech Research Farm southwest of the main Pantex Plant. Data collection at this playa will occur in the summer of 1994.

Playa 3, the subject of this report, is a nearly circular playa that is about 500 m in diameter and is located west of the burning grounds (fig. 2). It occupies a larger basin that is about 1.2 km in diameter and is open to the southeast. The playa floor is 8 m below the upland north and west of Playa 3 and is 5 m below the upland south and east of the playa. A small depression that is neither as deep nor as large as Playa 3 is located within the basin southeast of Playa 3 (fig. 2).

METHODS

Shallow seismic refraction and reflection techniques were used in this study. The seismic source chosen for the work is the Bison EWG-III, a noninvasive, stackable 500 lb (230 kg) accelerated weight drop unit (table 2). Data were acquired on a 48-channel Bison 9048 seismograph, transferred to a Macintosh computer, and processed using Seismic Processing Workshop (SPW) software on a Macintosh computer. Acquisition personnel included a survey crew of two who operated an optical theodolite and metric staff and surveyed shotpoint and geophone locations and a seismic crew of three who operated the seismograph, moved the source from shotpoint to shotpoint, fired the source, and moved and installed cables and geophones. Crew members were supplied by the Bureau of Economic Geology (BEG). All data were acquired in August 1993. Because the acquisition system uses metric units, discussion of acquisition parameters and geophysical properties is in metric units. Metric system units are also used in discussions of calculated depths, elevations, and on-the-ground distances.

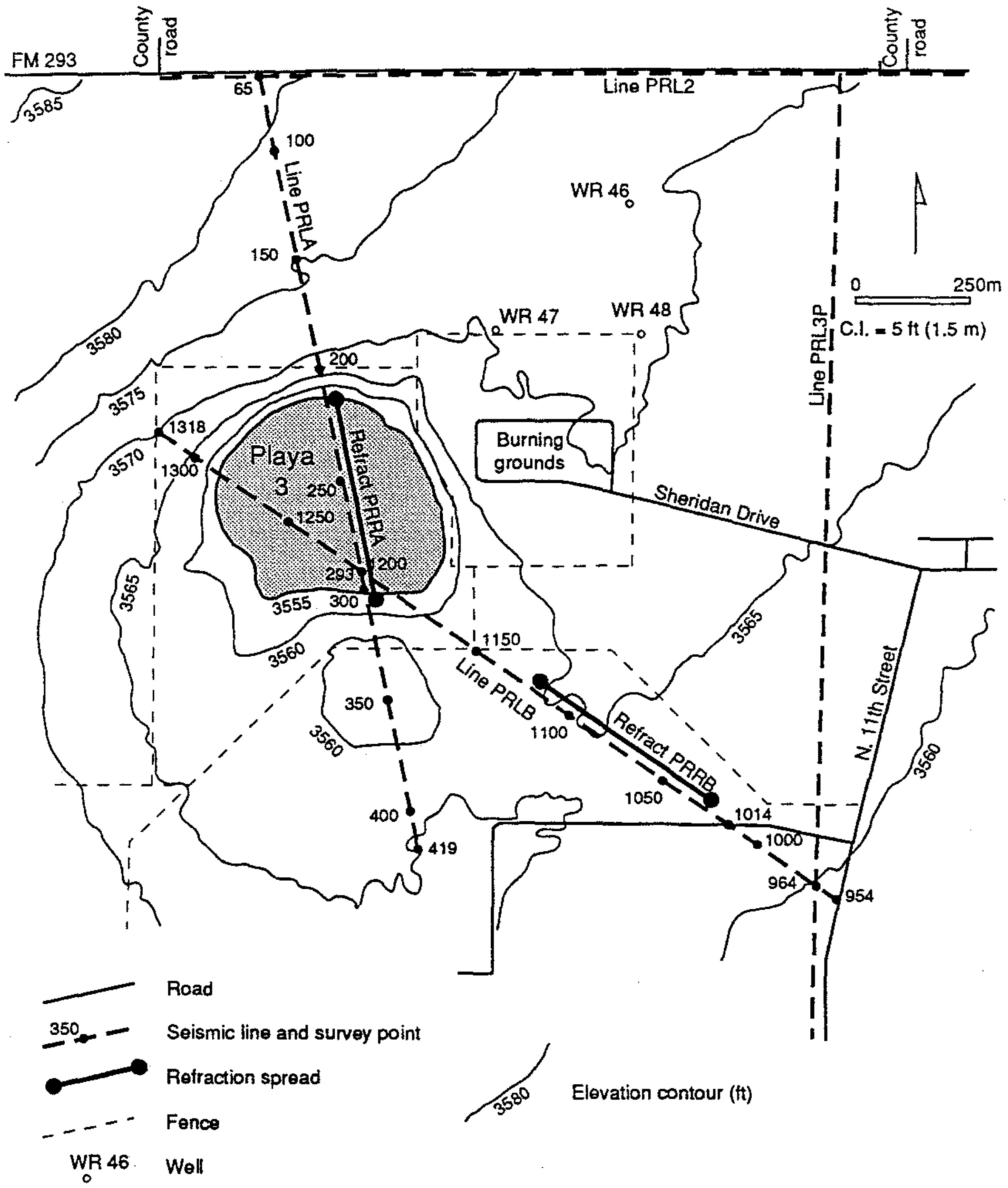

Figure 2. Location of seismic reflection lines PRLA and PRLB and refraction spreads PRRA and PRRB at Pantex Playa 3. Roads, fences, well locations, and elevation contours from U.S. Army Corps of Engineers 1-ft contour map of the Pantex Plant.

Table 2. Equipment, acquisition geometry, recording parameters, and field statistics for seismic refraction and reflection surveys at Playa 3, Pantex Plant.

	Refraction		Reflection	
	PRRA	PRRB	PRLA	PRLB
Equipment				
Seismic source	Bison EWG III	Bison EWG III	Bison EWG III	Bison EWG III
Geophones	40 Hz	40 Hz	40 Hz	40 Hz
Seismograph	Bison 9048	Bison 9048	Bison 9048	Bison 9048
Geometry				
Source offset	2.5 to 352.5 m	2.5 to 352.5 m	30 m	30 m
Source spacing	117.5 m	117.5 m	5 m	5 m
Spread length	235 m	235 m	235 m	235 m
Source-receiver geometry	-	-	End on	End on
Geophones in array	1	1	1	1
Geophone spacing	5 m	5 m	5 m	5 m
Recording parameters				
Recording channels	48	48	48	48
Sample interval	0.001 s	0.001 s	0.001 s	0.001 s
Record length	1 s	1 s	1 s	1 s
Analog low-cut filter	4 Hz	4 Hz	16 Hz	16 Hz
Analog high-cut filter	500 Hz	250 Hz	250 and 500 Hz	250 Hz
Statistics				
Line length	-	-	1755 m	1820 m
Orientation	N-S	NW-SE	N-S	NW-SE
Shots per shotpoint	6 to 18	4 to 18	4	4
Date acquired	8/17/93	8/19/93	8/17 to 8/18/93	8/19 to 8/20/93

Seismic Refraction

Refraction data were collected at two sites near Playa 3. One reversed spread (PRRA) was oriented approximately north–south along reflection line PRLA; the other reversed spread (PRRB) was oriented northwest–southeast along reflection line PRLB (fig. 2). The geophone spread consisted of 48 40-Hz geophones spaced at 5-m intervals along a surveyed line 235 m long (table 2). The weight-drop source was fired at five sites spaced 117.5 m apart: one at the center of the geophone spread, one at each end of the spread, and one 117.5 m beyond each end of the spread. Source to receiver offsets ranged from 2.5 to 352.5 m. The number of shots at each shotpoint increased from 4 or 6 at the center of the geophone spread to a maximum of 18 when the source was farthest from the geophones. Data were recorded on the seismograph with a 1 millisecond (ms) sample interval, a 1 s record length, and a 4 Hz low-cut filter, the lowest possible setting (table 2).

After the refraction data were transferred to a Macintosh computer, first arrivals were picked using SPW and then exported to a spreadsheet program, where layer assignments and apparent velocity measurements were made and zero-offset intercept times were calculated for critically refracted arrivals. True velocities, layer thicknesses, and apparent dip angles were calculated using the slope-intercept method (Palmer, 1986; Milsom, 1989).

Seismic Reflection

Acquisition Geometry

Two shallow seismic reflection lines were acquired across Playa 3 (fig. 2) using the common depth point method adapted to the shallow subsurface (Mayne, 1962; Steeples and Miller, 1990). These lines cover a total distance of 3.6 km and include one line oriented approximately north–south (PRLA) and another oriented approximately northwest–southeast (PRLB). Acquisition geometry was the same as that used for most other playa and interplaya seismic lines (Paine, 1992, 1993): 5-m source and receiver intervals, 30-m minimum source to receiver distance, 235-m maximum source to receiver distance, and 24-fold data acquisition (table 2). Acquisition geometry was asymmetric (end on) for lines PRLA and PRLB, with the weight-drop source trailing a 48-geophone spread (table 2). Single 40 Hz geophones were used at each geophone location for both lines.

Seismic Tests

Seismic tests performed at Playa 3 included noise, filter, and stacking tests. For these tests, the seismograph was connected to a spread of 48 geophones spaced at 5-m intervals. For the noise test, the seismograph recorded background seismic noise with no source activated. This test and observations made during the remainder of the survey revealed that only wind was an important source of noise. Wind noise was severe at times and was largely unavoidable.

The optimum source-receiver offset range for the reflection survey was determined during previous seismic surveys with walkaway tests. In these tests, the source was fired at successively greater distances from the geophone spread with the low-cut filter set to its lowest setting. The optimum offset range begins as close to the source as possible, but not so close that the nearest geophones are saturated with high-amplitude surface waves or source-related noise. The farthest offset should be equal to or greater than the depth of the deepest target. Based on these tests, a 30 m minimum source-receiver offset and a 5 m geophone spacing were chosen. Maximum source-receiver offset was thus 235 m.

Filter tests were conducted to determine the optimum setting for the analog low-cut filter. The intent was to raise the filter as high as possible to reduce unwanted surface wave noise, but low enough to allow the deepest events of interest to be recorded. Tests using the chosen acquisition geometry showed that the optimum filter setting was 16 Hz (table 2).

Stacking tests were also conducted using the source-receiver geometry selected for the reflection lines. The source was fired repeatedly into the geophone spread in an attempt to increase the signal to noise ratio by partly canceling random noise. Four source stacks per shotpoint were chosen as a reasonable compromise between improvement in data quality and the pace of the survey.

Other acquisition parameters chosen based on these tests included a seismograph sampling interval of 1 ms, a record length of 1 s, and an anti-alias (high cut) filter setting of 250 or 500 Hz depending on wind noise (table 2).

Processing

Seismic reflection data acquired at Playa 3 were transferred each evening to a Macintosh computer and stored on 8-mm digital tape. After the field work was completed, the data were processed at BEG on a Macintosh Quadra 700 computer using the software SPW. Processing procedures (table 3) were those common to many types of reflection processing (Yilmaz, 1987).

At BEG, the first processing step was to convert the data files from seismograph format to SPW format. Next, trace headers were created that combined the seismic data with acquisition geometry information recorded by the seismograph operator and the surveyor. Dead or excessively noisy traces were then deleted from the data set, which was resampled to a 2-ms sample interval to reduce the size of the data set. Automatic gain control was applied to amplify weak arrivals at late times or far offsets. A mute function was designed to delete the first arrivals from each shot gather to prevent them from stacking as a false reflector. Another mute function was designed to remove the air wave, or the sound of the source weight striking the ground plate, from each shot gather. Datum corrections were then made to each trace that effectively shifted them to a common elevation. A low pass filter was then applied to remove high-frequency wind noise. A dip filter was applied in the frequency–wave number domain to attenuate high amplitude, slow-moving surface waves. This step was followed by shot deconvolution, which attempts to collapse the long and reverberatory source wavelet into a sharper wavelet that is easier to interpret on a stacked section. Velocity analysis was conducted by fitting reflection hyperbolas to events on common midpoint (CMP) gathers, or gathers of all traces that have the same source-receiver midpoint. For 24-fold data, there are 24 traces in a CMP gather. A bandpass filter was then applied to remove unwanted low- and high-frequency noise.

Table 3. Processing steps, parameters, and purpose of each step used to convert seismic reflection data collected at Playa 3 to final seismic sections. Data processed using Seismic Processing Workshop (Parallel Geoscience Corporation).

Processing step	Parameters	Purpose
SEG-2 input	1 ms sample rate, 1 s record length	Convert seismic data from Bison format to processing format
Create trace headers	Seismic data, surveyor and observer notes	Combine acquisition geometry and shot records
Trace edit		Remove bad traces
Resample	2 ms sample rate	Reduce size of data set
Automatic gain control	400 ms window	Amplify weak arrivals at late times or far offsets
Early and surgical mute		Mute first break and air wave
Datum correction	1087 m datum, 800 m/s velocity	Adjust all traces to common elevation datum
Low pass filter	100 Hz, 18dB/octave rolloff	Attenuate high-frequency wind noise
Dip filter	Reject 10 to 500 m/s, < 200 Hz	Attenuate surface waves
Shot deconvolution	Predictive, 1 % whitening 100 ms inverse filter length 0 ms design window start 500 ms design window length 20 ms prediction length	Shrink wavelet
Common midpoint sort		Collect all traces with same source-receiver midpoint (CMP)
Velocity analysis	Semblance plot, 400 to 1900 m/s Hyperbola picking	Pick stacking velocities for moveout correction
Bandpass filter	Pass 10 to 70 Hz	Remove unwanted low- and high-frequency noise
Normal moveout correction	Velocity function every 20 CMPs (50 m)	Simulate zero offset for all traces
Common midpoint stack	All traces	Stack all traces with same source-receiver midpoint (CMP)
Apply static shifts	800 m/s; 1093 m elevation	Move all traces to final datum (1093 m)

The velocity function derived from the CMP gathers was used to correct each trace in the CMP gather for normal moveout (the delay in arrival time caused by increasing source-receiver offset) and to simulate zero offset for all traces. Each velocity-corrected trace in a CMP gather was summed to produce a single composite trace. A stacked seismic section is a display of these composite traces. The final step was to shift each trace in the stacked section by a constant time interval to move the stacked section to the same datum elevation used for other seismic lines in the area.

RESULTS AND INTERPRETATIONS

Considering the relatively poor sonic characteristics of the near-surface formations at Pantex (low moisture content, unconsolidated, and relatively coarse grained), seismic data collected at Playa 3 were reasonably good (fig. 3). Types of seismic energy visible on the sample field record include (a) surface waves, which are high-amplitude, low-frequency, and low-velocity waves that are a major source of noise in virtually all shallow seismic surveys; (b) air wave, which is a high-frequency noise source that propagates at the speed of sound in air across the recording spread and represents the sound of the seismic source striking a metal plate on the ground; (c) direct and refracted waves, which are the first arrivals at geophones along the spread and represent compressional waves that travel either directly from the source to the receiver in the surface layer or travel at least part of the distance between the source and receiver along subsurface acoustic boundaries; and (d) reflected waves, which form hyperbolas on field records and represent compressional waves that originated at the source, bounced off an acoustic boundary in the subsurface, traveled back to the surface, and were recorded by the geophone. In this study, refracted waves were used to determine compressional velocities of near-surface material and reflected waves were used to construct seismic images of the subsurface.

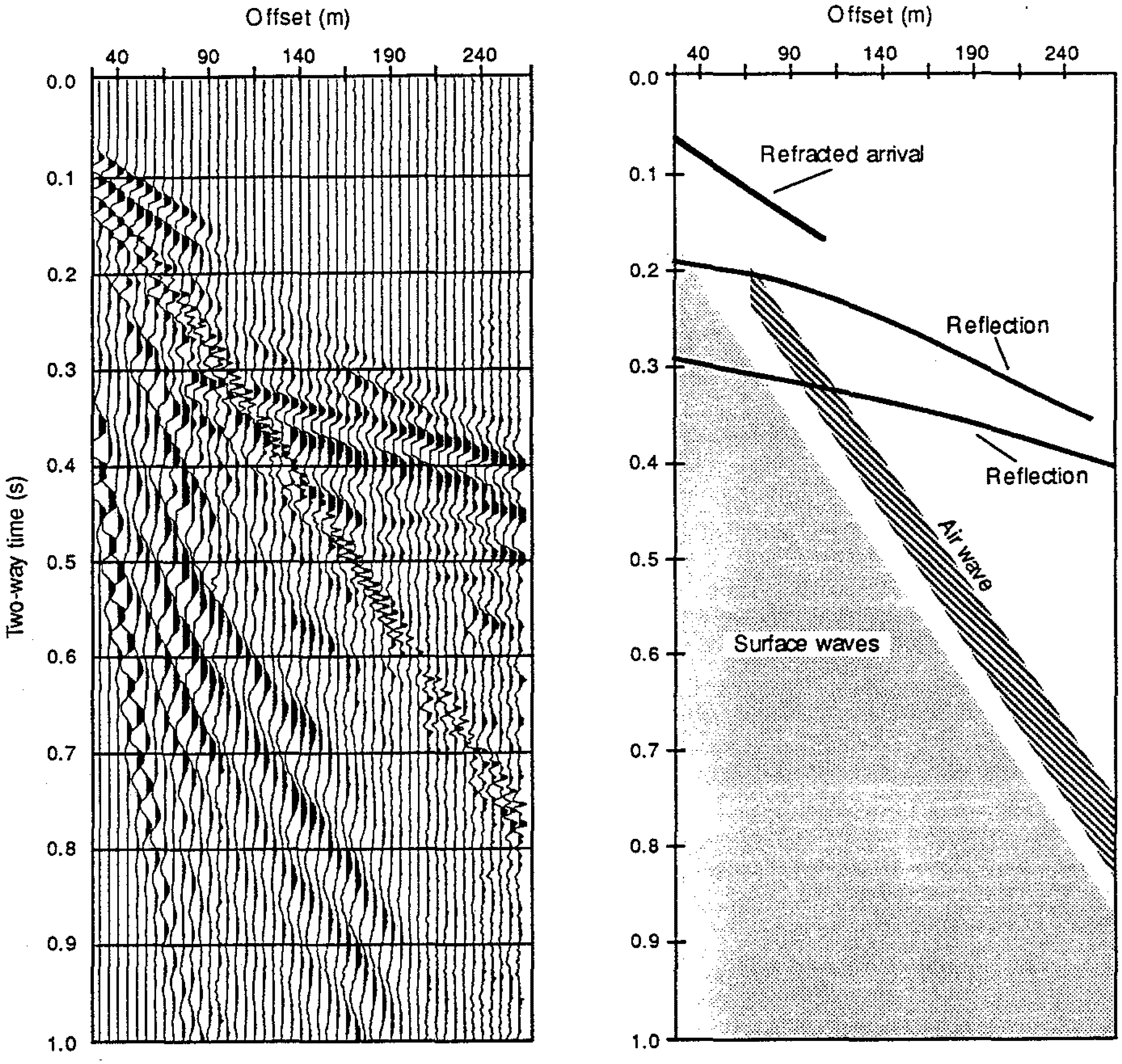

Figure 3. Field record PRLB0092 from reflection line PRLB. Uninterpreted shot gather shown at left; interpreted types of seismic energy shown at right.

Refraction Spreads PRRA and PRRB

The direct wave was the first arrival on field records from refraction spread PRRA, located on the floor of Playa 3 (fig. 2), between source-receiver offsets of 2.5 to between 10 and 15 m. For spread PRRB, located on the upland southeast of Playa 3, the direct wave was the first arrival to a source-receiver offset of 20 to 25 m. Compressional velocities calculated for the thin surface layer from the direct wave arrival times were 320 m/s on the playa floor and 334 m/s on the upland. Beyond 10 m offset for PRRA and 20 m offset for PRRB, a critically refracted wave was the first arrival out to an offset of about 80 m on both spreads. This wave traversed the playa floor spread at about 700 m/s and the upland spread at about 1200 m/s, indicating a layer with significantly higher velocities lies at a depth of a few meters below the surface. Beyond about 80 m from the source on both spreads, the first critically refracted wave dies out. No well-defined second critically refracted wave was observed between 80 m and the maximum source-receiver offset of 352.5 m, indicating that no layers were encountered deeper than the layer that produced the first critically refracted wave.

Reflection Data

Reflection surveys typically produce images of the subsurface that are presented as cross sections in time (figs. 4 and 5). Two-way arrival times can be converted to depth if it is known how fast seismic waves travel in the subsurface. Velocity picks made from subsurface reflectors on both lines PRLA and PRLB (fig. 6) show that velocities increase fairly regularly with two-way time (and thus depth) between about 100 and 400 ms, and then increase rapidly between about 400 and 600 ms. The change in slope probably represents a subsurface change from largely unconsolidated sediments of the Ogallala Formation to lithified Permian or Triassic units that underlie the Ogallala Formation. Because we are interested mainly in the features at and above the bedrock contact, we used only the velocity picks between 0 and 400 ms of two-way time to calculate a velocity function for PRLA and PRLB that can be used to convert reflector

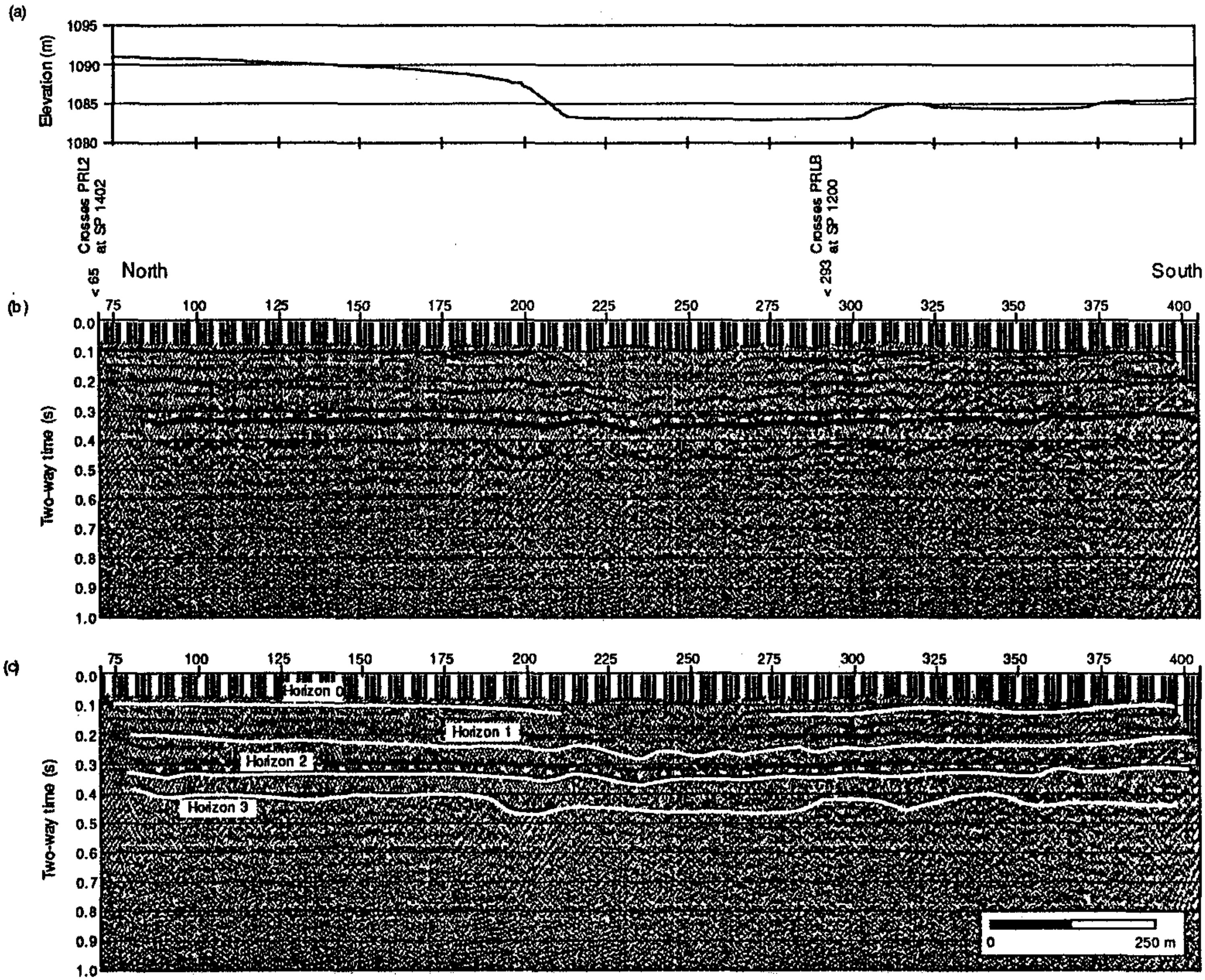

Figure 4. Surface elevation (a), uninterpreted seismic section (b), and interpreted seismic section (c) along reflection line PRLA across Playa 3. Horizon 0 is interpreted as the top of the Ogallala Formation, Horizon 1 is interpreted to a perching horizon within the upper part of the Ogallala Formation, Horizon 2 is a major reflecting horizon within the lower part of the Ogallala Formation, and Horizon 3 is interpreted as the top of bedrock. Survey points are shown on x-axis.

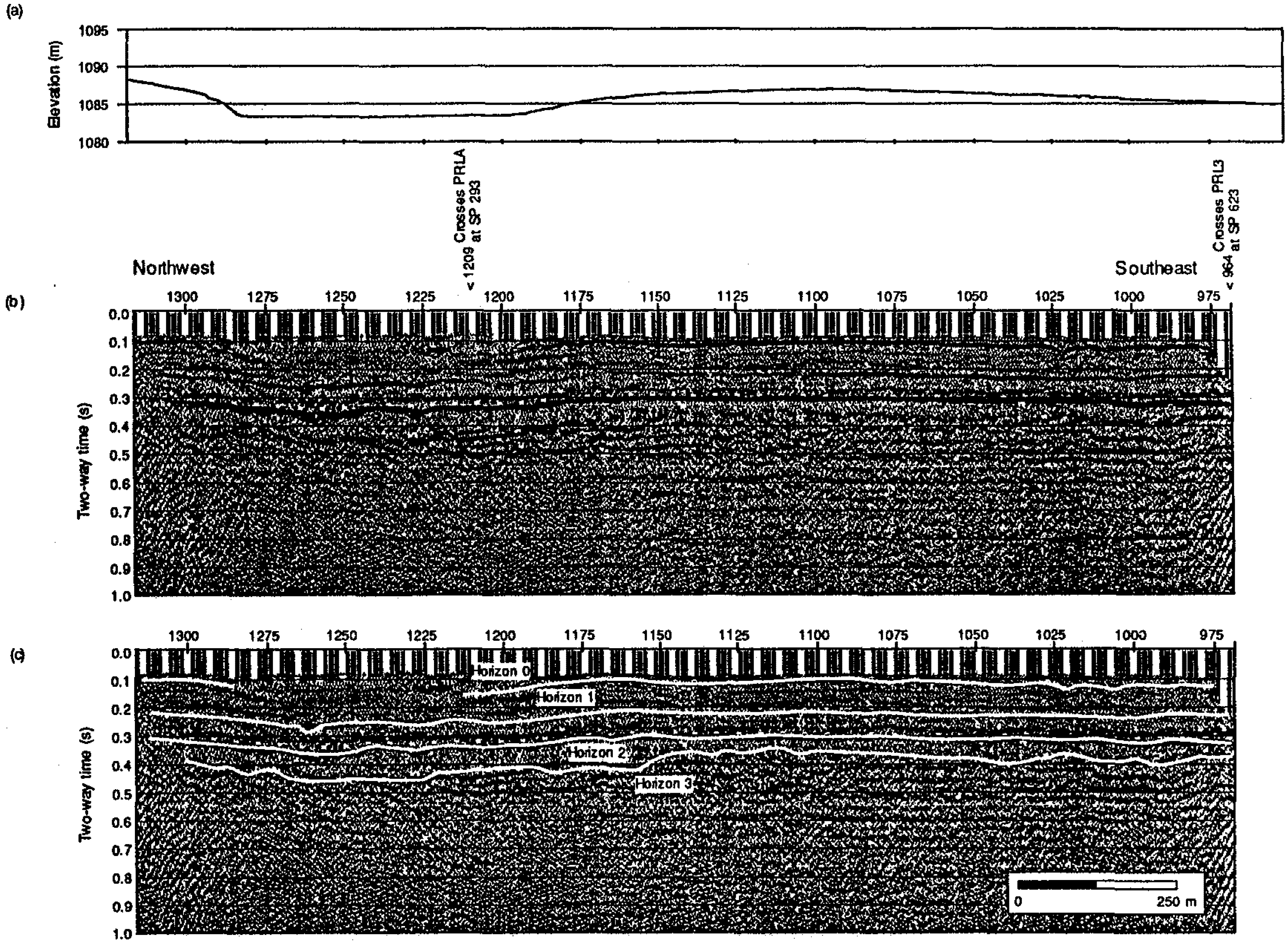

Figure 5. Surface elevation (a), uninterpreted seismic section (b), and interpreted seismic section (c) along reflection line PRLB across Playa 3. Horizon 0 is interpreted as the top of the Ogallala Formation, Horizon 1 is interpreted to be a perching horizon within the upper part of the Ogallala Formation, Horizon 2 is a major reflecting horizon within the lower part of the Ogallala Formation, and Horizon 3 is interpreted as the top of bedrock. Survey points are shown on x-axis.

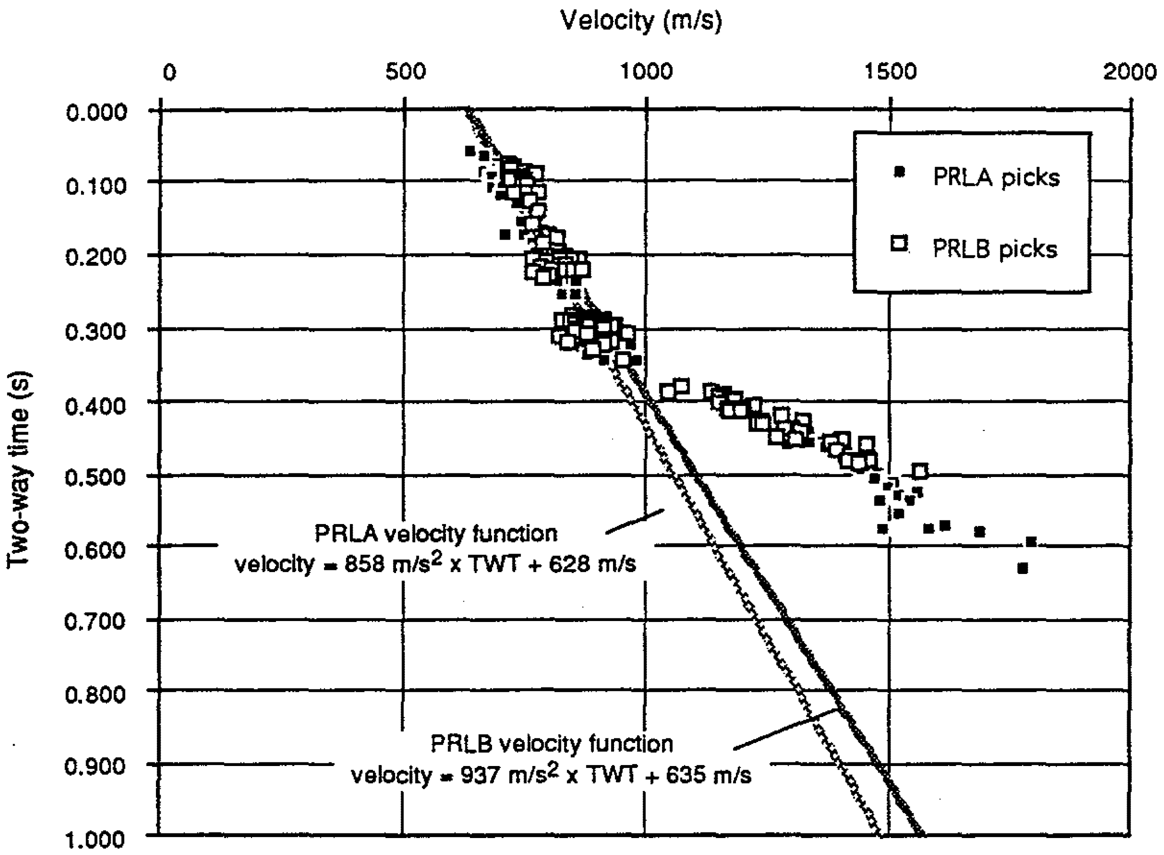

Figure 6. Stacking velocity picks and best-fit velocity functions calculated from velocity picks less than 0.4 s two-way time for lines PRLA and PRLB.

two-way times to depths and elevations (fig. 6). These functions, as expected, provide very similar velocity estimates for the time range of interest.

Line PRLA

Line PRLA is oriented north-northwest to south-southeast and is about 1.8 km long (fig. 2). It intersects regional interplaya seismic line PRL2 at PRLA survey point (SP) 65 and PRL2 SP 1403 and intersects line PRLB on the floor of Playa 3 at PRLA SP 293 and PRLB SP 1200. Line PRLA begins on the upland north of Playa 3, continues across the floor of the playa and across a small depression just south of the main playa, and then ends on the upland south of Playa 3. There is about 8 m of relief between the playa floor and the upland north of Playa 3 and about 5 m of relief south of the playa (figs. 2 and 4a). As was true at Sevenmile Basin (Paine, 1993), the playa basin margin has a steeper slope on the north side of the playa than on the south.

Four major reflecting horizons, named Horizons 0, 1, 2, and 3, are visible on line PRLA (fig. 4b and c). The shallowest, Horizon 0, occurs at about 100 ms of two-way time. This reflector is continuous north of SP 200 at the north edge of Playa 3, is absent or discontinuous beneath the playa floor between SP 200 and SP 350, and becomes continuous again south of SP 350. Where a correlative reflector does occur beneath the playa floor, it is at slightly later two-way times of as much as 120 ms.

After converting the two-way times for major reflecting horizons to depth using the velocity function calculated for line PRLA (fig. 7), these depths were subtracted from surveyed surface elevations to produce an elevation section across Playa 3 (fig. 8). Calculated depths to Horizon 0 range from 29 to 40 m and deepen slightly toward the playa floor (fig. 7). The calculated elevation for this horizon, where present, ranges from 1042 to 1058 m, again generally lower near the basin and higher outside of the basin (fig. 8). Total relief on this surface is 16 m, which is double the maximum surface relief across the basin of 8 m.

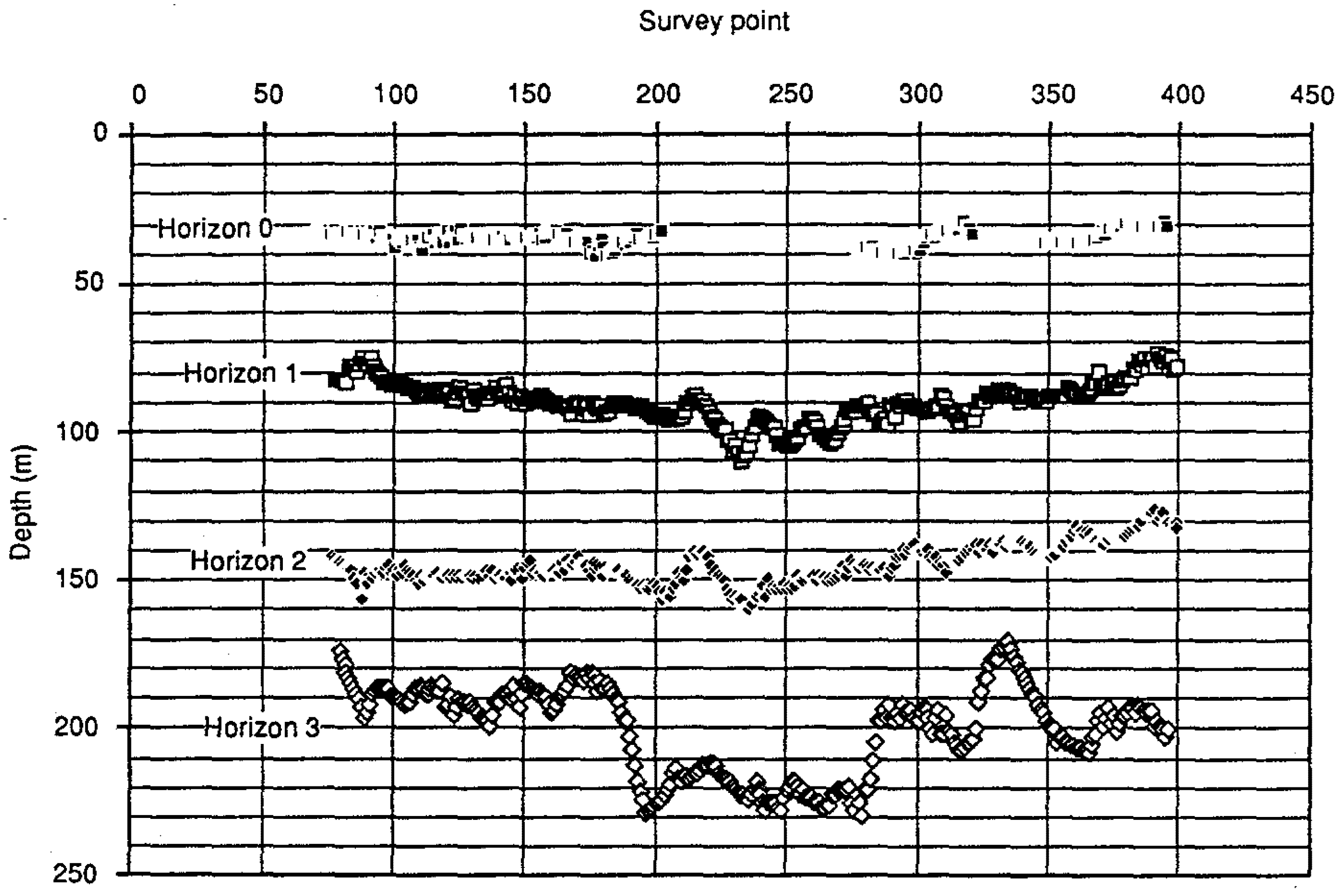

Figure 7. Calculated depths to major reflecting horizons interpreted from line PRLA.

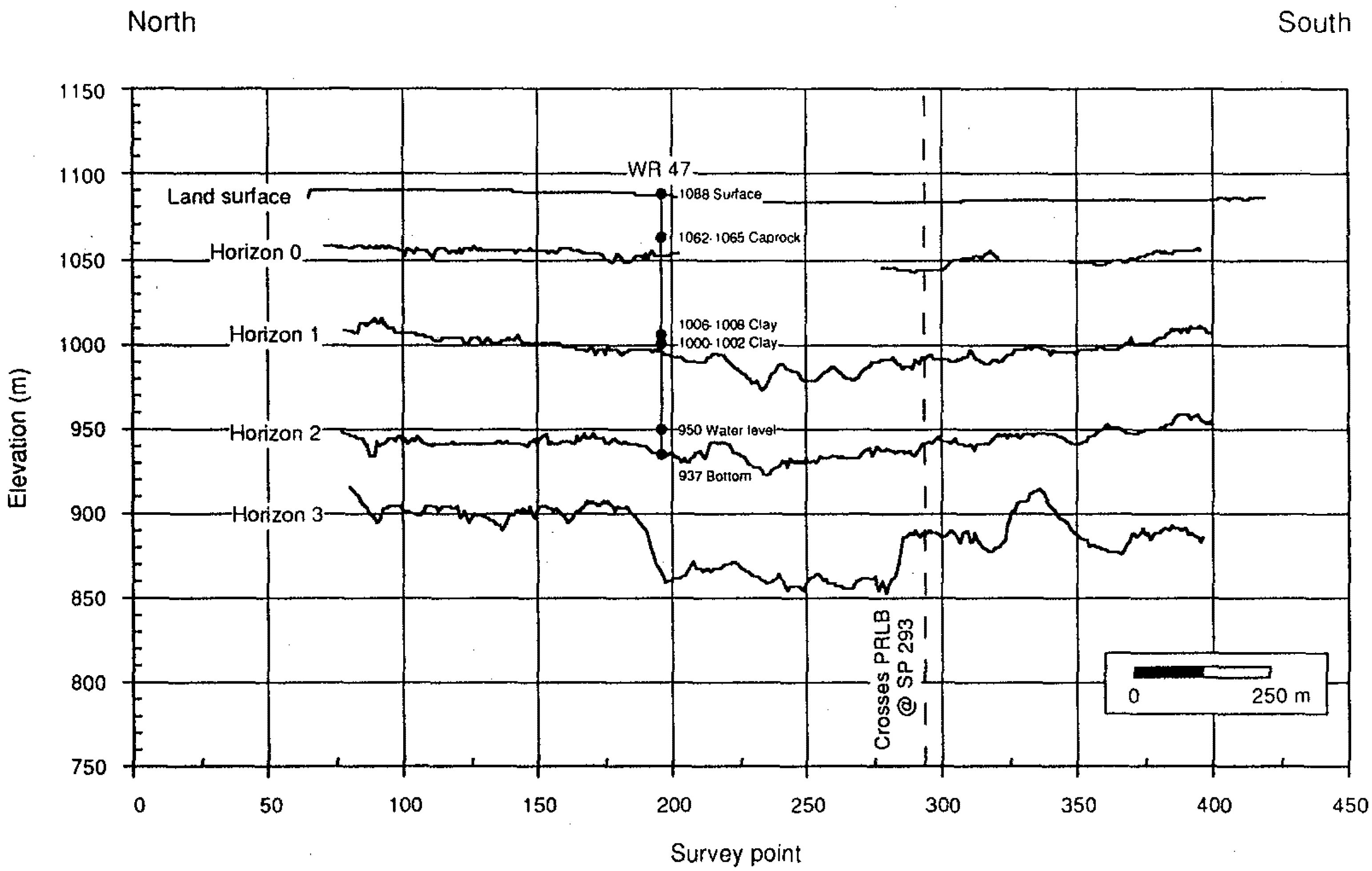

Figure 8. Cross section along line PRLA showing elevations of interpreted Horizons 0 (top of the Ogallala Formation), 1 (Ogallala perching horizon), 2 (lower Ogallala reflector), and 3 (top of bedrock). Key elevations from nearby well WR 47 also shown.

It is likely that Horizon 0 is a reflection from the Ogallala caprock. Lithologic descriptions from nearby wells WR 47, WR 48, and WR 49 (fig. 2) show that these wells penetrated the caprock at depths of 21 to 27 m. These depths are slightly shallower than those calculated for Horizon 0 along line PRLA, but the seismic velocity function for the shallowest part of the section is not well constrained and the calculated depths for this horizon may be too deep. Well WR 47, located about 400 m northeast of SP 195 on line PRLA (fig. 2), is the closest well to the seismic line. The caprock is about 3 m thick in this well and has an elevation of 1062 to 1065 m, which is a few meters above the calculated elevation for Horizon 0 at the closest tie point (fig. 8). The partial or complete absence of this reflector directly beneath Playa 3 suggests that either the caprock never developed there or it has been removed by erosion or dissolution.

Horizon 1 is not as strong a reflector on line PRLA as it is on other BEG seismic lines, but it is relatively continuous across the basin (fig. 4b and c). This reflection arrives later beneath the playa floor (250 to 280 ms two-way time) than it does beneath the upland (about 200 ms); there is also a slight depression of about 10 ms in this reflection beneath the small basin just south of Playa 3. Calculated depths for Horizon 1 increase from 80 m beneath the upland to between 90 and 110 m beneath the playa floor (fig. 7). Elevations range from a low of 972 m beneath the playa floor to a high of 1015 m beneath the upland north of Playa 3 (fig. 8). Relief on this surface is generally about 30 m but reaches a maximum of 43 m.

Outside of the playa basin, calculated elevations for Horizon 1 are 1000 to 1010 m. These values are similar to elevations reported for a ground water perching horizon composed of interbedded clays and fine sands in other parts of the Pantex Plant. This reflector also correlates to a similar reflector on line PRL2, where analysis of geophysical logs reveals the presence of one or more fine-grained zones that together may serve as the "perching horizon" above the main Ogallala aquifer. Lithologic descriptions of well WR 47 indicate the presence of two thin, clayey intervals at elevations of 1006 to 1008 m and 1000 to 1002 m (fig. 8), further strengthening the interpretation of Horizon 1 as a fine-grained perching interval that correlates with similar strata farther east on the Pantex Plant.

Horizon 2 is the strongest reflector that is continuous across the basin (fig. 4b and c). This reflector is clearly shown on virtually all field records between about 300 and 400 ms two-way time (fig. 3). The reflector deepens from about 330 ms beneath the upland north of Playa 3 (SP 200 northward) to 350 to 380 ms beneath the playa floor, and then shallows to about 300 ms south of Playa 3 (SP 300 southward). A minor depression of about 10 ms occurs on Horizon 2 below the small surface low south of Playa 3.

Horizon 2 does not exactly follow the pattern established by the major reflecting horizons above and below it of a pronounced deepening beneath Playa 3 (fig. 7). While the greatest calculated depths to Horizon 2 (up to 160 m) do occur beneath the playa floor, Horizon 2 also generally deepens to the north, from about 130 m below the surface near SP 400 to about 150 m below the surface north of SP 200. In other words, the thinning of material above this horizon is not as pronounced north of Playa 3 as it is for the material above other horizons.

Elevations on Horizon 2 are 940 to 950 m north of the playa floor (SP 200 northward), 940 to 960 m south of the playa floor (SP 300 southward), and generally drop to 925 to 945 m directly beneath Playa 3 (fig. 8). Maximum relief is about 35 m, which is comparable to that observed in overlying Horizon 1.

This reflector may represent a lower Ogallala fine-grained zone that has been recognized as a seismic reflector on line PRL2 and in borehole geophysical logs tied to that line, or it may be a reflection from a horizon related to a current or past Ogallala water level. Recent water levels of about 950 m in nearby wells such as WR 47 are near the calculated elevations of Horizon 2 (fig. 8). However, the presence of relief on Horizon 2 supports a possible interpretation of this horizon as a partly cemented and originally flat surface near a past Ogallala water level; this horizon was subsequently deformed to its present shape by subsidence.

The deepest of the major reflectors is Horizon 3, which occurs continuously along line PRLA but is difficult to follow in places (fig. 4b and c). This reflector occurs later in time beneath the playa floor than it does north or south of Playa 3; it arrives at 450 to 460 ms beneath the playa floor but shallows to 400 to 420 ms north of Playa 3 and to 400 to 450 ms south of Playa 3. There is no clear depression on Horizon 3 beneath the small topographic low south of Playa 3.

Depths calculated from Horizon 3 arrival times and the PRLA velocity function (fig. 6) are less accurate for this horizon than for overlying ones because (a) the reflector was difficult to pick in places, and (b) higher seismic velocities magnify erroneous time picks. Nevertheless, it is clear that depths to Horizon 3 increase beneath the floor of Playa 3 (fig. 7). On the upland north of Playa 3, calculated depths to Horizon 3 are 180 to 200 m. This depth increases to 210 to 230 m beneath the playa floor and decreases to 190 to 210 m south of Playa 3. Calculated elevations of Horizon 3 are about 900 m north of Playa 3, 850 to 870 m beneath the playa floor, and 880 to 900 m south of the playa (fig. 8). Relief on this surface is generally 50 m but reaches a maximum of 65 m.

None of the wells near PRLA are deep enough to reach the calculated elevations of Horizon 3. This reflector does correlate with a reflector on line PRL2 that is interpreted (from geophysical well log data) to be from the Permian or Triassic bedrock.

Line PRLB

Reflection line PRLB is 1.8 km long and is oriented northwest–southeast across Playa 3 (table 1 and fig. 2). The line begins on the upland northwest of Playa 3, crosses the southwest part of the playa floor, and ends on the upland southeast of Playa 3. It intersects line PRLA on the playa floor at PRLB SP 1200 and PRLA SP 293 and intersects regional interplaya line PRL3P at PRLB SP 964 and PRL3P SP 623. Relief along this line is greatest to the northwest, where the upland is more than 6 m above the playa floor (fig. 5a). The upland is about 4 m above the playa floor southeast of Playa 3. Line PRLB passes through an outlet in the playa basin southeast of Playa 3 that is indicated by the 3565 ft (1087 m) elevation contour (fig. 2).

As on line PRLA, there are four major reflecting horizons that are visible on line PRLB (fig. 5b and c). These four horizons can be correlated to Horizons 0, 1, 2, and 3 at the intersection of lines PRLA and PRLB. Horizon 0 is the shallowest of the major reflectors; it occurs generally between 100 and 120 ms, but it deepens near the northwest and southeast edges of Playa 3. The horizon is missing directly beneath Playa 3.

Depths calculated for Horizon 0 from two-way times and the velocity function for line PRLB (fig. 6) generally range from 29 to 40 m beneath the upland and deepen to more than 40 m near the edges of Playa 3 (fig. 9). Calculated elevations are between 1040 and 1060 m beneath the upland and are as low as 1030 m near the edge of Playa 3 (fig. 10). The higher elevations are found beneath a slight surface rise southeast of the playa.

Horizon 0 was interpreted as the reflection from the Ogallala caprock on line PRLA on the basis of nearby lithologic logs. These logs indicate that calculated depths to the horizon may be too great and calculated elevations too low. A likely cause of this discrepancy is that the velocity function produces a velocity that is too high for this time range.

The next deeper reflector is Horizon 1, which is continuous across the entire line but is relatively weak in places (SP 1100 to 1200, fig. 5b and c). This reflector arrives at 200 to 220 ms two-way time on the uplands near Playa 3, is slightly later (210 to 230 ms) on the southeast half of the line, and is latest beneath the playa floor (220 to 290 ms between SP 1175 and 1275). Calculated depths range from 80 to 110 m and are deepest (90 to 110 m) beneath the playa floor (fig. 9). Elevations calculated for Horizon 1 (fig. 10) are relatively consistent beneath the uplands at 990 to 1010 m (southeast of SP 1175 and northwest of SP 1275). The lowest elevations, 970 to 990 m, are found beneath the floor of Playa 3; elevation also decreases somewhat beneath the upland southeast of the playa. There is a minor low on this surface between SP 990 and SP 1050. Relief on Horizon 1 is generally about 25 m between the low beneath Playa 3 and the highs beneath the uplands, but it reaches a maximum of 39 m.

Horizon 1 correlates with Horizon 1 on line PRLA, which is interpreted as a fine-grained zone according to lithologic data from well WR 47 and geophysical well log data from wells along line PRL2. This horizon may serve as a perching horizon above the main Ogallala aquifer.

The strongest reflector visible on line PRLB is Horizon 2 (fig. 5b and c). This horizon persistently occurs at about 300 ms beneath the upland southeast of Playa 3 (SP 1175

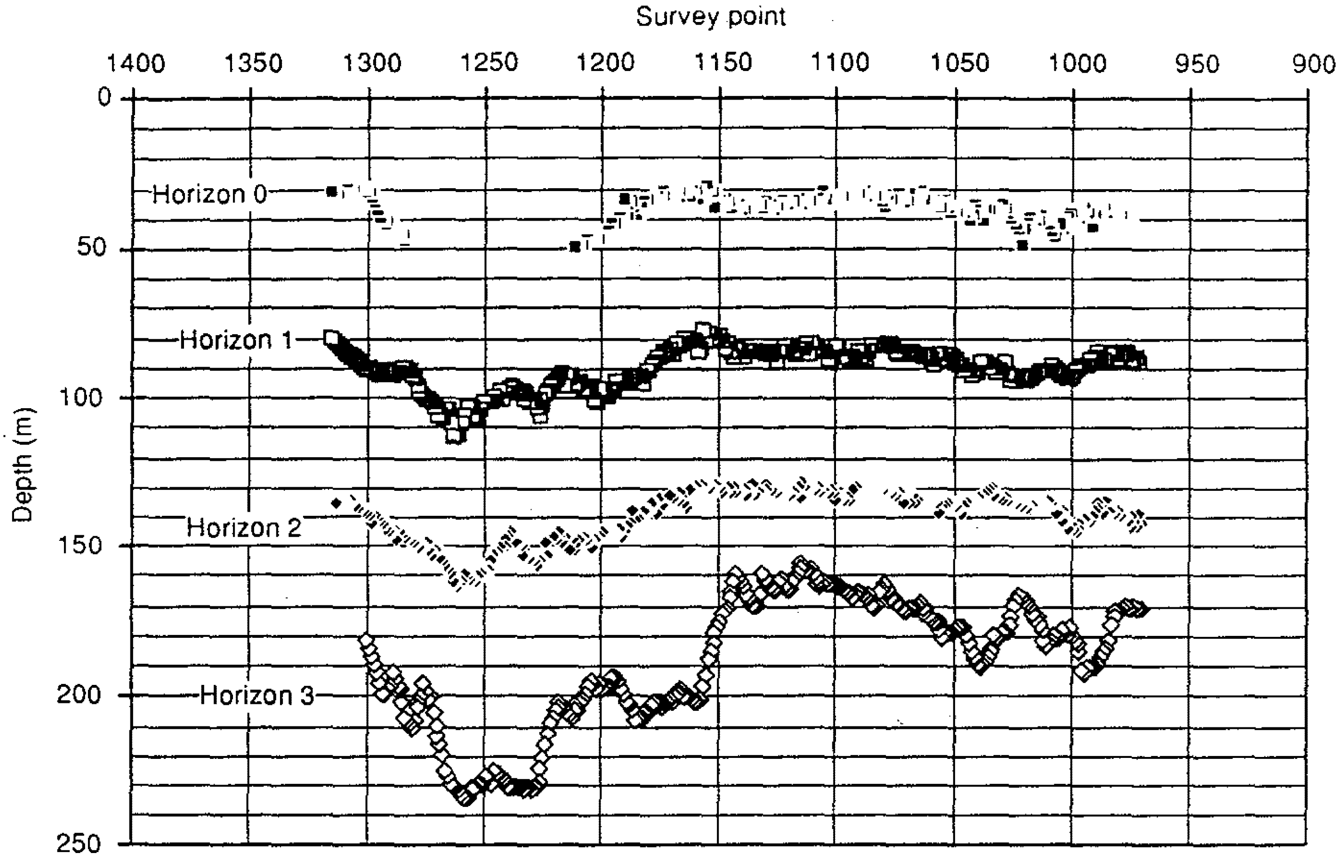

Figure 9. Calculated depths to major reflecting horizons interpreted from line PRLB.

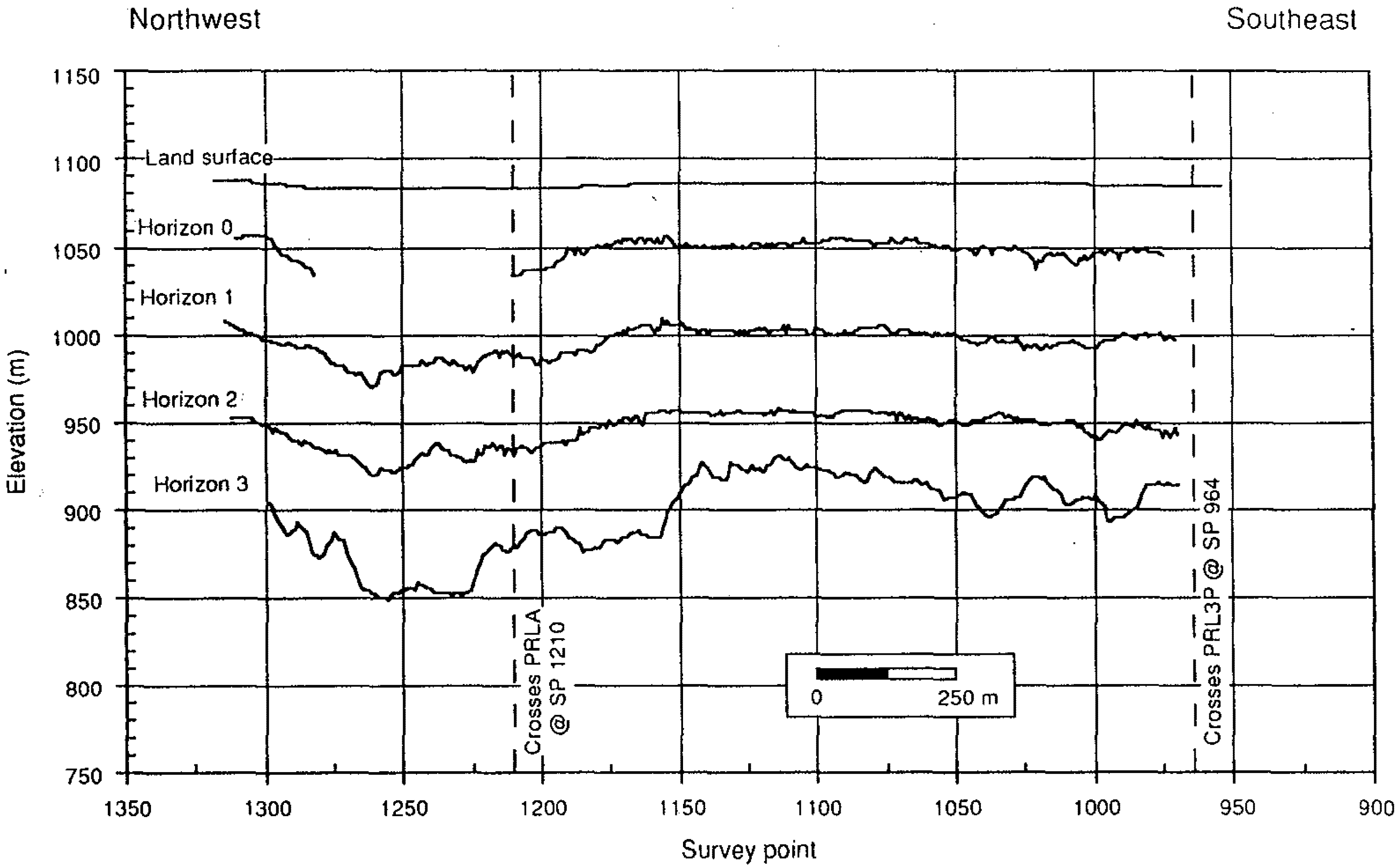

Figure 10. Cross section along line PRLB showing elevations of interpreted Horizons 0 (top of the Ogallala Formation), 1 (Ogallala perching horizon), 2 (lower Ogallala reflector), and 3 (top of bedrock).

southeastward), deepens to 370 or possibly 390 ms beneath Playa 3, and then rises back to about 300 ms northwest of the playa. Calculated depths to this horizon are 130 to 140 m beneath the upland and 130 to more than 160 m beneath the playa floor (fig. 9). Horizon 2 also deepens gradually beneath the upland southeast of SP 1150. On an elevation section (fig. 10), there is a pronounced low beneath Playa 3; calculated elevations beneath the upland are 950 to 960 m, whereas beneath the playa floor they are as low as 920 m. Maximum relief on Horizon 2 beneath the playa floor and the upland is about 35 m. Elevations of Horizon 2 also show a gradual drop to the southeast from 960 to 940 m.

Horizon 2 correlates with Horizon 2 on PRLA, which was interpreted as either a horizon related to present or past Ogallala water levels or a stratigraphic unit in the lower Ogallala Formation. On line PRLB, Horizon 2 has relief about equal to that on Horizon 1, which suggests that little subsidence of the basin containing Playa 3 occurred between formation of Horizons 1 and 2.

The deepest major reflector visible on line PRLB is Horizon 3 (fig. 5b and c). This reflector is difficult to carry through some areas, particularly between SP 1050 and SP 1175, but its overall appearance is similar to overlying horizons in that the horizon clearly deepens beneath Playa 3. Arrival times for this reflector are estimated to be 350 to 400 ms beneath the upland southeast and northwest of Playa 3 and 400 to 450 ms beneath the floor of the playa. Depth calculations are likely to be less accurate than those for overlying horizons because velocities are higher at these depths and because there is more uncertainty in the chosen arrival times. Calculated depths are 160 to 190 m beneath the uplands, deepening to 190 to 235 m beneath the playa floor (fig. 9). Horizon 2 also apparently deepens irregularly southeast of Playa 3 from 160 to 180 m below the surface. Total range in elevation of Horizon 2 is 850 to 930 m; maximum relief is thus 80 m (fig. 10). Typical elevations are 850 to 890 m beneath the floor of Playa 3 and 890 to 930 m beneath the uplands. The surface drops irregularly southeast of the playa from about 930 to 900 m.

Horizon 3 ties to Horizon 3 on line PRLA, which is interpreted as Permian or Triassic bedrock from seismic and well log ties to regional interplaya line PRL2. The rough and irregular appearance of Horizon 2 is probably due to (a) subsidence, particularly beneath Playa 3; (b) differential erosion before Ogallala deposition; and (c) difficulties in picking correct bedrock reflectors on the seismic section. Nevertheless, there is clear evidence of a bedrock basin beneath Playa 3.

DISCUSSION

Major reflectors visible on reflection lines PRLA and PRLB show increasing relief with depth and age (figs. 8, 10, and 11). The modern surface has 8 m of relief, which increases downward to about 24 m on Horizon 0 (interpreted Ogallala caprock), 30 m on Horizon 1 (upper Ogallala fine-grained zone and potential ground water perching layer), 35 m on Horizon 2 (lower Ogallala stratigraphic unit or ground water-related horizon), and 75 m on Horizon 3 (interpreted top of bedrock). These horizons also mimic surface topography; the lowest elevations on each horizon are found beneath the floor of Playa 3. This relationship, combined with the presence of internal bedrock reflectors near the margins of Playa 3 that dip toward the center of the playa (figs. 4b and c and 5b and c), supports an interpretation that (1) Playa 3 occupies a basin that has existed throughout the time interval represented by Ogallala and Blackwater Draw Formation deposition and (2) subsidence, probably related to dissolution of underlying Permian evaporites (Gustavson, 1986; McGookey and others, 1988), has played a major role in the formation of the basin. Calculated depths to the interpreted bedrock reflector (Horizon 3) are markedly deeper across a distance of about 500 m directly beneath Playa 3. Overlying horizons exhibit more gradual elevation declines over longer distances away from the playa. The apparent lack of a caprock reflector directly beneath Playa 3 can be attributed to either wetter conditions in a persistent topographic low (no caprock ever formed there) or local dissolution of the caprock by downward movement of ground water (Osterkamp and Wood, 1987; Wood and Osterkamp, 1987).

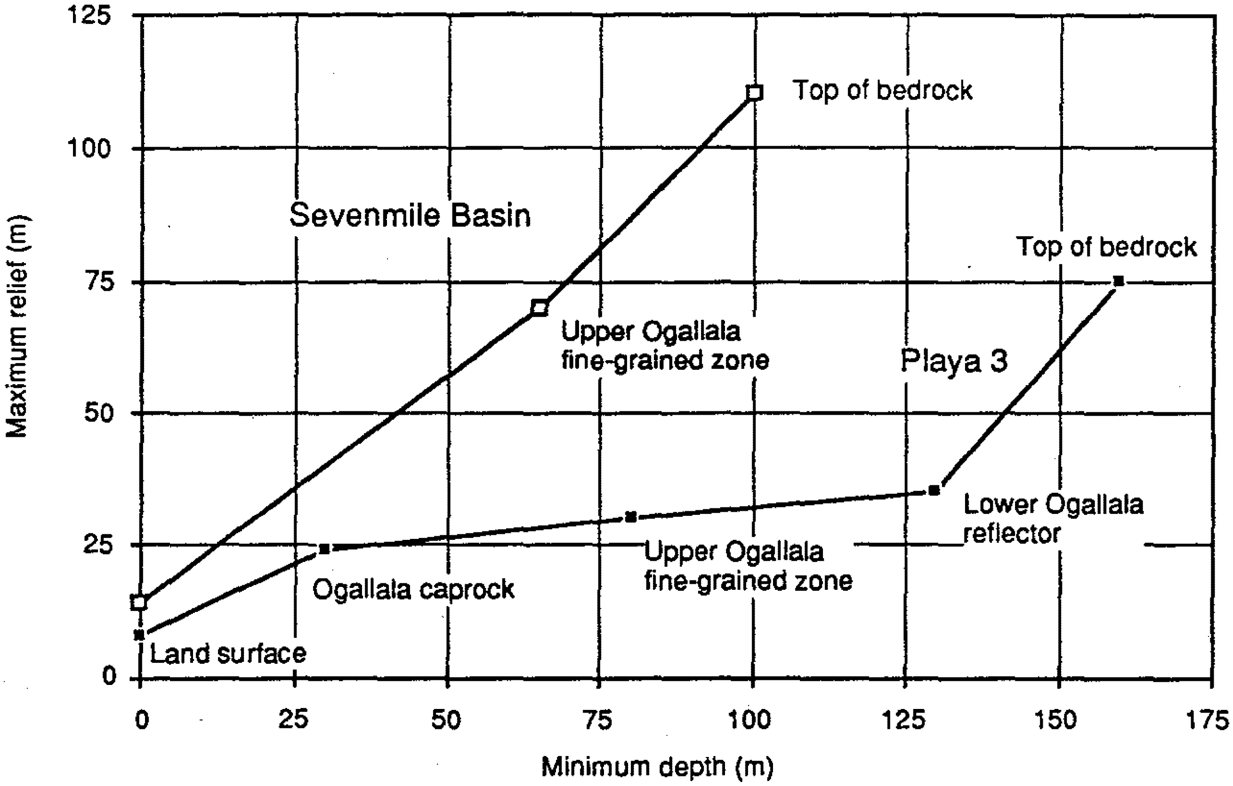

Figure 11. Relationship between maximum relief on major reflecting horizons and depths to horizons at Sevenmile Basin (Paine, 1993) and Playa 3. Playa 3 values are composites from reflection lines PRLA and PRLB.

More apparent relief on the bedrock surface (Horizon 3) than on the lower Ogallala horizon (Horizon 2) suggests that subsidence began before deposition of Horizon 2 (fig. 11). More relief on the Ogallala caprock (Horizon 0) than at the surface indicates that subsidence probably continued through the times of formation of the upper Ogallala fine-grained zone (Horizon 1) and the caprock. Absolute subsidence rates cannot be calculated until ages of key Ogallala horizons are known, but it is clear that the average rates (expressed by the relationship between maximum relief on a surface and its burial depth) at Playa 3 are lower than those for Sevenmile Basin (fig. 11). The presence of a basin at the surface today suggests that subsidence may be continuing or that other processes, such as eolian deflation, help maintain the basin.

CONCLUSIONS

There are four major reflecting horizons on reflection lines PRLA and PRLB that are interpreted to represent: (1) the Ogallala caprock (Horizon 0), (2) an upper Ogallala fine-grained zone (Horizon 1) that may be a perching horizon for ground water, (3) a lower Ogallala stratigraphic unit or horizon related to past Ogallala water level (Horizon 2), and (4) the top of Permian or Triassic bedrock (Horizon 3). Each of the major reflectors mimics surface topography; lowest elevations on each horizon are found directly beneath Playa 3.

Maximum relief on the horizons increases downward: 8 m at the surface, 24 m on Horizon 0, 30 m on Horizon 1, 35 m on Horizon 2, and 75 m on Horizon 3.

Internal bedrock reflectors dip basinward beneath the margins of Playa 3, which suggests that subsidence is the most likely cause of basin formation. Evaporite dissolution in underlying Permian strata probably caused the subsidence.

Horizon 0 (Ogallala caprock) appears to be absent directly beneath Playa 3. It either formed and was later dissolved or might never have formed in the persistent basin at Playa 3.

Subsidence, which has occurred at a lower rate than beneath Sevenmile Basin, probably began before formation of Horizon 2 and continued after formation of Horizon 0. It may continue to the present.

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