

Evaluation of the Role of Evaporite Karst in the Hutchinson, Kansas, Gas Explosions, January 17 and 18, 2001

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DISCLAIMER

This study is designed to provide insights into the geology related to the gas transport that culminated in the gas explosions at Hutchinson, Kansas. Multiple scenarios have been invoked regarding the source of gas released and how gas has been transmitted in the subsurface. This paper takes no direct position on this matter.

ABSTRACT.—On January 17 and 18, 2001, a series of natural-gas explosions and geysers occurred at widely spaced locations within the City of Hutchinson in central Kansas. A major natural-gas leak, estimated later to have been 143 million cubic feet, was reported at the Yaggy gas-storage field 7 mi northwest of Hutchinson. The Kansas Geological Survey (KGS) was involved from the outset to understand the transmission of natural gas through the subsurface. Subsequent vent and observation wells drilled adjacent to the Yaggy gas-storage field, between Yaggy and Hutchinson, and in the City of Hutchinson, encountered natural gas in shallow dolomite beds referred to as the 3-finger dolomite. The KGS also acquired two seismic lines to image the gas zone. The dolomite-bearing interval is probably equivalent to the Milan Limestone Member, at the top of the Lower Permian Wellington Formation of the Sumner Group. The 3-finger dolomite refers to the three lobes imaged on a gamma-ray log that were used to correlate the gas-bearing zone.

The current investigation into the potential role of evaporite dissolution in the formation of geological pathways for gas migration is focused on interpretation of high-resolution stratigraphic correlation and mapping of 14 intervals within the Permian strata ranging from the upper salt beds in the Hutchinson Salt Member to intervals above the 3-finger dolomite. Well logs used in the analysis represent 116 wells covering 150 mi² in the area surrounding Hutchinson. Also, detailed interpretations were made of two seismic lines, one crossing a broad, westerly plunging anticline between Yaggy and Hutchinson, and the other at the crest of the anticline on the west side of Hutchinson. General findings indicate that this anticline forms the northern margin of a much larger (~3-mi-wide) northwest-trending structural feature referred to here as the Arkansas River Lineament (ARL) that extends beyond the mapped area and probably between Great Bend and Wichita based on other regional mapping. This northwest-trending lineament is characterized by episodic structural activity that led to recurring minor vertical movements, including development of fractures and minor faults, probably linked to the distinctive southern boundary of the Midcontinent Rift graben. A second major regional structural feature, the Voshell Anticline, imparts a north-northeasterly “grain” to the maps, the crest of the anticline itself controlling the main dissolution front of the Hutchinson Salt Member east of Hutchinson. Fractures paralleling the Voshell Anticline are probably responsible for creating small-scale (~10–15 ft of thinning over a distance of 1 mi), linear northeast-trending paleodissolution margins of salt beds within the uppermost Hutchinson Salt Member within central and eastern Hutchinson.

A set of northwest-trending fractures associated with the ARL apparently episodically acted as conduits for contact between undersaturated ground water and uppermost halite beds that led to an extensive, elongated area of dissolution of an upper salt bed in the Hutchinson Salt Member immediately south of the Yaggy–Hutchinson anticline. Episodes of dissolution include Permian (just after deposition), pre–Equus Beds, and probably during

the early Holocene. Early Holocene and younger dissolution may be expressed by isolated areas of surface depressions seen west of Hutchinson along the Arkansas River as inferred from topographic maps. High-resolution isopach mapping reveals paleosubsidence resulting from salt dissolution that probably led to enhanced structural dip of the southern flank of the Yaggy–Hutchinson anticline. In addition, narrow zones (0.25 mi wide) of minor salt dissolution (several feet), interpreted as pre–Equus Beds in age, occurred on either side of the crestal area of the Yaggy–Hutchinson anticline, further accentuating local relief. Small faults are interpreted from the seismic lines at locations corresponding to the edges of these areas of salt dissolution, suggesting a role of fractures in episodic salt dissolution. Faulting is both deep-seated, extending below the Hutchinson Salt Member, and shallow, bottoming out in upper beds of halite that have undergone dissolution in the Hutchinson Salt Member. The narrow northwest–southeast bands of salt dissolution probably reflect the location of a tectonic fracture system that borders the northern edge of the ARL. The linear trend of this dissolved salt may also delimit locations of fractures attributed to either later stage salt dissolution or tectonic origin. North-northeast linear trends of dissolved salt in eastern Hutchinson probably have similar affiliations to fracture systems that parallel the Voshell Anticline trend, as discussed in the paper.

INTRODUCTION AND BACKGROUND

While the stated objective of this paper is to evaluate the role of evaporite karst in the gas explosions at Hutchinson, the investigation results from the general goal to improve the geologic understanding of apparently subtle geological features associated with the gas explosions and locations of active gas venting and observation wells in the Hutchinson area and adjacent to the Yaggy gas-storage field. The current seismic and geologic study attempts to improve understanding of the formation of the geologic features, particularly structures and lineaments, to better ascertain subsurface gas conduits. The study also attempts to resolve suspected occurrences of salt dissolution, including their timing and distribution, and to evaluate their relation to the geologic setting. Methodologies developed here could be generally useful in characterization of the geology related to gas containment. Color versions of the graphics in this paper are available on the Kansas Geological Survey's Hutchinson Response Project website, <http://www.kgs.ku.edu/Hydro/Hutch>.

Gas Explosions in Hutchinson, Kansas

On the morning of January 17, 2001, a gas explosion occurred in downtown Hutchinson, Kansas. Later that day, gas geysers began erupting 2 mi to the east, along the eastern edge of Hutchinson. The following day, a gas explosion at a trailer park near the geysers in eastern Hutchinson led to the death of two people. The outgassing in the city began 2^o days after a major gas leak in a natural-gas-storage well, S-1, at the Yaggy gas-storage facility, 7 mi northwest of Hutchinson (Fig. 1), where natural gas is stored in caverns in the Lower Permian Hutchinson Salt Member of the Wellington Formation of the Sumner Group (Fig. 2). An estimated 143 million standard ft³ of natural gas at high pressure (600+ psi) escaped from a casing leak at a depth of ~600 ft. The casing leak was stratigraphically just below the top of the Hutchinson Salt Member (bedded halite and shale) and 184 ft above the top of the salt cavern in which the natural

gas had been stored. The salt-storage cavern itself was not breached nor directly involved in the loss of gas. The Yaggy gas-storage facility was originally developed in the early 1980s to store liquid propane. The wells were later removed from service and in 1989 were plugged by filling the casings with cement on top of bridge plugs. In the early 1990s the cement was drilled out and the wells converted to store high-pressure natural gas. It is believed that the casing in the S-1 well was damaged at the depth of the leak when a metal obstruction was milled during reentry in the cemented well. The metal obstruction in the S-1 well was apparently part of the tubing used in the cement injection above the bridge plug that was not removed, but left in the well. The S-1 had a satisfactory casing-pressure test, as required by the Kansas Department of Health and Environment, demonstrating the integrity of the casing at that time. However, the well at the depth of the leak was never tested to the maximum pressure that would be experienced in service. New Kansas Department of Health and Environment regulations require a much more rigorous well-testing program.

In order to find and vent remaining gas from beneath Hutchinson, a vent-well drilling program commenced. Observation wells near Yaggy encountered gas at a depth of 420 ft, in a stratigraphic interval ~170 ft above the level of the casing leak at the top of the Hutchinson Salt Member. Vent wells drilled in eastern Hutchinson encountered gas as shallow as 240 ft in an equivalent stratigraphic zone, reflecting regional westerly structural dip typical of bedrock in this area of Kansas. With the exception of DDV (deep drill vent) no. 64, gas was confined to a 17–21-ft-thick interval encompassing three thin (2–3-ft) beds of dolomicrite. DDV 64, on the western edge of Hutchinson, is unique in that, on July 7, 2001, it suddenly vented gas measured at 330 psi with an estimated 30–40-ft flare. Gas pressure diminished to 6 psi after 3 days (Allison, 2001a). This gas seems to have originated from a zone 70 ft below the gas interval in the other wells.

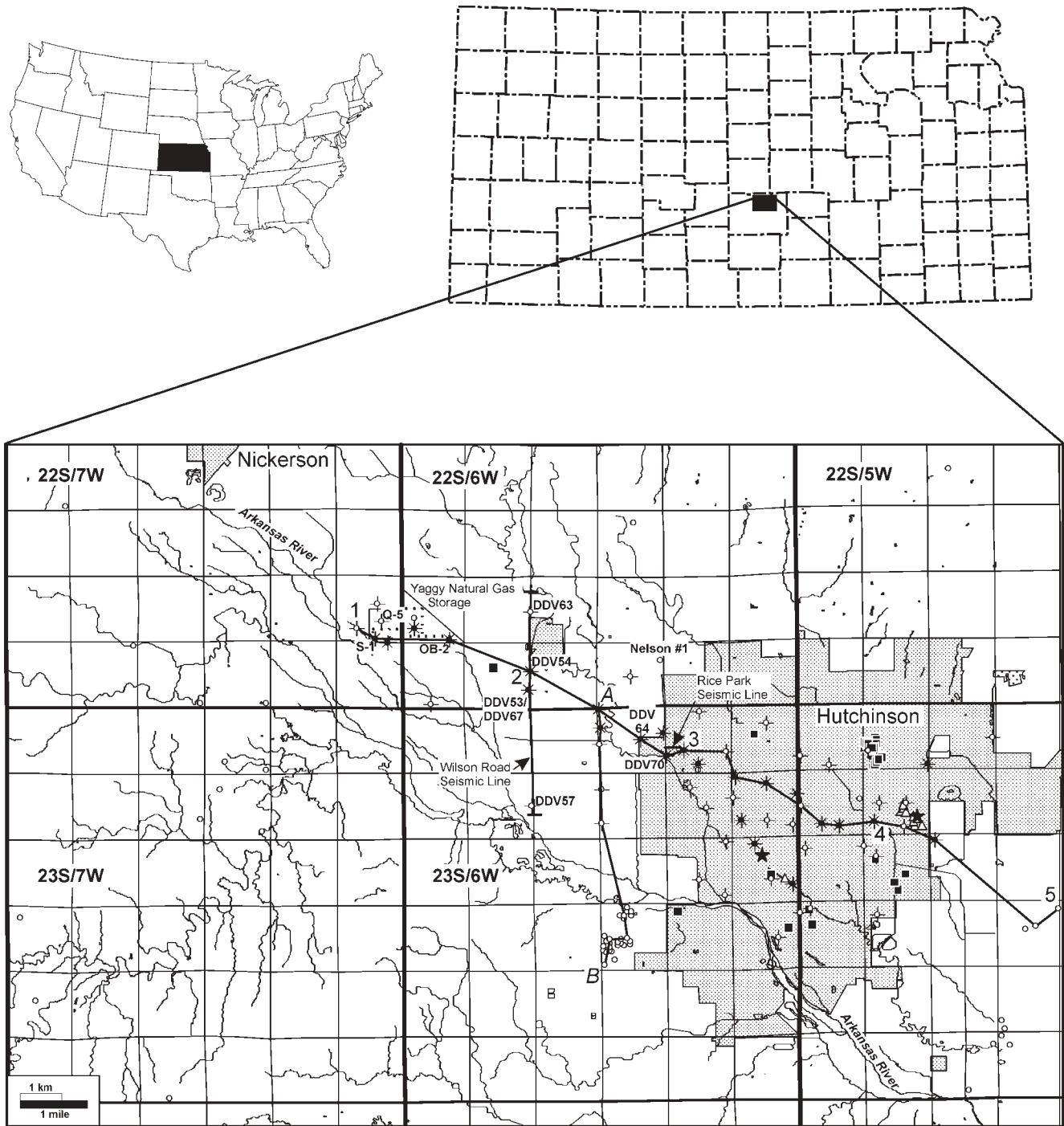


Figure 1. Surface-drainage map of the detailed study area around Hutchinson and the Yaggy natural-gas-storage facility. Locations of gas geysers are shown by white triangles, and explosion sites are shown by black stars. Observation and vent wells that vented natural gas are indicated by black producing-well symbols. Vent wells that did not produce gas are indicated by dry-hole symbols. Additional wells used for log correlations are shown by open circles. Wells discussed in the text are labeled. Locations of log cross sections in Figures 6 and 7 and seismic lines in Figures 8 and 9 are indicated. Known areas of subsidence are shown by black squares.

In general, engineering-test results have noted higher surface shut-in pressures in vent and observation wells closer to Yaggy, forming a linear trend of gas-producing wells on the north side of a broad, westerly dipping asymmetric anticline. Surface shut-in

pressures, measured only after the pressures were low enough to shut in the wells safely, beginning in March 2001, have decreased and are now subhydrostatic, with no measurable flow at any of the vent wells currently open. Maps showing bottom-hole pressures in the gas-

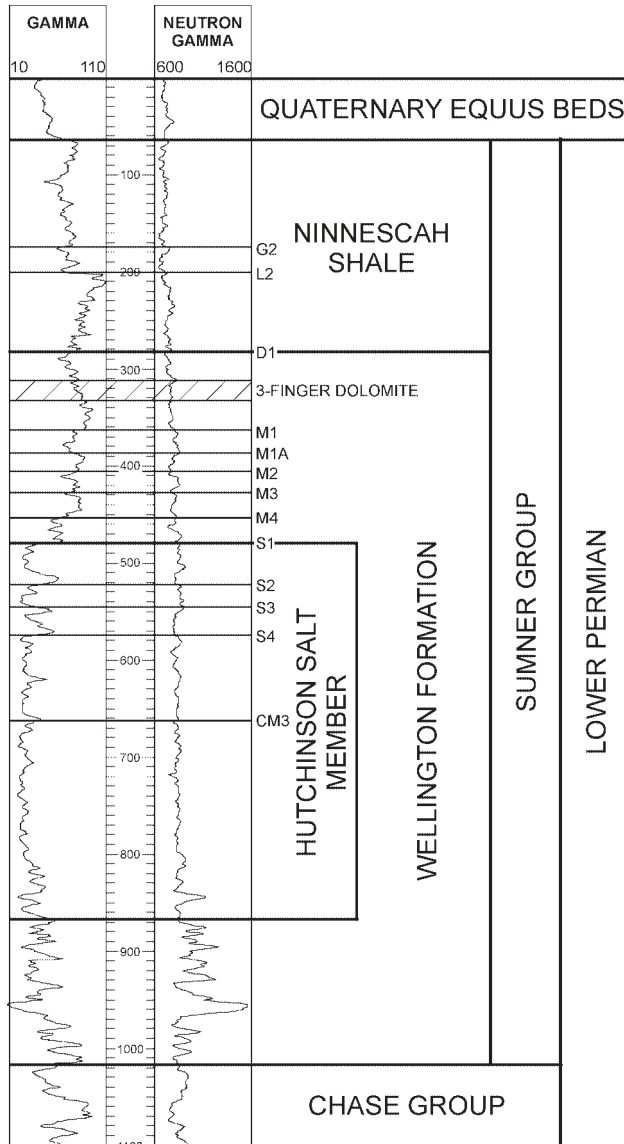


Figure 2. Natural-gamma-ray and unscaled neutron-porosity logs from the No. 1 Nelson well in sec. 34, T. 22 S., R. 6 W., showing distinctive log responses of stratal members significant to the study, including Lower Permian Leonardian Sumner Group containing the Hutchinson Salt Member of the Wellington Formation and the Ninnescah Shale, unconformably overlain by the Quaternary Equus Beds. Closely spaced marker beds G2 to S4 mapped in this study are shown as horizontal lines. The regional CM3 marker bed mapped in Watney and others (1988), which divides the upper and lower Hutchinson Salt Member, is also indicated.

bearing zone under shut-in conditions (March 2001 and July 2002) can be interpreted to indicate apparent continuity of a subsurface region pressurized by gas between producing vent wells in and around Hutchinson. Subsequent maps of pressures from later dates show a slow decline in subsurface (shut-in) pressures at the 3-finger dolomite associated with negligible gas flow at vent wells, indicating reduced permeabilities and perhaps loss of apparent connectivity (Bhattacharya and Watney, 2002). A fracture

model was proposed on the basis of linear trends of pressurized subsurface areas, fractures in a borehole-image log from a borehole adjacent to the Yaggy gas-storage facility, and faulting interpreted from seismic data acquired between Yaggy and Hutchinson and at the western edge of Hutchinson. Also, a lack of notable matrix porosity, as obtained from core plugs from vent well DDV 67, in the strata harboring the gas implied possible fracture control. Calculated static bottom-hole pressure of 250 psi at zones at depths of 300–400 ft translate to a pressure gradient that is close to the fracture gradient of the rock (roughly 0.8–1 psi/ft). Initial gas pressure in the gas-producing interval may have, for a limited time, parted preexisting fractures and/or allowed propagation of fractures and lateral gas migration comparable to published models and field data on stress-dependent porosity and permeability and fracture propagation (Settari and others, 1999). With declining gas pressure, the loss of permeability in the vent wells and accompanying negligible gas flow, as now observed in shut-in pressure tests, may be indicative of reduced and closed fracture apertures as a result of decreased pore pressure.

At the vent wells, multiple surveys of tubing-head shut-in pressures (THSPs) and corresponding static fluid columns were carried out, starting in March 2001. The shut-in times in the first survey were short, <30 hours for most wells, owing to safety concerns related to the surface equipment's ability to handle the buildup pressures. Shut-in times in later surveys varied from 72 to 96 hours. Pressure in the 3-finger dolomite was calculated by adding the THSP to the pressure exerted by the fluid column. Figure 3 shows the distribution of subsurface pressures as of March 2001 and July 2002. Automated triangulation gridding was used to generate the subsurface-pressure distribution because of the irregular distribution of data points. The pressure maps indicate that pressurized subsurface areas are aligned along the northern edge of the subtle north-west-trending anticline between Hutchinson and the Yaggy gas-storage facility. Subsurface pressures under the City of Hutchinson have decreased between March 2001 and July 2003. However, pressures as high as 180 psi (though sub-hydrostatic) still prevail in the vicinity of the Yaggy gas-storage facility (at vent well OB 2) as recently as the last series of reported pressure measurements taken in January 2003.

A rough calculation was carried out using estimated data to approximate the average effective permeability necessary for gas to be transmitted laterally over significant distances—i.e., miles. The formulation used for this calculation includes viscous (laminar) gas flow in a homogeneous linear system and is given below and on the next page (Ahmed, 2000).

$$Q_{sc} = \frac{0.003164 T_{sc} A k (P_1^2 - P_2^2)}{P_{sc} T L z \mu_g} \quad (1)$$

Where:

Q_{sc} = gas flow rate at standard conditions, scf/d;

k = permeability, md;
 T = temperature, °R;
 μ_g = gas viscosity, cp;
 A = cross-sectional area available to gas, ft²;
 L = total length of the conduit, ft;
 z = gas-compressibility factor.

The preceding formulation assumes constant z and μ_g over the range of the pressure gradient and is therefore valid for applications where the pressure is below 2,000 psi. It was assumed that the upstream pressure in the flow system was 650 psi (pod pressure at Yaggy).

Along with the gas explosions, a geyser erupted in downtown Hutchinson. Also in the current model, the depth of the 3-finger dolomite under the city is 250–300 ft. Lacking other data, it was assumed that the downstream pressure in the flow conduit was at least 130 psi (using a water gradient of 0.433 psi/ft). A gas gravity of 0.66 was assumed in these flow calculations. The total volume of gas that leaked from the Yaggy facility is estimated at 143 MMscf. Gas surfaced in the city of Hutchinson through abandoned, unplugged brine wells within 2.5 days after the reported leak. Vent wells drilled in and around the city continued to produce measurable quantities of gas for another 3 months. To estimate the average permeability of the gas conduit in this scenario, the gas-flow rate was calculated by assuming that this leaked volume took at least 90 days to bleed off. Also, it is unknown what fraction of the leaked volume would make it to the city. Thus, two cases were modeled: (1) assume that all of the leaked gas came toward the city, and (2) assume that only one-tenth of the leaked volume came toward the city. Using equation (1), a conduit with 460-darcy permeability would be necessary to transmit all of the leaked gas volume from Yaggy storage to Hutchinson's city center. However, if one assumes that only one-tenth of the leaked volume traveled toward the city, the conduit permeability must be in the range of 46 darcies. It is not unreasonable to think that a fracture system could have permeabilities ranging from tens to hundreds of darcies.

New geologic data described in this paper provide further support for several extensive kilometer-scale lineaments and associated fracture systems that could have served as conduits for gas migration in and around Hutchinson. Also, the implication important to the City of Hutchinson is that if fracture continuity were developed between the gas source and its release point, darcy-level permeability could have vented a considerable amount of the pressurized gas in a short period of time (days to months) (Watney and others, 2003). Furthermore, the implication is that certain geological elements, such as fracture systems and lineaments, may present inherent risks for focused lateral migration of gas stored under pressure.

Geology of the Hutchinson Area

The Quaternary Equus Beds, an extensive unconfined freshwater aquifer, unconformably overlies the

Permian strata in the vicinity of Hutchinson, ranging from zero to as much as 100 ft thick (Fig. 2). The Lower Permian Hutchinson Salt Member of the Wellington Formation of the Sumner Group, ~350 ft thick in the area of Hutchinson and the Yaggy gas-storage facility, unconformably underlies the Equus Beds and dips westward at 20 ft/mi beneath the storage facility from the subcrop, a natural, regional salt-dissolution front ~13 mi east of the storage facility and 6 mi east of Hutchinson (Fig. 4). The Hutchinson Salt Member is overlain by ~450 ft of Permian gypsiferous shales that are interbedded with thin (1–3-ft-thick) intervals of gypsum, anhydrite, and dolomite. The Permian section above the Hutchinson Salt Member is divided into the upper Wellington Formation, a gray gypsiferous shale, and the Ninnescah Shale, a reddish, more silty gypsiferous shale.

A 15–20-ft-thick zone of thin interbedded dolomite and shale ~160–170 ft above the top of the Hutchinson Salt Member, informally referred to as the 3-finger dolomite, provided the primary conduit along which natural gas migrated through the area. This unit is probably equivalent to the Milan Limestone Member of the upper Wellington Formation. The 3-finger dolomite refers to three characteristic lobes observed on the gamma-ray log trace, the primary logging tool that was used to define and correlate the interval between vent and observation wells (Fig. 2). The dolomite beds, while approximately less than 3 ft in thickness and variable in shale content, are continuous throughout the immediate study area.

The gypsiferous shales of the upper Wellington Formation contain abundant irregular satin-spar veins/fractures, which probably formed during volume increase that occurred during hydration of anhydrite to gypsum as the overlying strata were removed by erosion, burial depths decreased, and undersaturated water contacted these strata. These fractures may have been involved in movement of high-pressure gas, but no data are available to corroborate this.

Evaporite Dissolution and Evaporite Karst Near Hutchinson

Natural Dissolution

Dissolution along a part of the eastern margin of the Hutchinson Salt Member in central Kansas has been well documented, most recently using seismic data (Steeple and others, 1984; Anderson and others, 1994; Anderson and others, 1995a,b; Anderson and others, 1998; Miller, 2002). The prominent dissolution front, characterized by abrupt loss of the entire Hutchinson Salt Member over several miles, lies 7.5 mi east of Hutchinson (Fig. 4), where halite beds come to within 200 ft of the surface (Watney and others, 1988). The primary mechanism for dissolution of the shallow salt beds is believed to be contact with meteoric ground water. The area east of the salt-dissolution front near Hutchinson is inferred once to have

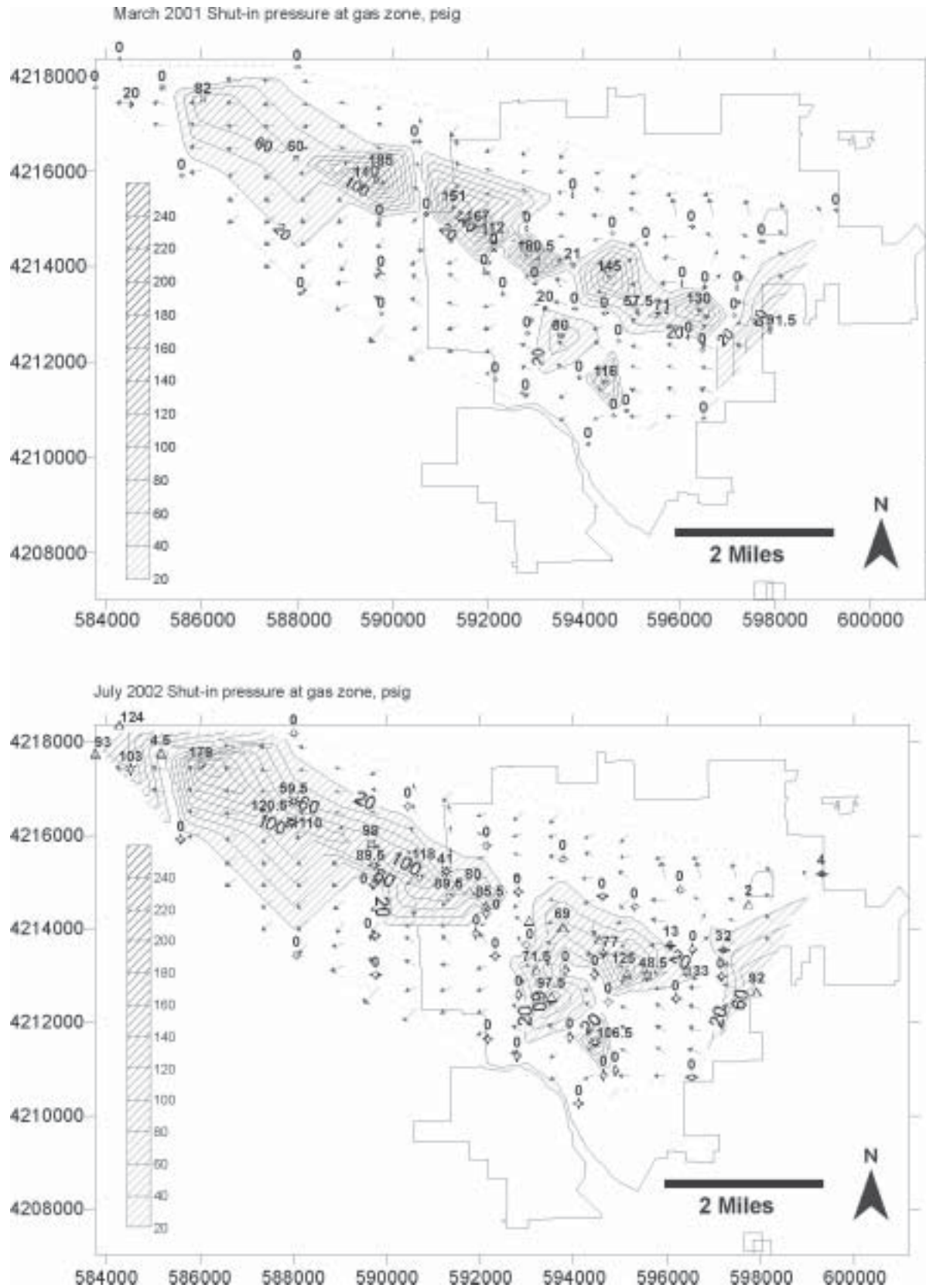


Figure 3. (A) March 2001 shut-in-pressure map gridded by triangulation, showing pressures in psig units. Dip vectors at the top of the 3-finger dolomite are also shown. Shut-in pressures were not taken in several active gas-venting wells owing to excessive pressure and safety concerns. Shut-in pressures are calculated at the 3-finger dolomite using recorded surface pressures and standing fluid columns. (B) July 2002 shut-in pressure calculated at the 3-finger dolomite.

contained bedded salt, and which now contains collapsed Permian strata called the Wellington aquifer. Quaternary alluvial sediments, the Equus Beds, were deposited in the surface depression left by the collapse of the upper Wellington Shale resulting from the dissolved halite strata. The Equus Beds in aggregate accumulated as part of large, ancient river systems that drained the Rocky Mountains during wetter interglacial periods, contrasting with today's setting. Upward of 200 ft of salt was dissolved along a corridor between Wichita and McPherson, forming a bedrock low some 50 mi long, covering 300 mi² (Lane and Miller, 1965).

The uppermost salt beds progressively pinch out eastward at depths shallower than 300 ft below the surface and some 15 mi west of the inferred maximum limit of deposition (Watney and others, 1988; Anderson and others, 1994). A broad stair-stepped salt-dissolution margin was formed. The pinch-outs may have been depositional as halite accumulation came to a close, or the result of later dissolution that led to truncation of the edges of the salt (Miller, 2002).

A regional net-salt map (Fig. 5A) reveals the dominant north-northeast trend of the primary salt front between the cities of Hutchinson and Salina. A promi-

nent salient or embayment of the main dissolution front was formed at the juncture of the dissolution front and the Arkansas River southeast of Hutchinson (Figs. 4, 5A). Local north-northeast-trending secondary salt dissolution behind (west) and parallel to the primary salt front immediately east of Hutchinson is attributed to a fracture zone along the Voshell Anticline (Anderson and others, 1994). The greater McPherson–Voshell Anticline closely corresponds to a deep-seated magnetic lineament in the underlying Precambrian Midcontinent Rift system and is a prominent, ~50-mi-long, faulted anticline affecting Paleozoic strata (Xia and others, 1995a,b; Newell and Hatch, 1999). The southern terminus of this lineament corresponds to the southern end of the sediment-filled portion of the Midcontinent Rift. Lineaments corresponding to the Arkansas River and the Voshell Anticline are also shown on a preliminary State lineament map for Kansas (Gerhard, 2003).

Recent 2-D-seismic surveys acquired ~6.5 mi southeast of the eastern Hutchinson explosion sites along U.S. Highway 50 in the Arkansas River Valley by Miller (2002) indicate that a moderate-sized (300-ft-diameter) sinkhole developed at the surface along the highway. Miller found that this surface expression is only a small part of a much larger area of subsidence in the subsurface, as much as 1,500 ft wide and elongated west to east, immediately west of the main dissolution front. Sinkhole development probably began in earnest during the late Tertiary during a significant erosion and valley-incision event, prior to deposition of the Equus Beds (Miller, 2002). Widespread ponding of surface waters in this general area within several miles of the solution front suggests recent natural subsidence in addition to that along U.S. Highway 50. Seismic data show that 135 ft of salt remains at the Highway 50 location within 0.5 mi of the salt front, suggesting that some 200 ft of the Hutchinson Salt Member has been removed by dissolution.

The Wellington aquifer, the deformed Permian section that lies above the dissolved Hutchinson Salt Member, closely corresponds to areas of dissolved salt (Gogel, 1981). The younger Quaternary Equus Beds aquifer also occupies space created by dissolution of underlying salt. The Equus Beds locally extend westward beyond the main dissolution front as valley-fill sands, including the Yaggy–Hutchinson area. Modern surface drainage dominated by the northwest-trending Arkansas River Valley closely coincides with the major trunk valley and tributary systems of the Equus Beds, as inferred from the map depicting the configuration of the base of these beds (see Fig. 10A). Based on new seismic data (Miller, 2002), major paleosinkhole development was probably concurrent with the erosion and deposition of the Neogene Equus Beds and was probably related to a greater flux of undersaturated water associated with a wetter climate, elevated stream flow, erosion, and valley incision associated with these deposits (Lane and Miller, 1965). Subse-

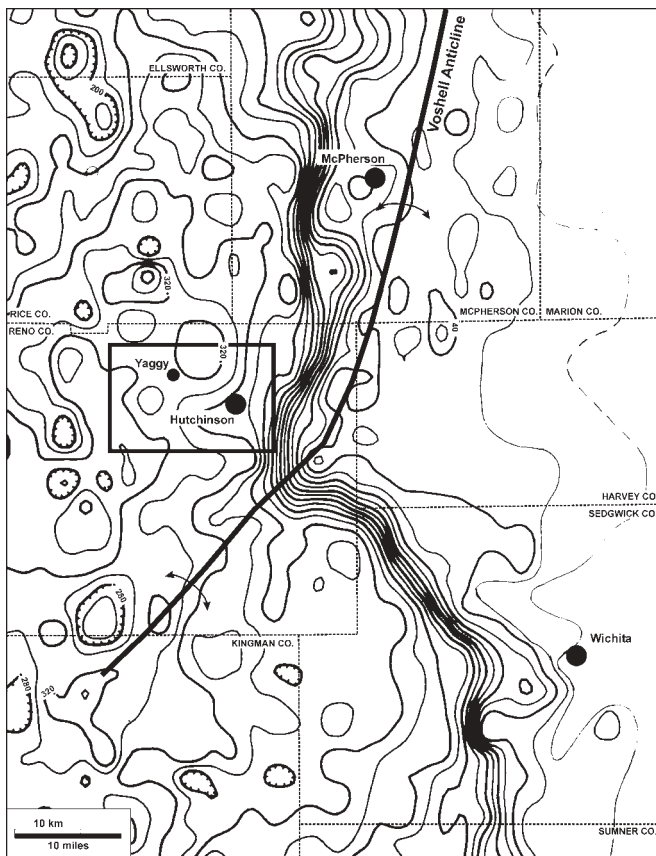


Figure 4. Net-salt isopach map of the Hutchinson area from Watney and Paul (1980). Contour interval = 20 ft. The axis of the Voshell Anticline, believed to be related to north-northeast-trending salt dissolution, is shown. The box outlines the detailed study area in Figure 1.

quent sinkhole development also has continued to the present, including reactivation of earlier subsidence as indicated in recent seismic lines acquired along a surface sinkhole on U.S. Highway 50 southeast of Hutchinson (Miller, 2002).

Surface sinks and closed surface depressions are numerous in areas west of Hutchinson along the greater Arkansas River Valley as seen on 7.5-minute topographic maps. Reported surface sinks, such as in the Yaggy townsite near the Yaggy gas-storage facility, have an unknown origin (Kansas Department of Health and Environment, 2001). Reported surface subsidence and sinks in the Hutchinson area have been annotated on the map in Figure 1. Ver Wiebe (1937) described a surface locality exhibiting faulted and up-turned Permian beds in a road cut beneath flat-lying Cretaceous Dakota Sandstone in east-central Ellsworth County ~40 mi north of Hutchinson. He attributed deformation to an early episode of dissolution of the Hutchinson Salt Member that is ~300 ft thick at a depth of 650 ft. This location is ~15 mi west of the main salt-dissolution front.

Anthropogenic Dissolution

Brine-recovery wells are used to dissolve bedded salt at shallow depths near the eastern margin of the Hutchinson Salt Member. Those brine wells, developed prior to the 1960s, typically dissolved the upper salt beds at depths of ~400 ft, some leading to collapse of the relatively weak shales overlying the salt, and occasionally to sinkhole development (Walters, 1978; Miller and others, 1993). Well-documented sinkholes, 300 to 500 ft in diameter, developed in Hutchinson, with both subtle and catastrophic surface subsidence ranging from a few inches to several tens of feet of vertical relief (Young, 1926; Walters, 1978; Miller and others, 1993).

Abandoned brine wells served as the pathways for natural gas to reach the surface at the Hutchinson explosion and geyser sites. Known sinkholes associated with abandoned brine wells did not appear to contribute significant gas migration or gas buildup in the Hutchinson area, a scenario that was considered immediately following the gas explosions. Gas found in vent wells was, with the exception of DDV 64 as noted previously, confined to the 3-finger dolomite interval, with no evidence of gas in known surface sinks. The gas seems to have moved into the unplugged brine

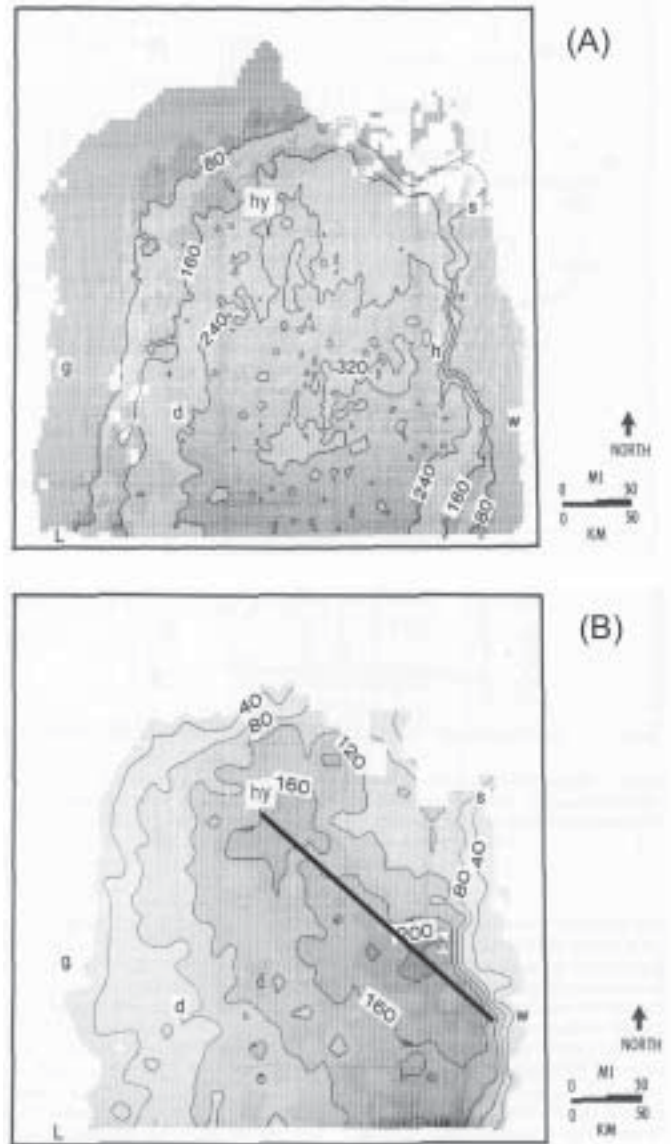


Figure 5 (right). (A) Regional total net-halite isopach map of the Hutchinson Salt Member. (B) Regional net-halite isopach map of lower Hutchinson Salt Member below CM3 marker shown in Figure 2. Mapped area covers most of western Kansas, as shown by index map below. Mapped area developed from >3,700 wells, representing sampling of one well per 77 mi². Letters on maps refer to city references: g, Garden City; L, Liberal; d, Dodge City; hy, Hayes; s, Salina; h, Hutchinson; and w, Wichita. Contours are in feet. Lineament aligned with Arkansas River shown on lower map. Salt-dissolution front indicated by closely spaced contours along southeastern margin of the salt.

wells at the depth of the 3-finger dolomite and then to the surface. Recently acquired sonar and gamma-ray logs and televiewer photos from 11 unplugged brine wells in Hutchinson indicate that no significant collapse has occurred in solution-mined cavities in the Hutchinson Salt Member (Burns and McDonnell Engineering Company, Inc., 2003).

METHODOLOGY IN NEW MAPPING AND SEISMIC INTERPRETATION

A regional stratigraphic and sedimentologic database obtained in the 1980s was used to establish the general geologic setting of the salt-bearing strata in the Hutchinson area. Some 3,700 wells are included in the database covering the region underlain by the Hutchinson Salt Member, which encompasses >37,000 mi² of central and western Kansas (Watney and others, 1988). The stratigraphic interval described in the database extends from the Lower Permian Stone Coral Formation to the top of the Chase Group, including the interval of interest in this current investigation (Fig. 2). A datum ~30 ft above the 3-finger dolomite was mapped in the regional database at the approximate contact between the Wellington Formation and Ninescah Shale.

Over the course of several months after the initial gas leak and explosions, 57 vent wells and five observation wells were drilled in the vicinity of Yaggy and Hutchinson (Fig. 1). Twenty-four of these wells produced gas. Natural-gamma-ray and temperature logs were acquired from all of the vent wells, and additional logs from several wells. Surface elevations and locations were accurately measured, and logging was done over a span of several months. Most of these wells penetrated the Hutchinson Salt Member, providing new data on the distribution of the upper Hutchinson Salt Member and overlying layers at a high degree of spatial resolution. The gamma-ray logs from these wells, along with gamma-ray logs from nearby oil wells and gas-storage wells, and lithologic logs from KGS Bulletins and water-well completion reports, were used to generate new cross sections and structure and isopach maps of the upper Hutchinson Salt Member and overlying layers for an area of ~150 mi² around Hutchinson. The new data were used to identify and refine structural and sedimentological features that helped resolve characteristics of potential gas-migration pathways and to define the role of salt dissolution in the formation of these pathways.

In February 2001, the Kansas Geological Survey acquired two high-resolution seismic-reflection surveys in the Hutchinson area. A 0.3-mi-long line was shot in Rice Park on the west side of Hutchinson, adjacent to a gas-producing vent well, DDV 5, and a 3.4-mi-long north-south line was acquired along Wilson Road, midway between the western city limit of Hutchinson and the Yaggy gas-storage facility (Fig. 1). High-resolution reflection data were acquired by a minivib (vibroiseis) survey and vertical-component geophones. The source interval was 5 m, and the re-

ceiver-group spacing was 2.5 m. A 6-s record with a sample interval of 0.5 ms was recorded. The data were filtered with a trapezoidal band-pass filter with corner frequencies of 61, 122, 250, and 300 Hz. Common-midpoint (CMP) stacked data have folds ranging from 1 to 31 and a CMP spacing of 1.25 m. The fold is 15 or greater for 0.27 mi of the Rice Park seismic line and 3.31 mi of the Wilson Road seismic line. The displays shown in Figures 8 and 9 were scaled using automatic gain control (AGC) over a 200-ms sliding window. The Rice Park line was selected to determine if the gas zone produced a seismic anomaly, and the Wilson Road line was selected to identify potential gas pathways between Yaggy and Hutchinson (Nissen and others, 2002). Two amplitude anomalies at the level of the proposed gas-bearing interval were identified and drilled on the Wilson Road line. Gas was found at both sites (DDV 53 and 54). In March 2001, DDV 67 was drilled ~70 ft southwest of DDV 53 to core the gas zone and obtain density and sonic logs to calibrate the seismic line. Two dry holes (DDV 57 and 63) also were drilled at the northern and southern ends of the Wilson Road line to provide core (DDV 63 only) and sonic and density logs. A sonic log also was acquired in DDV 5 in Rice Park in October 2001. These data were used to correlate the seismic profiles with the stratigraphic units encountered in these wells. Although the Wilson Road and Rice Park seismic lines are spatially limited, they provided information locally on the lateral variation in salt thickness between wells (i.e., gradual versus sharp thickness changes) and allowed for the identification of structural elements such as faults, which may have controlled the gas-migration pathways. Findings from other seismic surveys in the area also were considered to help in the geological and geophysical characterization (Miller, 2002; Anderson and others, 1994; Anderson and others, 1995a; Anderson and others, 1998).

A borehole-imaging log was acquired in observation well OB 2, adjacent to the southeast corner of Yaggy, for fracture characterization.

Core data were examined to characterize the 3-finger dolomite interval and the upper Hutchinson Salt Member. After the Hutchinson incident, two cores were acquired along Wilson Road. One was from a gas-producing well, DDV 67, and the other was from a dry hole, DDV 63. The core from the Q-5 gas-storage well in the Yaggy gas-storage facility was acquired by the facility operator before the Hutchinson incident to characterize the salt-containment system. This core was described for the interval just above and into the top of the Hutchinson Salt Member. A core obtained in 1970 from the Atomic Energy Commission (AEC) no. 1 test hole near Lyons, 20 mi northwest of Hutchinson in Rice County, was used initially to establish the stratigraphy of the interval equivalent to the gas-bearing zone in Hutchinson (Allison, 2001a; Stockstad, 2002). Surface exposures also were used to help characterize the local character of the thin do-

lomite beds in the upper Wellington Formation, which are roughly equivalent to the gas-bearing zone.

RESULTS

Regional Mapping

Information on formation tops and net halite content for the stratigraphic interval between the top of the Stone Corral Formation to the top of the Chase Group was reviewed to ascertain depositional and stratigraphic trends and the nature of the salt-dissolution front (Watney and others, 1988). Several regional geologic studies also were reviewed to better understand the stratigraphy and structural setting (Swineford, 1955; Bayne, 1956). Swineford (1955) delimited small-scale sedimentary cycles in the outcrop that culminate in thin carbonate or gypsum beds that probably are the basis for the marker beds used here in the high-resolution stratigraphic mapping. Bayne (1956) delineated the extent of the Equus Beds in Reno County.

A structural map depicting the top of the Wellington marker (slightly above the gas-bearing 3-finger dolomite) was originally based on previous regional mapping using approximately five wells per township. This map reveals only gradual, steady westerly dip of ~20 ft/mi between Yaggy and Hutchinson (<http://www.kgs.ukans.edu/Hydro/Hutch/StructureMaps/index.html>). New mapping of a 10- to 16-mi area surrounding the City of Hutchinson incorporates data from 116 wells (including the 62 new vent and observation wells), allowing the top of the 3-finger dolomite to be mapped in more detail, and revealing features not previously depicted on the regional map of the top of the Wellington marker.

A regional map of the net halite in the Hutchinson Salt Member indicates that thickness slowly decreases from 325 ft of net halite near Yaggy to 250 ft 3 mi east of Hutchinson (gradient of 25 ft/mi) (Fig. 4). These changes in thickness are typical of those along the salt-basin margins and suggest local depositional changes. Alternatively, these minor thickness changes may be indicative of minor dissolution at the top of the salt as observed in all cores that have been examined in the area. East of Hutchinson the net halite decreases dramatically, defining the primary salt-dissolution front, which is characterized by greater changes in salt thickness (83 ft/mi).

Net-halite maps of the Hutchinson Salt Member (Figs. 4, 5A) show several marked changes in the local salt section in the Hutchinson area, including abrupt thinning along the eastern margin, defining the salt-dissolution front, and a local embayment along the salt-dissolution front extending between Hutchinson and Wichita. A much more gradual change in salt thickness (5.3 ft/mi) occurs south of Wichita. This reduced gradient in net halite suggests predominantly depositional thinning south of Wichita, corresponding to the eastern margin of the Hutchinson salt basin. Nevertheless, local halite dissolution in this area

still occurs. The net halite in the lower part of the Hutchinson Salt Member (below the CM3 marker, as illustrated in Fig. 5B) reveals a large northwest-trending region of thick halite in the middle part of the salt basin. Its northern border is aligned with an extension of the northwest-trending salt-dissolution margin between Hutchinson and Wichita. This linear trend, some 50 mi in length, extends at least to Great Bend.

Current and past geologic conditions along the northeastern margins of the salt basin are dynamic, reflecting the interaction of deposition, dissolution, hydrologic, and structural processes. More detailed mapping is required to resolve the contribution of these processes in controlling the migration of gas.

Detailed Mapping Incorporating Observation- and Vent-Well Data

Fifteen closely spaced marker beds were correlated among 116 gamma-ray well logs within a 150-mi² area encompassing Hutchinson and Yaggy. Ten marker beds (including the top and base of the 3-finger dolomite) were defined and correlated within the Ninnescah and upper Wellington shales (Figs. 2, 6, 7). The M1A marker corresponds to the lower gas zone in DDV 64 and is also a prominent seismic reflector (Figs. 8, 9). Also, the top of the Hutchinson Salt Member (S1) and four marker beds within the upper Hutchinson Salt Member were correlated within the study area. The S2 marker is equivalent to the regional CM5 marker, and the S4 marker is equivalent to the regional CM4 marker of Watney and others (1988). At the eastern edge of the study area the S1, S2, and S3 salt markers are correlative with thinner beds exhibiting higher gamma-ray values (M5, M6, and M7, respectively), suggesting that the uppermost salt in this area may have undergone a lateral facies change associated with the depositional edge of the salt basin (Fig. 6). This regressive stratigraphic framework is supported by Watney and others (1988).

Automated structure and isopach maps of the marker beds were generated using triangulation and a least-squares algorithm to define the shape of the gridded surface. Consistent gridding parameters were used for all maps.

The mapping of structure, thickness, and natural-gamma-ray values of the 3-finger dolomite interval helps explain the occurrence of gas production from vent wells. First, the gas-productive vent wells indicate a northwest-trending line between Yaggy and Hutchinson. A map of the elevation at the top of the upper bed of the 3-finger dolomite interval delimits a broad (1-mi-wide), low-relief (<15-ft), west- to northwest-trending and plunging (20–25 ft/mi) asymmetric anticline (Fig. 10B). The dip along the south flank of the anticline is roughly 15 ft/mi, double that of the north flank. The locations of the gas-producing vent wells closely correspond to the northern edge of the anticline. A ~2.5-mi-wide break in the overall westerly stratigraphic dip occurs along the crest of the

anticline in western Hutchinson. Regional dip decreases from ~20 ft/mi to 10 ft/mi or less. To the east of this feature, a regional dip of ~20 ft/mi ensues, and the anticline becomes a series of more complex structural undulations at a point where a linear trend of gas-producing wells between Yaggy and Hutchinson separates to follow these various structural undulations. Thus, in eastern Hutchinson two separate trends of gas wells are evident.

Local tectonic stresses along the crest of the anticline could have resulted in oriented fractures/joints that subparallel the anticline axis. Scattered discontinuous fractures observed in the dolomicrite and gypsum-filled veins in the DDV 67 core appear to be unrelated to structure. However, two sets of "partial" fractures, as interpreted on a formation micro-imaging log from observation well OB 2, adjacent to the Yaggy gas-storage facility, are west-east and north-south oriented and at a high angle (50°), occurring in the middle and lower zones of the 3-finger dolomite (Fig. 11). OB 2 has flowed significant amounts of gas and maintained the greatest pressures over the longest period of time (Bhattacharya and Watney, 2002), suggesting that the distinctive fractures in this well may be associated with the anticlinal trend and that they may correlate with the high, sustained shut-in pressures.

Cross sections and detailed structure maps of the marker beds indicate several other features that may have had an impact on gas migration:

1. The anticline along which the gas migrated persists with depth in all of the mapped marker beds between G2 and S4 and is also expressed as a local elevated northwest-trending ridge on the configuration map of the base of the Equus Beds (Fig. 10A). The consistent relief suggests that the anticline includes post-Ninnescah structural deformation. Additionally, the anticline seems to have greater relief above S2 in proportion to the thinning of the uppermost salt (Fig. 10C, D; Fig. 12C), indicating that structural relief was enhanced by salt dissolution along the flanks of the anticline.

2. DDV 64 is located on a closed high along the crest of the anticline at all mapped intervals. This structurally high position apparently made DDV 64 a focus for gas migration and was the only site of gas flow from zone M1A, ~70 ft beneath the 3-finger dolomite.

3. The headward end of a north-northeast-trending secondary (tributary) valley adjacent to the main trunk valley, inferred from the map of the configuration of the base of the Equus Beds and interpreted as a buried erosion surface (Fig. 10A), terminates immediately adjacent to the crest of the ridge near DDV 64. Its position intersects the ridge where the plunge angle of the anticline is notably diminished (i.e., flattened) to the east. This north-northeast-trending valley also corresponds to an apparent local area of salt dissolution as inferred from isopach maps that are discussed below. Local surface drainage and salt dissolution possibly are influenced by the same local structural de-

formation, in this case paralleling the trend of the Voshell Anticline. Fractures or faults are observed in a nearby seismic line in Rice Park (Fig. 9). The structural features may have been pathways for gas migration.

Isopach maps of the intervals between 15 marker beds were used to establish patterns and trends to aid in interpretation of the succession and interaction of processes including deposition, dissolution, erosion, and structure. One objective was to evaluate the possible role of minor dissolution of upper Hutchinson Salt Member beds in the gas-migration event.

The isopach of the lowermost salt interval mapped (S3–S4) indicates no eastward thinning of the salt, suggesting that salt dissolution has not reached this depth within the study area (Fig. 12A).

The isopach of the S2–S3 salt interval (Fig. 12B) shows little variation over the western three-quarters of the study area. However, in central Hutchinson, there is rather abrupt thinning from west to east, forming a 1-mi-wide, north-northeast-trending wedge. The halite bed thins from a consistent 22–27 ft at Yaggy and western Hutchinson down to 3 ft in central Hutchinson, where a north-northeast-trending linear zone <0.5 mi wide constitutes an isopach of only 3–5 ft in thickness. Eastward over a distance of 1 mi, the layer thickens again to ~10–11 ft before thinning again to 4 ft at the extreme eastern edge of the study area. A facies change from halite to sulfate or carbonate occurs along this eastern edge, suggested by lateral gradation from a low gamma-ray response to intermediate values (Fig. 6). In the area of local thinning of the S2–S3 interval, the overlying S1–S2 isopach thickens by up to 8 ft (Fig. 12C; Fig. 6, DDV 42), suggesting that the accommodation space for the upper salt bed may have been formed by early, interformational dissolution of the underlying layer prior to deposition of the S1–S2 interval. Dissolution and precipitation of halite likely occurred along the edges of the Hutchinson salt basin concurrent with deposition. This is observed in salt mines in deeper halite beds within the salt where halite-dominated cycles are capped by erosion surfaces exhibiting karstic pipes and local scallop-shaped dissolution surfaces. The apparent dissolution event in the S2–S3 interval appears to be unrelated to the natural-gas migration because (1) dissolution was early (syndepositional), (2) dissolution resulted in a thicker S1–S2 interval but did not affect strata above S1 (supporting early dissolution), and (3) a dry well is in the trend. The distinct north-northeast trend suggests a structural control, such as fracturing, that may have at one time facilitated access of water to the salt bed. This trend also parallels the main dissolution front of the salt that follows the axis of the Voshell Anticline.

The uppermost salt interval (S1–S2) (Fig. 12C) also shows an abrupt eastward thinning from 38 to 24 ft over a distance of 0.7 mi in the eastern part of the study area. The north-northeast-trending thinning of this uppermost salt layer occurs ~0.7 mi to the east of

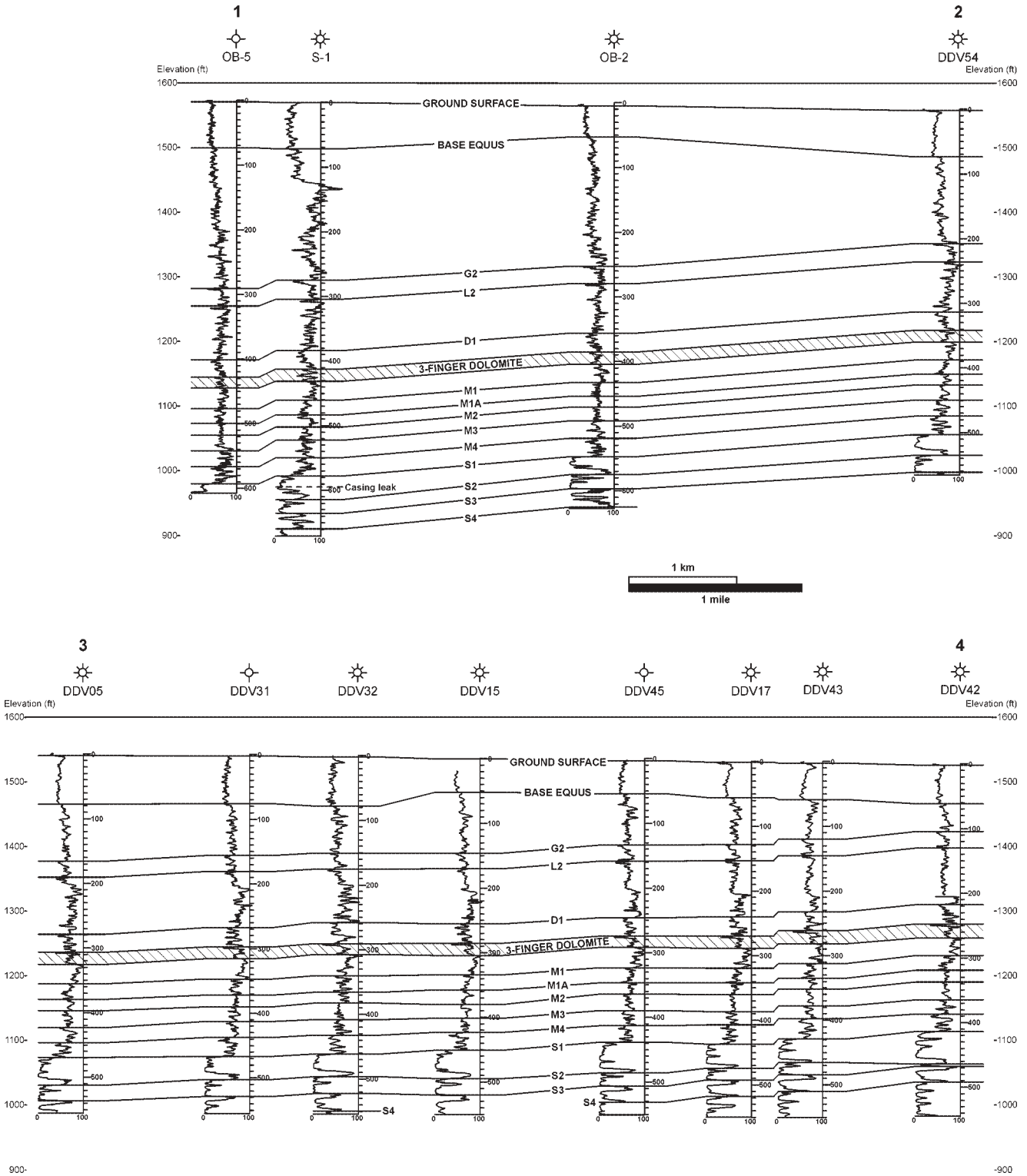


Figure 6 (above and facing page). West-east cross section between Yaggy and Hutchinson. Line of section shown in Figure 1. Normalized gamma-ray logs, in which units range from 0 (salt) to 100 (shale), show the log responses of the correlated marker beds.

the thinning in the underlying S2-S3 interval. This thinning may be depositional, corresponding with an apparent facies change in the S1-S2 interval between the eastern edge of Hutchinson and the eastern edge of the study area (Fig. 6), or local dissolution behind

and parallel to the main dissolution front, which is ~5 mi to the east.

A broad (1-2-mi-wide) zone of thinning is present in the S1-S2 isopach along the Arkansas River to the south and west of Hutchinson, parallel and adjacent

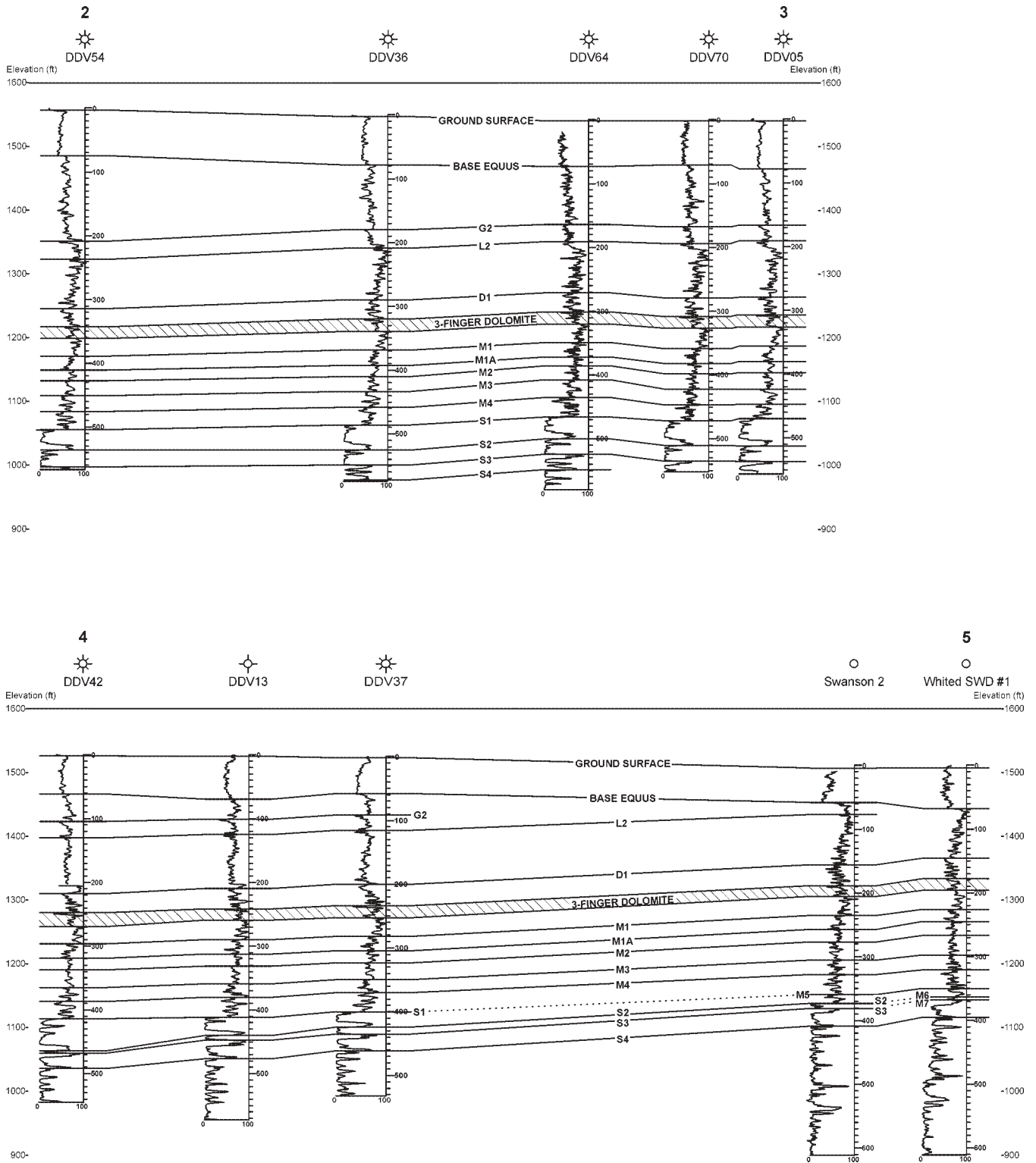


Figure 6.—Continued.

to the Yaggy–Hutchinson anticline. The area of thinning is interpreted as a dissolution reentrant extending west of the main dissolution front. The underlying isopachs show no clear change in thickness along this trend. Focused local thinning by up to 20 ft over a distance of less than 350 ft also occurs approximately

0.9 mi to the south of the Arkansas River. North–south cross sections (Figs. 7, 8) clearly show both regional and local thinning. The presence of local thins in the S1–S2 isopach along the Arkansas River suggests that salt dissolution occurred adjacent to the Arkansas River, resulting from ground water that at one time contacted

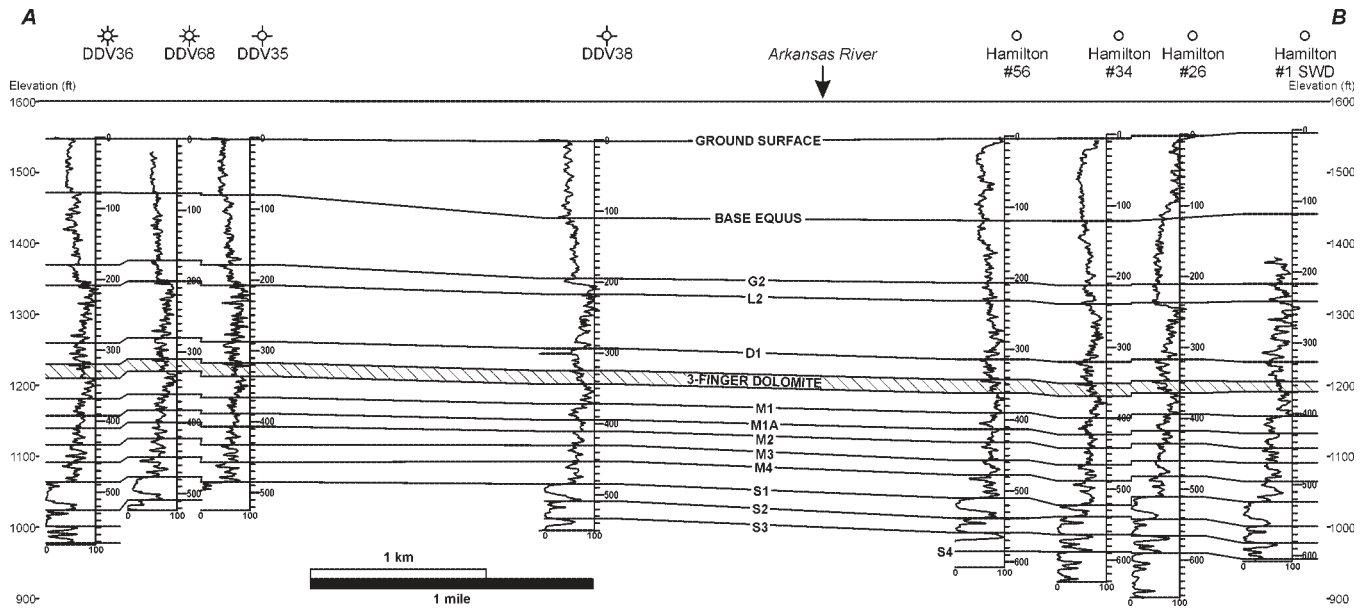


Figure 7. North-south cross section, intersecting the natural-gas pathway from Yaggy to Hutchinson. A is north, and B is south. Line of section shown in Figure 1. Normalized gamma-ray logs, scaled as in Figure 5, are shown.

the upper salt, probably along natural fractures, as inferred from the linearity of the feature (Fig. 13).

North of, and parallel to, the crest of the Yaggy-Hutchinson anticline, another zone of thinning occurs in the S1-S2 isopach. This thinning is much more subtle (<4 ft of local thinning occurs in an area less than a mile wide), but its presence further indicates a structural relationship between the anticline and adjacent zones of salt dissolution. The parallel elongate sets of thicks and thins may be closely linked to previously mapped structure, suggesting possible cause and effect.

Yet another area of thinning in the S1-S2 isopach occurs at the western edge of Hutchinson, coincident with the north-northeast-trending valley in the Equus Beds mentioned above.

In general, the S1-S2 map illustrates distinctive sets of northwest- and northeast-trending lineaments, dominated by the northwest trend (Fig. 13). Moreover, the trend of gas-bearing vent wells between Yaggy and Hutchinson corresponds closely to the subtle northwesterly trends of elongate thinning and thickening of the uppermost salt beds. In Hutchinson, the relationships of gas wells and the S1-S2 isopach are not clearly defined owing to apparent interaction between these nearly orthogonal sets of lineaments.

The M4-S1 isopach (Fig. 12D) shows an elongated area of thickening along the Arkansas River south and west of Hutchinson, closely corresponding to a similar elongated area of thinning in the underlying S1-S2 isopach. This indicates that at least some of the dissolution of the uppermost salt was early, occurring prior to deposition of the overlying M4-S1 clastic-dominated interval. However, only a maximum of 5 ft of local thinning in the S1-S2 isopach along the Arkansas River is compensated by M4-S1 sedimentation,

indicating that the remaining 15 ft of local thinning resulted from later dissolution. Overlying isopachs up to G2 (Fig. 12E-H) do not show preferred deposition along the Arkansas River trend, which would be expected if there were episodes of renewed salt dissolution along this trend during the M4 to G2 time interval. This indicates that the majority of the S1-S2 salt dissolution along the Arkansas River was post-Permian. Isopach maps of intervals between M4 and G2 show new patterns of generally northerly trending thicks and thins, suggesting a fundamental shift in depositional pattern. These isopachs represent strata that constitute the uppermost Wellington Formation and the Ninescah Shale, which from previous studies (Swineford, 1955; Watney and others, 1988) indicate an abrupt change to more continental conditions, reflecting the waning regressive stage of the evaporite-filled embayment in which the Hutchinson Salt

Figure 8 (facing page). *Top*: Correlated well-log cross section along Wilson Road, midway between Hutchinson and the Yaggy gas-storage facility. Line of section shown in Figure 1. Gamma-ray logs, scaled as in Figure 5, are shown. *Middle*: Wilson Road seismic line. Seismic peaks are black; troughs are white. Synthetic seismograms calculated from sonic and density logs in the DDV 57, 67, and 63 wells are shown. The seismic reflections corresponding to the top of the 3-finger dolomite, the M1A marker, and the top of the Hutchinson Salt Member (S1) are highlighted. Heavy black lines are interpreted faults. *Bottom*: Seismic isochron of the uppermost salt layer (S1-S1A). The S1-S1A isopach from well control is shown for comparison. Thickness and time scales are coincident, assuming a seismic velocity of 14,000 ft/s. Locations where the interpreted faults intersect the S1 seismic reflection are highlighted by arrows.

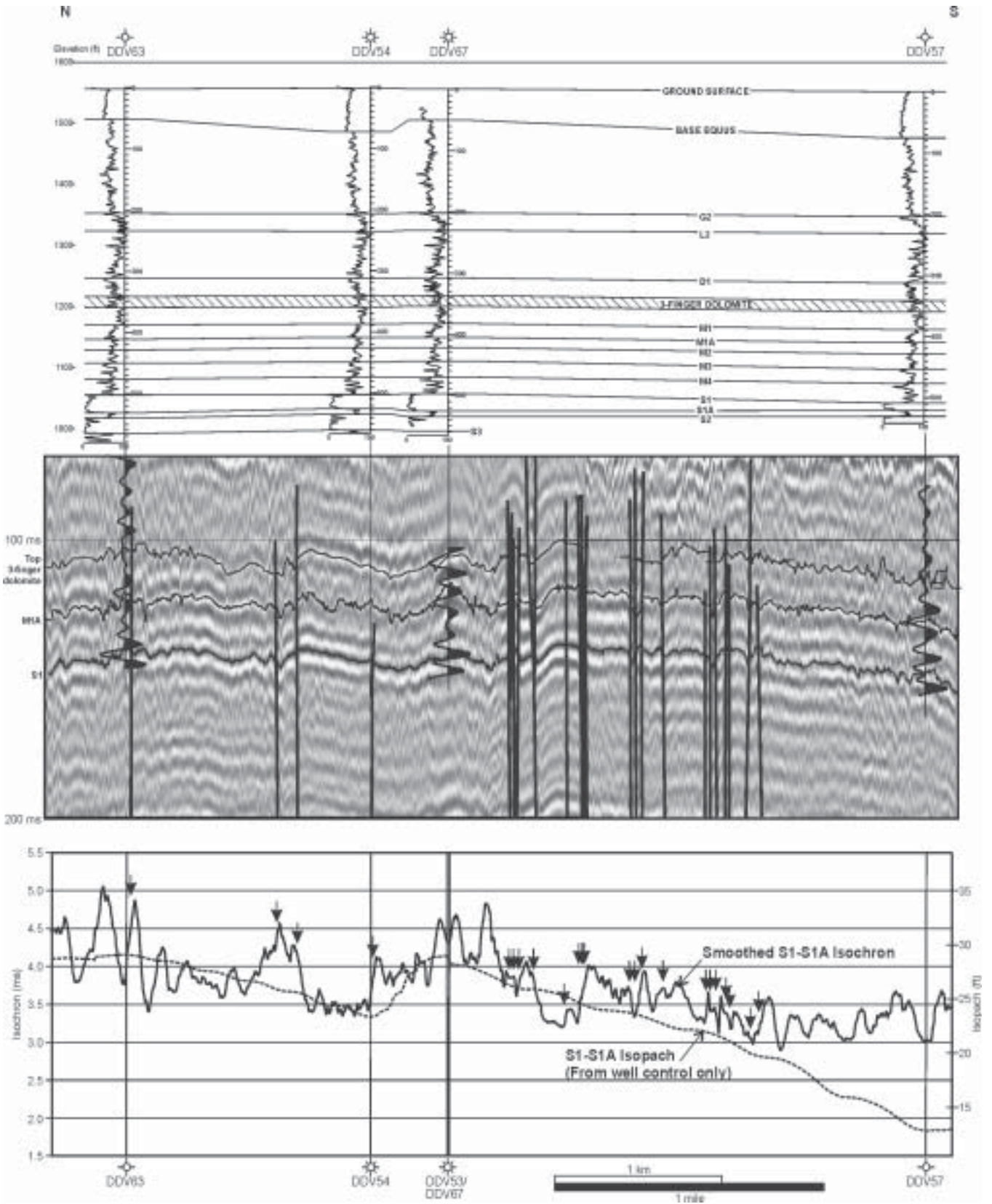


Figure 8.—See caption on facing page.

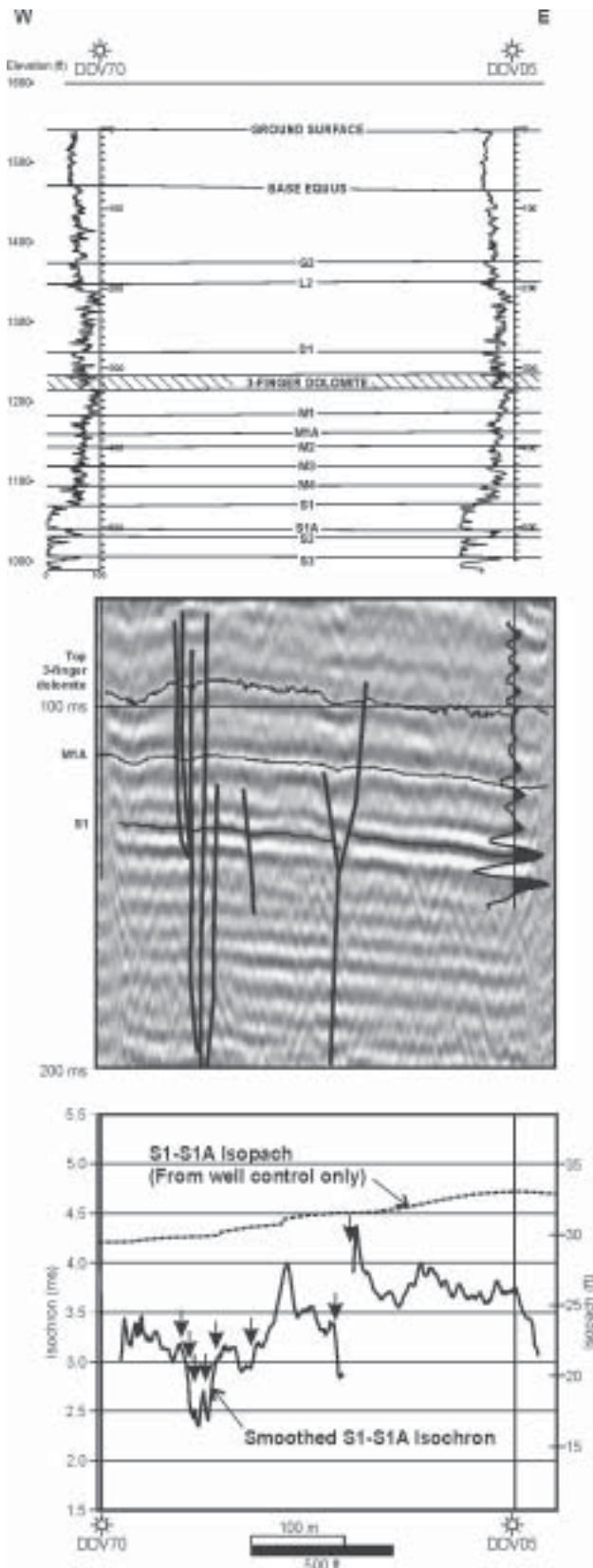


Figure 9. Well-log cross section, seismic line, and S1–S1A seismic isochron for Rice Park. Line of section shown in Figure 1. Instruction is the same as for Figure 8.

Member was deposited. The variations in thickness seem simply to reflect local sedimentation, perhaps both continental and marginal marine, along the shrinking basin margin.

Post-Permian dissolution of the S1–S2 salt bed along the Arkansas River trend extends northward to the southern edge of the Yaggy–Hutchinson anticline, which suggests structural linkage between the northwest-trending anticline and the parallel elongate area of salt dissolution.

The Arkansas River dissolution trend corresponds with a valley seen on the map of the configuration of the base of the Equus Beds (Fig. 10A). The configuration of the Equus Beds is believed to reflect patterns of incised valley development. The maximum area of elongated S1–S2 salt dissolution occurs north of the maximum elongated thickness of the Equus Beds, but both trends are closely parallel, as they are to the Yaggy–Hutchinson anticline. The main incised paleo-valley in the Equus Beds continues northwestward beyond the mapped area of the current study, closely following the current Arkansas River Valley. The corresponding patterns suggest some common control, possibly a reflection of episodic structural activation along a zone of basement structural weakness.

Seismic Data

Sonic and density logs have been collected for DDV 57, 67, and 63. Synthetic seismograms calculated from these logs indicate that the top of the Hutchinson Salt Member (S1) corresponds to a moderate-amplitude seismic peak for DDV 63 and 67 (Fig. 8, middle panel). For DDV 57, the amplitude of the top salt reflector is significantly lower. This is largely due to a thinner uppermost salt layer (S1–S1A) at this location. At DDV 57, the S1–S1A thickness is 13 ft, compared to 28 ft at DDV 67 and 29 ft at DDV 63. A seismic model (Fig. 14), constructed using average velocities and densities from the logs and a 100-Hz Ricker wavelet, which approximates the seismic source of the Wilson Road and Rice Park seismic lines, shows how the uppermost salt isochron and amplitude vary as the S1–S1A interval thins.

The seismic reflectors corresponding to S1 and S1A (the trough just below the S1 peak) were interpreted on both the Wilson Road and Rice Park seismic lines, and an isochron was extracted (Fig. 8, bottom panel) to see if the thinning of the uppermost salt observed on log cross sections and in the S1–S2 isopach map could be seen in more detail. Because of noise in the seismic data, this isochron was smoothed using a 49-point running average prior to display. On the Wilson Road seismic line, the smoothed isochron varies between 3 and 5 ms. The isochron averages 4 ms on the northern half of the line. However, beginning just south of DDV 67, there is a regional decrease in the isochron toward the south. The average isochron decreases to ~3 ms over a distance of 1 mi. This change is corroborated by thinning of the S1–S1A isopach be-

tween DDV 67 and 57. These results suggest that the thinning of the uppermost salt interval associated with the Arkansas River trend began ~2 mi to the north of the river along Wilson Road and was gradual, in contrast to the apparent abrupt thinning to the south of the river (Fig. 7). Over the southernmost 0.7 mi of the Wilson Road line the isochron flattens at ~3 ms, even though the isopach suggests continued thinning. This apparent discrepancy can be explained by viewing the seismic model, which shows that the temporal resolution of our seismic data is ~3 ms.

The Wilson Road seismic line shows a number of apparent faults, all of which extend below the salt (the base of salt is estimated to be ~40–50 ms below the top of salt). Most of these faults are also apparent in the sedimentary section above the 3-finger dolomite. The pervasive nature and extent of these faults indicate that they are related to a deep-seated structural activity including movement that followed deposition of the 3-finger dolomite. These faults were not produced by salt dissolution, although they may have influenced salt dissolution and provided a possible gas pathway. Indeed, the diffuse southward thinning of the uppermost salt interval along the Wilson Road line is associated with a high concentration of faults. The orientations of the faults are unknown, but they may be hypothesized to parallel other structural lineaments in the area (Fig. 13).

Two local thins in the S1–S1A isochron, bounded by faults, occur on the flanks of the anticline along which gas migrated. DDV 54 sits on the southern edge of the northern thin, which is 0.25 mi wide. The southern thin resides 0.3 mi south of DDV 67 and is 0.2 mi wide. If salt dissolution was responsible for these thins, it also may have caused local enhanced structural relief of the flanks of the anticline and elevated tensional forces along the crest of the anticline. Thus, fractures oriented parallel to the anticlinal crest may have more likely been continuous and prone to opening owing to high-pressure gas.

Two zones of faulting have been identified on the Rice Park seismic line (Fig. 9). At the center of the line two conjugate faults are visible, which markedly offset the S1 reflector and form a depression in the overlying strata. Overlying strata, at least up to the 3-finger dolomite, are affected, although there is no known surface expression of this feature. The S1 reflector is offset by 4 ms (~20 ft) on the east and 2 ms (~10 ft) on the west. The feature is 33 ft wide at S1 and 139 ft wide at the 3-finger dolomite interval. The faults appear to converge at approximately the S2 reflector. A faulted zone seems to extend well below the S2 horizon, but deeper reflectors do not show significant offset along the fault. This suggests that the shallow faults resulted from salt dissolution above S2, focused along a deeper seated structural element.

On the western half of the Rice Park line is an apparent swarm of faults that penetrates from the shallow section to below the Hutchinson Salt Member.

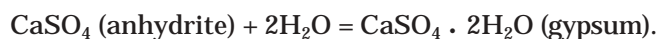
Although no major offsets are seen in the S1 horizon at these faults, the S1–S1A isochron shows marked thinning in this zone, and there is apparent sag in overlying reflectors at this location, again suggesting possible salt dissolution associated with deeper seated structural elements.

The proposed salt dissolution on the Rice Park seismic line seems to have occurred over a very localized area, which is too small to be detected by well control alone. The isopach map, constructed using control points at DDV 5 and 70, gives no indication of local thinning of the upper salt in this area but rather shows only 2 ft of thickness variation.

Because the orientations of the faults on the Rice Park seismic line cannot be determined, the structural elements on the Rice Park line may be associated either with the northwest-trending anticline or with the north-northeast-trending structure, which is proposed to have been responsible for a nearby tributary valley in the Equus Beds and local S1–S2 salt dissolution (Fig. 13). Whatever the controlling structural elements, the presence of faults in proximity to the anticline may have provided conduits to both vertical and lateral gas migration, including charging of the lower gas zone in DDV 64.

Rock Properties

Pervasive veins of satin-spar gypsum permeate the upper Wellington Formation shales, as observed in cores available from the Hutchinson and Lyons areas in locations tens of miles west of the salt-dissolution front. The mechanical stress caused by the change in volume of approximately 40% for hydration of anhydrite to gypsum probably led to the emplacement of the veins in the shale through the reaction:



Sulfate-rich waters probably slowly precipitated in the stress fractures to form the satin spar as observed in core. Shales are gypsiferous in the upper Wellington Formation as calculated from Rhomma-Umma plots from density–neutron–photoelectric logs. Transformation to gypsum probably occurred during the late Tertiary, when the Permian strata were eroded to current depths of burial, under 1,000 ft (300 m), the approximate burial depth for the stability of anhydrite. Water apparently was more readily accessible to drive the sulfate hydration reaction as also evidenced by halite dissolution at the top of the Hutchinson Salt Member that occurred near the same time.

The top of the Hutchinson Salt Member in the Q-5 core at the Yaggy gas-storage facility reveals small, centimeter-scale interformational disrupted bedding, brecciated shale, mud cracks, and veins of red halite. This suggests an early dissolution event that occurred shortly after deposition, a situation not dissimilar to what is observed deeper in the Hutchinson Salt Member at the tops of other halite beds (Watney and oth-

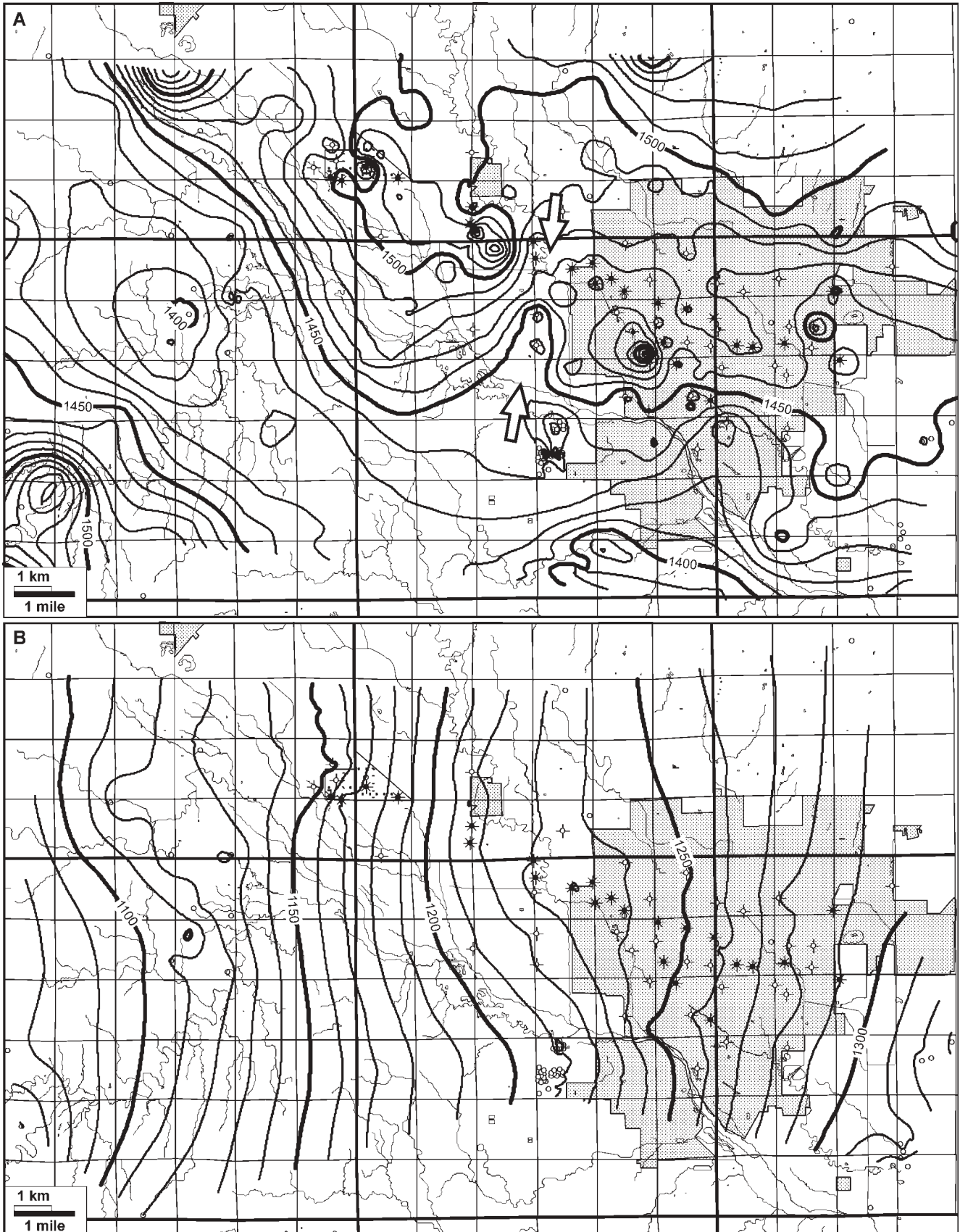


Figure 10 (above and facing page). Structure maps of the following horizons for the study area shown in Figure 1: (A) base of Quaternary Equus Beds, (B) top of 3-finger dolomite, (C) top of Hutchinson Salt Member (S1 marker), and (D) S2 marker. Contour interval = 10 ft. Arrows in (A) highlight a north-northeast-trending tributary valley that parallels the Voshell Anticline and overlies an area of subtle thinning in the uppermost salt.

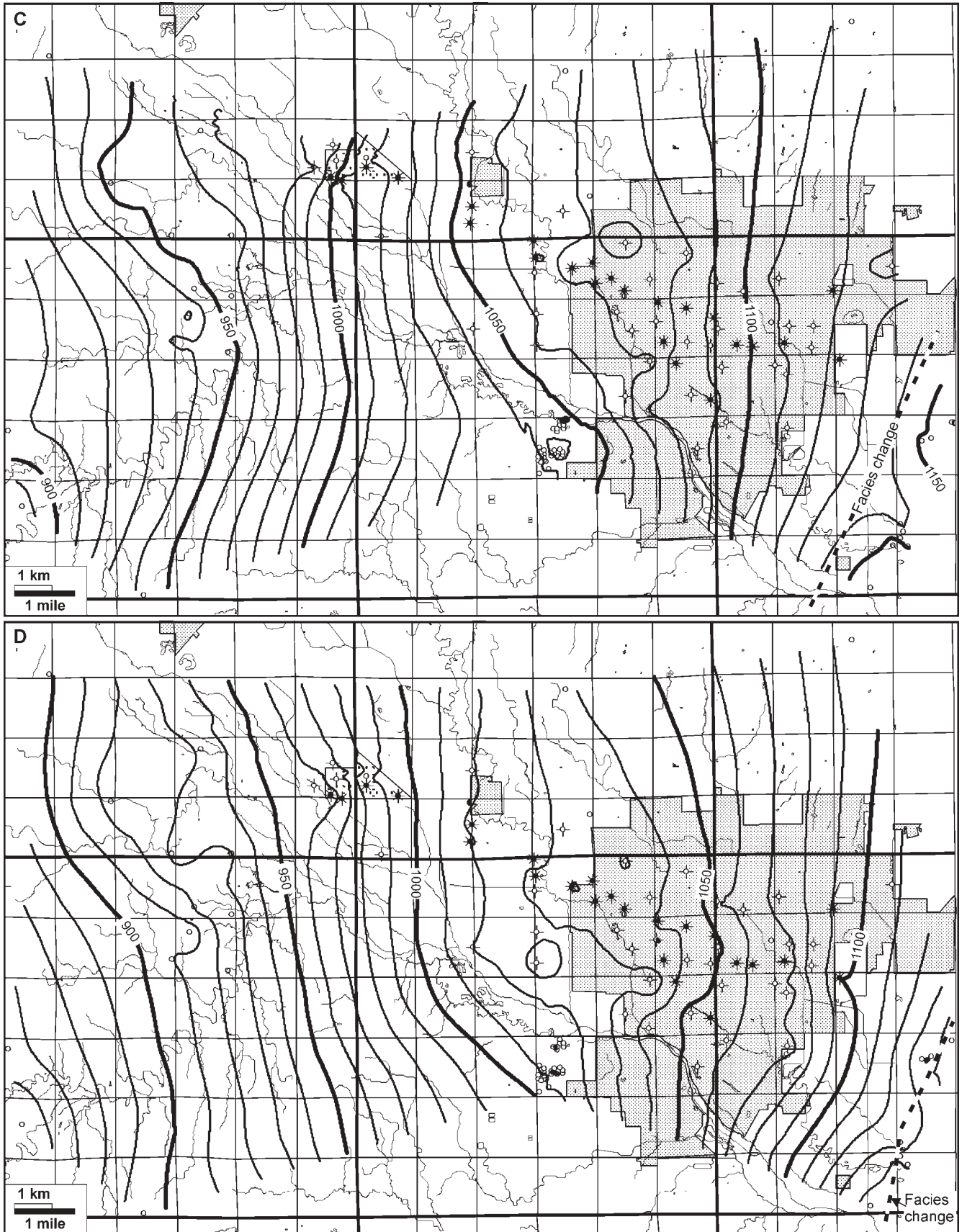


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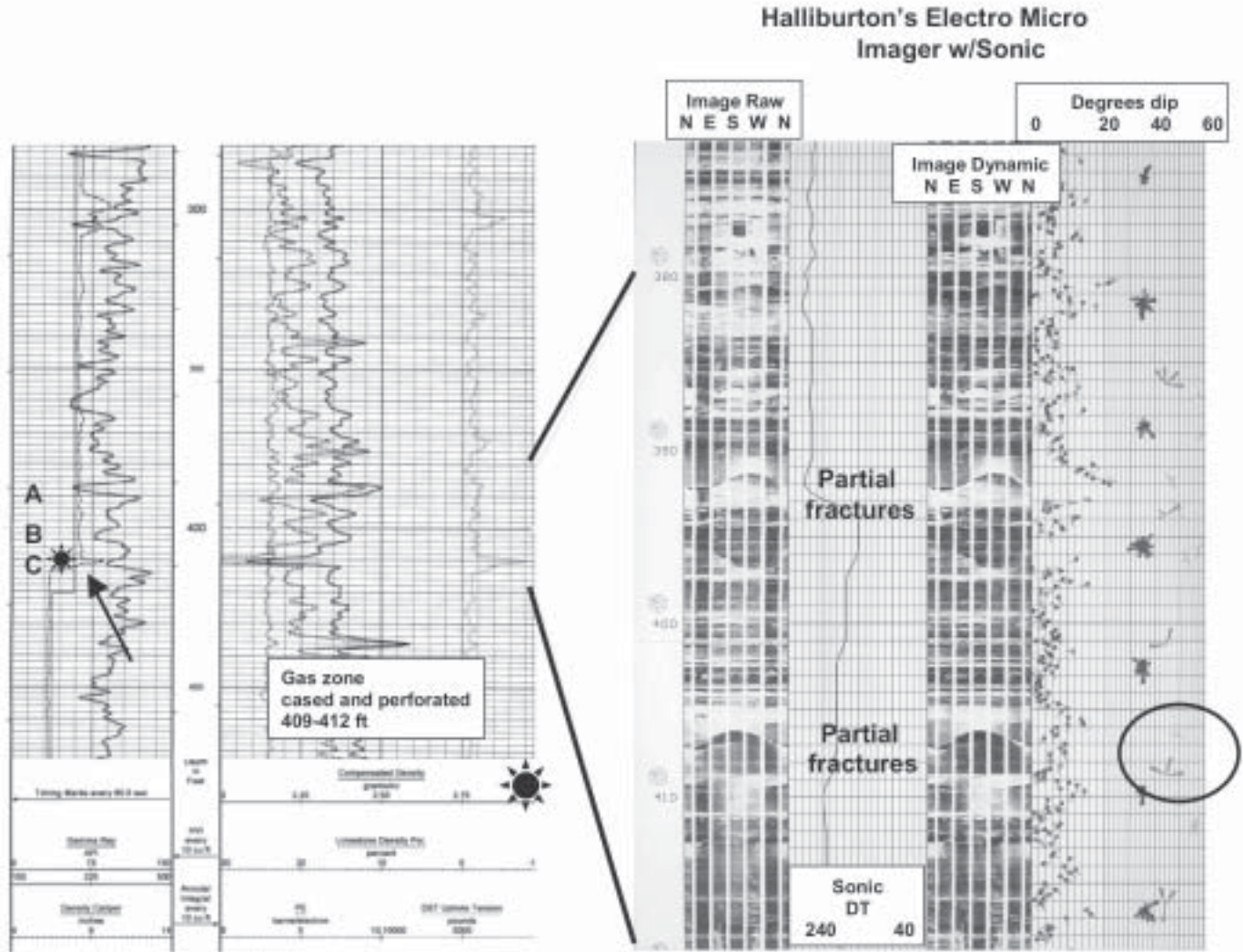


Figure 11. Formation micro-imaging log on right alongside conventional gamma-ray-caliper-neutron-density-photoelectric log on left for observation well OB 2. On left, 3-finger dolomite is labeled with letters A, B, and C. The C zone is a gas-bearing dolomite interval in this well, exhibiting washout and gas show on drilling. Washout creates anomalously high porosity-log response. Formation micro-imaging log shown on an expanded scale. Lighter parts of image correlate with gypsum and dolomite beds. Scalloped patterns are fractures with dips of $\sim 50^\circ$. Orientation of fractures in the gas-bearing C zone are dominated by a west-northwest trend, with a minor north-northeast trend.

ers, 1988). Porosity and permeability in this zone appear to be minor. Examination of core from the AEC no. 1 test well in Rice County (20 mi northwest of Hutchinson) similarly shows centimeter-scale breccia with clasts of shale and halite interbedded with contorted shale and halite at the top of the Hutchinson Salt Member.

Evidence of fracturing was obtained from a borehole micro-imaging log that was run in observation well OB 2, adjacent to the east edge of the Yaggy gas-storage facility. Cavitation of the borehole occurred between 409 and 412 ft, suggesting the interval of gas release, which corresponds with the lowest dolomite layer in the 3-finger dolomite. Fracture sets are observed on the micro-imaging log. Partial fractures in the interval encompassing the gas-bearing interval are

oriented east-west, dipping at 50° , while healed fractures occur along north-south axes (Halliburton Energy Services, 2001) (Fig. 11). These fractures parallel the two major lineaments observed in the mapping, including the crest of the proximal anticline. OB 2 had the highest recorded surface shut-in pressure of ~ 250 psi, with the gas-bearing zone at 410 ft. Shut-in pressures continued to be high (172 psi) in this well in January 2003. A pressure-buildup test in late 2001 indicated low permeability, approximately 2 md. Outcrops of similar thin dolomites in the upper Wellington Formation exhibit oriented joint sets. Also, higher values of the dynamic Young's modulus calculated from dipole sonic and density logs for the equivalent dolomite in eastern Hutchinson indicate greater strength and ability to maintain inherited fractures

from local and regional stress (Joe Ratigan, 2001, personal communication).

Dolomite beds are composed of dolomicrite with negligible matrix porosity and permeability.

DISCUSSION

Integrated Geologic Model

Evidence for fracture-controlled gas-bearing conduits include (1) the presence of linear trends of gas-bearing wells that parallel mapped lineaments, (2) elevated pressure in wells along fracture trends, and (3) faults interpreted from seismic data corresponding with mapped lineaments and structural features such as the anticline between Yaggy and Hutchinson. Pressure-induced parting of preexisting fractures in a shallow dolomite seems to be a likely mechanism for directing natural gas to the unplugged brine wells. The fractures may be associated with faulting that extends beneath the Hutchinson Salt Member as interpreted from the Wilson Road and Rice Park seismic profiles. Core, well-log, and seismic data further reveal that episodic dissolution of the uppermost bed of the Hutchinson Salt Member occurred locally along the northern and southern flanks of the anticline along the area between Yaggy and Hutchinson. Mapping also indicates episodic dissolution along northeasterly and northerly trends in eastern and central Hutchinson that parallel the main dissolution front of the Hutchinson Salt Member. Associated preexisting fractures preserved in the dolomite layer may have been opened in the high-pressure-gas event to transmit gas under the city only to be closed once pore pressures declined below the parting pressure. Adjoining shales would less likely be able to mechanically support this organized fracture system and thus not be in a position to transmit the gas.

The southern area of northwest-trending salt dissolution forms an elongated trough ~2–3 mi wide, a feature closely aligned with the Yaggy–Hutchinson anticline (which forms the northern boundary) and the main valley systems of the current Arkansas River and early Neogene Equus channels. Preexisting fractures seem to have provided conduits for water movement beneath the major fluvial drainages of the Equus Beds and Arkansas River, leading to episodic dissolution of parts of the upper beds of Hutchinson salt. Fractures also may have influenced the formation of the distinctive northwest linear trends of the drainages.

This multi-episode, broad-scale salt dissolution, which extends at least 12 mi behind the main dissolution front and beyond the western boundary of the mapped area, increases the dip of the southern flank of the Yaggy–Hutchinson anticline as the upper salt beds thin. The loss of section and increased dip may have contributed to tensional forces focused on the coincident northern edge of salt dissolution and crest of this anticline. Other localized north-northeast trends of salt dissolution could have similarly created tensional forces and oriented fractures.

The regional alignment of these geologic features suggests subtle but episodic activation of a deep-seated basement structure. The area is in general coincident with the southern boundary of the Precambrian Midcontinent Rift, expressed by magnetic, gravity, basement-structure, and compositional patterns. The basement heterogeneity may represent a site of localized crustal stress release spanning a time frame from at least the Late Permian, Neogene, and into the Holocene. Subtle structural activation along deep-seated basement features in a cratonic setting and their impact on local geology are common, and their recognition can provide a template that can unify and strengthen interpretations (e.g., regional Pennsylvanian sedimentation controlled by structural blocks—Watney and others, 1999; Upper Pennsylvanian incised valleys in the Tonganoxie Sandstone Member occupying boundaries between basement blocks—Beaty and others, 1999; a basement lineament controlling Mississippian chert reservoirs corresponding to the southwest extension of a basement feature associated with the Voshell Anticline—Watney and others, 2001).

Structural Controls and Salt Dissolution: A Case for the Voshell and Arkansas River Lineaments

Episodic activation of the Voshell Anticline was suggested by Anderson and others (1994) to have influenced sites of salt dissolution. Differential activation of basement structure likely served as a template for orthogonal and linear patterns of subsidence, sediment accommodation, local structural deformation, and salt dissolution. Deep-seated, structurally related fractures and faulting appear to have affected the orientation of the primary salt-dissolution front and dissolution trends within the upper salt deposit behind the primary dissolution front. Similar structural controls are suggested for other salt-dissolution fronts including (1) the eastern edge of the Flowerpot Shale in western Kansas (Holdaway, 1978), which corresponds with the Oakley Anticline and the basement structure associated with the Eubank–Pleasant Prairie fields in Haskell County, Kansas; and (2) weak northwesterly and northeasterly trends that define the northeastern dissolution margin of the Upper Permian Cimarron salt member of the Ninnescah Shale in south-central Kansas over the Pratt Anticline and southern Central Kansas Uplift (Martinez and others, 1996). These correlations with basement lineaments support the possible interpretation that intermittent basement activation acted as a control on preserved geometries of other salt bodies in the subsurface, and consequently their expression and impact on the overlying strata and land surface.

The anticline between Hutchinson and Yaggy is a minor expression of an apparently larger scale structural system, the northwest-trending Arkansas River Lineament. The lineament encompasses a 60-mi linear section of the Arkansas River extending at least

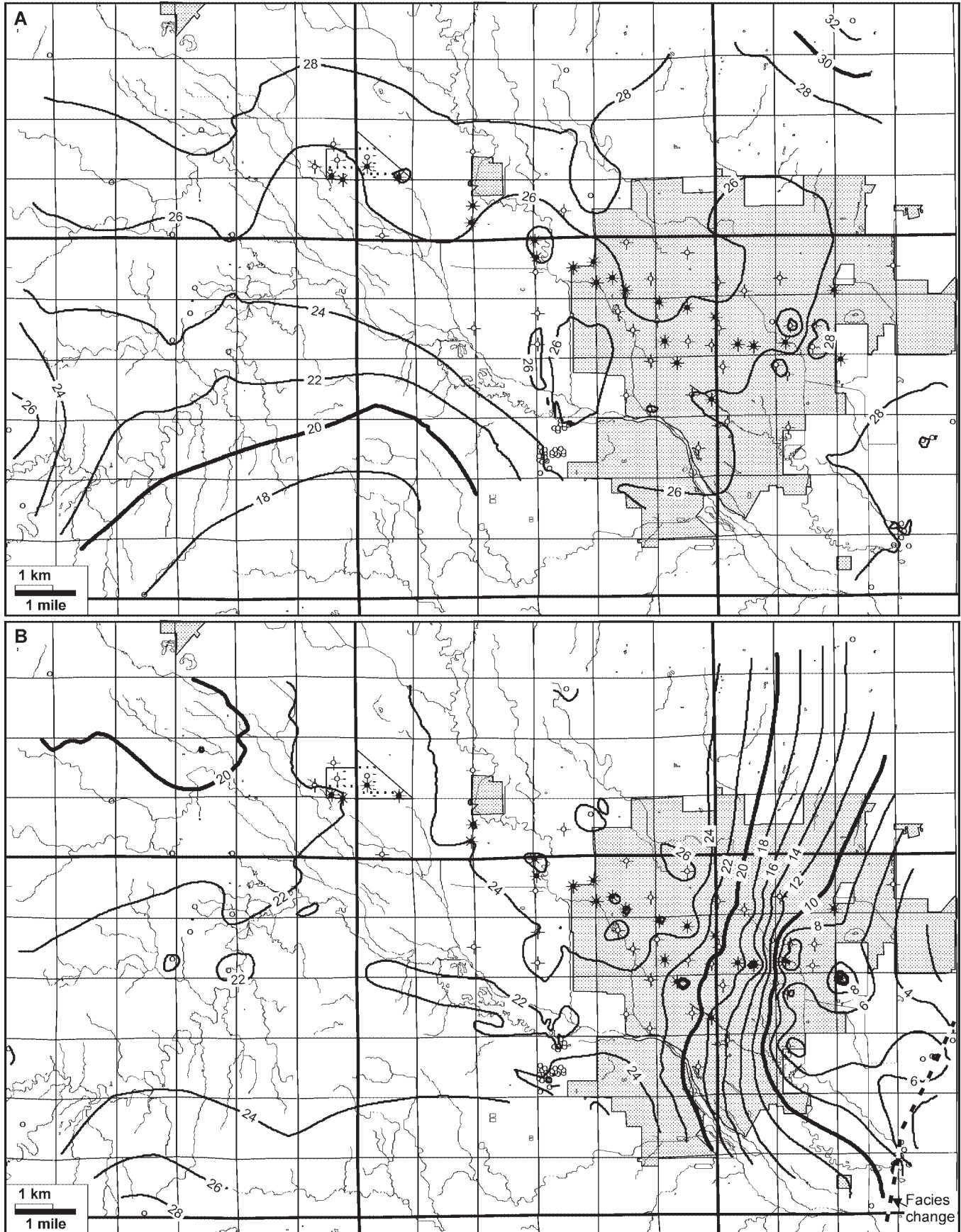


Figure 12 (above and next three pages). Isopach maps of the following intervals for the study area shown in Figure 1: (A) S4-S3, (B) S3-S2, (C) S2-S1, (D) M4-S1, (E) M3-M4, (F) top 3-finger-M3, (G) L2-top 3-finger, (H) G2-L2. Contour interval = 2 ft. Arrows in (C) highlight a zone of subtle local thinning in the uppermost salt interval north of, and parallel to, the crest of the Yaggy-Hutchinson anticline.

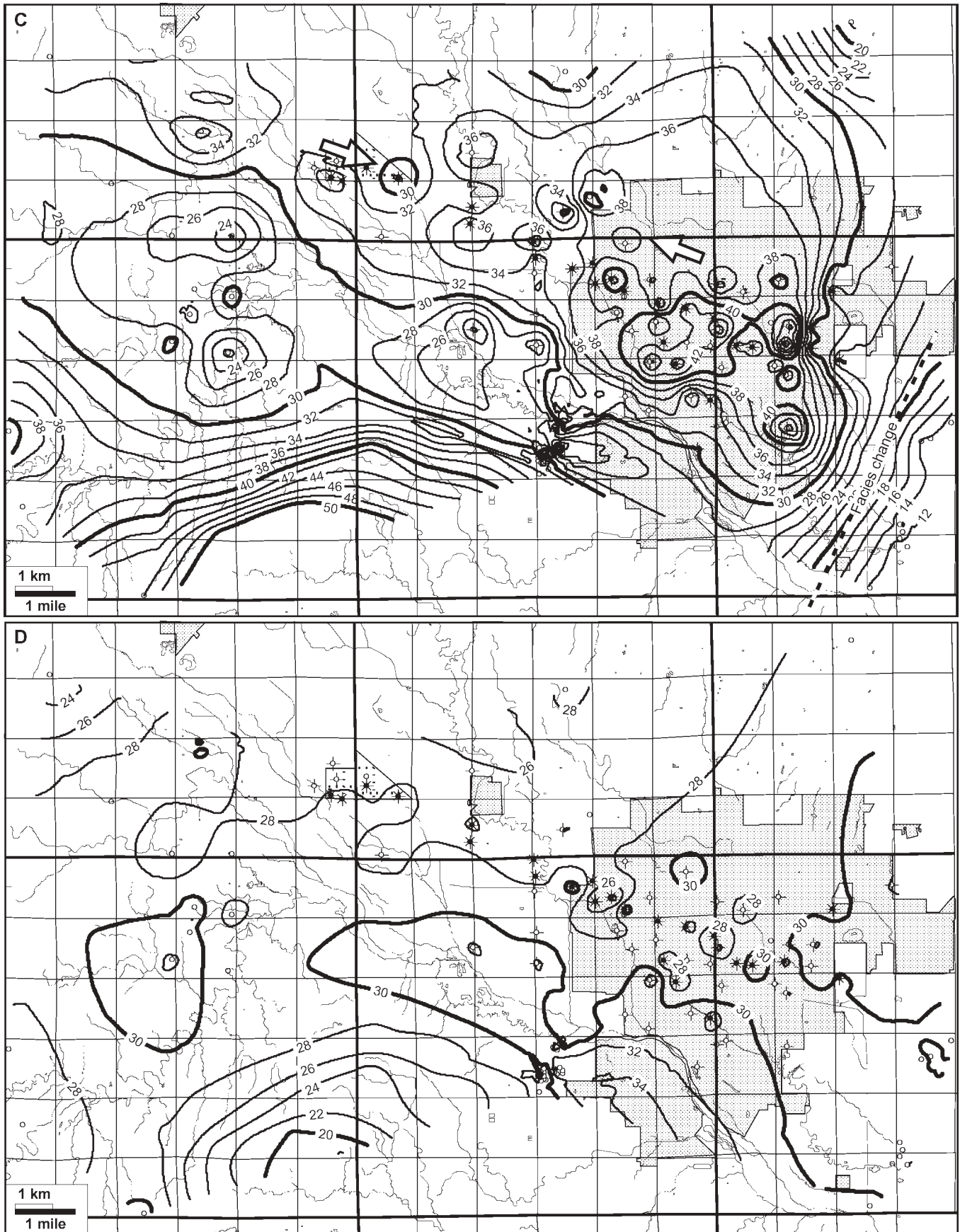


Figure 12.—Continued above and next two pages.

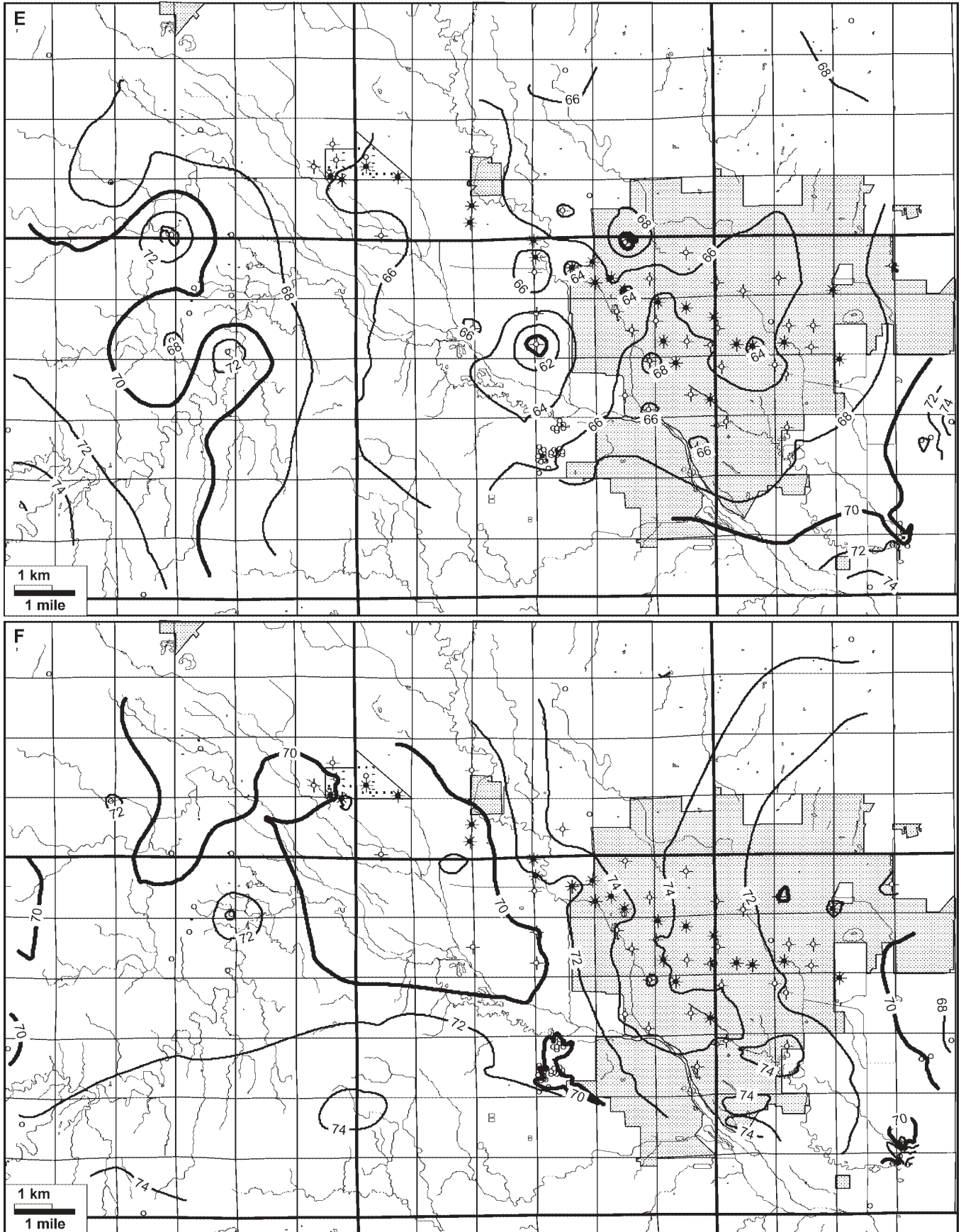


Figure 12.—Continued above and facing page.

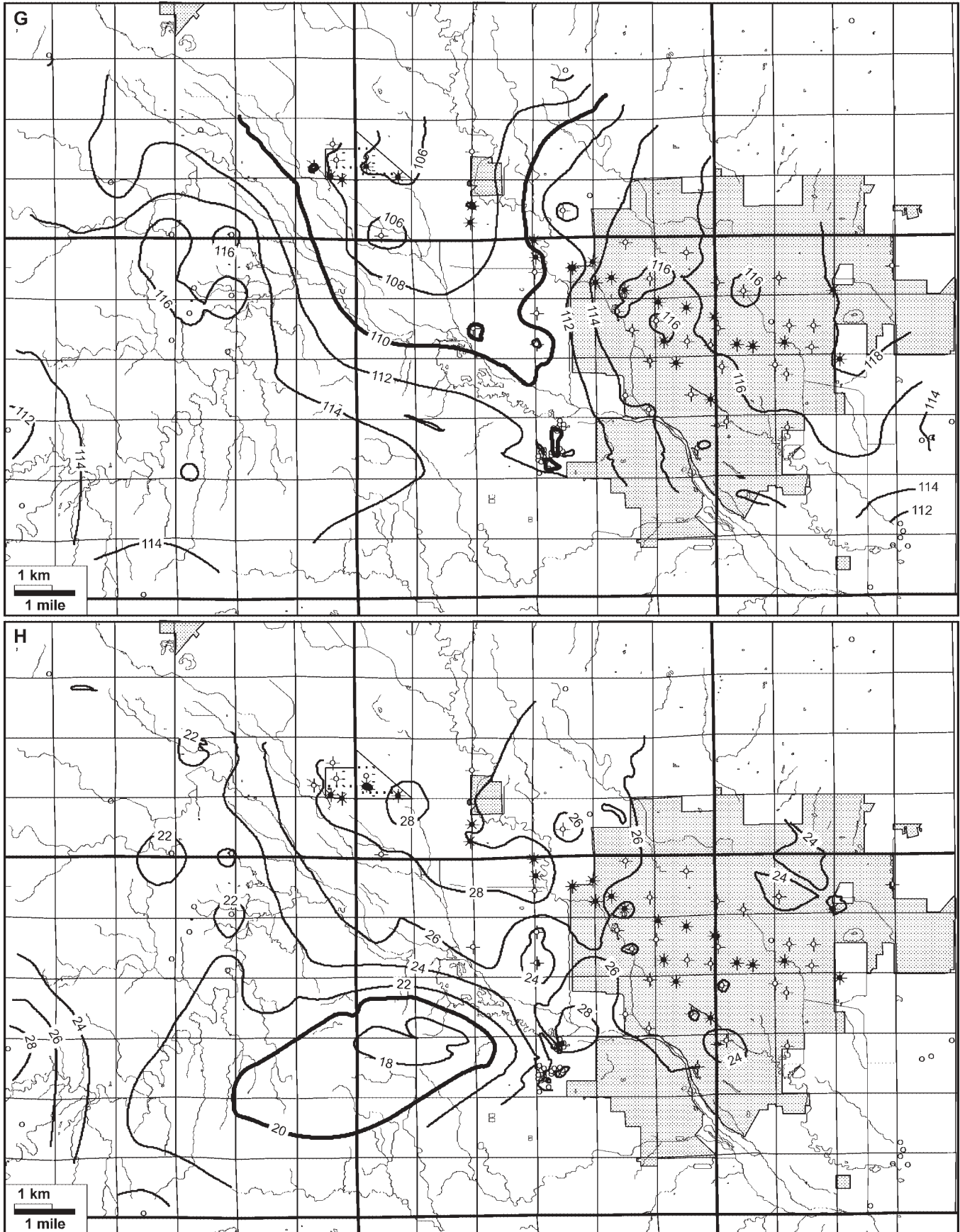


Figure 12.—Continued.

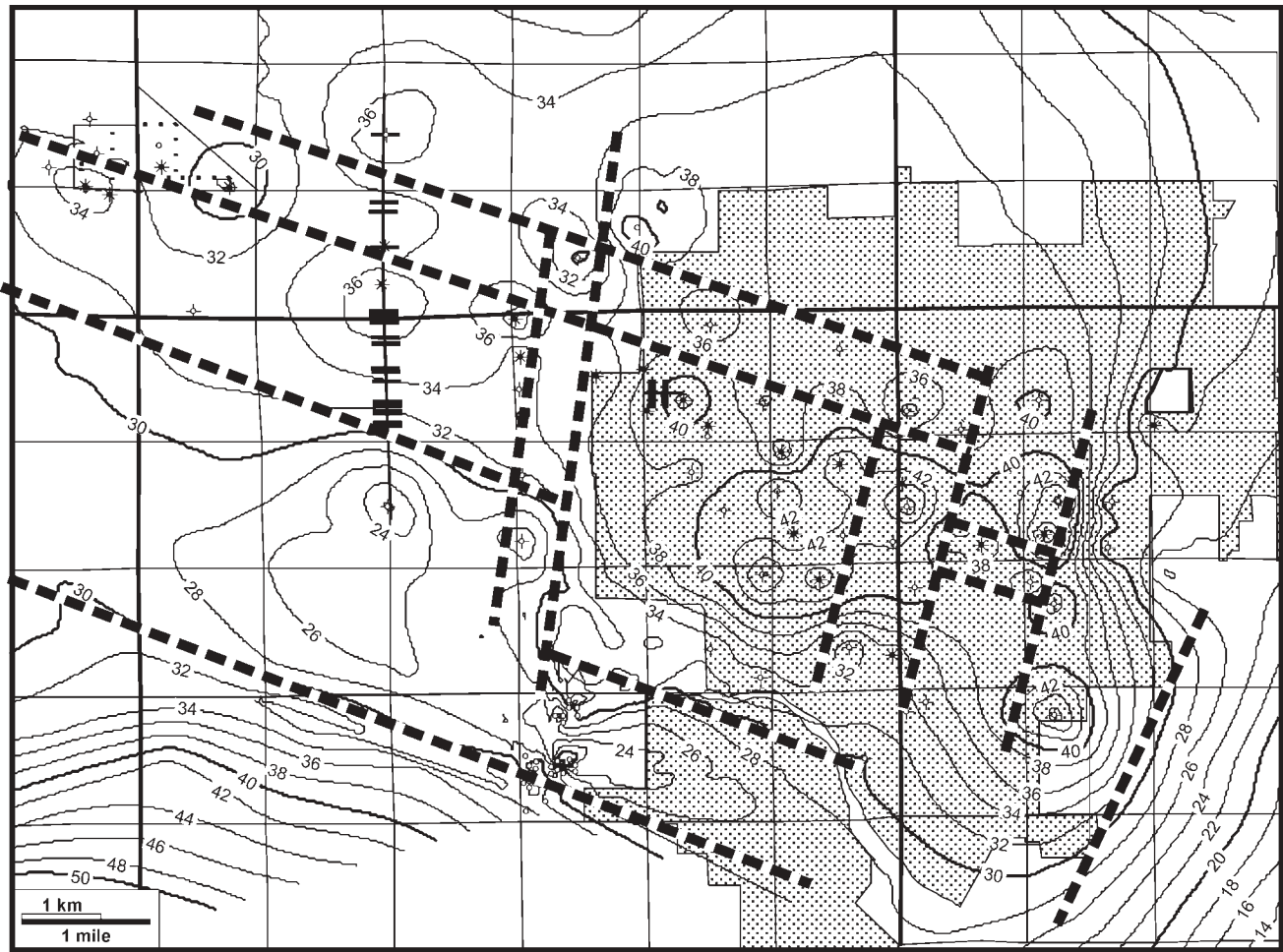


Figure 13. S2–S1 isopach map for the Yaggy–Hutchinson area, with a preliminary interpretation of structural lineaments superimposed (heavy dashed lines). Contour interval = 2 ft. Locations of faults intersecting the S1 horizon, as interpreted from the Wilson Road and Rice Park seismic lines, are shown as short, heavy black lines.

between Wichita and Great Bend to the northwest. The northwesterly trending incised paleovalley mapped at the base of the Pleistocene–Tertiary Equus Beds is closely aligned with this feature (Fig. 15). In addition, the lineament coincides with a regional 125-mi-long linear northern border of the lower part of the Hutchinson Salt Member (Fig. 5B) and is in proximity to the northwest-trending contact between contrasting Precambrian basement terranes—the southern edge of the Precambrian sediment-filled portion of the Midcontinent Rift graben and the northern edge of the rhyolite–granite basement terrane (Van Schmus and others, 1996). The intersection of the Arkansas River with the eastern dissolution margin of the Hutchinson Salt Member forms a 15-mi westward retreat in the salt-dissolution front, which suggests enhanced dissolution activity along this lineament. In addition, documented sinkholes occur within 20 mi on either side of this northwest-trending lineament, including Cheyenne Bottoms, a natural lake possibly related to partial solution of the underlying Hutchin-

son Salt Member (Bayne, 1977; Anderson and others, 1995a).

SUMMARY AND CONCLUSIONS

Geologic, geophysical, and engineering evidence supports the existence of extended trends of fractures and episodic salt dissolution along subtle geologic structures, including the northwest-trending anticline between the Yaggy gas-storage facility and Hutchinson as part of the Arkansas River Lineament (ARL). Similar northeast-trending geologic features associated with the Voshell Anticline are also indicated. An expanded subsurface-study area covering 150 mi² surrounding Hutchinson identified fractures, faults, and a subtle anticline that reside along the northern edge of the larger ARL. Episodic movement along the ARL led to subtle folding, fracturing, and minor faulting along parts of a northwest–southeast-trending 3-mi-wide corridor that extends through the mapped area. Fractures episodically allowed undersaturated water to access Permian salt (halite) beds and led to occa-

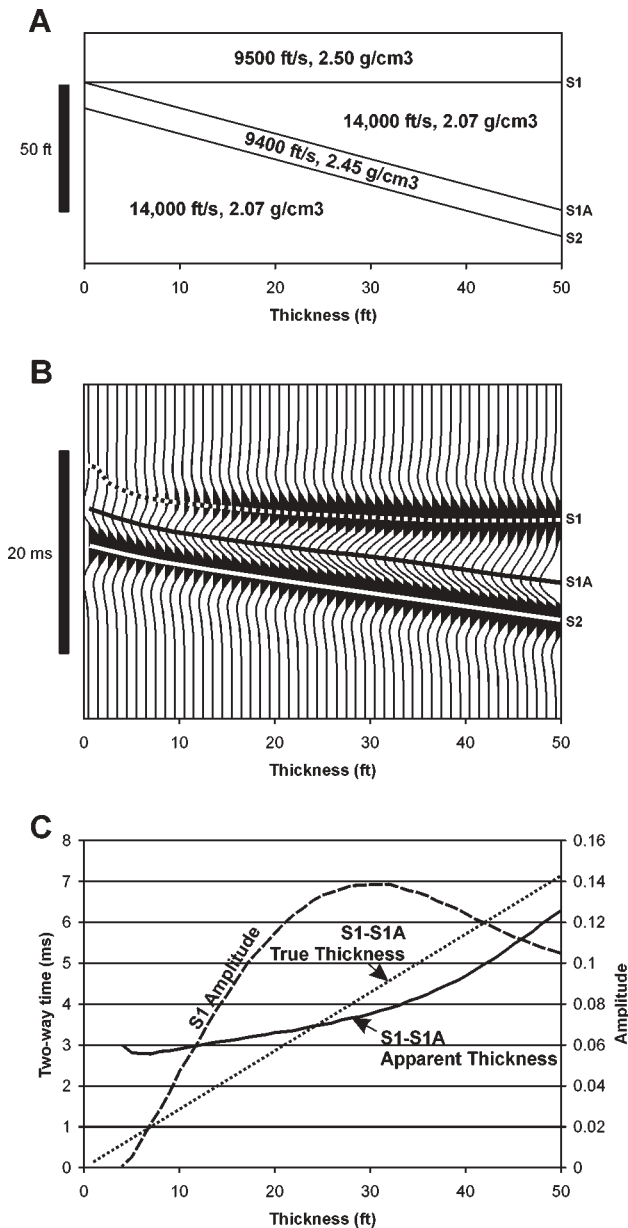


Figure 14. Model showing seismic effects of varying thickness of the uppermost salt (S1–S1A). (A) Depth model in which uppermost salt varies from 0 to 50 ft in thickness. Velocities and densities assigned to each of the modeled layers are shown. (B) Synthetic seismic traces created by convolving a reflectivity series calculated from the velocities and densities in (A) with a 100-Hz Ricker wavelet. (C) Plot of S1 amplitude (dashed line) and S1–S1A apparent time thickness (solid line) extracted from (B), compared to S1–S1A true time thickness.

sional dissolution, albeit subtle (on the order of tens of feet thick, mile or fractions of a mile wide, and apparently miles in length), in mapped areas that lie west of the main dissolution front. Dissolution in the uppermost salt bed of the Hutchinson Salt Member forms an elongate northwest-trending trough following the ARL. While some thinning was very early, shortly after deposition, later dissolution that is post-

Permian in age is also indicated. This later dissolution occurred in spite of current burial depths >500 ft. The widespread, predominantly post-Permian salt dissolution along the 3-mi-wide corridor is bordered on the north by the Yaggy–Hutchinson anticline, apparently leading to increased dip of the southern flank of this anticline along the entire structure west of the city. This subsidence enhanced the deep-seated structural deformation. Moreover, a narrow (<1-mi-wide) salt-dissolution-trough zone formed on either side of the crest of the anticline. This dissolution zone is associated with localized deep-seated and salt-based fracturing and faulting, suggesting episodic access of undersaturated water along the faults followed by additional fracturing from salt subsidence. The subsidence probably led to further flexure and probable tensional forces that helped maintain the oriented fractures over this extended distance.

The Voshell Anticline also has exerted a strong influence on the location of the main dissolution front of the Hutchinson Salt Member east of Hutchinson. Associated fractures and faults are inferred to have exerted control on the location of Holocene drainage, in turn creating access of undersaturated water facilitating salt dissolution. The north-northeast-trending grain (anisotropy) of the isopach maps, particularly in central and eastern Hutchinson well behind the main salt-dissolution front, parallels the trend of the Voshell Anticline. Local thinning of mapped intervals follows this trend and has been attributed to additional salt dissolution on the basis of well-log data. North-northeast-trending sets of gas-bearing vent wells in eastern Hutchinson may follow these fracture elements lying oblique to the ARL.

Gas migration apparently followed these inferred fracture systems, based on the correspondence of gas-bearing vent wells with some of these structures. Also, it is possible that anthropogenic salt dissolution may have been involved—e.g., subsidence of strata overlying shallow collapsing salt caverns associated with brine-extraction wells. In particular, a series of interconnected brine wells, caverns, and collapse features could move gas laterally; but gas would have accumulated in caverns, and there is no evidence of this phenomenon to date. However, no gas is known to have escaped through any collapse features with surface expression. Also, recent logging of 11 unplugged brine wells in Hutchinson revealed no significant collapse of the brine caverns.

The timing of salt dissolution ranges from shortly after deposition of the affected uppermost beds of the Hutchinson Salt Member to post-Permian, pre-Equus Beds, and into the Holocene. The post-Permian, pre-Equus Beds activation of the Yaggy–Hutchinson anticline is suggested by the coincidence of an interfluvial high mapped on the configuration of the base of the Equus Beds and the crest of the anticline.

Since early Holocene time, local streamflow has led to incised valleys that appear to be influenced by the

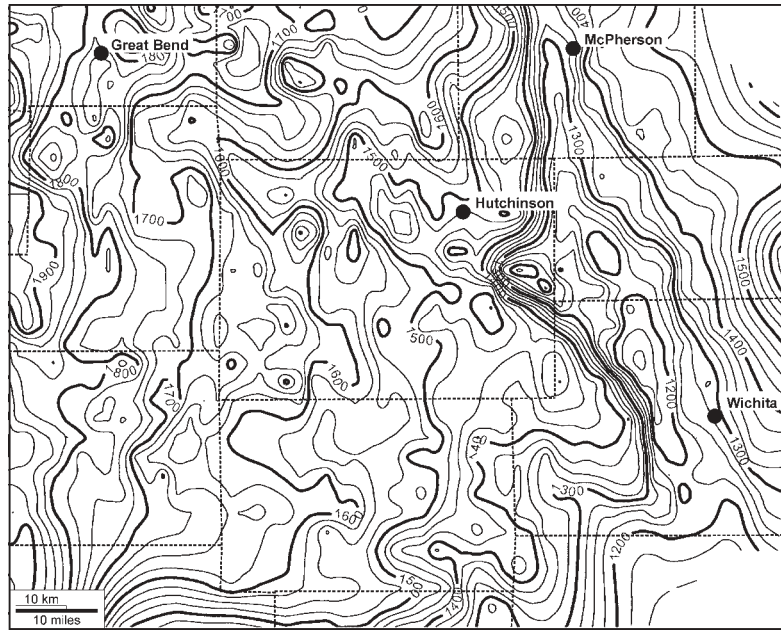


Figure 15. Configuration map of the base of the Equus Beds, showing the northwesterly trending incised paleovalley between Wichita and Great Bend. Contour interval = 25 ft. Dashed lines are county boundaries.

northwest-trending ARL and structures paralleling the Voshell Anticline. Meteoric water supplied by these streams apparently penetrated Permian strata and locally led to salt dissolution. Besides dissolution of clearly defined beds of halite, shale-dominated gypsiferous intervals that have been mapped above the Hutchinson Salt Member may have similarly undergone even more subtle local thinning through dissolution of more dispersed halite or sulfates.

Validation of basement-related lineaments as templates for salt dissolution may add an element of understanding and prediction in assessing salt stability and structural integrity of overlying strata useful in siting underground gas-storage facilities or establishing potential pathways for lateral gas migration. Areas may be more predisposed to dissolution, either natural or man-made, and could help target sites for further geologic investigation. Integrated high-resolution mapping, including subregional-structure, isopach, lithofacies, and engineering-data maps integrated with seismic interpretation, provides useful perspectives of the spatial and temporal geologic history.

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