Salt Dissolution and Surface Subsidence in Central Kansas: A Seismic Investigation of the Anthropogenic and Natural Origin Models

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Case History

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ABSTRACT

Gradual subsidence in the Punkin Center study area, northeast Reno County, Kansas, has resulted in ponding of surface waters, abandonment of at least one oil well, and damage to county roads. Because the Punkin Center area is within the Burrton oil field and is underlain by the Hutchinson Salt Member, surface subsidence historically has been attributed to salt dissolution of anthropogenic origin. Subsidence that occurred significant distances from any known well sites has been attributed to unrecorded abandoned wells or complex asymmetric patterns of salt dissolution that originated at a drillhole.

To ascertain the validity of the widely accepted anthropogenic salt-dissolution model, a 4-km seismic reflection profile was acquired along an east–west-oriented county road adjacent to an abandoned oil well. The expectation was that the residual Hutchinson Salt Member would be anomalously thin where maximum recorded surface subsidence occurred and thicker elsewhere. Contrary to expectations, the residual Hutchinson Salt Member is relatively thick (20–30 m) below areas of significant recent surface subsidence. There is no evidence of recent surface subsidence at those locations along the seismic profile where the rock salt has been totally leached. At these sites dissolution and subsidence is interpreted to predate European settlement in Kansas and to be of natural origin.

The presence of dissolution and subsidence features related to natural processes has implications for developing an understanding of the potentially complex relationship between anthropogenic activities and pre-existing geologic conditions. Sinkhole development is apparently a natural and expected process along an irregular salt dissolution front. The geometry of this front may be influenced strongly by geologic factors (e.g., fracture patterns and facies distribution). The results are that not all modern sinkhole development has a clear-cut anthropogenic cause, and the potential for adverse impact resulting from anthropogenic activities will be influenced strongly by pre-existing geologic conditions. Efficient management decisions along the dissolution front related to well location and well-site practices should take into account natural processes that previously have and will continue to have an effect on salt dissolution and surface subsidence.

INTRODUCTION

Subsidence caused by salt dissolution is a problem in central Kansas. Several dozen sinkholes that formed within the last 100 years have been studied and documented in the literature (Walters, 1978, 1980, 1991). All of these documented subsidence features (with the exception of those associated with salt mining activities) developed along the eastern active dissolution front of the Permian Hutchinson Salt (Figures 1 and 2) as a result of localized solutioning. The tendency has been to attribute such dissolution to oil- and gas-related activities (or in rare instances to salt mining activities), rather than to natural processes. The Punkin Center site (Figure 2) was selected for this seismic study for two reasons. First, over the past several decades sustained surface subsidence on the order of

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centimeters per year has resulted in ponding of surface waters, abandonment of at least one producing oil well, and damage to county roads. Second, the study area is within the Burrton oil field, and surface subsidence has been attributed historically to oil and gas activities.

A 4-km-long reflection-seismic profile was acquired in the Punkin Center area in order to explain fully (1) why some sinkholes developed significant distances from any recorded well location; (2) why early exploratory wells encountered anomalously thin rock salt in some localized areas along the dissolution margin (Watney and Paul, 1980); and (3) why all documented sinkholes (with the exception of those associated with mining activities) developed along the natural dissolution margin of the Hutchinson Salt Member.

Contrary to expectations, the seismic data showed that (1) the thickness of the Hutchinson Salt Member is highly variable to the west of the margin edge, being up to 40 m thick in places and absent elsewhere; (2) the rock salt attains thicknesses of up to 30 m within 100 m of the margin edge; (3) sites where surface subsidence has been documented overlie areas of relatively thick residual rock salt; and (4) there is no evidence of recent surface subsidence above those areas to the west of the margin edge where the rock salt has been totally leached. These latter sites are interpreted to be infilled "paleosinkholes" and to predate documented history in Kansas. Based on this evidence, we believe sinkholes also form in response to natural dissolution of bedded salts in central Kansas.

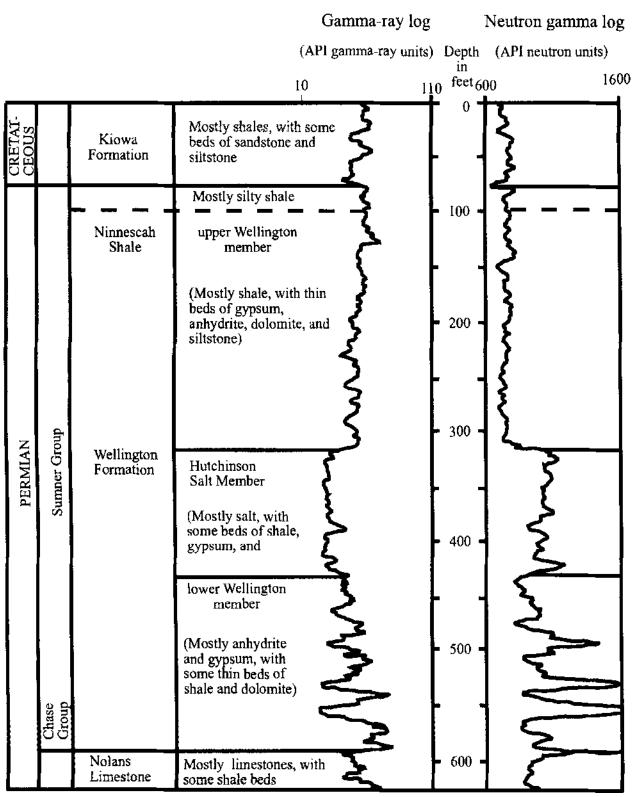

FIG. 1. Gamma ray–neutron log of well 16-4W-22ADB, depicting the characteristic log signature of the Wellington Formation in central Kansas (after Gogel, 1981). The well encountered about 35 m of residual Hutchinson Salt Member. On the order of 50 m of rock salt was probably dissolved at this well site during the Quaternary.

GEOLOGIC BACKGROUND

The Wellington Formation (Permian, Leonardian) in central Kansas (Figure 1) consists of three members: a lower member of cyclic anhydrite and shale, the Hutchinson Salt Member, and an unnamed upper shale (Frye, 1950; Kulstad, 1959; Dellwig, 1963; Merriam, 1963; Holdoway, 1978; Walters, 1978, 1980; Watney and Paul, 1980; and Watney et al., 1988). The Hutchinson Salt Member consists of stacked successions of many thin but apparently laterally extensive halite-dominated marine hemicycles. Figures 2 and 3 show that the rock salt attains maximum net thicknesses of approximately 85 m and support the thesis that western and northern margins of the Hutchinson Salt in Kansas are depositional, whereas the eastern margin is dissolutional.

During the late Tertiary, the eastern margin of the Hutchinson Salt Member (some 30 km to the east of Punkin Center at that time; Figure 2) was exposed to the near-surface environment and leaching initiated along a more-or-less continuous front (Williams and Lohman, 1949 and Bayne, 1956). This main dissolution front has migrated progressively westward since its inception due to sustained contact with undersaturated groundwater from shallow aquifers (Gillespie and Hargadine, 1981; Gogel, 1981; Johnson, 1981; Macfarlane et al., 1992; and Anderson et al., 1994b) (Figures 5 and 6). The leaching and westward migration of the eastern margin has resulted in the subsidence of the surficial Permian and Cretaceous rocks and the contemporaneous deposition of Quaternary alluvium with thicknesses approximating those of the dissolved rock salt (Fader, 1975; Walters, 1978, 1980; Watney and Paul, 1980; Gogel, 1981; and Watney et al., 1988). Regional trends indicate that about 85 m of Permian Hutchinson rock salt were initially deposited in the Punkin Center study area. However, as a result of the progressive migration of the eastern salt dissolution margin, much of the original salt has been leached from the rock record (Anderson et al., 1994b; Figures 4, 5, and 7).

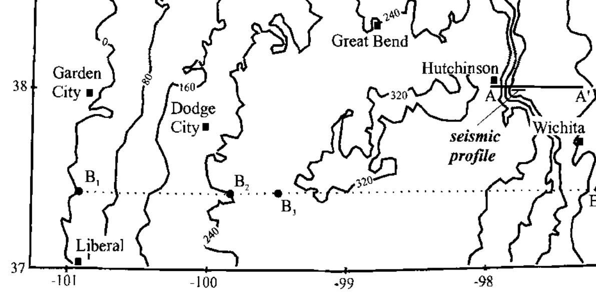

FIG. 2. Net salt thickness map for the Hutchinson Salt Member in Kansas (after Watney and Paul, 1980). The locations of the seismic line (Figure 8) and the wells incorporated into geologic cross-sections A–A′ and B_1–B_4 (Figure 5 and 3, respectively) are highlighted. Maximum net depositional thicknesses are on the order of 85 to 90 m.

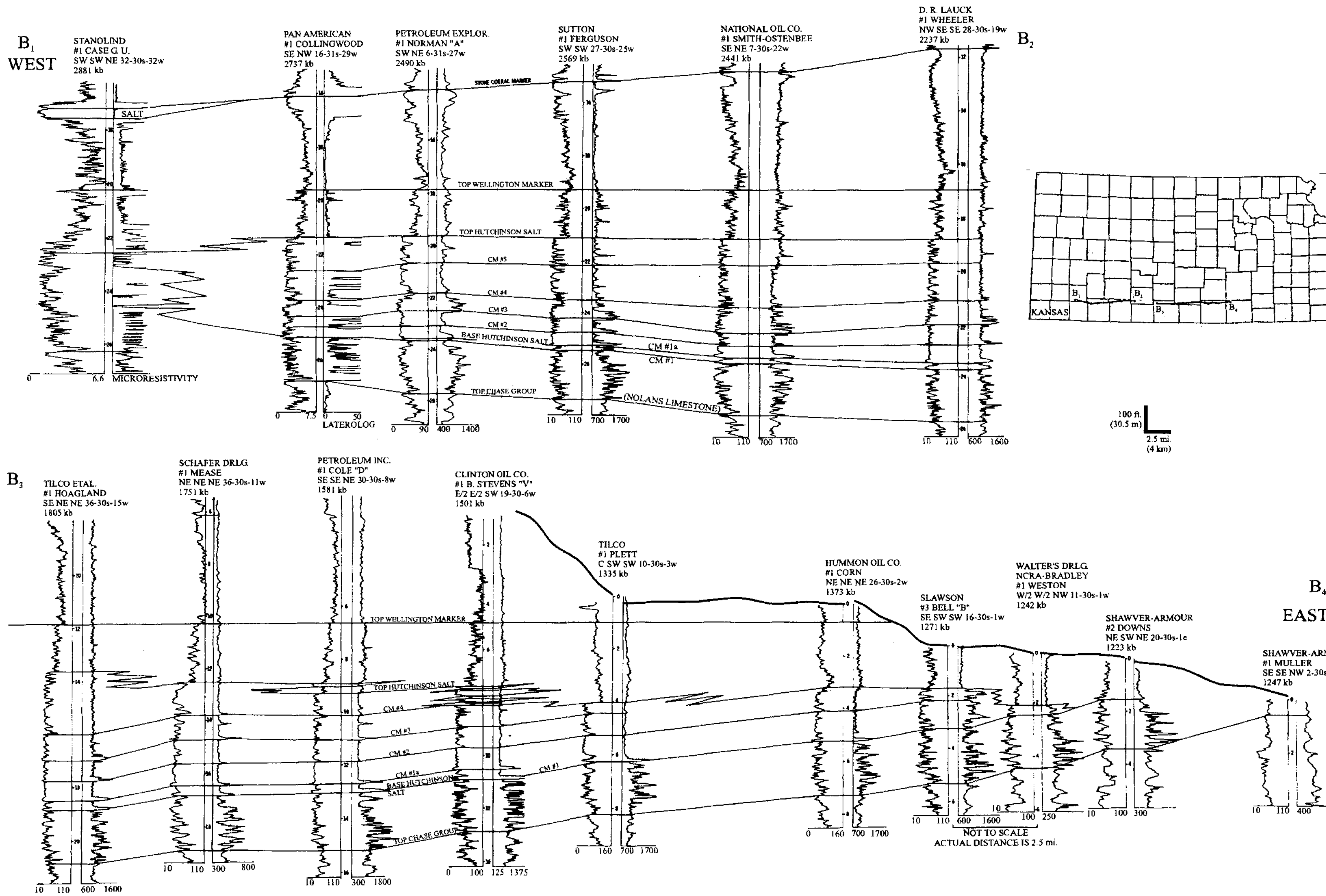

FIG. 3. Regional geologic profile of the upper Permian in central Kansas (modified after Watney and Paul, 1980). From a regional perspective, the eastern dissolutional margin of the Hutchinson Salt Member thickens in a stepwise manner from east to west, ultimately attaining net thicknesses on the order of 90 m.

METHODOLOGY

The seismic profile was oriented so it would cross the eastern edge of the active dissolution margin and image the residual rock salt in the vicinity of an abandoned oil well in the Punkin Center, Kansas, area (Figures 4, 6, 7, 8, and 9). The expectation was that the rock salt would be shown to thicken gradually (from 0 to about 40 m) to the west of the margin edge. Up to several meters of localized thinning was anticipated below sites of recent surface subsidence and in the immediate vicinity of an abandoned well.

The seismic reflection data were acquired using an EG&G 48-channel Model 2401X engineering seismograph and single high-resolution Mark Products L40A 100-Hz geophones. The split-spread receiver array employed a 5-m receiver spacing; the near offset was 2.5 m in-line and 9 m off-line. The source consisted of a single downhole .50-caliber shell.

INTERPRETATIONS

Several key events have been correlated across the reverse-polarity seismic data (increase in acoustic impedance generates a trough). In Figure 8, event *FB* is interpreted as the refraction from the water table; the *Q* events are intra-Quaternary reflections (probably paleosols and major boundary surfaces between sequences); event *BQ/TP* is the sub-Quaternary unconformity (Permian subcrop); the *P* events are seismically correlatable intra-Permian horizons; and events *TS* (or SALT) and BS represent the top and base (or equivalent) of the Hutchinson Salt Member. The top and base of the Hutchinson Salt are manifested as a relatively high-amplitude trough and peak, respectively. This is to be expected as the rock salt (2.3 g/cc, 4200 m/s) is overlain by fractured, lower-velocity shales and underlain by more competent, lower-velocity, denser shale.

The seismic data image the eastern edge of the main dissolution front near trace 960 and three paleosinkholes, centered at traces 1200, 1415, and 1615, respectively (Figures 8–13). Extensive surface subsidence has been documented between traces 1000 and 1160 and between traces 1320 and 1360. The abandoned well site is adjacent to trace 1120. On the seismic data, the western edge of the main dissolution front (Figures 8, 9, and 10) is characterized by several key features.

1) **The first seismically identifiable occurrence of contiguous rock salt.**—To the east of the main dissolution front,

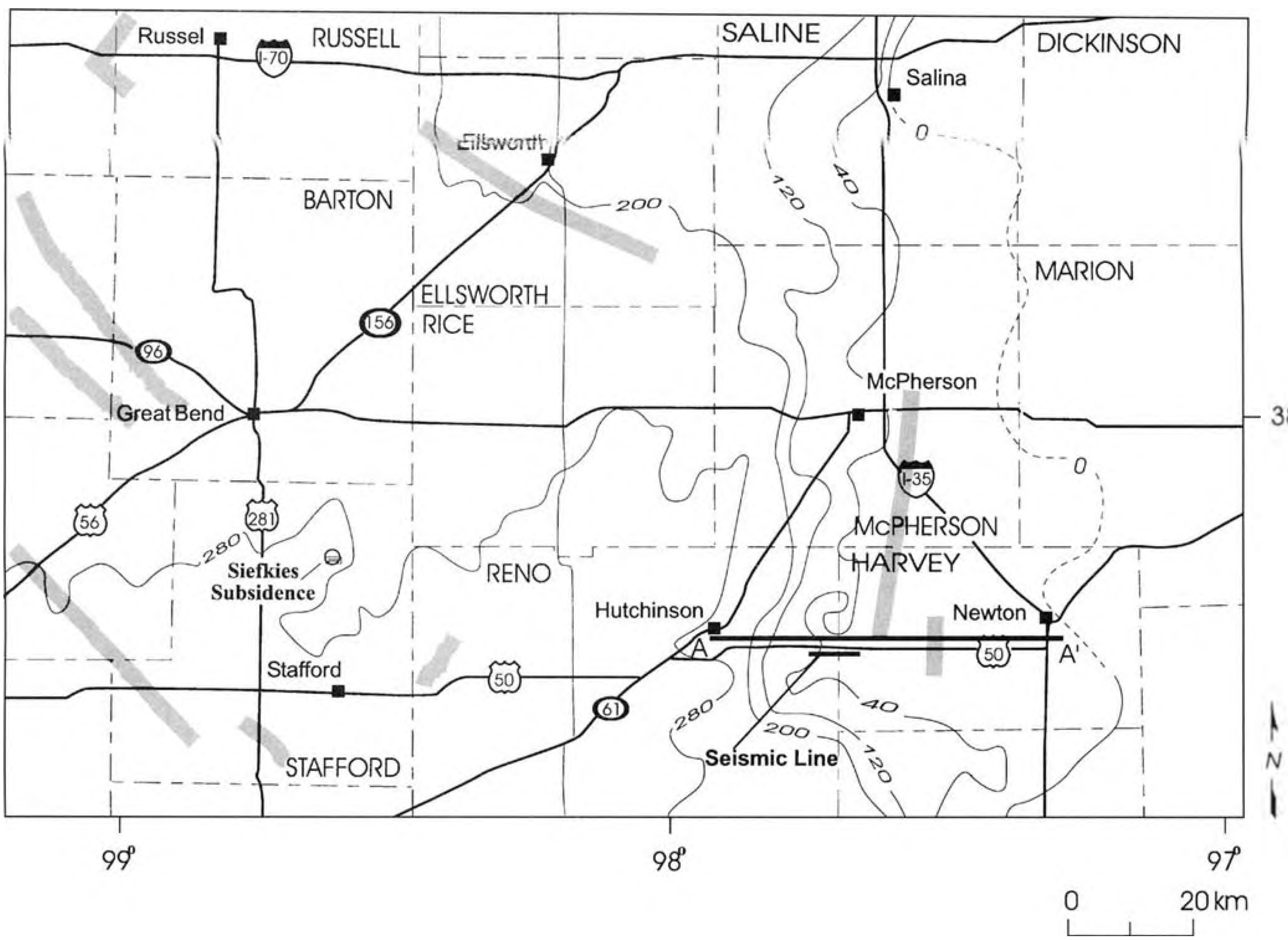

FIG. 4. Net salt thickness map for the Hutchinson Salt Member in central Kansas. The location of the seismic profile (Figure 8), the well sites incorporated into cross-section A–A′ (Figure 5), and significant geographic features are shown. The shaded lineaments represent prominent basement structural features such as the Voshell Ridge (ancestral basement structure trending north-northeast through Harvey and McPherson counties; Lam and Yarger, 1989).

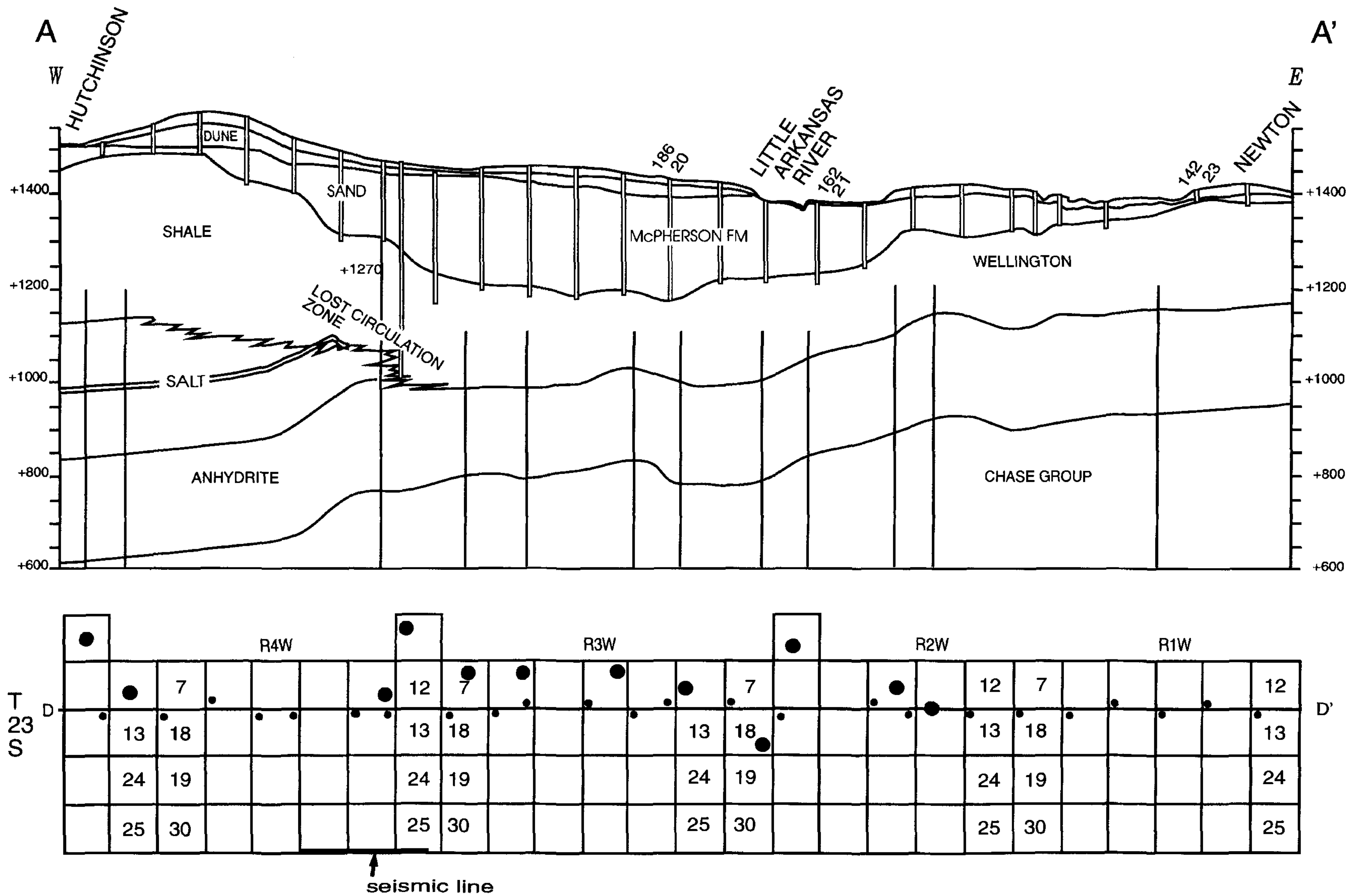

FIG. 5. Geologic profile of the upper Permian and Quaternary between Hutchinson and Newton (modified after Walters, 1980). The locations of the seismic line and the wells (shallow, small dots; deep, large dots) incorporated into the geologic profile are shown on the accompanying base map.

the rock salt has been leached from the geologic section. Immediately to the west (between traces 1000 and 1160), the rock salt thickens to 30 m. The presalt events are pulled up (by up to 20 ms) beneath the residual salt as a result of the velocity contrast between the residual rock salt (4200 m/s) and an equivalent thickness of Quaternary strata (about 1800 m/s).

2) **Lateral continuity in the seismic image of the postsalt Permian strata.**—The postsalt Permian strata drape across the residual rock salt but do not thin appreciably, indicating that dissolution occurred during post-Permian time.
3) **An appreciable thickening of the Quaternary strata.**—The post-Permian strata are up to 30 m thicker to the east of trace 960 than between traces 1000 and 1160, indicating that leaching occurred during the Quaternary.

The paleosinkholes (centered at traces 1200, 1415, and 1615; Figures 8, 11, 12, and 13) are characterized by the following features.

1) **Anomalous thinning of the residual rock salt.**—Near the centers of the paleosinkholes, the rock salt has been extensively (or totally) leached (Figure 6). Away from the centers, the thickness of the rock salt increases rather abruptly by up to 40 m.
2) **Lateral discontinuities within the seismic images of the postsalt Permian strata.**—The postsalt Permian strata have subsided into the zone of most extensive dissolution but do not thicken appreciably, indicating that leaching within these zones occurred in post-Permian time. These strata, however, are extensively dislocated, indicating that they were elastically deformed (in a large-scale sense). The zone of subsidence within the Permian section increases in width at shallower depths, in a manner similar to the "upward expanding zones of seismically observable subsidence" associated with the fault-controlled salt dissolutional features described by Anderson and Brown (1991, 1992, 1996), Anderson and Cederwall (1993), Anderson and Knapp (1993), Anderson et al. (1994a, 1996a,b), and Brown et al. (1996).
3) **Anomalous thickening of the Quaternary section.**—The thickness of the Quaternary strata within the secondary dissolution fronts can be correlated directly to the thickness of the residual salt, being up 40 m thicker where the rock salt is absent. These observations indicate that dissolution occurred during the Quaternary.

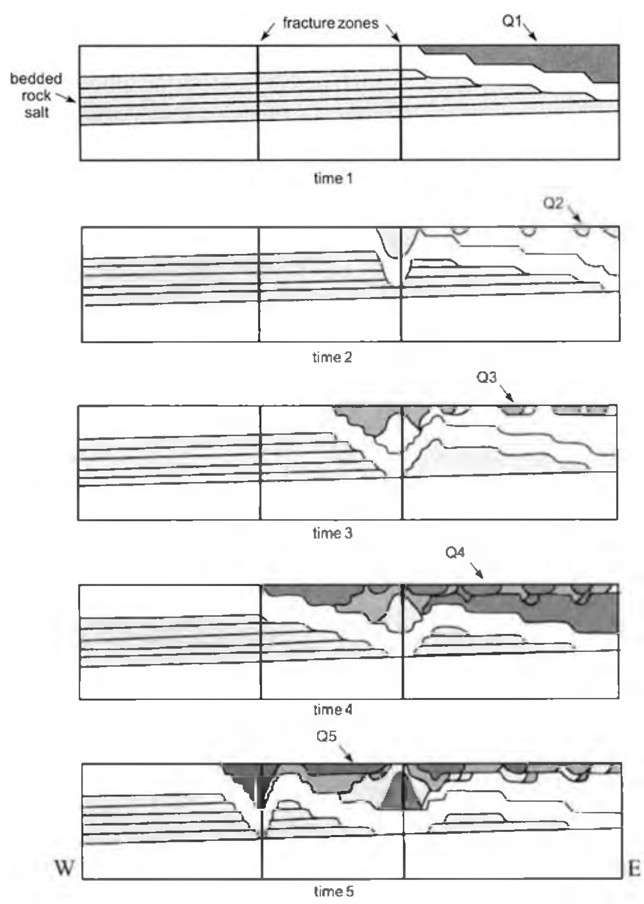

FIG. 6. Series of schematic diagrams illustrating the recession of the eastern margin of the Hutchinson rock salt over a period of time. In this model, secondary dissolution fronts are shown to develop at those sites where the main dissolution front impinges on preexisting fracture zones. Ultimately, the secondary fronts merge with the outer edge of the advancing main front.

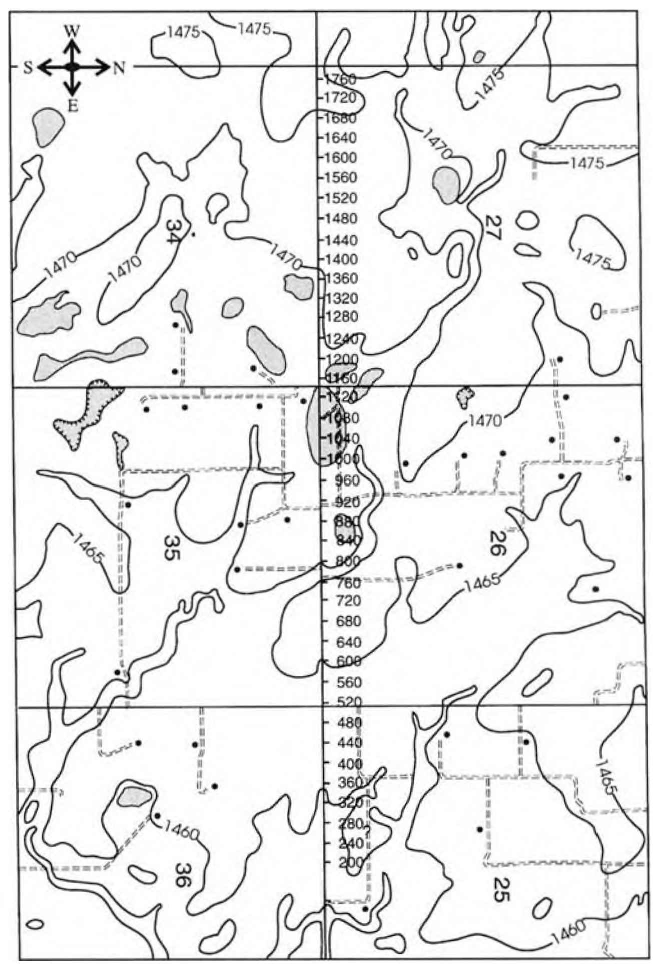

FIG. 7. Geographic, elevation, and seismic shotpoint map for the Punkin Center area, east-central Reno County. Well locations are indicated by dots. Possible surface subsidence features are shaded.

4) **Anomalous velocity-generated time-structural relief along presalt events.**—The presalt events are pulled up by up to 25 ms beneath the residual salt as a result of the velocity contrast between the residual rock salt (4200 m/s) and the infill Quaternary strata (1800 m/s).

Maximum surface subsidence (during recent recorded history) has occurred between traces 1000 and 1160 and between traces 1320 and 1360 (Figures 8 and 9). At these sites, the Hutchinson is up to 40 m thick. Initially, we had expected that the rock salt would thin below sites of recent surface subsidence and thicken or be completely absent where the ground has been stable. (A total absence of salt would imply that no more subsidence due to dissolution is possible).

DISSOLUTION MODELS

It has recently been proposed that these paleosinkholes developed where the Hutchinson Salt Member and overlying aquitard units had been previously fractured, possibly as a result of the reactivation of basement faults (Steeples et al., 1984; Lam and Yarger, 1989; Walters, 1991; Anderson et al., 1994b, 1995; and Barrs, 1995). In the fracture zones, the interbedded insoluble shale layers within the rock salt were dislocated, greatly increasing vertical permeability and susceptibility of the rock salt unit to dissolution. Dissolution along these lineaments is thought to have initiated after the westernmost edge of the receding dissolution margin impinged upon the fracture zones, envisioned as having been relatively rapid (Figure 6).

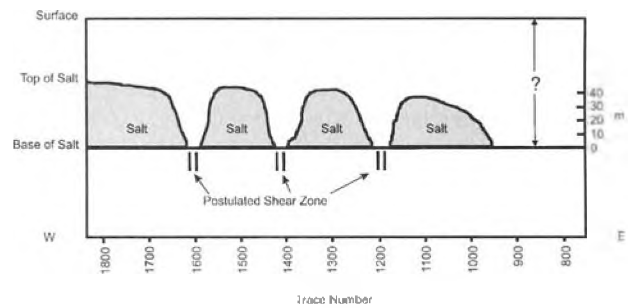

FIG. 9. Geologic section corresponding to the seismic profile of Figure 8 (flattened at base of salt level).

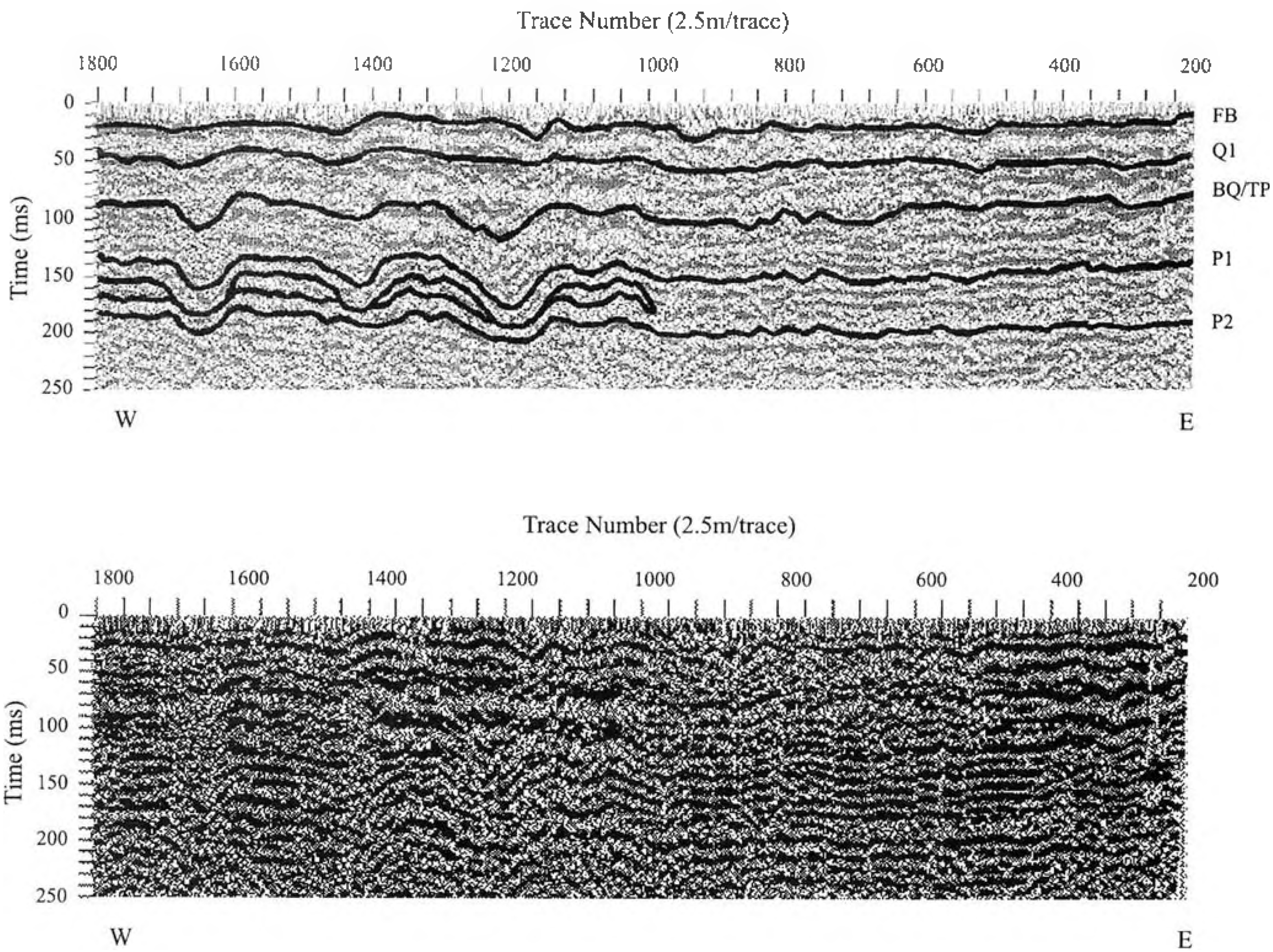

FIG. 8. Seismic profile, interpreted and uninterpreted (Figure 7). The main dissolution front extends from trace 960 (near-zero edge of contiguous rock salt) to the westernmost edge of continuous dissolution (to the west of the seismic line). The secondary fronts (centered at traces 1200, 1415, and 1615) are encompassed by the main front. These developed along preexisting fracture zones and are differentiated because of the anomalously high rate at which the associated salt dissolution occurs initially.

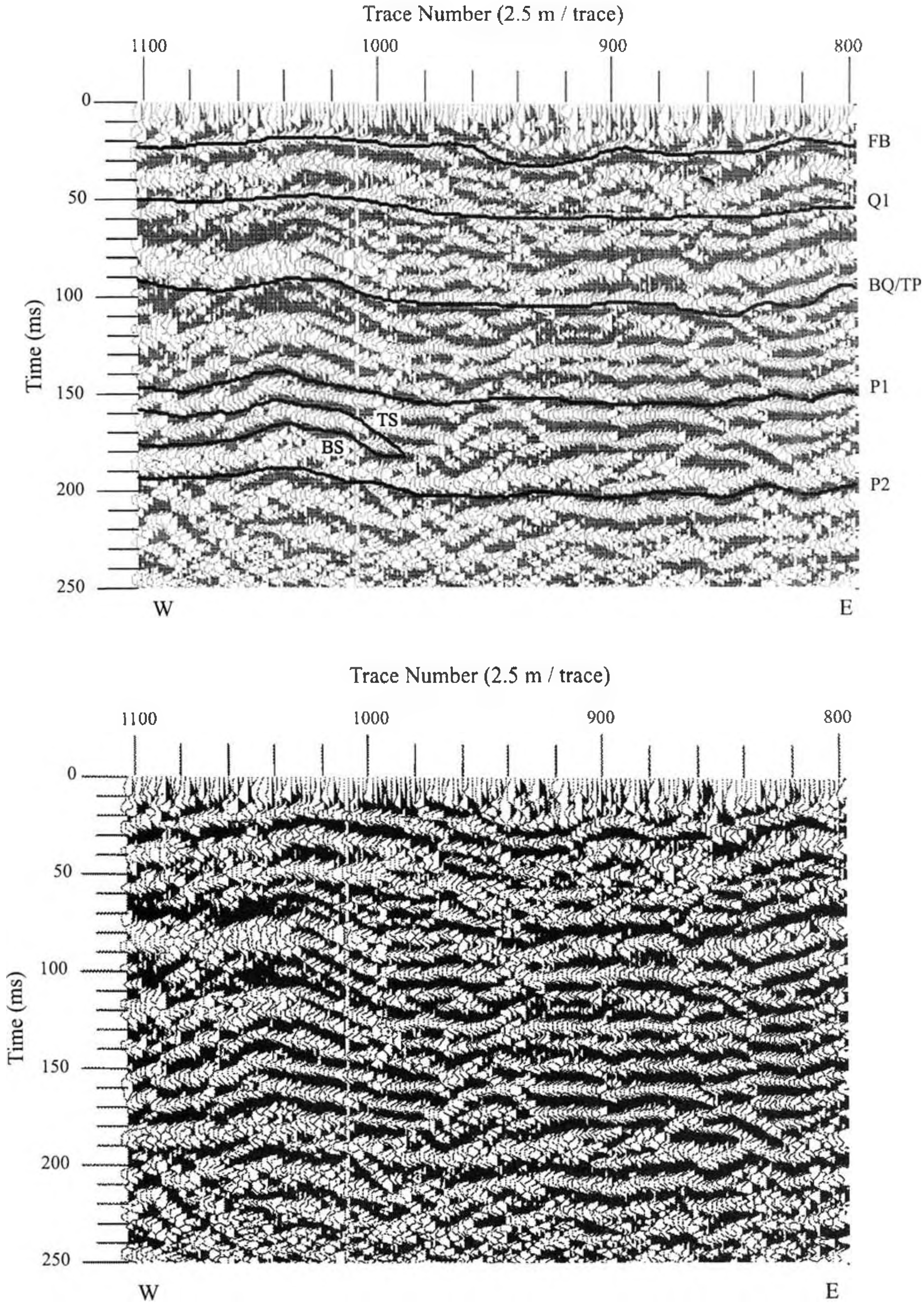

FIG. 10. Seismic image, interpreted and uninterpreted, of the eastern edge of the main dissolution front (Figure 8). The main dissolution front is characterized, from a regional perspective, by the gradual (stepwise) westward increase in the thickness of the residual rock salt. This regional trend is disrupted locally by secondary fronts (Figures 6 and 10). The regional pattern is consistent with the thesis that the rock salt along the main front has been progressively leached in a stepwise manner from the top down and laterally (east to west) along the uppermost remaining soluble layers.

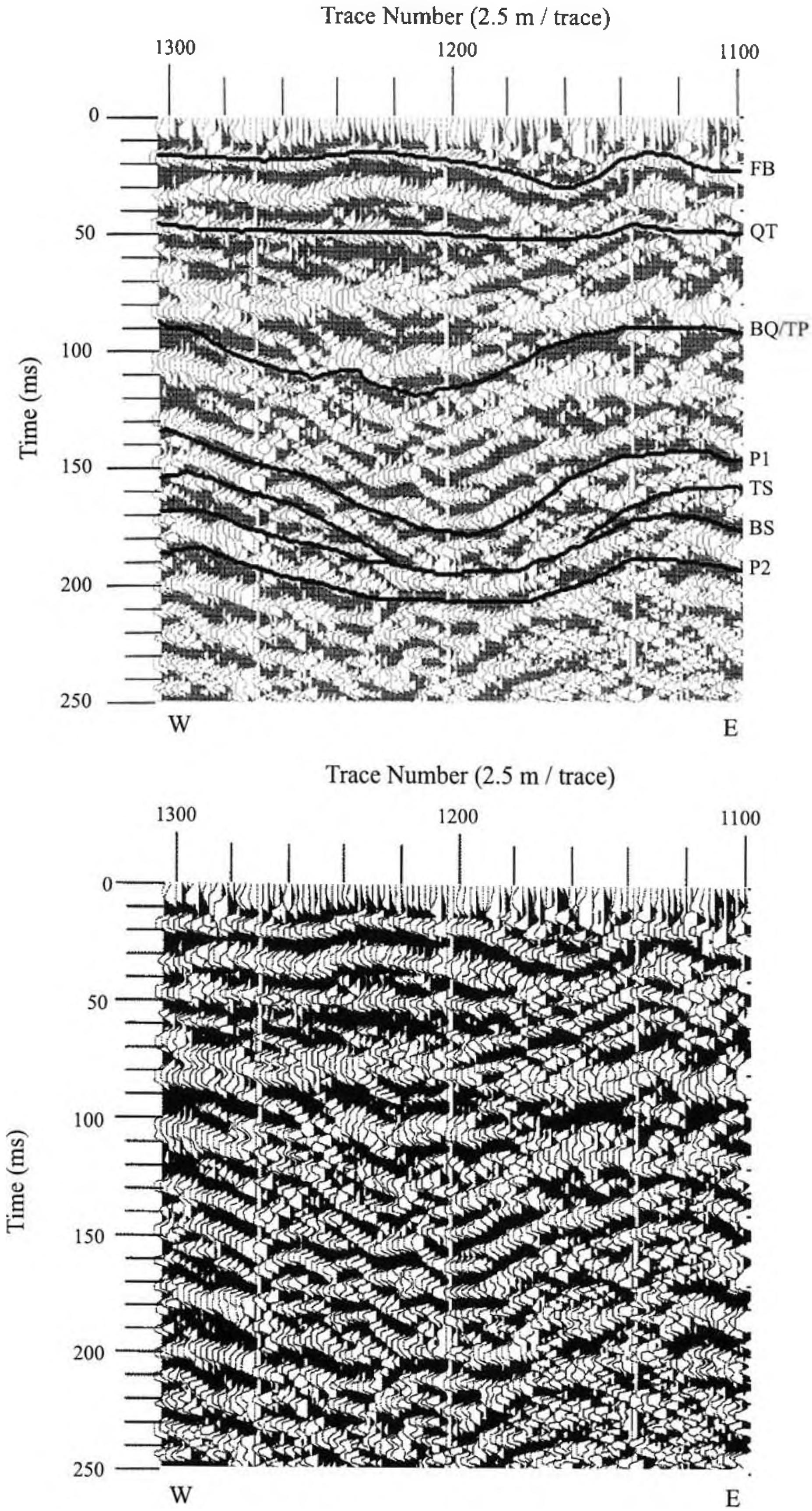

FIG. 11. Seismic image, interpreted and uninterpreted, of a secondary dissolution front (centered at trace 1200; Figure 8). The secondary fronts are characterized by (1) a rapid initial phase of leaching; (2) the brittle (and perhaps catastrophic) collapse of the postsalt strata; and (3) a thick lens of basal (relative to adjacent areas) Quaternary strata (Figure 6).

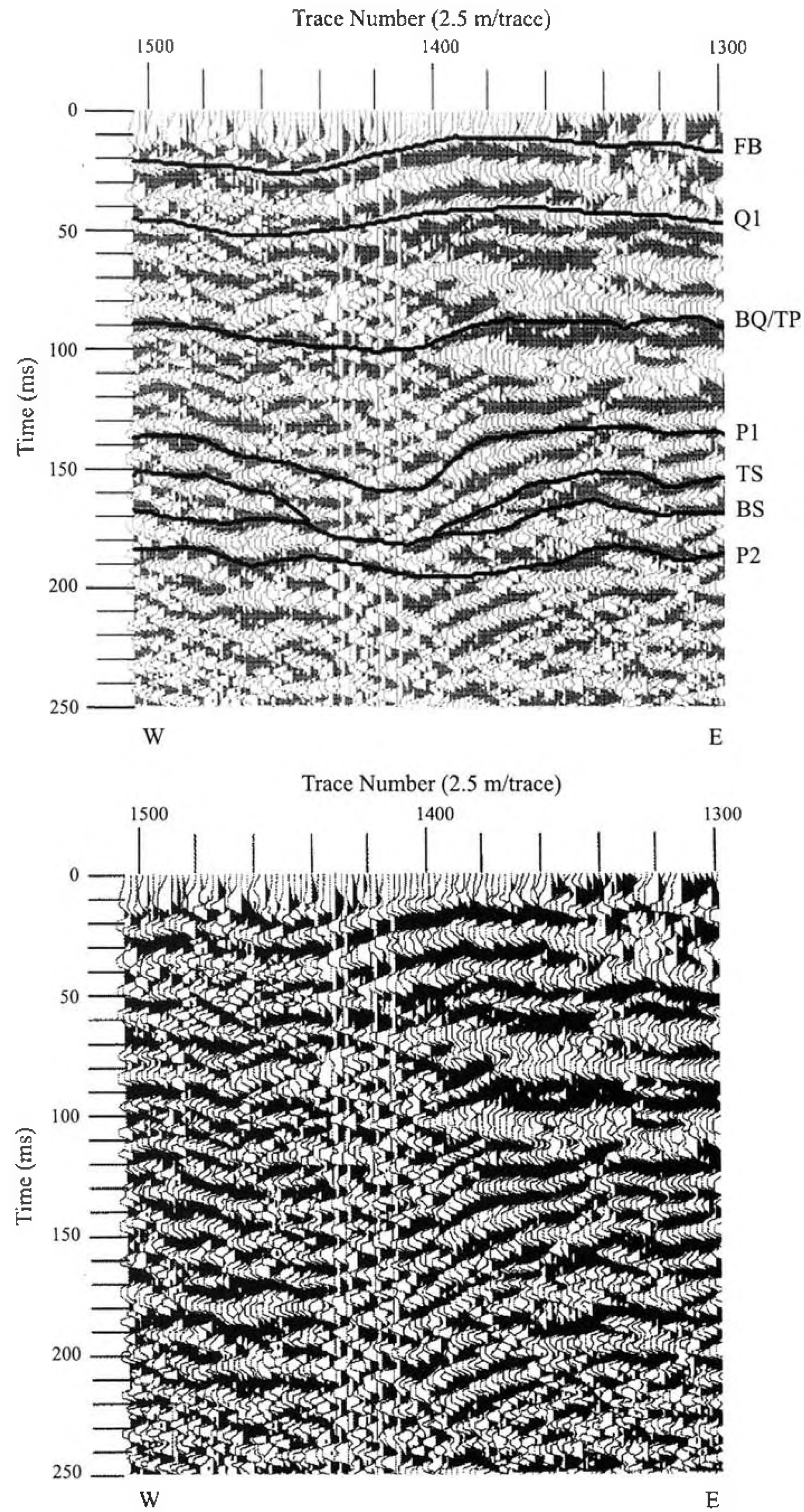

FIG. 12. Seismic image, interpreted and uninterpreted, of a secondary dissolution front (centered at trace 1415; Figure 8).

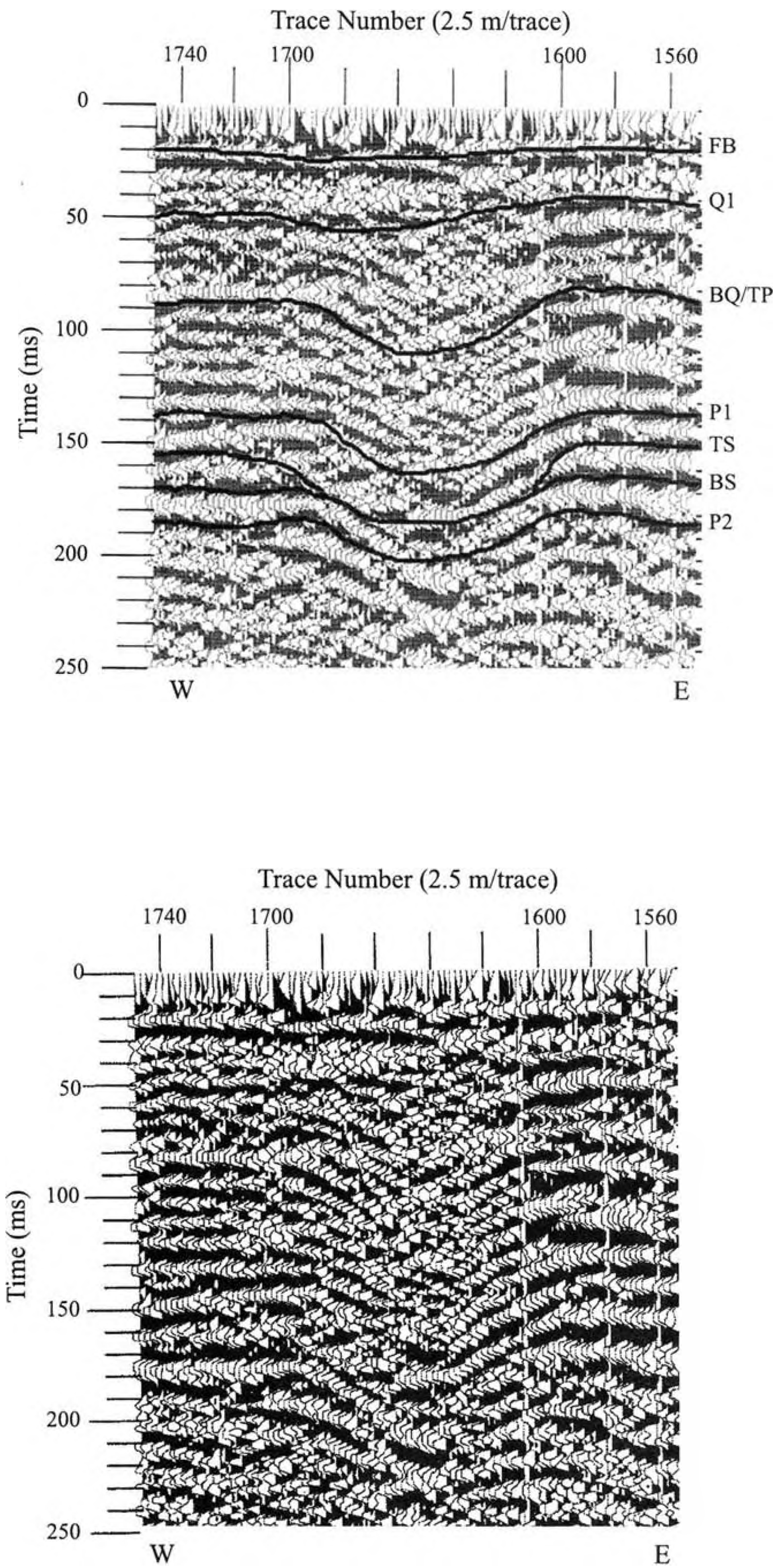

FIG. 13. Seismic image, interpreted and uninterpreted, of a secondary dissolution front (centered at trace 1615; Figure 8).

If the paleosinkholes in the Punkin Center area developed in a manner consistent with the fracture zone model, then these features initiated when the western edge of the receding margin initially passed through the study area. The exact geologic rate of salt dissolution is not well constrained. However, the leading edge of the salt dissolution margin is now 15 to 20 km west of the study area, and the original depositional margin is believed to have been about 30 km to the east (Watney and Paul, 1980 and Anderson et al., 1994b). These distances imply that paleosinkholes could have been developing over a period of several hundred thousand years.

The documentation of paleosubsidence features in the Punkin Center area indicates that subsidence features are, in part, a natural process related to dissolution of the Hutchinson Salt Member. Similar patterns of paleosinkhole development have been inferred from the salt dissolution zone in the Stone Corral Formation of the deep subsurface in western Kansas. Therefore, in Kansas, sinkholes and other subsidence features are not recent phenomena related strictly to anthropogenic activities (Walters, 1978). Several dozen recently formed (within the last 100 years) sinkholes have been studied and documented in the literature (Walters, 1978, 1980, 1991). All of these documented subsidence features (with the exception of those associated with mining activities) developed along the active dissolution front. All of these have been attributed to oil and gas activities (or in rare instances to mining activities), while the contributions of natural processes of dissolution and natural subsidence were not considered. The restriction of such modern subsidence features to the area of the active dissolution front and the documentation on the seismic data of paleosubsidence features in the Punkin Center area indicate that preexisting geologic features and ongoing natural processes are important components in an improved understanding and mitigation of anthropogenic subsidence features.

Natural dissolution along the eastern margin of the Hutchinson Salt Member is caused by the fracturing of the postsalt Permian shale aquitard in response to gradual subsidence associated with the progressive westward migration of the main dissolution front. This process satisfactorily accounts for the overall gradual westward thickening of the rock salt across the dissolution margin. The irregular nature of the margin and the formation of sinkholes have been reported along similar active salt dissolution fronts (e.g., Oldham, 1995). Rapid changes in remnant salt thicknesses from 0 to 40 m in less than 100 m may be related to inherited or self-actuated breaks in the continuity of the overlying shales and solution residuum. The improved access of undersaturated water to the evaporites along these conduits could result in localized areas of accelerated sinkhole development.

With respect to oil- and gas-related activities, the anthropogenic-origin models are usually consistent with the ideas that (1) improper well completion or abandonment procedures allowed groundwater to come into contact with the Hutchinson Salt Member or (2) as a result of corrosion and casing failure, undersaturated waste disposal brines were inadvertently injected directly into the rock salt strata (Walters, 1978; Johnson, 1989). In both scenarios, the preexisting geologic conditions may affect the continuity of the overlying aquitard and accelerate ongoing natural dissolution and subsidence processes. These conditions may result in a significant predisposition for surface subsidence problems related to oil and gas activities. For example, in local areas of active sinkhole collapse, such as along the boundaries of paleosinks, mechanical stresses may result in casing leaks and failure. Also, significant salinity gradients would be expected in the areas of actively dissolving remnant Hutchinson salt. Salinity gradients could form an electrical cell with the oil-well casing, resulting in accelerated corrosion at the casing anode. Both of these natural processes could lead to loss of casing integrity and access of undersaturated oil-field brines with the remnant Hutchinson salt.

DISCUSSION AND SUMMARY

Recent surface subsidence in the areas of Kansas underlain by the Hutchinson Salt Member has been attributed historically to anthropogenic salt dissolution. The explanations generally involve improper drilling, well completion, production, abandonment procedures, or casing failure as a result of corrosion. The strongest supporting arguments are that (1) all documented sinkholes in Kansas have occurred in the general vicinity of mine sites or oil and gas wells, (2) there were no documented cases of rapid surface subsidence prior to invasive activities in Kansas, and (3) the average rate of natural salt dissolution was too low to cause substantive surface subsidence over a period of years. The weaknesses in the anthropogenic origin model are that it does not satisfactorily explain (1) why some sinkholes develop significant distances from any recorded well location, (2) why early exploratory wells encountered anomalously thin rock salt in some areas along the dissolution margin, and (3) why all documented sinkholes have developed along the natural dissolution margin of the Hutchinson Salt Member (as opposed to farther west).

The seismic data presented herein are evidence that sinkholes (both ancient and modern) can develop naturally in the Punkin Center area. Knapp et al. (1988) also point out that sinkholes may develop naturally because of overlying fractured aquitards. These conclusions refute the argument that the natural rates of salt dissolution are too low to cause noticeable surface subsidence. Additionally, in the Punkin Center area, surface subsidence has occurred significant distances from any known well site, invalidating the argument that all documented recent subsidence features have occurred adjacent to sites of invasive activities.

The seismic data support the thesis that recent subsidence at Punkin Center is the result of ongoing salt dissolution of natural origin and the fracture zone model. The fracture zone model not only explains the pattern of salt dissolution and surface subsidence at Punkin Center but is consistent with several other important observations as well. Specifically, the natural dissolution model is consistent with the fact that exploratory wells have encountered anomalously thin residual rock salt in places along the active margin. It also explains why recent surface subsidence has been documented only along the active margin (except where associated with salt-mining activities). However, salt dissolution may be taking place to the west at depth, causing very little to no surface subsidence. If oil and gas activities were the only cause of leaching and subsidence, then these processes would probably not be restricted to the active margin where natural dissolution was known to occur.

In areas of active salt dissolution, such as along the edge of the Hutchinson Salt Member, anthropogenic activities must be monitored carefully. Preexisting geologic conditions and ongoing natural processes affect the continuity of the overlying aquitard and accelerate ongoing natural dissolution and subsidence processes. These conditions may result in a significant predisposition for surface subsidence problems related to oil and gas activities.

Our conclusion, based on the Punkin Center data and the observation that all documented dissolution/subsidence features (other than those related to mining) are situated on the active dissolutional margin, is that recent land subsidence in Kansas is mostly natural in origin. From the perspective of the oil industry, the interpretation that rapid surface subsidence (sinkholes) can occur naturally is important because such features have been attributed historically to anthropogenic activity (usually related to oil and gas; Walters, 1978).

It should be noted that the fracture zone and anthropogenic origin theses are not necessarily mutually exclusive. Natural processes contributing to surface subsidence may enhance anthropogenic contributions to salt dissolution. In the study area, 40 m of salt section have been removed. The Permian aquitard has most likely been fractured, thus decreasing its effectiveness as an aquitard. For example, subsidence as a result of natural salt dissolution could cause the casing at a brine disposal well to rupture at or above the level of the salt. This could result in the injection of large volumes of undersaturated brine and greatly accelerate the rate of leaching. Fractures within the pre-salt strata could provide a vertical conduit for the dissolved salt and mask the problem until significant surface subsidence occurred. To an investigator, it might appear that the problem was solely of anthropogenic origin, when in fact natural processes were the principal cause.

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