GEOPHYSICS, VOL. 51, NO. 2 (FEBRUARY 1986); P. 295–301, 7 FIGS.

Seismic reflection investigations of sinkholes beneath Interstate Highway 70 in Kansas

Don W. Steeples*, Ralph W. Knapp*, and Carl D. McElwee*

ABSTRACT

Seismic reflection studies were performed across actively developing sinkholes located astride Interstate Highway 70 in Russell County, Kansas. Results indicate that high-resolution seismic reflection surveys are useful in the subsurface investigation of some sinkholes. In particular, we were able to delineate the subsurface vertical and horizontal extent of the sinkholes because of the excellent acoustical marker-bed characteristics of the Stone Corral anhydrite. The seismic reflection evidence presented here, combined with borehole information from 1967, suggest that the Stone Corral anhydrite has been down-dropped within one of the sinkholes as much as 30 m in 13 years. The seismic reflection method is potentially useful in engineering studies of other sinkholes and karst features. The seismic data presented here were obtained in the presence of relatively heavy highway traffic (i.e., up to a few dozen vehicles per minute) using the MiniSOSIE recording technique.

INTRODUCTION

While sinkholes are known to have formed in Kansas prior to the onset of modern oil, gas, and mineral exploration (Smith, 1940), there seems to be little question that the activities of man have either increased their number or accelerated their development (or both). The following discussion is pertinent to almost all Kansas sinkholes that were geologically investigated. A more extensive discussion of geologic investigations of these sinkholes is given in Walters (1977).

During the past 25 years, progressive development of at least three sinkholes has occurred beneath Interstate Highway 70 (I-70) in Russell County, Kansas. The sinkholes are all centered at sites of salt-water disposal wells associated with the Gorham oil field. Sinking at ground surface has occurred at the rate of roughly 0.15 to 0.30 m per year since the late 1950s. The highway was rebuilt twice to grade and the gradual sinking was monitored with caution but without great alarm. Concern for public safety mounted in 1978 when another sinkhole developed catastrophically and without apparent warning at a salt-water disposal well about 25 km to the northwest in Ellis County.

The area is underlain by the 100 m thick Hutchinson salt member of the Permian Wellington formation at a depth of about 400 to 500 m (Figures 1 and 2). The formation of all of the sinkholes is consistent with dissolution of the Hutchinson salt by undersaturated brines introduced into leaky disposal wells or by fresh to brackish waters leaking downward along the outsides of the well casings. Either cause involves leaky pipes or insufficient cement sealing of the salt beds. Rock units above the salt-dissolution cavity progressively cave into the water-filled void, eventually reaching the surface as a gentle depression or as a catastrophic collapse.

The Crawford sinkhole on I-70 was drilled and geophysically logged by the Kansas Department of Transportation in

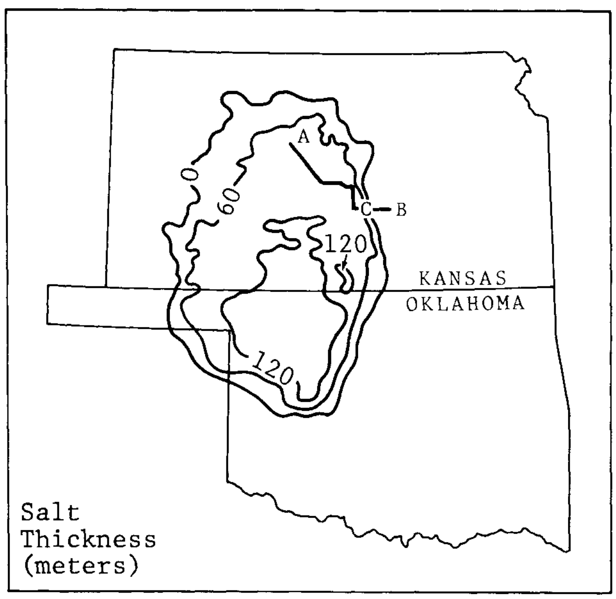
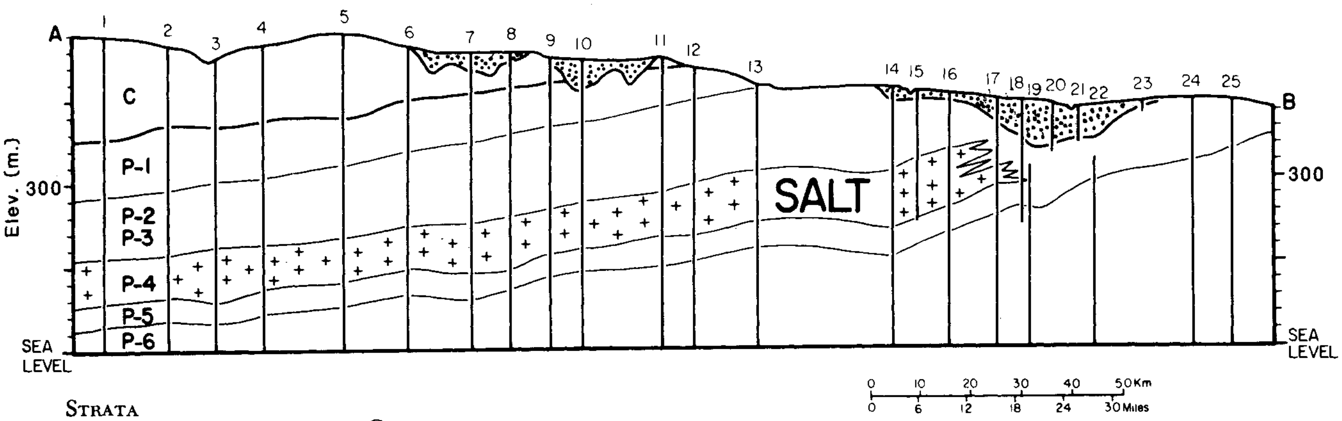


FIG. 1. Generalized extent and thickness of Hutchinson salt member of the Permian Wellington formation. Location of cross-section A-B is shown for Figure 2. The sinkholes discussed are located within a few kilometers of A. Modified from Walters (1977).

Manuscript received by the Editor September 1, 1983; Revised manuscript received July 12, 1985.
*Kansas Geological Survey, 1930 Constant Avenue, Lawrence, KS 66044.



STRATA

C			Cretaceous
P			Permian
	P-1		Nippewalla Group
	P-2 to P-5		Sumner Group
		P-2	Ninnescah Shale
		P-3	Wellington Shale
		P-4	Hutchinson Salt Member
		P-5	Wellington Shale-Anhydrite
	P-6		Chase Group

FIG. 2. Cross-section A-B of Figure 1. Rock unit names below the figure correspond to labels on the figure. Locations of wells drilled for oil, gas, and water are depicted by numbers along the top of the cross-section. Modified from Walters (1977) where the well locations are listed and discussed.

1967, and the results are summarized in Figure 3. Note that at that time the tops of the Stone Corral anhydrite and the Hutchinson salt were about 12 m and 35 m below normal elevation, respectively. Seismic reflection data presented here indicate that the Stone Corral in particular has dropped almost 30 m since 1967.

To mitigate public concern about the safety of the highway in Russell County after catastrophic formation of the Nielsen sinkhole in Ellis County, the Kansas Geological Survey performed a seismic reflection survey along I-70. We obtained about 4 km of six-fold common-depth-point (CDP) seismic reflection data by the MiniSOSIE method. The Stone Corral anhydrite at a depth of about 300 m is an excellent marker bed for seismic reflections. In addition to the Stone Corral, we imaged both the top and bottom of the salt at critical points in the vicinity of the largest sinkhole.

The structure in the sinkholes is that of a classic graben when imaged in cross-section. In the largest sinkhole, the Stone Corral had been down-dropped by as much as 45 m by 1980. This finding is based on seismic evidence presented later. The remaining salt thickness is less than half of the original. At least four normal faults symmetrically bound the graben blocks that are down-dropped into the sinkhole. The seismic records indicate that collapse apparently has occurred gradually, with progressive salt dissolution, and that substantial bridging of voids in the sinkhole vicinity was not present in 1980. We believe that catastrophic collapse of known sinkholes along I-70 is unlikely because of the brecciated nature of the material between the Earth's surface and the top of the still-dissolving salt.

Finally, note that this seismic reflection survey was performed along the shoulder of I-70 in the presence of normal traffic including heavy trucks. The MiniSOSIE method used (Barbier et al., 1976) is an excellent recording technique for use in a noisy environment. The technique provides substantial energy in the frequency range of 80 to 120 Hz, providing relatively high resolution.

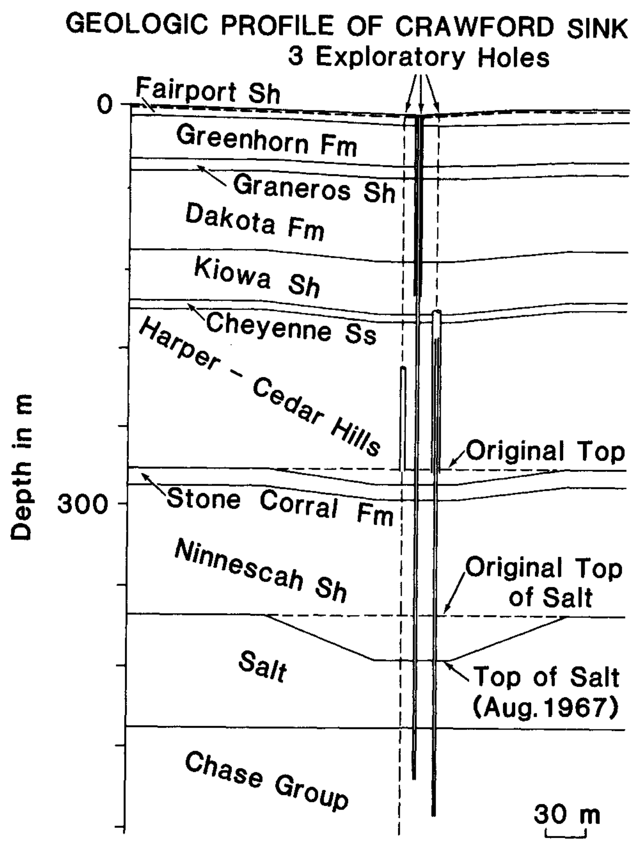


FIG. 3. Cross-section from Kansas Department of Transportation based on drilling and logging in 1967. The seismic data in Figure 6 indicate that the Stone Corral dropped several meters between 1967 and 1980.

SEISMIC METHODS

In May 1979 we examined the feasibility of using seismic reflection techniques to investigate the subsurface structure of the I-70 sinkholes. Using an eight-channel Input/Output, Inc. DHR 1632 digital seismograph, we obtained the data displayed in Figure 4. Because of failure of three channels, we only obtained 5/8 of full coverage. The energy source was 6.6 kg of high explosive placed at the bottom of 5 m auger holes. Geophone groups consisting of three 10 Hz phones 1.5 m apart were placed at 12 m group intervals. Maximum offset between the shotpoint and the most distant geophone was about 120 m, providing very little moveout of reflections on the seismograms.

The data in Figure 4 are tracings of field records with 200 ms of muting on each trace with no static or moveout correction applied. In other words, no computer processing was applied to the data. Several reflectors are apparent, particularly at the east end of the line shown in Figure 4. The Stone Corral anhydrite at between 250 and 300 ms appeared to have strong potential as a marker bed for further reflection studies.

Common-depth-point (CDP) reflection techniques (Mayne, 1962) were employed for all seismic data collected for use here except for Figure 4. The CDP method is equivalent to doing several surveys along the same line. Corrections for geometrical differences related to distance between the shotpoint and the geophones are made, and the results are added using a computer. Data for this report were shot at six-fold or 600 percent CDP coverage. This means that each point in the subsurface that acted as a reflection point (using ray theory) was replicated six times during the course of the survey. The data are recorded on digital tape in the field and processed by digital techniques in a large computation facility.

Data are finally displayed in a "record-section" format showing reflection amplitudes in a time (depth)-versus-horizontal distance plot. We include versions of the seismic record sections with the geologic interpretations done by slightly darkening the best reflectors. A discussion of conclusions drawn from the record sections along the I-70 sinks in Russell County follows.

DISCUSSION OF CDP SEISMIC SECTIONS

Two seismic profiles were run in the vicinity of the I-70 sinks. The first profile runs from .98 km east of the Crawford sink overpass to 1.05 km west of the overpass along the north road ditch of I-70. The second line intersects the first at right angles at the Crawford sink overpass and extends from 0.48 km south of the north lane of I-70 to 0.47 km north of the north lane of I-70. The MiniSOSIE recording process (Barbier et al., 1976) was used with two Wacker earth tampers providing seismic energy. Geophone groups consisted of six Mark Products L-25 geophones with resonant frequency of 28 Hz. Traffic on I-70 continued normally during the seismic recording with the MiniSOSIE process, which would not have been possible if explosives had been used for an energy source.

Conclusions drawn from the I-70 seismic profile are discussed from west to east.

Witt sink (Figure 5)

The Witt sink shows up on the seismic profile between CDP 206 and CDP 222 with the Stone Corral anhydrite down-dropped about 15 m (10 ms two-way traveltime) along its west side (near CDP 223). The area to the west of Witt sink contains competent rock at all depths to well below the salt. At the center of the sink (near CDP 215), the Stone Corral is either down-dropped about 40 m or its upper surface has been broken up or partially dissolved. Stone Corral reflections exhibit incoherent or broken-up characteristics for about 400 m eastward from the center of Witt sink. The area east of Witt sink for about 400 m may subside in the future.

Between Witt sink and Crawford sink (Figures 5 and 6)

A zone of competent Stone Corral begins about 300 m west

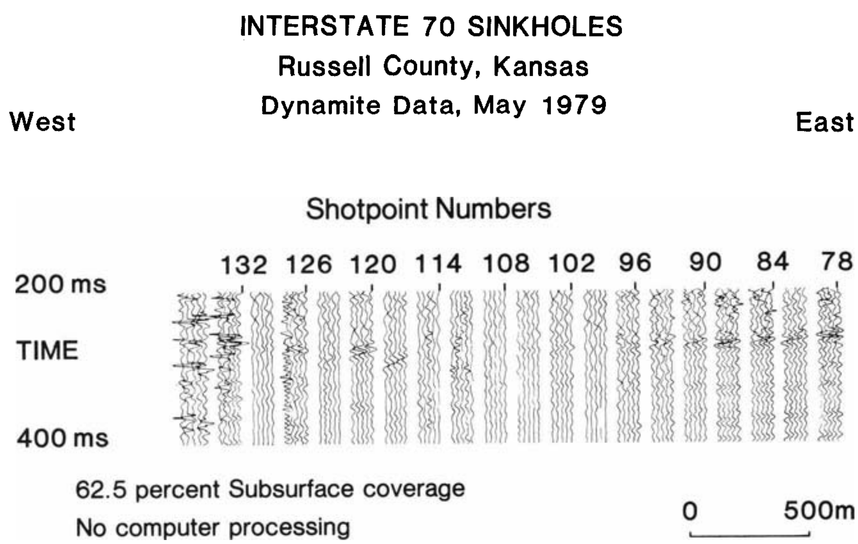


FIG. 4. Dynamite seismic reflection data from May 1979. The Stone Corral reflector is visible at a time of about 260 ms in the eastern one-third of the line. The shotpoint numbers of this figure can be correlated to CDP numbers of Figures 5, 6, and 7 by multiplying shotpoint numbers by 2. The sole purpose of including shotpoint numbers on this dynamite data is to allow correlation with the MiniSOSIE CDP data.

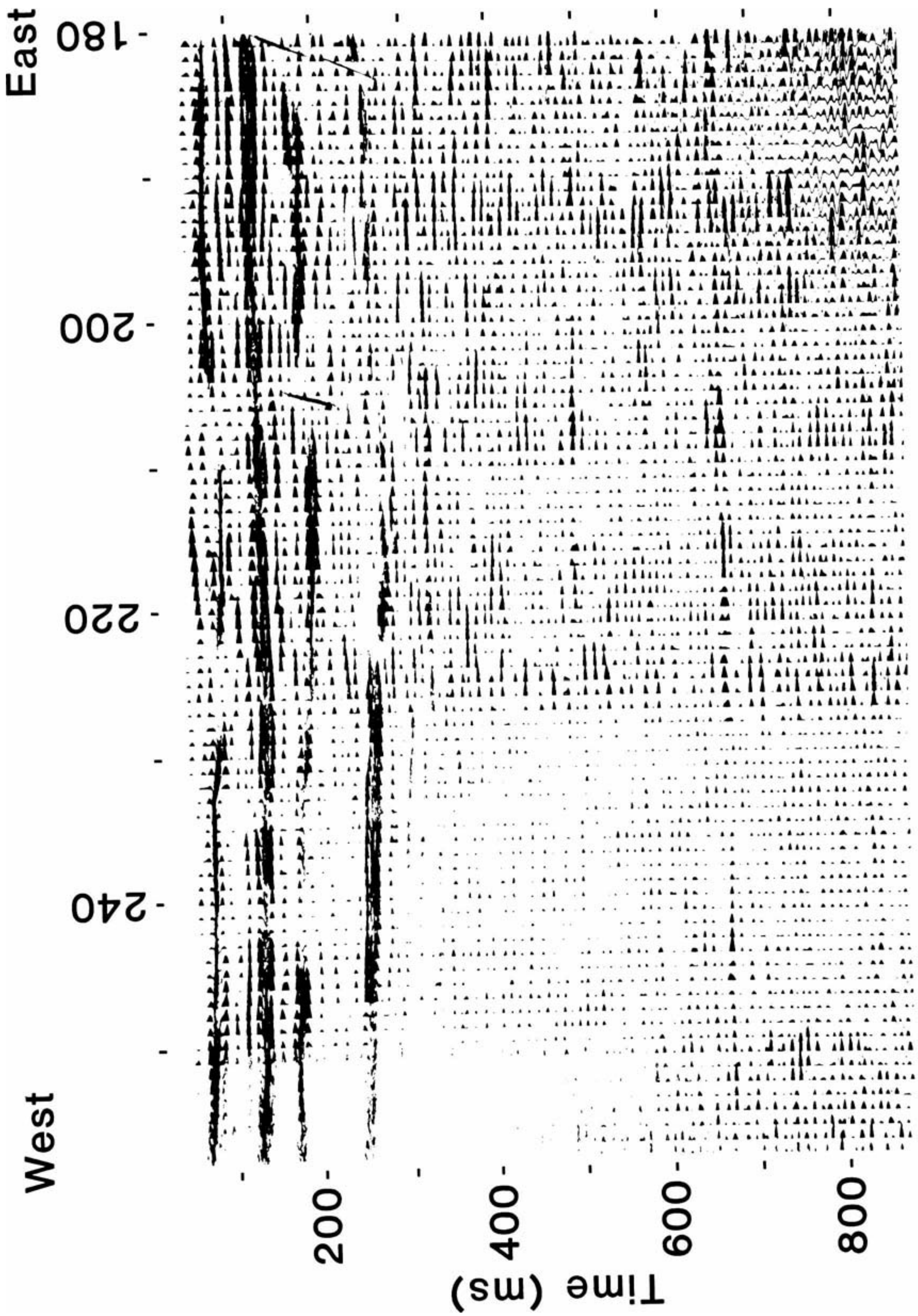


FIG. 5. Seismic reflection record sections for an east-west line along I-70 that crosses Witt sink (I-70 line 1A). Numbers along the zero time line are common depth points along the line, and they are 8 m apart. Figures 6 and 7 are labeled in identical fashion.

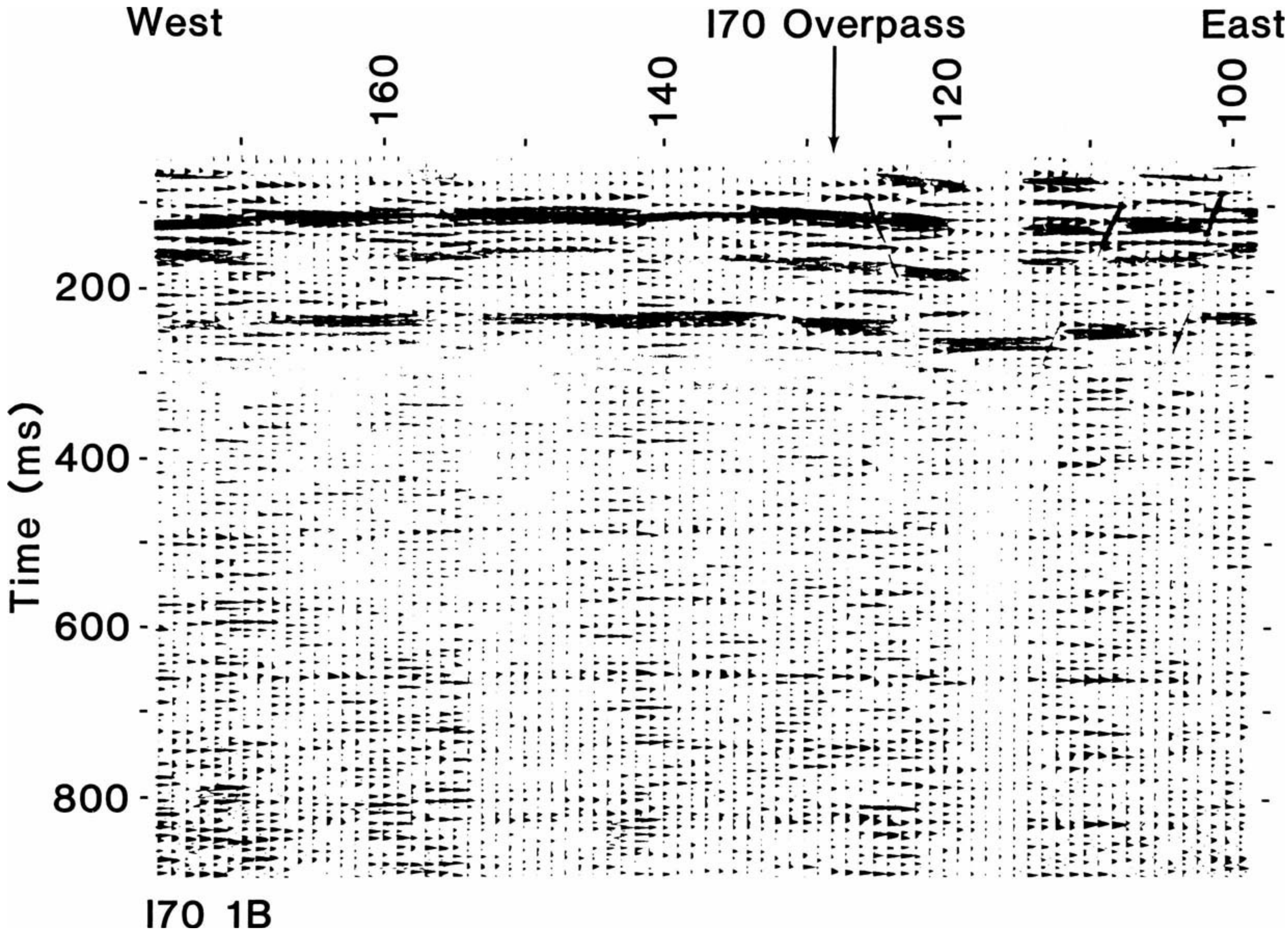


FIG. 6. Seismic reflection record section for east-west line along I-70 that traverses the area between Witt sink and Crawford sink (I-70 line 1B). The down-dropped Stone Corral in the Crawford sink is clearly visible at times of 200 to 300 ms between CDP numbers 100 and 130.

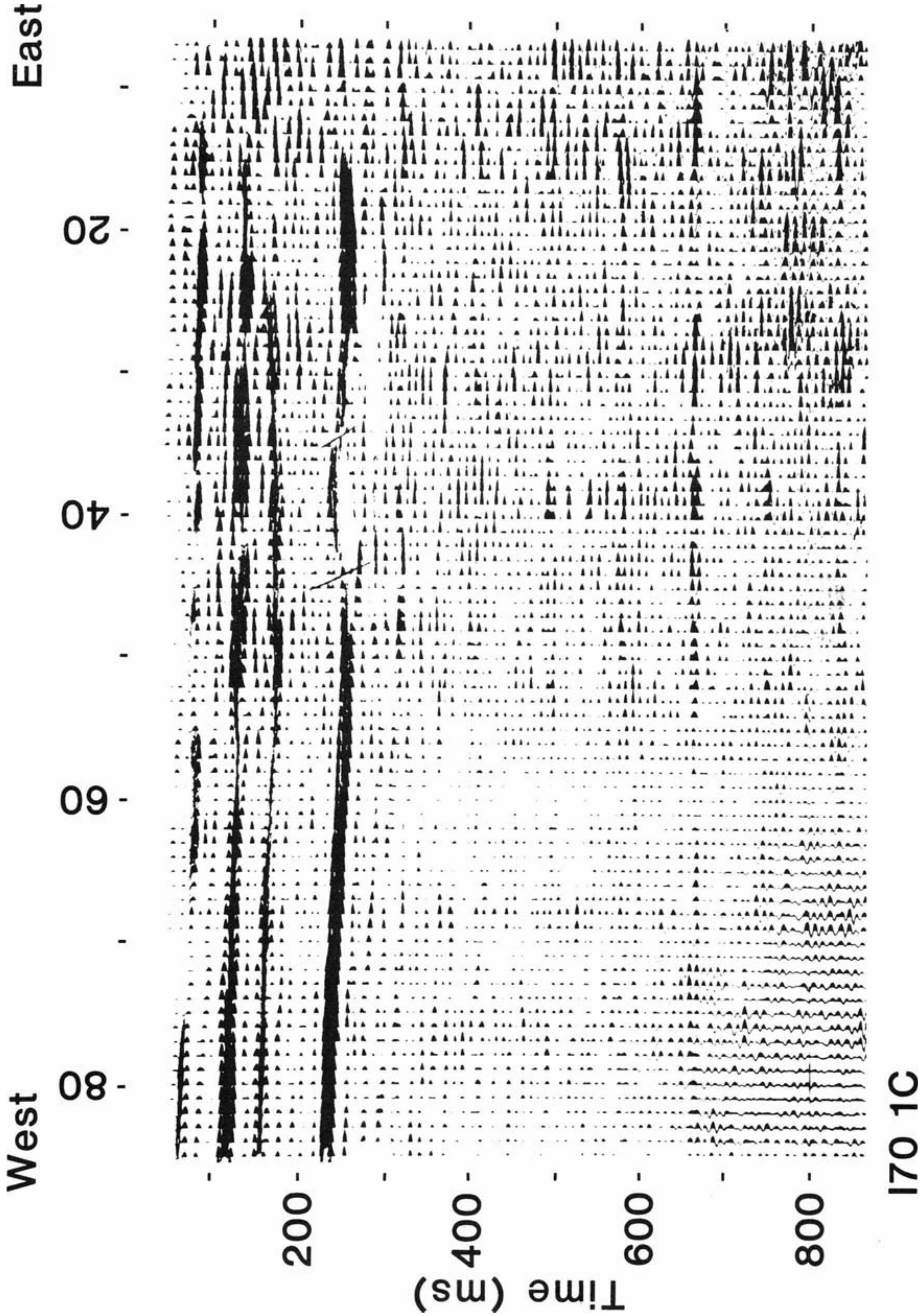


FIG. 7. Seismic reflection record section for east-west line along I-70 that traverses Rouback sink and possible incipient sink (I-70 line 1C). Note structural relief on Stone Corral at time of about 250 ms.

of the Crawford sink overpass and continues eastward from CDP 166 for about 240 m to CDP 134 about 60 m west of the Crawford sink overpass. This 240 m long zone would not be expected to subside.

Crawford sink (Figure 6)

East-West profile.—The Crawford sink begins in the subsurface at CDP 131, about 60 m west of the overpass, and extends to near CDP 98, about 260 m east of the overpass—its total east-west extent along I-70 slightly exceeds 300 m. The sink is marked at depth by at least five faults (four shown; one fault is just off the east edge of Figure 6) in the Stone Corral which is down-dropped in graben-like fashion into the central area of the sinkhole. The total vertical movement of the Stone Corral has been about 45 m (30 ms two-way traveltime) at the deepest part of the sinkhole along I-70. The highway does not pass exactly over the center of the sink, so it is not possible to evaluate conditions at the center of the sink from our data.

Approximately 50 percent of the thickness of the salt has been dissolved beneath the highway at the point of maximum drop in the Stone Corral. This compares favorably with a 40 percent dissolution estimate obtained by drilling done by the Highway Department in 1967 (Figure 3), suggesting that dissolution may have slowed since the mid-1960s, assuming the drilling was on or near the highway right-of-way.

North-south profile (not shown).—The north-south profile supports the Crawford sink interpretation discussed above for the east-west I-70 profile. The profile runs along the road that crosses over the top of the overpass and intersects the east-west line at CDP point 128. These data are not shown here, but are available from the authors.

Between Crawford sink and Rouback sink (Figure 7)

The Crawford and Rouback sinks have not yet coalesced in the subsurface—at least not beneath I-70. There is a competent zone of horizontal rock from CDP 96, about 260 m east of the overpass, to CDP 75, about 430 m east of the overpass. The salt appears to retain its full thickness in that area.

Rouback sink (Figure 7)

The Rouback sink begins in the subsurface near CDP 73, about 430 m east of the overpass, and continues to near CDP 43, about 670 m east of the overpass. The east edge of the Rouback sink is faulted at the Stone Corral, while the west side of the Rouback is more of an eastward dipping monocline. Total vertical displacement on the Stone Corral is about 30 m (20 ms two-way traveltime).

A new sink east of Rouback? (Figure 7)

The Stone Corral is at its normal depth from near CDP 41, about 670 m east of the overpass, to near CDP 35, about 750 m east of the overpass. At 750 m east of the overpass, near CDP 35, the Stone Corral appears to be down-dropped to the east by about 21 m (14 ms two-way traveltime). Our data end about 1.0 km east of the overpass, and it is not known what relief, if any, is present on the Stone Corral eastward beyond that point. It is suspected that subsidence will occur, if it has not already occurred, in an area from 760 m east of the overpass to at least 910 m east of the overpass.

CONCLUSIONS

The reflections from the crystalline basement and Topeka and Lansing limestones are essentially flat, indicating a lack of geologic structure below the Hutchinson salt, except beneath the Witt sink. There is a noticeable anticline in the basement surface in the vicinity of the Witt sink, with perhaps 6 to 8 m of upward flexure. No other pre-Hutchinson salt structures were noted on either the east-west profile (Figures 5–7) or the north-south profile (not shown).

The Stone Corral was used as a marker bed in a report to the Kansas Department of Health and Environment dated April 3, 1980. In that report, we were unable to trace the Stone Corral into the sinkholes using single-fold dynamite data. CDP methods and computer processing allowed us to trace the Stone Corral across the sinkholes, delineating structures with detail that was previously impossible. For the first time we were also able to delineate the top and bottom of the Hutchinson salt along part of the line.

Three areas should be closely monitored by surface elevation surveys in the immediate future.

(1) The Witt sink has an area on its east side that is disturbed in the subsurface for a distance of at least 360 m. This zone shows differences in seismic wavelet character for the Stone Corral reflection. This can best be seen in Figure 4 between shotpoints 90 and 98 which correspond in space to CDP 179 and CDP 195 on Figure 5, respectively. On both the dynamite data and the MiniSOSIE data in this area, the first positive peak is either subdued or missing, suggesting that the upper few meters of anhydrite either dissolved or were intensely fractured. This phenomenon is also noted at Nielsen sink in Ellis County (not shown).

(2) The Rouback sink can be expected to continue to develop based on down-dropping of the Stone Corral and apparent thinning of the salt.

(3) An area east of the Rouback sink appears to be an incipient sinkhole, again based upon down-dropping of the Stone Corral and thinning of the salt.

ACKNOWLEDGMENTS

Financial support and authorization to publish the data were provided by the Kansas Department of Health and Environment. The Kansas Department of Transportation provided logistical support. The Kansas Highway Patrol provided traffic control during the dynamite phase of the project. Jon Weigand kindly provided free access to data processing facilities for us to process the data.

REFERENCES

Barbier, M. G., Bondon, P., Mellinger, R., and Viallix, J., 1976, Mini-SOSIE for land seismology: Geophys. Prosp., **24**, 518–527.

Mayne, W. H., 1962, Common reflection point horizontal data stacking techniques: Geophysics, **27**, 927.

Smith, H. T. U., 1940, Geological studies of southwestern Kansas: Kansas Geol. Surv. Bull. **34**.

Walters, R. F., 1977, Land subsidence in central Kansas related to salt dissolution: Kansas Geol. Surv. Bull. **214**.