Salt Dissolution in the Permian Flowerpot and Blaine Formations Defines Limits of the Syracuse Basin in Western Kansas and Eastern Colorado

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ABSTRACT

The Syracuse Basin is a large region of about 8,100 mi² (21,000 km²) in western Kansas and eastern Colorado that is underlain by Permian-age salts in the Flowerpot and Blaine Formations of the Nippewalla Group. Originally thought to be a structural or depositional basin, detailed study around the perimeter of the basin shows that it is a dissolutional remnant wherein the salt beds are dissolved at all places around the basin's margins. The two main salt units, the Flowerpot salt and the middle Blaine salt, consist mainly of displacive halite in red-brown shales and siltstones (mudstones). The Flowerpot salt is generally 200–300 ft (61–91 m) thick within the basin, but where most or all of the salt is dissolved outside of the basin, equivalent strata are 50–150 ft (15–46 m) thick. The younger middle Blaine salt is typically 45–60 ft (14–18 m) thick in the basin, and equivalent strata are 5–10 ft (1.5–3 m) thick where the salt is dissolved.

Five areas selected for detailed study of the dissolution zone around the perimeter of the Syracuse Basin show that removal of about 250 ft (76 m) of Flowerpot salt occurs within horizontal distances ranging from about 930 ft (283 m) to as much as 14 mi (23 km). Structural cross sections show that sub-salt strata dip gently and uninterrupted beneath the dissolution zone, whereas strata above the salt are disrupted and are flexed down by an amount roughly equal to the amount of dissolved salt. This supports the thesis that the salt deposits are a dissolutional remnant and not a structural or depositional basin. In most areas, descending unsaturated groundwater dissolves the shallower middle Blaine salt first and then dissolves the deeper Flowerpot salt. But in two areas, unsaturated groundwater is sourced from a sub-salt aquifer, causing dissolution of the Flowerpot salt first and then the shallower middle Blaine salt.

Salt dissolution occurred at different times in different parts of the Syracuse Basin. In most areas, it occurred mainly during the Pliocene–Pleistocene–Holocene Epochs, but locally it started before deposition of the Cretaceous or even from Late Permian through Early Cretaceous time.

The original extent of the Flowerpot and middle Blaine salts went far beyond the current extent of the Syracuse Basin. Remnants of both salt units are present in six large regions that extend from

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the Denver Basin in northeast Colorado and western Nebraska on the north to the Anadarko and Palo Duro basins in Oklahoma, Texas, and New Mexico on the south, a total area of about 115,800 mi² (300,000 km²). In all these regions, the two salt units have dissolutional limits like those at the perimeter of the Syracuse Basin.

Dissolution of subsurface salt units can cause problems when or if underground cavities become so large that the roof of the cavity collapses and the cavity rises to the land surface to form a sinkhole or an area of ground subsidence. Problems can also arise when seismic-reflection surveys cross a dissolution boundary and false images of phantom structures are created in strata below the dissolution zone. Also, drilling through salt units must be done with care so that unsaturated drilling muds and formation waters do not cause cavity development in the salt. Dissolution of salt also can affect the quality of groundwater: Salt-dissolution brine can migrate into fresh groundwater aquifers and even render the water unusable for most purposes.

INTRODUCTION

The Syracuse Basin is at the northern end of the Greater Permian Evaporite Basin (GPEB) (fig. 1), an area of about 250,000 mi² (650,000 km²) where Permian-age rocks are largely characterized by the presence of evaporites—mainly salt (halite) and gypsum or anhydrite (Johnson, 2021a). The GPEB contains eight major evaporite sequences that collectively range from about 1,640 to 4,920 ft (500–1,500 m) thick in parts of Texas, New Mexico, Oklahoma, Kansas, and Colorado. The Flowerpot and Blaine evaporites of the Nippewalla Group are in the middle of these eight evaporite sequences.

The Syracuse Basin comprises about 8,100 mi² (21,000 km²) in the study region of western Kansas and eastern Colorado (figs. 1, 2) where Permian-age salt deposits in the Flowerpot and Blaine Formations are dissolved around the perimeter of the basin (figs. 2, 3; table 1). The Syracuse Basin was originally viewed as a structural or depositional basin containing the Flowerpot and middle Blaine salts, but the aim of the current study is to advance the thesis that the perimeter of these salt deposits is not structural or depositional but results from relatively abrupt dissolution and termination of the salt beds with little or no regard to regional or local structures. The term "Syracuse Basin" still has merit in that it defines a large region of western Kansas and eastern Colorado where the salts are separated, by dissolution, from other areas of Flowerpot and Blaine salts. Earlier studies by Benison et al. (2015) also show that dissolution occurs locally in these strata within the Syracuse Basin.

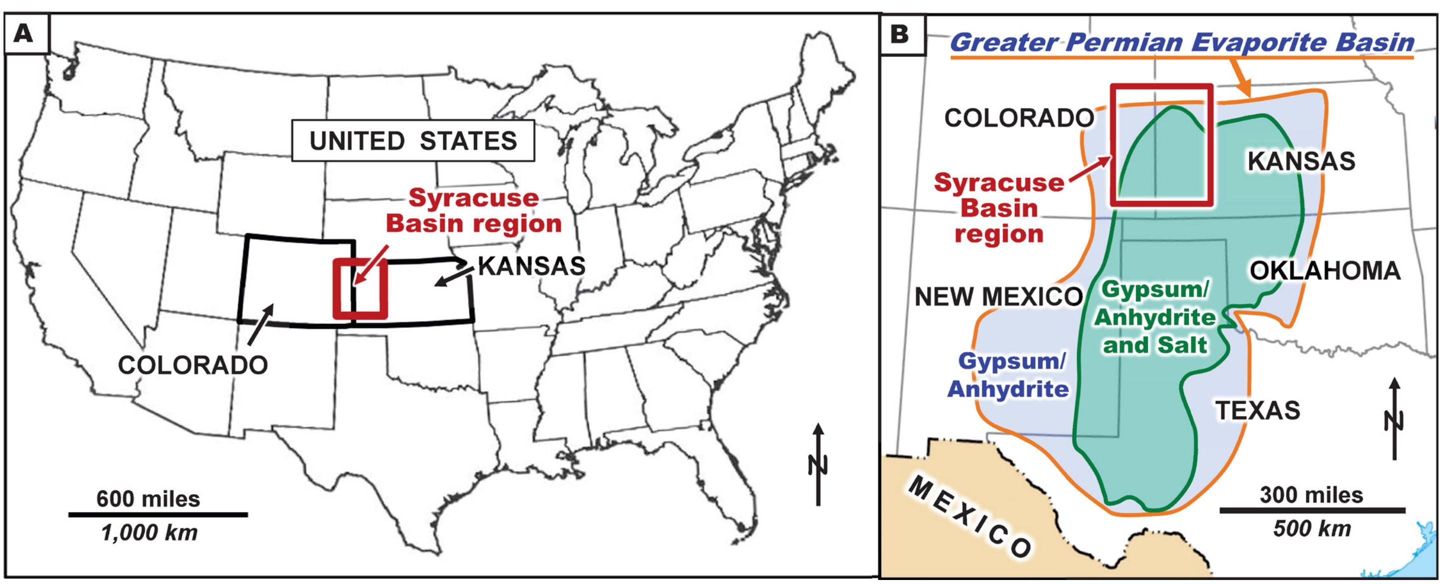

Figure 1. Maps showing location of Syracuse Basin region. A) Map of United States. B) Map of Greater Permian Evaporite Basin (Johnson et al., 2021).

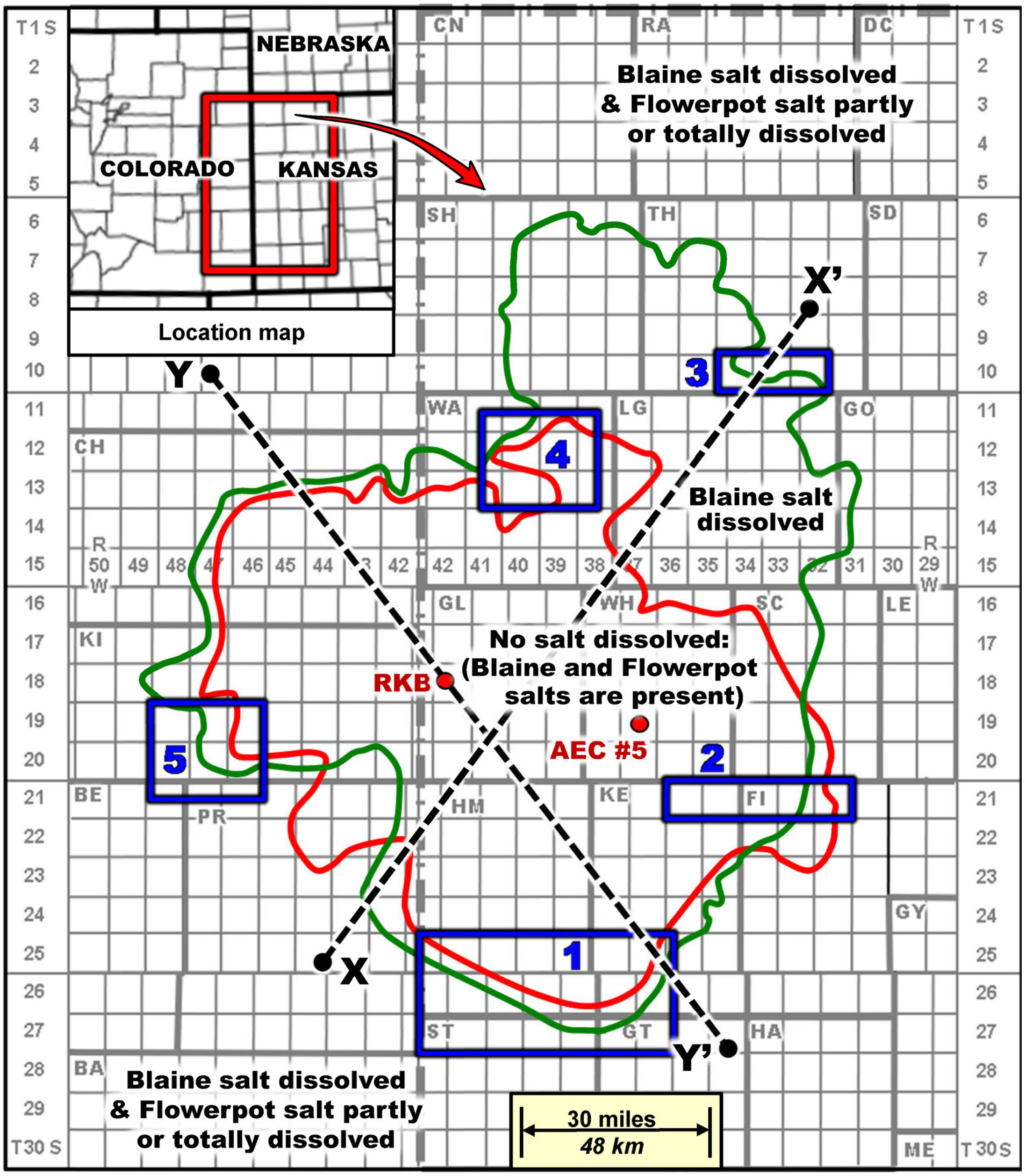

Figure 2. Map of Syracuse Basin in study region of western Kansas and eastern Colorado. Blue rectangles mark locations of five detailed-study areas: 1 = South Syracuse, 2 = Finney-Kearny, 3 = North Oakley, 4 = Sharon Springs, and 5 = Great Plains Reservoirs. Green line represents the limit of significantly thick Flowerpot salt. Red line represents the limit of middle Blaine salt. Red dots indicate the location of RKB and AEC #5 wells. Cross sections X–X’ and Y–Y’ are shown in fig. 3.

In carrying out this study, the geophysical logs of about 4,000 petroleum test wells were examined to identify the salt beds and map their distribution and geographic limits. Five areas around the perimeter of the basin were selected to demonstrate, by maps and cross sections, the dissolution of the salts and to show that the zones of dissolution are not affected by structural or depositional features.

Of special value in the study are two cores that were drilled through the Flowerpot and Blaine Formations (and associated strata) near the central part of the Syracuse Basin. Cores from these two wells — the Amoco Production Co., Rebecca K. Bounds #1 (RKB) core (Zambito et al., 2012; Benison et al., 2013) and the Union Carbide Corporation, AEC Test Hole #5 (AEC #5) core (Holdoway, 1978) — provided useful information about the character of the sedimentary rocks where they are not affected by dissolution.

PERMIAN STRATIGRAPHY

Included in this study are Permian strata in the Syracuse Basin region: the Leonardian-age Stone Corral Formation, at the top of the Sumner Group, and the following formations in the Nippewalla Group, of Guadalupian age: Harper Sandstone (oldest), Salt Plain Formation, Cedar Hills Sandstone, Flowerpot Formation, Blaine Formation, and Dog Creek Shale (youngest) (table 2). There is not agreement on the age of the Nippewalla Group in Kansas. The Kansas Geological Survey officially recognizes the

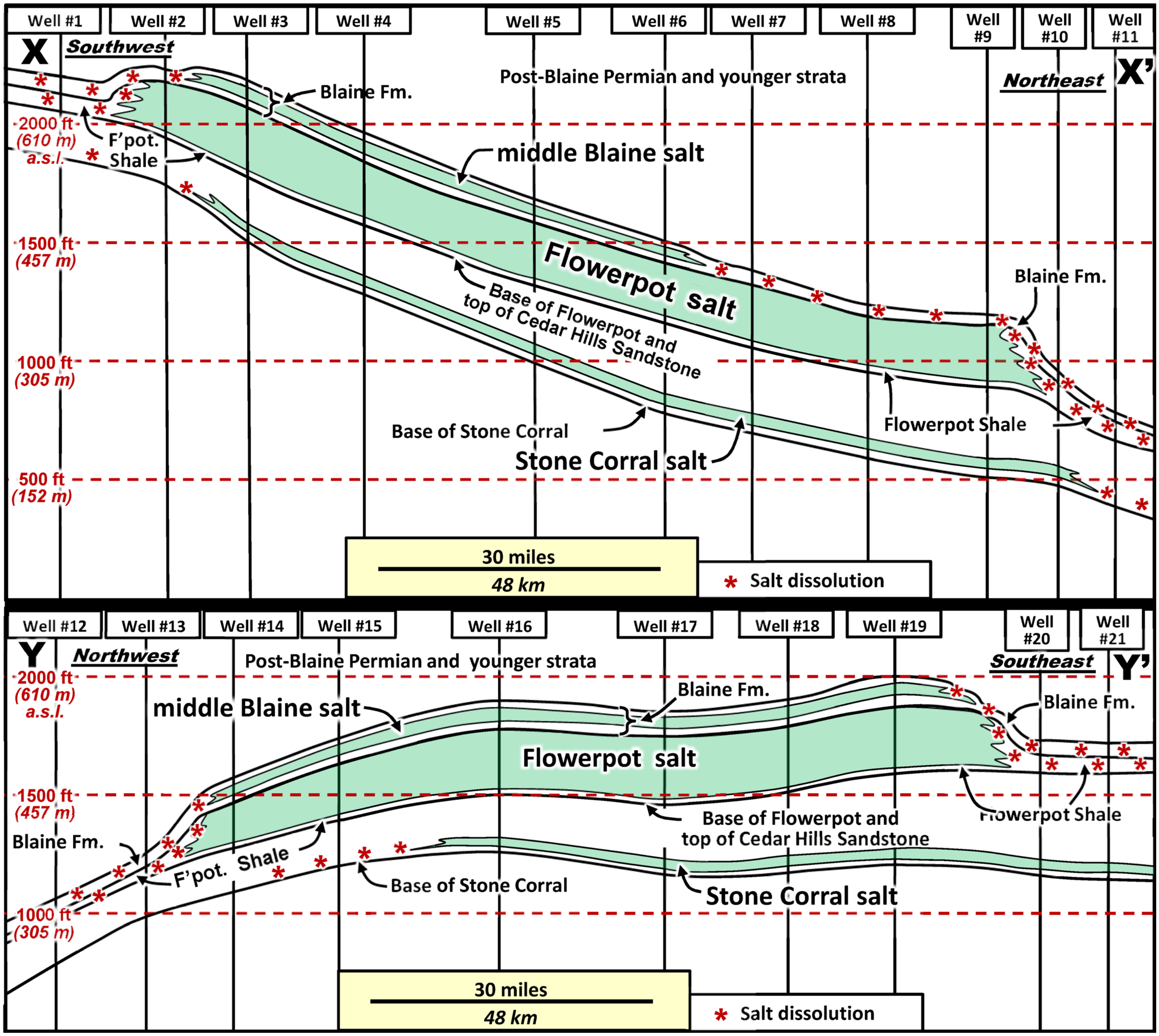

Figure 3. Cross sections X–X' (above) and Y–Y' (below) across the Syracuse Basin showing principal Permian salt units and their dissolution limits along the perimeter of the Syracuse Basin. Location of cross sections is shown in fig. 2. Wells used in cross sections are shown in table 1. Elevations are in feet *(meters)* above sea level.

Nippewalla as Leonardian (Zeller, 1968; Sawin et al., 2008; West et al., 2010; Foster et al., 2014). However, in the American Association of Petroleum Geologists COSUNA ("Correlation of Stratigraphic Units of North America") project, Hills and Kottlowski (1983) place the Nippewalla Group in the Guadalupian, as does Johnson (2021a). Hovorka et al. (1993) showed San Andres unit 5 and Upper San Andres strata (equivalent to the Blaine Formation in Oklahoma) to be Guadalupian. Recent work by Johnson (2021c) showed bed-by-bed correlation of Guadalupian San Andres Formation anhydrite beds with those in the Blaine Formation of southwest and northwest Oklahoma, and the Blaine Formation of northwest Oklahoma has long been correlated (bed-by-bed) with the Blaine Formation of Kansas (Fay, 1964). We therefore consider the Nippewalla Group (certainly the Blaine Formation part of the Nippewalla) to be Guadalupian in age.

Lithologic descriptions of these formations here are largely based on core descriptions for the AEC #5 well (Holdoway, 1978) and the RKB well (Zambito et al.,

Table 1. Wells used in cross sections shown in fig. 3.

Well #*	Company	Well	Location	State	API number
1	Thomas L. Spring	Barrett #1-29	29-23S-43W	Colorado	05-099-06875
2	Germany Investment Co.	Vaughen-Etter #1	18-23S-42W	Colorado	05-099-05027
3	Kansas-Nebraska Nat. Gas	Moran #1	16-22S-43W	Kansas	15-075-00014
4	Western Operating	Norris 13-1	13-20S-42W	Kansas	15-071-20870
5	Shaffer Oil Co	Tucker #1	12-18S-40W	Kansas	15-071-80025
6	Ginger Oil Co.	Prairie Sky #9-1	9-16S-38W	Kansas	15-203-20141
7	Cobalt Energy, LLC	KSF "A" No. 1-2	2-15S-37W	Kansas	15-109-21506
8	Fossil Resources, LLC	Plummer No. 1	11-13S-36W	Kansas	15-109-21499
9	Norstar Petroleum, Inc.	Taylor #1-18	18-11S-34W	Kansas	15-109-20793
10	White & Ellis Drilling Co.	#1-29 Cooper	29-10S-33W	Kansas	15-193-20664
11	Murfin Drilling Co.	Wilson #1-13	13-9S-33W	Kansas	15-193-20715
12	Bob Burch	Schneider #1	17-11S-46W	Colorado	05-063-06169
13	Bob Burch	Pelton No. 1	27-12S-45W	Colorado	05-017-06585
14	Mull Drilling Co.	Champlin-Pelton "A" #2	3-14S-44W	Colorado	05-017-06175
15	Amoco Production Co.	Dick's Brown 1-26	26-15S-43W	Colorado	05-017-07510
16	Amoco Production Co.	Rebecca K. Bounds #1	17-18S-42W	Kansas	15-071-20446
17	Horseshoe Operating, Inc.	King "L" #3	21-20S-40W	Kansas	15-071-20729
18	Woolsey Petroleum Corp.	Fritzemeier No. 1-21	21-22S-39W	Kansas	15-075-20365
19	Amoco Production Co.	Martin Gas Unit C 2HI	1-24S-38W	Kansas	15-093-21439
20	XTO Energy, Inc.	Lee 17-3-17	17-26S-36W	Kansas	15-093-21815
21	Mobile Oil Corp.	Maude Meyers Unit #3	17-27S-35W	Kansas	15-067-21008

*Number of well on cross section

Table 2. Permian stratigraphy and thickness of Nippewalla and Sumner Group strata in the Syracuse Basin region of western Kansas and eastern Colorado. Ages based on correlation charts in Dunbar et al. (1960), Hills and Kottlowski (1983), Johnson et al. (1989), Hovorka et al. (1993), and Johnson (2021a). Thicknesses based on data and cross sections in five areas studied for this paper.

Series	Group	Formation	Thickness, without salt	Thickness, with salt (no dissolution)
Guadalupian	Nippewalla Group	Dog Creek Shale	±100 ft (±30 m)	
		Blaine Formation	40 to 75 ft (12 to 23 m)	110 to 140 ft (34 to 43 m)
		Flowerpot Formation	30 to 65 ft (9 to 20 m)	230 to 275 ft (70 to 84 m)
		Cedar Hills Sandstone	30 to 185 ft (9 to 56 m)	
		Salt Plain Formation and Harper Sandstone	85 to 280 ft (26 to 85 m)	
Leonardian	Sumner Group	Stone Corral Formation	30 to 45 ft (9 to 14 m)	70 to 90 ft (21 to 27 m)

2012), and cores of some of the rock units in the RKB well are shown here in fig. 4. Descriptions of these units in outcrops are given in West et al. (2010). The Stone Corral, the Y-anhydrite, and the Blaine anhydrite beds are useful marker beds for correlation within, and outside of, the Syracuse Basin.

Because of its evaporite deposits, the Nippewalla Group in Kansas and Colorado was considered by early workers to be deposited either in a marine embayment fed by major transgressions of sea water from the south (Rascoe and Baars, 1972) or a restricted-marine environment alternating with brackish-water and alluvial-flat conditions (Mudge, 1967). Later work, based largely on petrologic and geochemical studies of the RKB and AEC #5 cores, has presented evidence that Nippewalla strata in Kansas were deposited in a non-marine, acid saline-lake, and mudflat environment (Holdoway, 1978; Hovorka et al., 1993; Benison and Goldstein, 2001; Zambito et al., 2012; Zambito and Benison, 2013; Benison et al., 2013, 2015; Soreghan et al., 2014).

Stone Corral Formation

The Stone Corral consists of anhydrite and dolomitic anhydrite in western Kansas (Merriam, 1963; Zambito et al., 2012), and in much of the region it contains a salt unit between lower and upper anhydrites (Merriam, 1963; Schumaker, 1966; Rascoe and Baars, 1972; Sorenson, 1996; West et al., 2010). Where the Stone Corral is only anhydrite or dolomitic anhydrite, it typically ranges from 30 to 45 ft (9–14 m) thick, and where it includes the middle salt, it is commonly 70–90 ft (21–27 m) thick (table 2). It appears that the limit of the Stone Corral salt is a dissolutional limit in most parts of the Syracuse Basin. The Stone Corral is correlative with the Cimarron Anhydrite to the south in Oklahoma and Texas.

Harper Sandstone and Salt Plain Formation

The Harper Sandstone and Salt Plain Formation are undifferentiated in this paper and consist mainly of reddish-orange and reddish-brown siltstone and silty shale (Holdoway, 1978; Zambito et al., 2012). Displacive salt and halite cement are common, but not abundant, in both formations within the basin (fig. 4F), although there are some areas where the salt/halite has been dissolved by groundwater. The combined thickness of the two formations is 85–280 ft (26–85 m) in the five areas studied in detail for this paper (table 2). Macfarlane et al. (1993) show that the thickness ranges from about 100 to 400 ft (30–122 m) in the Kansas portion of the basin.

Cedar Hills Sandstone

The Cedar Hills Sandstone is easily recognized by its moderate gamma-ray response and high resistivity on most geophysical logs in the region. This contrasts with the low gamma-ray response and higher resistivity of the overlying Flowerpot salt. It is predominantly a reddish-brown, fine- to medium-grained sandstone (fig. 4E) that is massive but locally has horizontal stratification or high-

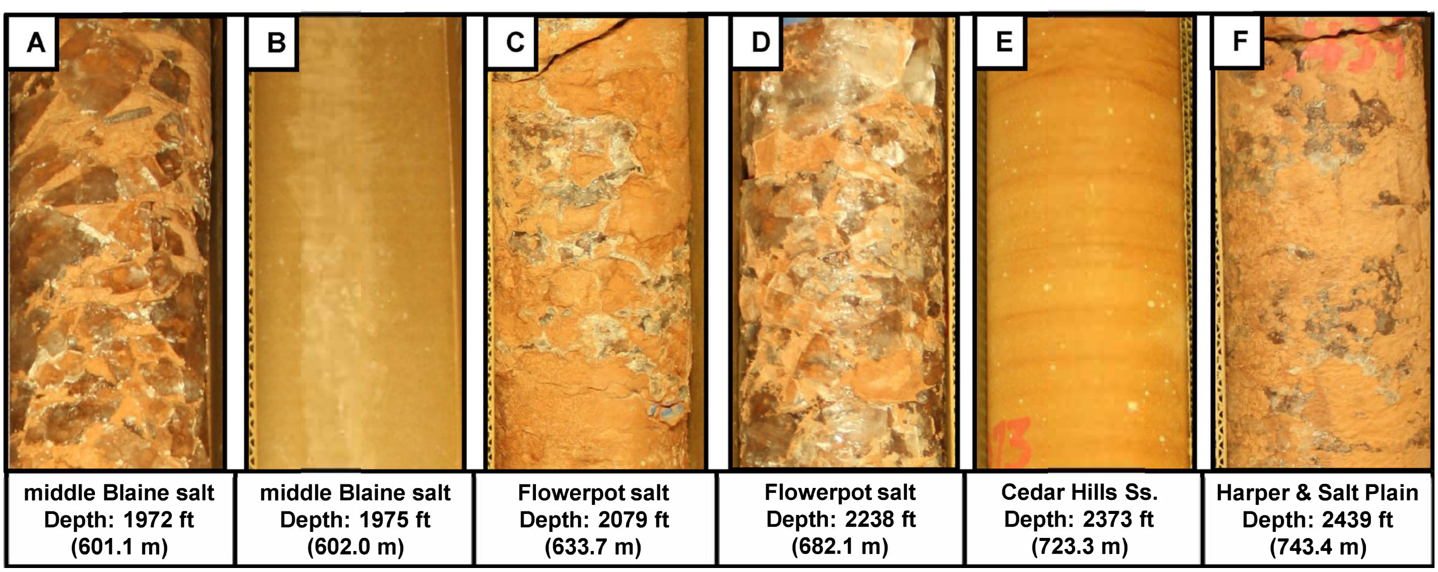

Figure 4. Photographs of cores from the RKB well, drilled in Greeley County, Kansas. All cores are about 3 in. (7.6 cm) wide. A) Typical displacive halite in mudstone in middle Blaine salt. B) Bedded halite in middle Blaine salt. C) Mudstone with small amount of displacive halite in Flowerpot salt. D) Typical displacive halite in mudstone in Flowerpot salt. E) Typical Cedar Hills Sandstone with halite cement. F) Mudstone in Harper and Salt Plain Formations with small amount of displacive halite.

angle cross beds (Holdoway, 1978; Zambito et al., 2012). The sandstone typically is cemented with halite, and displacive salt is also present locally. Displacive salt and salt cement are restricted to the more central part of the Syracuse Basin, because the Cedar Hills is an aquifer outside of the basin and groundwater has dissolved the salt around much of the basin's perimeter. Thickness of the Cedar Hills Sandstone ranges from 30 to 185 ft (9–56 m) in the five study areas of this paper (table 2); Holdoway (1978) shows that it is mostly 100–150 ft (30–46 m) thick in most parts of the basin in Kansas, whereas Macfarlane et al. (1993) show thicknesses range from 50 to 200 ft (15–61 m) in the same area.

A persistent anhydrite bed, referred to as the Y-anhydrite, is located at the top of the Cedar Hills Sandstone (Holdoway, 1978; Zambito et al., 2012; Benison et al., 2013). The Y-anhydrite is about 10–20 ft (3–6 m) thick in the northwest half of the Syracuse Basin, based on the current study, and is generally absent in the southeast half of the basin.

Flowerpot Shale and Flowerpot Salt

The Flowerpot Shale and Flowerpot salt, which comprise the Flowerpot Formation, overlie the Y-anhydrite of the Cedar Hills Sandstone. The name "Flowerpot" is variously spelled "Flower-pot" or "Flower pot" in other studies. In outcrops the formation is gypsiferous red-bed shales and siltstones (Fay, 1964), but in the subsurface of the Syracuse Basin most of the Flowerpot strata consist of displacive salt (halite) in reddish-brown to reddish-orange shale or siltstone (mudstone). Samples of the Flowerpot salt from the RKB well (Zambito et al., 2012) are shown in figs. 4C–D. The Flowerpot salt underlies all parts of the Syracuse Basin (figs. 2, 3) and is 230–275 ft (70–84 m) thick in the five areas studied for this paper (table 2). Schumaker (1966) shows the Flowerpot salt thickness ranges from about 150 to 300 ft (46–91 m) throughout the Kansas part of the Syracuse Basin. Holdoway (1978) shows that the Flowerpot (including the salt and the overlying and underlying thin shales) is more than 300 ft (91 m) thick in two places in the southern part of the basin. In most parts of the Syracuse Basin where salt dissolution has not occurred, about 5–20 ft (1.5–6 m) of Flowerpot Shale is at the base or top, or both, of the formation.

The net salt in the Flowerpot salt varies both horizontally and vertically in the basin. Benison et al. (2015) conducted experiments to determine semiquantitatively the amount of halite in displacive Flowerpot salt by measuring how much rock volume and thickness were lost by dissolution of salt from parts of the RKB core. Three displacive salt samples of the Flowerpot salt, similar to those in figs. 4C–D, were dissolved. Sample thicknesses ranged from 20 to 26.7 vertical centimeters (7.9–10.5 vertical inches) of core and aggregated a total 68 cm (26.8 in.) of core. After dissolution, net salt by thickness ranged from 53.2 to 88.0% and averaged 74.3%; net salt by mass ranged from 68.2 to 95.1% and averaged 85.5%. From these limited data, it appears that displacive Flowerpot salt consists of about 74–85% halite and 15–26% mudstone.

Outside the basin, where the Flowerpot salt has been dissolved naturally, the Flowerpot Shale (which includes the dissolution residue from the salt zone) is as little as 60 ft (18 m) thick in the south and as little as 40 ft (12 m) in the north (Holdoway, 1978). In the five detailed-study areas, described below, the Flowerpot is 30–65 ft (9–20 m) thick where it lacks salt. However, in much of the area outside of the basin, salt dissolution is incomplete and there is still some salt residue in the Flowerpot. This residual salt (salt outliers) beyond the dissolution front can increase the thickness of the Flowerpot Shale to 100 ft (30 m) or more. In general, 200–300 ft (61–91 m) of Flowerpot salt within the basin is reduced to 50–150 ft (15–46 m) of Flowerpot Shale (or somewhat salty Flowerpot Shale) outside of, or beyond, the dissolution front.

Blaine Formation and Middle Blaine Salt

The Blaine Formation overlies the Flowerpot and is one of the most persistent marker beds in the GPEB on geophysical logs. It is recognizable and can be correlated from the Palo Duro Basin in the Texas Panhandle (Johnson, 2021c) through the Syracuse Basin and at least as far north as the Denver Basin in western Nebraska and southeast Wyoming (Oldham, 1996, 1997). The Blaine consists of interbeds of anhydrite (gypsum in outcrops), reddish-brown shale/mudstone, thin dolomites at the base of some anhydrites, and salt as displacive halite in mudstone (fig. 4A) and as bedded halite (fig. 4B) (Holdoway, 1978; Zambito et al., 2012). The three lowest anhydrites in the Syracuse Basin are correlative with the Medicine Lodge (at bottom), Nescatunga, and Shimer Gypsum beds, as described in outcrops of northwest Oklahoma (Fay, 1964). At many places within the basin, one or several additional thinner anhydrites are present above the Shimer bed, and they are herein included in the Blaine Formation.

The middle Blaine salt, located between the Nescatunga and Shimer anhydrites, is present in almost all parts of the Syracuse Basin (figs. 2, 3). As described below, in the five detailed-study areas the Blaine Formation is 110–140 ft (34–43 m) thick where it contains salt (as in figs. 4A,B) but is only 40–75 ft (12–23 m) thick where salt is dissolved, beyond the perimeter of the basin (table 2). Schumaker (1966) and Holdoway (1978) show that where it is salt-bearing, the Blaine is generally 100–140 ft (30–43 m) thick in Kansas. At many places outside of the Syracuse Basin, the number and thickness of anhydrite beds is reduced because some of the anhydrite has probably been dissolved or because dissolution of the underlying Flowerpot salt has chaotically disrupted and displaced some of the overlying Blaine strata, or both.

The middle Blaine salt is 30–60 ft (9–18 m) thick in four of the five study areas (it is missing in the North Oakley Area) and is 55 ft (17 m) thick in the RKB and AEC #5 wells. In most other parts of the basin, the middle Blaine salt is 45–60 ft (14–18 m) thick. Where this salt is dissolved, outside of the basin, that interval consists only of shale that is typically 5–10 ft (1.5–3 m) thick.

As with the Flowerpot salt, the amount of halite in the middle Blaine salt varies both horizontally and vertically in the basin. Experiments conducted by Benison et al. (2015) determined semiquantitatively the amount of halite in displacive middle Blaine salt by measuring how much rock volume and thickness were lost by dissolution of salt from the RKB core. Three displacive salt samples of the middle Blaine salt, similar to fig. 4A, were dissolved. Sample thicknesses ranged from 5 to 22 vertical centimeters (2–8.7 vertical inches) of core and aggregated a total 41 cm (16.1 in.) of core. After dissolution, net salt by thickness ranged from 60.7 to 81.8% and averaged 74.2%; net salt by mass ranged from 81.7 to 92.7% and averaged 87.6%. From these limited data, it appears that displacive middle Blaine salt consists of about 75–88% halite and 12–25% mudstone, results nearly identical with those for displacive Flowerpot salt described above.

Dog Creek Shale

The youngest formation discussed here is the Dog Creek Shale, which overlies the Blaine Formation. The Dog Creek is mostly reddish-brown shale/mudstone with orange-red siltstone and sandstone layers (Zambito et al., 2012). In outcrops, the top of the Dog Creek is well defined at the contact with sandstone in the overlying Whitehorse Formation (Fay, 1964), but in the subsurface of the Syracuse Basin the geophysical logs do not show a sharp boundary: therefore, no determination of the top of the Dog Creek, or its thickness, was made in this study. However, Zambito et al. (2012) made a tentative pick for the Dog Creek–Whitehorse contact in the RKB core, which indicated a Dog Creek thickness of about 88 ft (27 m). It seems reasonable to say that the thickness of the Dog Creek Shale is probably about 100 ft (30 m) thick in the Syracuse Basin (table 2).

SYRACUSE BASIN

The Syracuse Basin refers to the large region in western Kansas and eastern Colorado where the Permian Nippewalla Group salts—the Flowerpot and Blaine salts—are separated from other areas of equivalent salts in the GPEB. Salts in the Syracuse basin underlie an area of about 8,100 mi^2 (21,000 km^2). The Syracuse Basin was first described as a structural basin by Lee and Merriam (1954) and then discussed and shown or inferred on maps and cross sections as a structural or depositional basin by Rascoe and Baars (1972), Holdoway (1978), and Macfarlane and Wilson (2006) (fig. 5). Although structural elements such as the Oakley anticline and the Las Animas arch border parts of the Syracuse Basin (fig. 5C), the Nippewalla Group salts originally extended well beyond their present limits in the Syracuse Basin and were continuous with other regions of Flowerpot and Blaine salts to the north and south.

The Las Animas arch formed mainly during the Late Cretaceous–Early Tertiary (Neogene) Laramide Orogeny (Clair and Volk, 1968) and is an anticlinal high that separates the Denver Basin of northeastern Colorado from the Hugoton embayment of southwest Kansas. Prior to the Laramide Orogeny, the area encompassing the arch and the Syracuse Basin was the northwest portion of the Hugoton embayment of the Anadarko Basin. The northeast dip of the Stone Corral on the east flank of the arch was accentuated after deposition of the Cretaceous Dakota Formation, affirming that the Las Animas arch is mainly a post-Cretaceous structural feature in Kansas (Lee and Merriam, 1954; Merriam, 1963).

The regional dip of Permian strata in the Syracuse Basin is toward the northeast and north at less than one degree, although this uniform dip is disrupted all around the perimeter of the basin by sharply flexed and down-dropped Blaine and post-Blaine strata above salt-dissolution fronts in the Flowerpot or middle Blaine salts. Structural maps drawn on sub-salt strata, such as the Stone Corral or Cedar Hills, show reasonably uniform and uninterrupted rates of dip to the northeast or north (Merriam, 1958, 1963; Macfarlane and Wilson, 2006; and all structure maps presented below in the five detailed-study areas), and the sub-salt structure is in no way affected by salt dissolution that occurred in overlying rocks. Structure maps drawn on top of the Blaine Formation or younger strata, however, show a pronounced drop in elevation of the datum bed where it

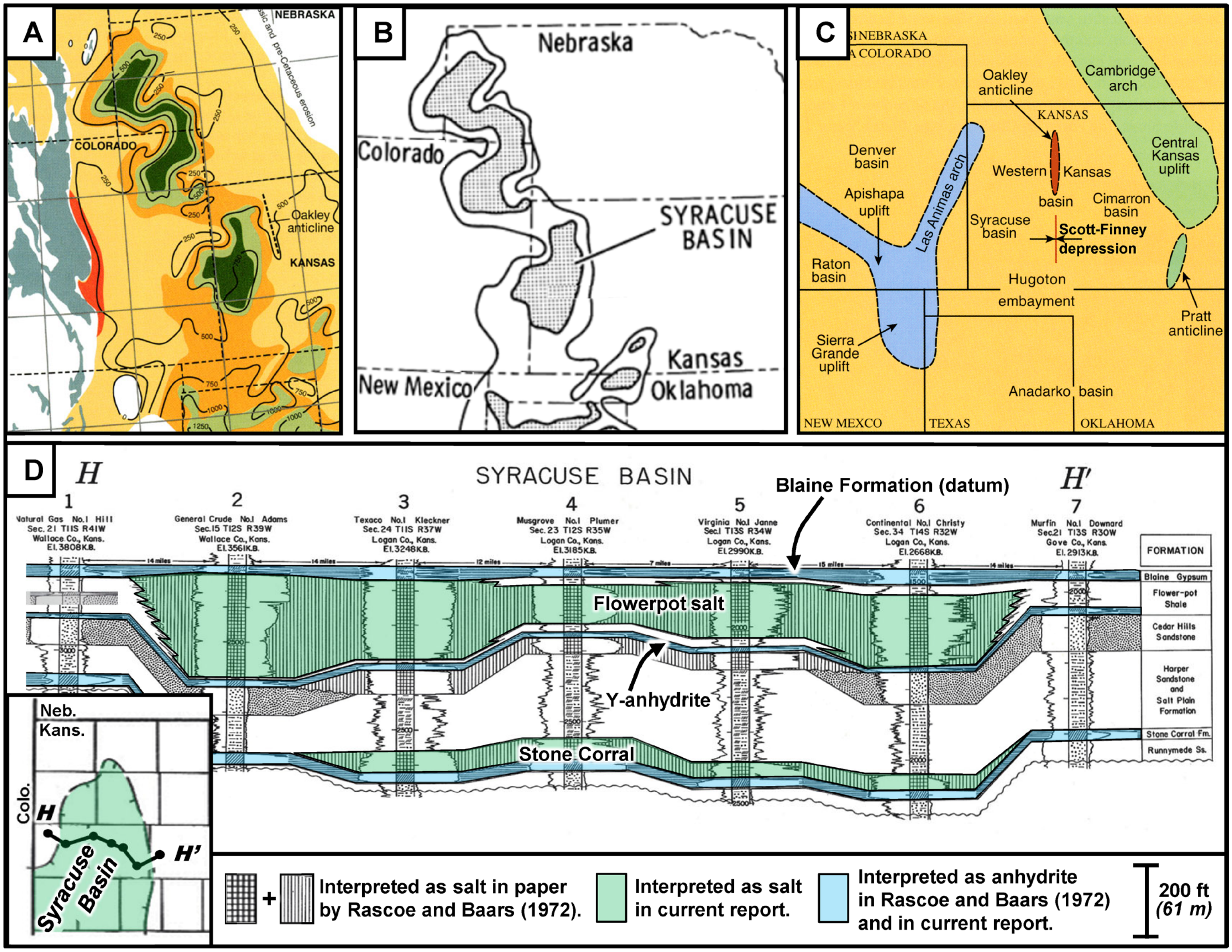

Figure 5. Earlier maps and stratigraphic cross section suggesting that the Syracuse Basin is a structural or depositional basin, rather than a remnant of salt dissolution. A) Map from Macfarlane and Wilson (2006), based on Rascoe and Baars (1972). B) Map from Holdoway (1978). C) Map from Macfarlane and Wilson (2006). D) Stratigraphic cross section modified from Rascoe and Baars (1972). Cross section D, with Blaine Formation as the datum, appears to show a salt-filled depositional or structural basin; but if presented as a structural cross section, the salt margins would clearly be dissolutional. In cross section D, salt is shown in the Cedar Hills Sandstone in wells 3, 4, and 5 in the original (vertical lines). In fact, the Cedar Hills is only salty (with halite cement and perhaps some displacive salt) in these three wells, and the halite has been dissolved from the Cedar Hills (and the underlying Harper and Salt Plain Formations) in the other wells, as shown by low-resistivity values on the resistivity curves (right side of each log).

crosses parts of the dissolution boundary (Macfarlane and Wilson, 2006; Johnson, 2021d,e).

Stratigraphic cross sections of the Syracuse Basin that use the Blaine or younger strata as a datum do suggest that the salts were deposited in a well-defined structural or depositional basin (fig. 5D). However, structural cross sections in the Syracuse Basin show that it is not a structural or depositional basin (fig. 3). And as shown in the five study areas (below), structural cross sections, or those drawn with the Stone Corral or Cedar Hills as a stratigraphic datum, show that sub-salt strata dip uniformly and undisturbed beneath the dissolution zone and that the lateral limits of the salt beds are definitely dissolutional limits.

Therefore, the region referred to as the Syracuse Basin is a salt-dissolution remnant of the Flowerpot and middle Blaine salts in western Kansas and eastern Colorado. The present limits of the Syracuse Basin result from salt dissolution along all of its perimeter in the two-state region. This is evidenced by abrupt termination of the salt units along the outer edges of the "basin," as shown by the maps and cross sections in this study. So, although the Syracuse

Basin is primarily the result of salt dissolution, and not a structural or depositional feature, the term "Syracuse Basin" has merit in that it defines the large region of western Kansas and eastern Colorado where the salts are separated by dissolution from the remainder of Flowerpot and Blaine salts in the GPEB. This large region also has a long history (nearly 70 years) of being referred to as the "Syracuse Basin."

Although maps in this paper show the main dissolution front of the salt units, there are many outliers beyond the dissolution front where patches or masses of undissolved or partly dissolved salt are still present. Likewise, there also are several inliers where partial or total dissolution has occurred within the main salt body, behind the dissolution front. These inliers may be places where the salt is thin, or absent, and may even result in sinkholes that reach the land surface, such as the Wallace Sinkhole and other sinks in the Sharon Springs study area (Johnson, 2021d, and below). A good example where inliers of dissolved Flowerpot salt are present is in the Sharon Springs study area and adjacent parts of Kansas and Colorado (fig. 6), where several dissolutional inliers are located 1–10 mi (1.6–16 km) south of the main dissolution front. Outliers of Flowerpot salt are also shown below in discussions of the South Syracuse and Great Plains Reservoirs study areas. Other examples of outliers of Flowerpot and middle Blaine salts in Colorado, well beyond the Syracuse Basin, are described in Oldham (1996, 1997), Askew (2013), and Berry (2018).

Salt dissolution around the perimeter of the Syracuse Basin results mainly from lateral and downward movement of unsaturated water, as attested by the absence of the younger middle Blaine salt around most of the basin perimeter where the deeper Flowerpot salt is still present (fig. 2). However, two areas around the perimeter are anomalous, in that the Flowerpot salt is dissolved but the younger middle Blaine salt is still present: 1) parts of Finney and Scott counties, Kansas, that include the Finney-Kearny County study area; and 2) parts of Prowers and Kiowa counties, Colorado, just southeast of the Great Plains Reservoirs study area (fig. 2). Clearly the Flowerpot salt was deposited in both these areas, but the unsaturated, salt-dissolving waters came not from above but were introduced through the underlying Cedar Hills Sandstone. This is discussed further in the Finney-Kearny County Area section of this paper.

CORES OF FLOWERPOT AND BLAINE FORMATIONS IN SYRACUSE BASIN

Two wells drilled in the middle part of the Syracuse Basin were cored through the Flowerpot and Blaine evaporite section: 1) the Amoco Production Co., Rebecca K. Bounds #1 (RKB well) and 2) the Union Carbide Corporation, AEC Test Hole #5 (AEC #5 well) (fig. 2). Cores from these wells are extremely valuable because they provide information about the nature of the evaporite units far from the dissolution front that surrounds the Syracuse Basin. They also allow the calibration of geophysical logs to lithological features, thus improving the ability of researchers to interpret the much-more-abundant geophysical logs. Lithologic logs of these cores are herein plotted along

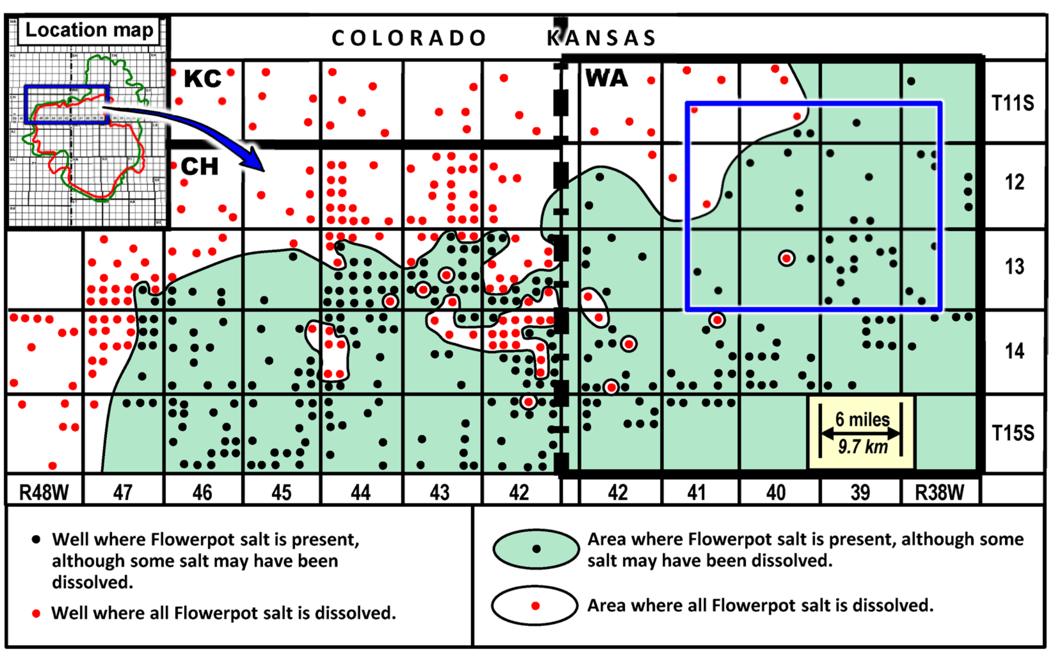

Figure 6. Map showing dissolution front of Flowerpot salt and inliers of dissolved Flowerpot salt in the Sharon Springs area and adjacent parts of Kansas and Colorado. Blue rectangle is the Sharon Springs study area. The thickness of undissolved Flowerpot salt in this area is generally 220–240 ft (67–73 m) thick in Kansas and 180–200 ft (55–61 m) thick in Colorado.

with the suite of geophysical logs from the same wells, and this assists in recognizing and correlating the various stratigraphic markers on other well logs throughout the region where core is unavailable. Interpretation of geophysical logs in evaporite sequences has been discussed in papers by Alger and Crain (1966), Nurmi (1978), and Johnson (2021b), which provide guidance for the interpretations herein.

Amoco Production Co., Rebecca K. Bounds #1 (RKB) Core

The Rebecca K. Bounds #1 well, drilled in 1988 by the Amoco Production Co. in Greeley County, west-central Kansas (fig. 2), recovered continuous core of about 1,800 ft (549 m) of Permian strata, including the Flowerpot and Blaine evaporite sequence. The well and core have commonly been referred to as the "RKB well" and the "RKB core," and that will be followed in the current paper. Comprehensive discussions of Permian evaporites in the RKB core are given in Zambito et al. (2012) and Benison et al. (2013), and photos of the entire core are available through the Kansas Geological Survey (KGS) list of wells with core images: https://chasm.kgs.ku.edu/ords/qualified.cimg2.CoreImages?f_well=1006067111

The RKB well was drilled in NE SE NE sec. 17, T. 18 S., R. 42 W. (API #15-071-20446). A second well, the Beard Oil Co., Bounds #1-17 (API #15-071-20555), was drilled (but not cored) in 1991–92, just 100 ft (30 m) west of the RKB well. This well is important because it should have the same lithology as the RKB core, but it has a different suite of geophysical logs that also are an aid in identifying rock units on logs elsewhere in the Syracuse Basin.

Figure 7 shows the lithology of strata between the Stone Corral and the Blaine Formation, based upon core descriptions in Zambito et al. (2012) and Benison et al. (2013) as well as examination of the core photos on the KGS website. The RKB core data are shown on the RKB #1 well log, on the left of fig. 7, and the same core lithologies are plotted on the Bounds #1-17 well log on the right. Inasmuch

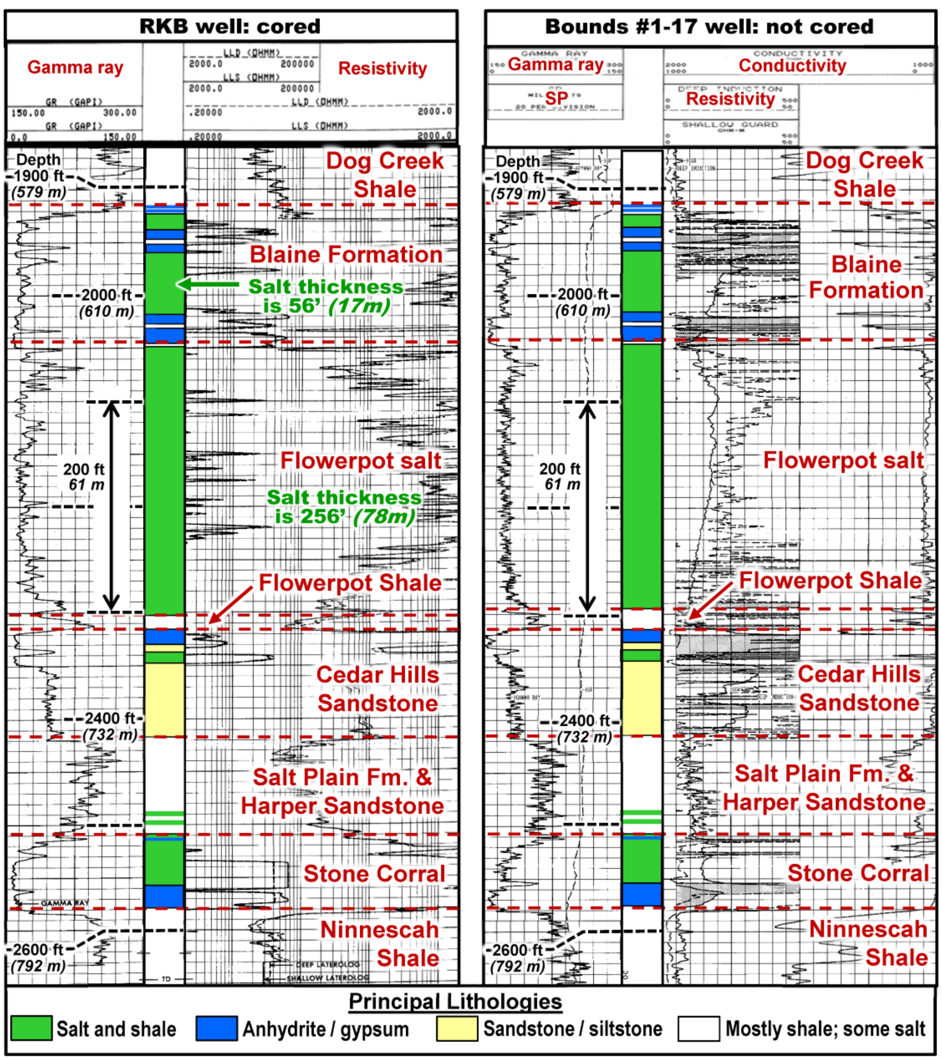

Figure 7. Geophysical logs and lithology based on cores from the RKB well (on left): core descriptions from Zambito et al. (2012) and Benison et al. (2013). The RKB well was continuously cored through this entire section. The geophysical log of the Bounds #1-17 well (on right), drilled only 100 ft (30 m) from the cored RKB well, is included here to show the response on a different log suite (thus comparing a dual laterolog, on left, with a dual-induction log, on right): lithology shown for Bounds #1-17 well is taken from core description of the RKB well.

as the wells are only 100 ft (30 m) apart, it is assumed that if the Bounds #1-17 was cored, it would be essentially the same as core from RKB #1. Showing the core lithology on both well logs enables seeing the response of two different geophysical logs in this evaporite sequence: a dual laterolog on the left and a dual induction log on the right. The gamma-ray logs for both wells are essentially identical.

Salt is the major constituent of the Stone Corral, Flowerpot, and Blaine Formations in the RKB core. Salt thicknesses in the core are 43 ft (13 m) in the Stone Corral, 256 ft (78 m) in the Flowerpot, and a total of 72 ft (22 m) in the Blaine—the middle Blaine salt alone is 56 ft (17 m) thick. High-purity bedded salt, with no shale inclusions, is limited to 1) several 1 to 2 ft thick (0.3–0.6 m thick) beds in the middle and upper Blaine salts (fig. 4B); 2) a couple of 5 to 8 ft thick (1.5–2.4 m thick) beds in the Flowerpot salt; and 3) most of the lower half of the Stone Corral salt (Zambito et al. [2012] considered this salt to be part of the Harper Sandstone, but Rascoe and Baars [1972] placed it in the Stone Corral). Other than those few layers of bedded salt, the remainder of the salt beds are displacive salt, wherein halite occurs mainly as large, blocky, and clear crystals that have grown randomly in (and displaced) a red-bed matrix of clay, silt, and mud (figs. 4A,C,D). Benison et al. (2013) note that halite crystals make up about 20% to about 95% of the various displacive salt units, and this range in amount of halite crystals is shown in the core photos (figs. 4A,C,D,F).

Anhydrite beds in the RKB core are excellent marker beds for local and regional correlation. Most of these beds are about 10–20 ft (3–6 m) thick, and they give distinctive responses on geophysical logs. Anhydrite ($CaSO_4$) is typically hydrated to gypsum ($CaSO_4 \bullet 2H_2O$) in outcrops, in the shallow subsurface, or in areas where anhydrite is closely associated with waters that have dissolved salt. On most geophysical logs, anhydrite and gypsum have similar responses. They can, however, be distinguished from each other on neutron, sonic, or density logs (Johnson, 2021b).

Siliciclastic strata in the RKB core consist of red-bed clay, shale, mudstone, siltstone, and sandstone. Most of the siliciclastic units from the Stone Corral to the Blaine Formation are described as containing displacive halite (fig. 1 in Benison et al., 2013), and most of these siliciclastics are, in fact, in the Blaine and Flowerpot salt units. The Harper Sandstone and Salt Plain Formation also have zones of displacive salt (fig. 4F), but the amount of halite is considerably less than what is present in the Blaine and Flowerpot salts. The Cedar Hills Sandstone is salty, although it contains no large crystals of displacive salt. Zambito et al. (2012) describe the Cedar Hills core as a "sandstone that is poorly cemented with halite" (fig. 4E).

Union Carbide Corporation, AEC Test Hole #5 (AEC #5) Core

The Atomic Energy Commission Test Hole #5 was drilled by Union Carbide Corp. in 1972 in Wichita County, west-central Kansas (fig. 2), to evaluate the possibility of storing high-level radioactive waste in the thick Flowerpot salt. Because of the impure nature of the Flowerpot salt, it was deemed unsuitable for waste storage and the program was stopped (Holdoway, 1978). About 518 ft (158 m) of core was recovered between the lower Dog Creek Shale and the upper Salt Plain Formation, including all of the Blaine and Flowerpot evaporites. The well and core have commonly been referred to as the "AEC #5 well" and the "AEC #5 core," and that will be followed in this paper. A field description of the core was recorded in the AEC #5 Driller's Log (1972), and the most comprehensive discussion of the core, accompanied by core photographs, is given in Holdoway (1978). Additional discussion of the core, along with its mineralogy, is in Bayne and Brinkley (1972) and Benison and Goldstein (2001). The AEC #5 Driller's Log (1972) description is the main basis for the "core description" (lithologic log) shown in fig. 8.

The studies mentioned above documented that the lithology of the Flowerpot and Blaine evaporite sequence in the AEC #5 core is similar to that in the RKB core. The core location is also near the middle of the Syracuse Basin, far-removed from its marginal salt-dissolution zones. The well was drilled 150 ft (46 m) north and 150 ft (46 m) east of the center of sec. 22, T. 19 S., R. 37 W. (Kansas Well ID 1005427913). The comprehensive suite of geophysical logs run on this well (fig. 8) is very useful in aiding recognition of the different lithologies in this evaporite sequence on other geophysical logs.

Salt is the main rock in the Stone Corral, Flowerpot, and Blaine Formations in this core. Salt thicknesses are about 56 ft (17 m) in the Stone Corral, 273 ft (83 m) in the Flowerpot, and a total of 67 ft (20 m) in the Blaine—the middle Blaine salt alone is 57 ft (17 m) thick. These salt thicknesses are reasonably similar to those in the RKB well, which is located about 33 mi (53 km) to the west. Salt beds in the Blaine and Flowerpot are described in the following manner in the AEC #5 Driller's Log (1972): Most salt is clear or milky red, with inclusions of red-brown shale (i.e., "displacive salt"); some salt is described as "clear" (i.e., "high-purity salt"); some salt zones are described as being 25–75% shale (probably "displacive salt"); and some salt units contain salty shale beds that are 0.2–5 ft (0.06–1.5 m) thick.

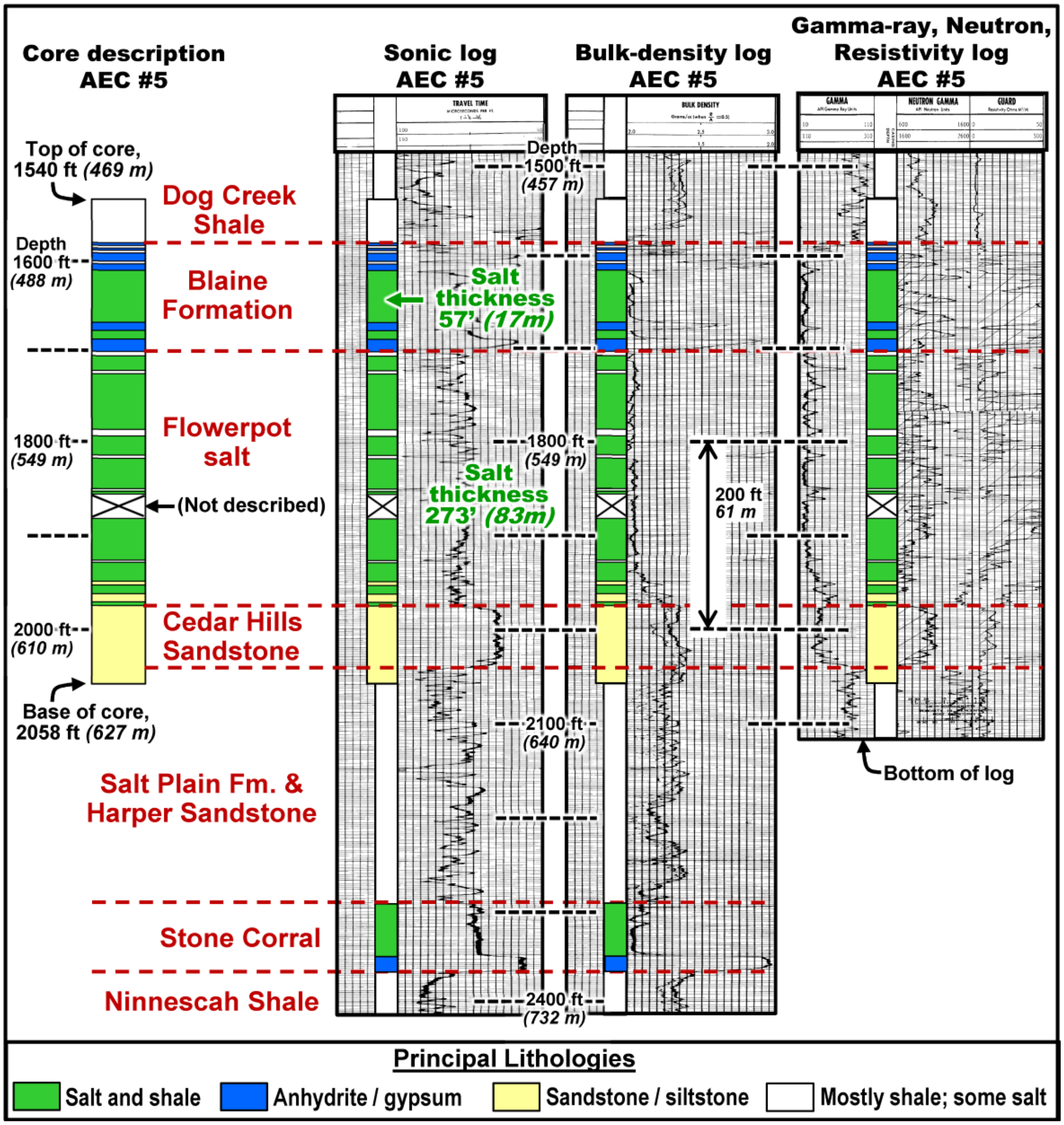

Figure 8. Geophysical logs and lithology based on cores from the AEC #5 well: core descriptions from the AEC #5 Driller's Log (1972) and Holdoway (1978). The core, limited to depths of 1,540–2,058 ft (469–627 m), is shown on the three logs run on the well; lithologies above and below the core are interpreted from the logs.

Anhydrite beds in the AEC #5 well are excellent marker beds for correlation throughout the Syracuse Basin and beyond. Most of the Blaine anhydrites are 6–13 ft (1.8–4 m) thick, although there are two beds at the top of the formation that are only about 2 ft (0.6 m) thick. The anhydrite at the base of the Stone Corral is about 17 ft (5.2 m) thick. Anhydrite beds are described in the AEC #5 Driller's Log (1972) as being reddish gray and banded or white to gray with scattered salt crystals.

Siliciclastic beds in the AEC #5 core are mainly described as red-brown, silty shale in the Blaine and Dog Creek Formations and red-brown salty shale or shale with large crystals of salt in the Flowerpot (AEC #5 Driller's Log, 1972). The Cedar Hills Sandstone is described as reddish-brown, salty, very fine- to medium-grained sandstone, with salt estimated to be 30–40%. It also is referred to as a "salt-cemented" sandstone. Although it is mostly reddish brown, some of the sandstone is white, and there are a few scattered anhydrite inclusions.

RECOGNIZING HALITE DISSOLUTION IN SILICICLASTICS ON GEOPHYSICAL LOGS

Interpretation of evaporite beds on geophysical logs has been discussed by Alger and Crain (1966), Nurmi (1978), and Johnson (2021b), but recognition of halite (salt) in the siliciclastic beds associated with evaporites is also important in the current study because it shows the way that unsaturated groundwater in the Cedar Hills Sandstone has locally dissolved halite in the adjacent siliciclastic beds, as well as the Flowerpot and middle Blaine salts.

Dissolution of halite cement from Nippewalla Group siliciclastics is readily identified on the resistivity/

conductivity curves of geophysical logs in the Syracuse Basin. A resistivity log measures how strongly a rock (and the fluids it contains) in a borehole resists the flow of an electric current. Conversely, a conductivity curve measures how readily a rock (and its fluids) conducts an electric current. Oil and gas operators are generally required by the governing regulatory agency to run at least one logging tool from total depth of the well to the surface, or to surface casing. Operators almost always choose the resistivity and/or gamma-ray tool to be run to the surface casing for shallow-formation correlation and detection purposes.

Resistivity logs in salt-cemented siliciclastic sediments exhibit readings ranging from about 3 ohm-meters to more than 50 ohm-meters, depending on the lithology and the amount of salt cement. In stark contrast, where salt cement has been dissolved by unsaturated groundwater, extremely low resistivity values, in the range of 0.1–0.5 ohm-meters, show the lack of salt cement and the presence of hypersaline brines that remain in the siliciclastic sediments. The dissolution boundary between a zone with salt cement and a zone where salt has been dissolved is typically very abrupt, occurring over an interval of no more than 1–3 ft (0.3–1 m) vertically (no more than the resolution of the logging tool).

Recognition of the presence or absence of salt cement in siliciclastics, based on resistivity logs, is demonstrated in fig. 5D and in discussions of the Finney-Kearny County and North Oakley study areas, below. In fig. 5D, salt cement is present in siliciclastic layers above the Stone Corral in wells 3, 4, and 5 (as shown by the moderate resistivity curve on the right side of the logs) but has been dissolved from those strata in all other wells (as shown by little or no resistivity). Dissolution of salt in siliciclastics between the Stone Corral and Flowerpot Formations helps affirm that unsaturated water in the Cedar Hills Sandstone is the cause of salt dissolution at several sites around the perimeter of the Syracuse Basin.

The regional dissolution limits of salt cement in Nippewalla Group siliciclastics also can be mapped in significant detail with available well control in the Syracuse Basin. The position of the dissolution front can be identified downward from the top of the Cedar Hills Sandstone through the Salt Plain Formation, the Harper Sandstone, and ultimately through the Stone Corral salt to the underlying Stone Corral anhydrite. The resulting map reflects a broad halo that further demonstrates the dissolutional boundaries of salts and salt cements within Nippewalla Group sediments in the Syracuse Basin.

AREAS FOR DETAILED STUDY OF SALT DISSOLUTION

Five areas were selected to show details of salt dissolution in the Flowerpot and middle Blaine salts around the perimeter of the Syracuse Basin. These are the South Syracuse, Finney-Kearny County, North Oakley, Sharon Springs, and Great Plains Reservoirs areas (fig. 2). In each area, two cross sections are presented: One, a stratigraphic section using the base of the Stone Corral as the datum, shows details of salt dissolution as it progresses from outside of the basin toward the center; and the second, a structural cross section, shows (along with a structure map drawn on a sub-salt stratum) that strata beneath the salt dip gently and uninterrupted beneath the dissolution zone and that it is only strata above the dissolved salts that are disrupted. These cross sections and structure maps demonstrate that the basin boundary is a result of salt dissolution and that the Syracuse Basin is not a structural or depositional feature.

In most of these areas, dissolution occurs due to descending groundwater removing the shallowest (middle Blaine) salt first and then removing the deeper Flowerpot salt. However, in one area, the Finney-Kearny County area, the dissolving, unsaturated groundwater is in the still deeper Cedar Hills Sandstone, and therefore the Flowerpot salt is dissolved first and then the shallower middle Blaine salt.

Area 1: South Syracuse Area

The South Syracuse study area, located about 5 mi (8 km) south of the city of Syracuse and at the south end of the Syracuse Basin (figs. 2, 9, 10), contains the most conspicuous surface evidence of salt dissolution along the entire dissolution front of the Syracuse Basin. A series of natural subsidence- and sinkhole-related streams, lakes, and ponds in southwest Kansas are aligned in a west-northwest–east-southeast orientation for about 30 mi (48 km) in Hamilton and Stanton counties, and they continue as an arcuate belt another 12 mi (19 km) to the north-northeast in Grant and Kearny counties (fig. 9). This feature has been referred to as the Bear Creek Fault Zone, the Syracuse anticline, the Syracuse fault, and the Syracuse flexure. Previous investigations of this structure were thoroughly described by Macfarlane and Wilson (2006). Gutentag et al. (1981, their plate 1) and Macfarlane et al. (1993, their plate 13) show this structure as a fault, with 100–250 ft (30–76 m) of displacement, that follows Bear Creek in an east-southeast direction and then trends to the north-northeast across most of Kearny County. Although early descriptions referred to the Bear Creek–Syracuse

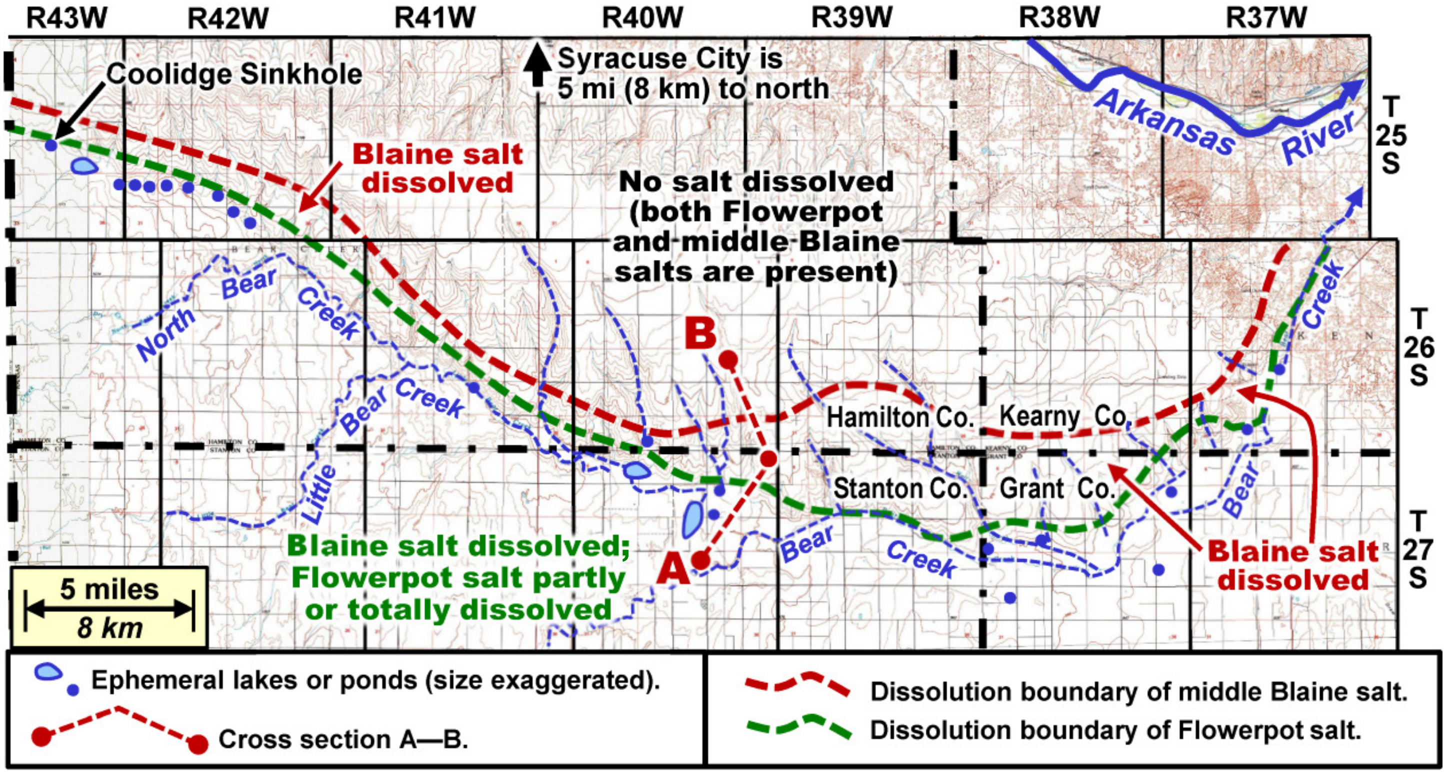

Figure 9. Map showing approximate dissolution limits of the Flowerpot and middle Blaine salts in the South Syracuse area of Hamilton, Stanton, Kearny, and Grant counties in southwest Kansas (based on data in fig. 10A). The alignment of ephemeral lakes or ponds and the several Bear Creeks results from subsidence or collapse features due to salt dissolution. Base maps are the USGS 30 X 60-minute quadrangle metric maps for Ulysses, Kansas, and Two Buttes Reservoir, Colorado-Kansas. Cross section A–B shown in figs. 11 and 12.

structure as a fault, Macfarlane and Wilson (2006, p. 1) correctly referred to it as a "dissolution front characterized by sinkholes, coalesced subsidence basins, and local faulting with minor displacement."

The Bear Creek–Syracuse structure is herein referred to as the Bear Creek flexure. This term is preferred because the structure is formed chiefly along Bear Creek, and it results from dissolution of (mainly) the Flowerpot salt, now at depths of about 1,100–1,300 ft (335–396 m); it is not a true fault. The top of the Blaine and overlying Permian and Mesozoic formations arch over the dissolution zone as a monoclinal flexure that is locally disrupted with fractures, minor faults, and offsets that result from uneven amounts of dissolution of underlying salts. Strata beneath the Flowerpot salt, including the Stone Corral anhydrite, dip without interruption (i.e., no faults or disruption) at 10–25 ft/mi (2–5 m/km) (about 0.1–0.3 degree) to the northeast (fig. 10B).

North of the Bear Creek flexure, in areas unaffected by dissolution, the Flowerpot salt ranges from about 260 to 290 ft (79–88 m) thick, and the middle Blaine salt is mostly 40–60 ft (12–18 m) thick (figs. 11, 12). South of the flexure, all the middle Blaine salt is gone, but some of the Flowerpot salt is still present in several places. Although the Flowerpot salt is completely missing in much of this area, there are outliers of salt that locally are 30–200 ft (9–61 m) thick. The thickness of the Flowerpot salt decreases sharply at some places along and south of the Bear Creek flexure. Extreme examples show the loss of about 200 ft (61 m) of salt within about 1,000 ft (305 m) horizontally.

Bear Creek and Little Bear Creek, which flow to the east-southeast and then to the north-northeast directly above the dissolution zone, are locally discontinuous. At places, they terminate and drain into small ponds or into alluvium and then appear a few hundred meters away as though they are new or different creeks. This probably happens because the land surface above the dissolution zone has subsided at different rates in different places. Thus, a creek that flowed across a small depression may terminate in the depression, but its downstream portion continues its original course, independent of being cut off from the upstream portion.

Northwest of North Bear Creek, in T. 25 S., are a series of nine ephemeral ponds or lakes, each about 4–160 acres (1.6–65 hectares) in size, that occupy local shallow depressions caused by salt dissolution (fig. 9). Examination

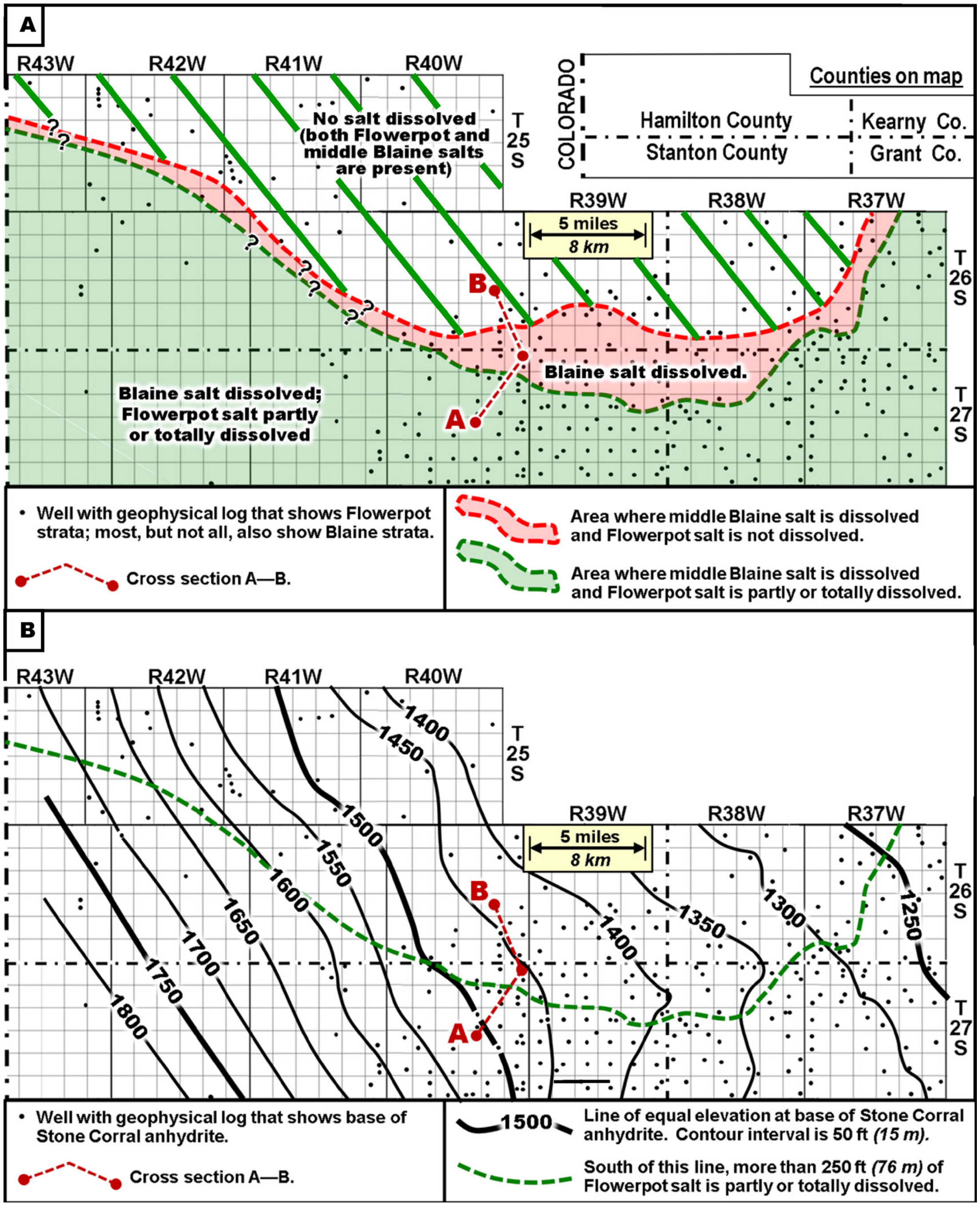

Figure 10. Maps of the South Syracuse area in Hamilton, Stanton, Kearny, and Grant counties in southwest Kansas. A) Dissolution limits of the Flowerpot and middle Blaine salts. B) Elevation of base of the Stone Corral anhydrite. Cross section A–B shown in figs. 11 and 12.

of a series of Google Earth photos shows that these nine depressions rarely contain water; they are dry except after long or heavy rains. Most Google Earth photos from August 1991 through May 2022 show small pools or moist ground in at least some of the shallow depressions. These ephemeral ponds or lakes, looking like a "string of pearls," are best identified on two USGS 1:24,000-scale topographic maps—the Syracuse West SW and Durkee Creek quadrangles.

At the west end of this "string of pearls" is the Coolidge Sinkhole, a natural sink that formed in December 1929 in the northeast corner of sec. 22, T. 25 S., R. 43 W. (figs. 9, 13). As originally described in Bass (1931), the sinkhole was 60 ft (18 m) wide and about 40 ft (12 m) deep in July 1930, and it then expanded to about 104 ft (32 m) wide and 68 ft (21 m) deep one month later. Originally, three sets of crevices encircled the sink, extending as much as 45 ft (14 m) from the edge of the

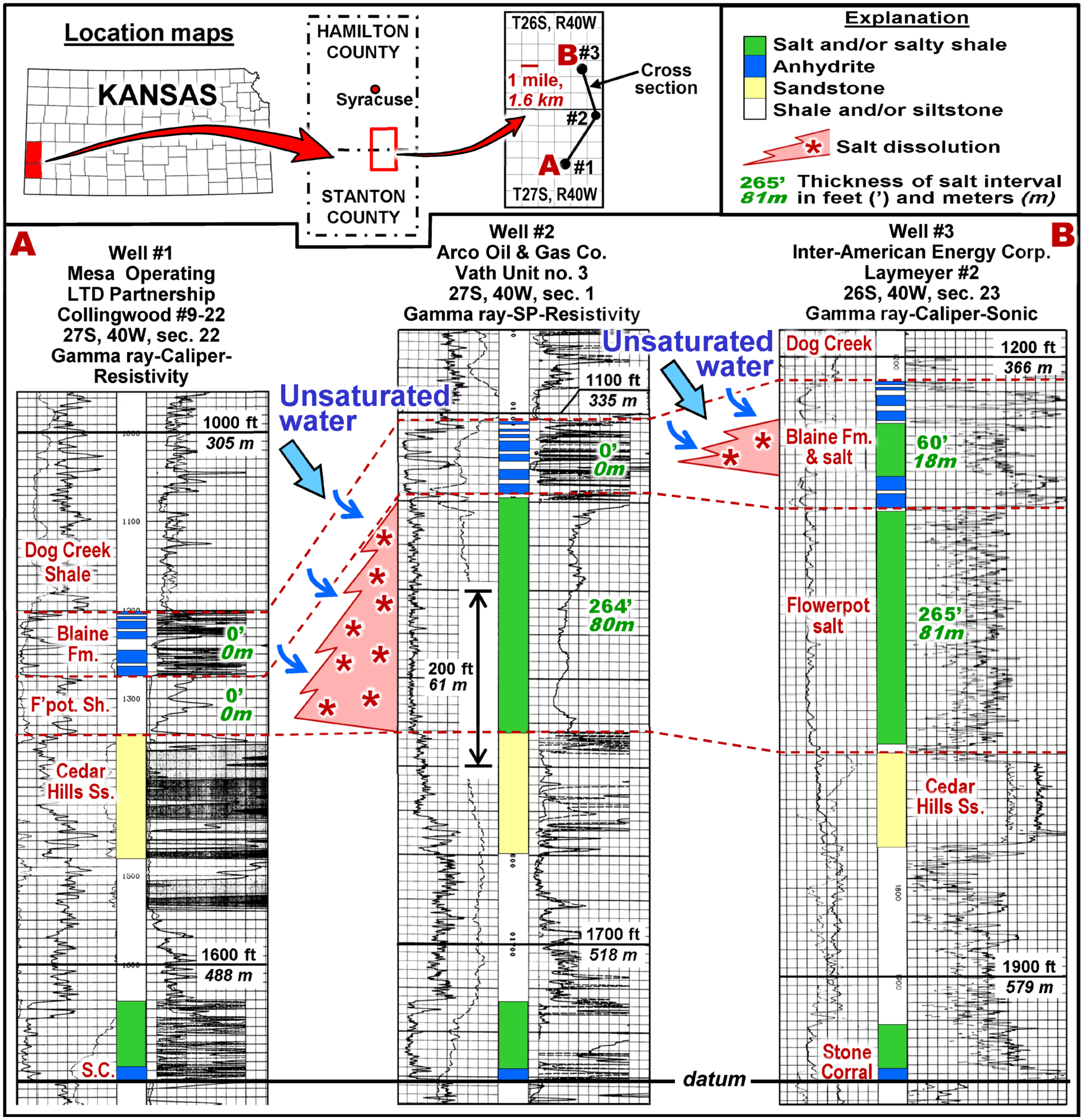

Figure 11. Stratigraphic cross section A–B shows that dissolution of salt in the South Syracuse area progresses toward the north and downward. Unsaturated water first dissolves all the middle Blaine salt (wells #1 and #2), and then all the Flowerpot salt (well #1). Location of cross section A–B shown in figs. 9 and 10.

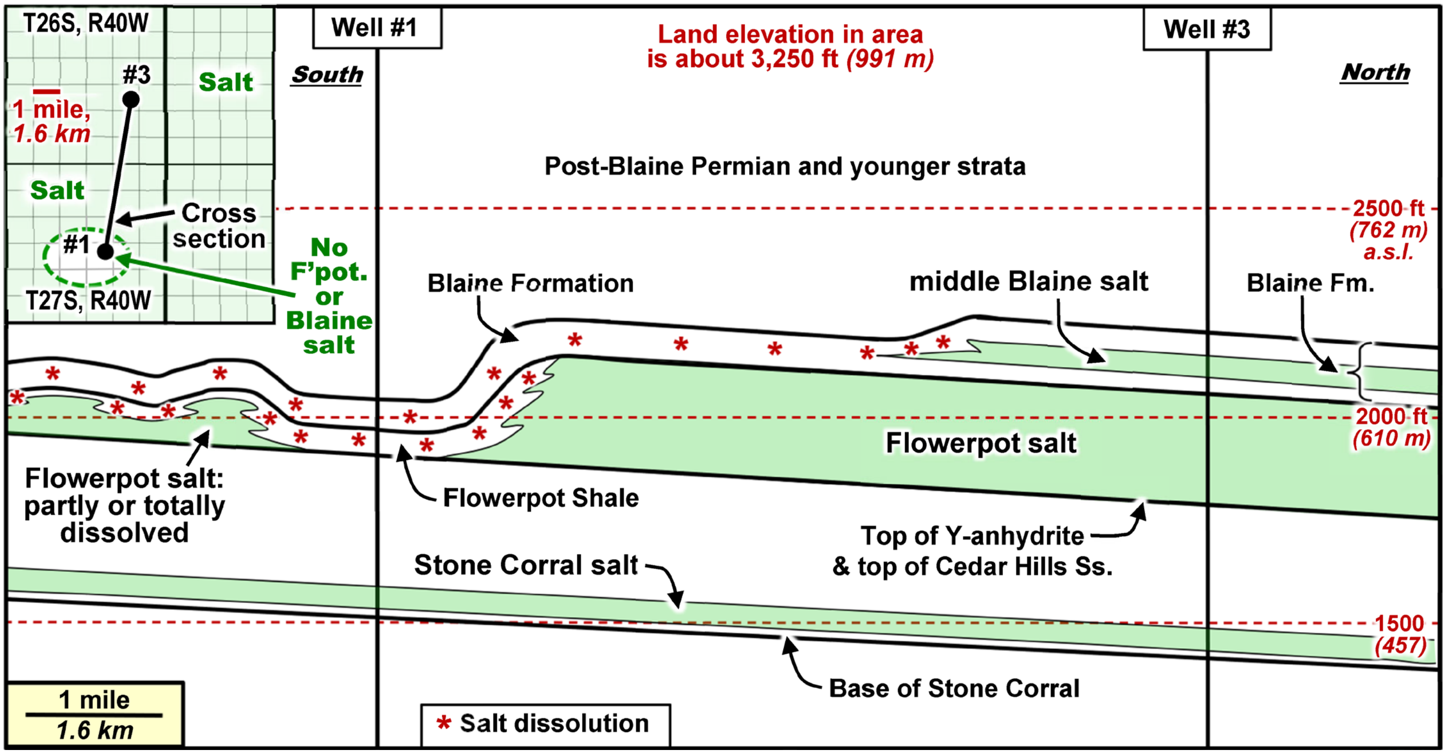

Figure 12. Schematic north-south structural cross section in the South Syracuse area showing dissolution of Flowerpot and middle Blaine salts and subsidence of overlying strata. Based on well data in fig. 11. Elevations are in feet *(meters)* above sea level.

sink. Recently, the water-filled sink was about 100 ft (30 m) in diameter (Google Earth photograph, August 2022), although the size of the water area increases or decreases, depending upon precipitation.

As a result of long-term subsidence of the area south of the Bear Creek flexure, more than 200 ft (61 m) of alluvium has accumulated beneath Bear Creek and its tributaries (McLaughlin, 1943; Fader et al., 1964; Lobmeyer and Sauer, 1974). These authors all point out that the thick alluvial sediment south of the Bear Creek flexure resulted from subsidence and concurrent deposition during Late Tertiary (Neogene) and Pleistocene time. Furthermore, in cross sections they all show that Cretaceous strata and the eroded Cretaceous bedrock surface beneath the alluvium south of the flexure are about 150–250 ft (46–76 m) lower than just to the north. Macfarlane and Wilson (2006, their plate 1B) show that the bedrock surface drops 250–300 ft (76–91 m) across the flexure. The area of thick alluvium south of the flexure is a subsidence trough similar to, but on a smaller scale than, those in the Delaware Basin of West Texas and southeast New Mexico, where more than 1,475 ft (450 m) of Cenozoic sediment fills two large salt-dissolution troughs (Maley and Huffington, 1953). The "string of pearls" depressions have formed in the same manner as the Great Plains Reservoirs subsidence features, as described below.

Area 2: Finney-Kearny County Area

The Finney-Kearny County study area has evidence of dissolution of Flowerpot and Blaine salts in southwest Kansas (figs. 2, 14A). Both salts are present and not dissolved in the west part of the area, but they are partly and then totally removed by dissolution toward the east (figs. 15–17). Where unaffected by dissolution, the Flowerpot salt is 240–260 ft (73–79 m) thick and the middle Blaine salt is generally 40–55 ft (12–17 m) thick. An additional salt unit — typically 10–20 ft (3–6 m) thick — is present in the lower part of the Blaine Formation, between the Medicine Lodge and Nescatunga anhydrite beds.

The salt-dissolution zone here is quite wide, in comparison to the narrower zone of dissolution in other areas around the Syracuse Basin, and salt here is dissolved by water ascending from the underlying Cedar Hills Sandstone. The Flowerpot salt loses some of its lowest salt layers in R. 35 W. but then loses all its salt about 14 mi (23 km) to the east in R. 33 W. (fig. 14A). From that point on, the middle Blaine salt is dissolved within about 4 mi (6.4 km) farther east. The dissolution zone in this area extends

Figure 13. Two views of Coolidge Sinkhole, located in the northeast corner of sec. 22, T. 25 S., R. 43 W., Hamilton County, Kansas (shown in extreme west of fig. 9). A) Sinkhole as it appeared in 1930 (Bass, 1931). B) Sinkhole as it appeared in 1939 (Smith, 1940). This natural sink, formed in 1929, was reported to be about 104 ft (32 m) wide and 68 ft (21 m) deep (Bass, 1931). Numbers 1 and 2 in photo A show the location of crevices (dark lines) that partly encircle the sink.

north across Scott County, where it is referred to as the Scott-Finney depression (Macfarlane and Wilson, 2006). The Scott-Finney depression is a relatively narrow zone, about 2–5 mi (3.2–8 km) wide, where the bedrock surface is dropped down about 100–200 ft (30–61 m) owing to salt dissolution along the east side of the Syracuse Basin. The depression above the bedrock surface is filled with Ogallala and Quaternary sediments.

Salt dissolution in the Finney-Kearny County area does not result from descending unsaturated water, as in most other parts of the Syracuse Basin, but is due to water moving toward the west in the sub-salt Cedar Hills Sandstone aquifer and dissolving salt from both overlying and underlying strata (figs. 15, 16). Salt is present as halite cement in the Cedar Hills Sandstone in both the RKB and AEC #5 cores, where those cores are far from any salt-dissolution zone, and it is reasonable to assume halite was also originally present in the Cedar Hills throughout the Finney-Kearny County area. Examination of the resistivity curves in the eight wells comprising figs. 15 and 16 indicates that salt is still present in the Cedar Hills in well #1 (fig. 15), but it has been removed from the Cedar Hills in all the other wells farther to the east. Where salt cement in the siliciclastic strata has been dissolved and hypersaline brines occupy pore spaces, the geophysical logs show lower resistivity values.

Dissolution of the lowest Flowerpot salt beds first in a westward direction is affirmed by tracing three shale

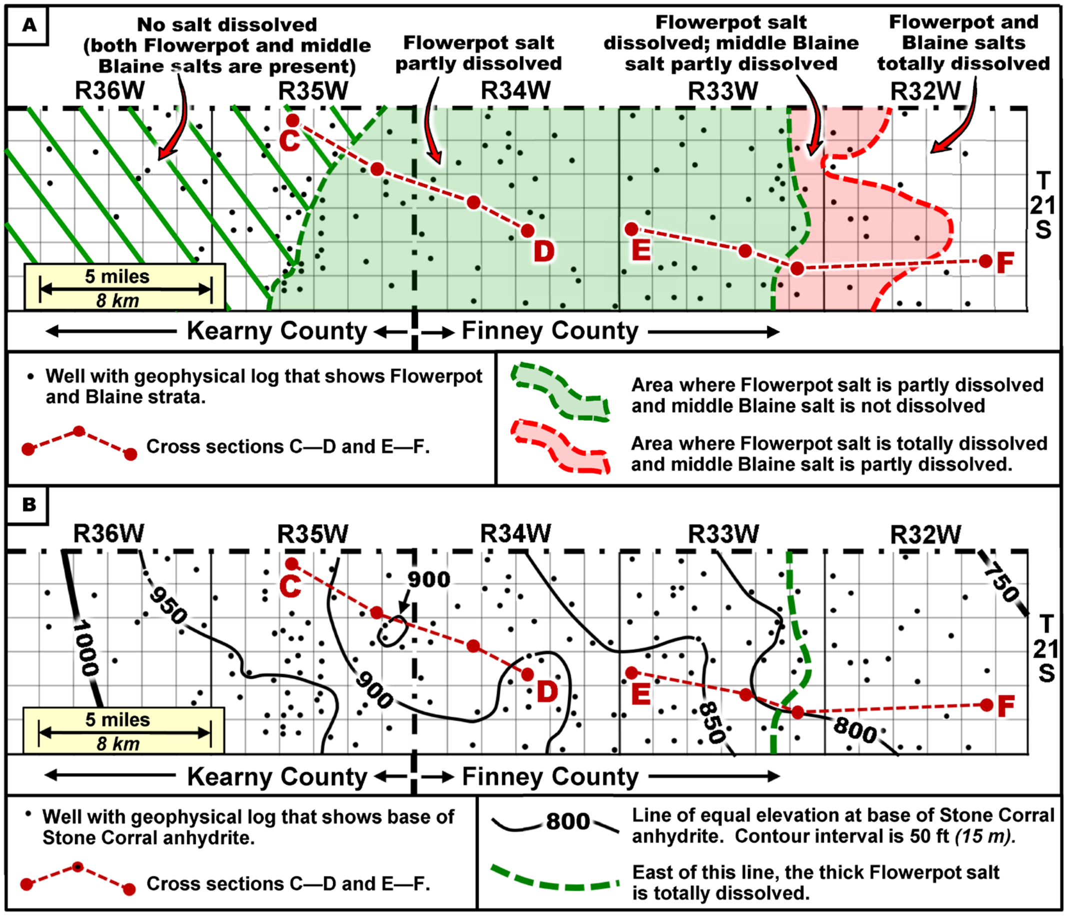

Figure 14. Maps of the Finney-Kearny County area in southwest Kansas. A) Dissolution limits of the Flowerpot and middle Blaine salts. B) Elevation of base of the Stone Corral anhydrite. Cross sections C–D and E–F shown in figs. 15–17.

marker beds (a, b, and c) in the Flowerpot salt (figs. 15, 16). All three shale marker beds are recognizable in wells #1 and #2, but, due to dissolution of the lower half of the Flowerpot salt, bed a can't be identified in well #3, and bed b can't be identified in well #4. Only shale marker bed c, about 20 ft (6 m) below the top of the Flowerpot salt, extends across wells #1–5 but then can't be identified in wells #6–8 (fig. 16). The loss of these three thin shale marker beds from west to east shows that the Flowerpot salt has been dissolved by groundwater that has come from the east and from below, and the water has dissolved successively higher beds of salt.

During the Permian, regional groundwater flow in the Midcontinent region was from east to west, but the later Laramide Orogeny (Late Cretaceous) caused the regional groundwater to flow from west to east (Jorgensen et al., 1993). So, prior to the onset of the Laramide Orogeny, the Cedar Hills Sandstone aquifer transported unsaturated water from the east into the Finney-Kearny area. Groundwater coming from the east is demonstrated by the greater amount of salt dissolution above and below the Cedar Hills in the east than in the west (figs. 15, 16) and by the fact that only in the westernmost well (well #1, fig. 15) does the Cedar Hills still consist of halite-cemented sandstone. Soon after deposition of the Nippewalla Group, the area to the east of the Hugoton embayment was uplifted and an east-to-west regional groundwater flow system was initiated (Jorgensen et al., 1993). The ultimate source of the unsaturated water charging the Cedar Hills Sandstone remains unknown, but water entering the Cedar Hills could have percolated down from an overlying aquifer, such as the Lower Cretaceous Dakota and Cheyenne Sandstones or the Upper Jurassic (Morrison?) strata.

Structural geology of sub-salt strata in this part of Finney and Kearny counties is simple (fig. 14B). Mapping at the base of the Stone Corral anhydrite indicates a general dip toward the northeast at 10–50 ft/mi (2–9 m/km), or about 0.1–0.5 degree. The Stone Corral is below the salt-dissolution zones and therefore is not affected by structures or subsidence of strata within or above the Flowerpot or Blaine salts (fig. 17).

Area 3: North Oakley Area

The North Oakley study area is in southern Thomas County, just north of the city of Oakley, in northwest Kansas

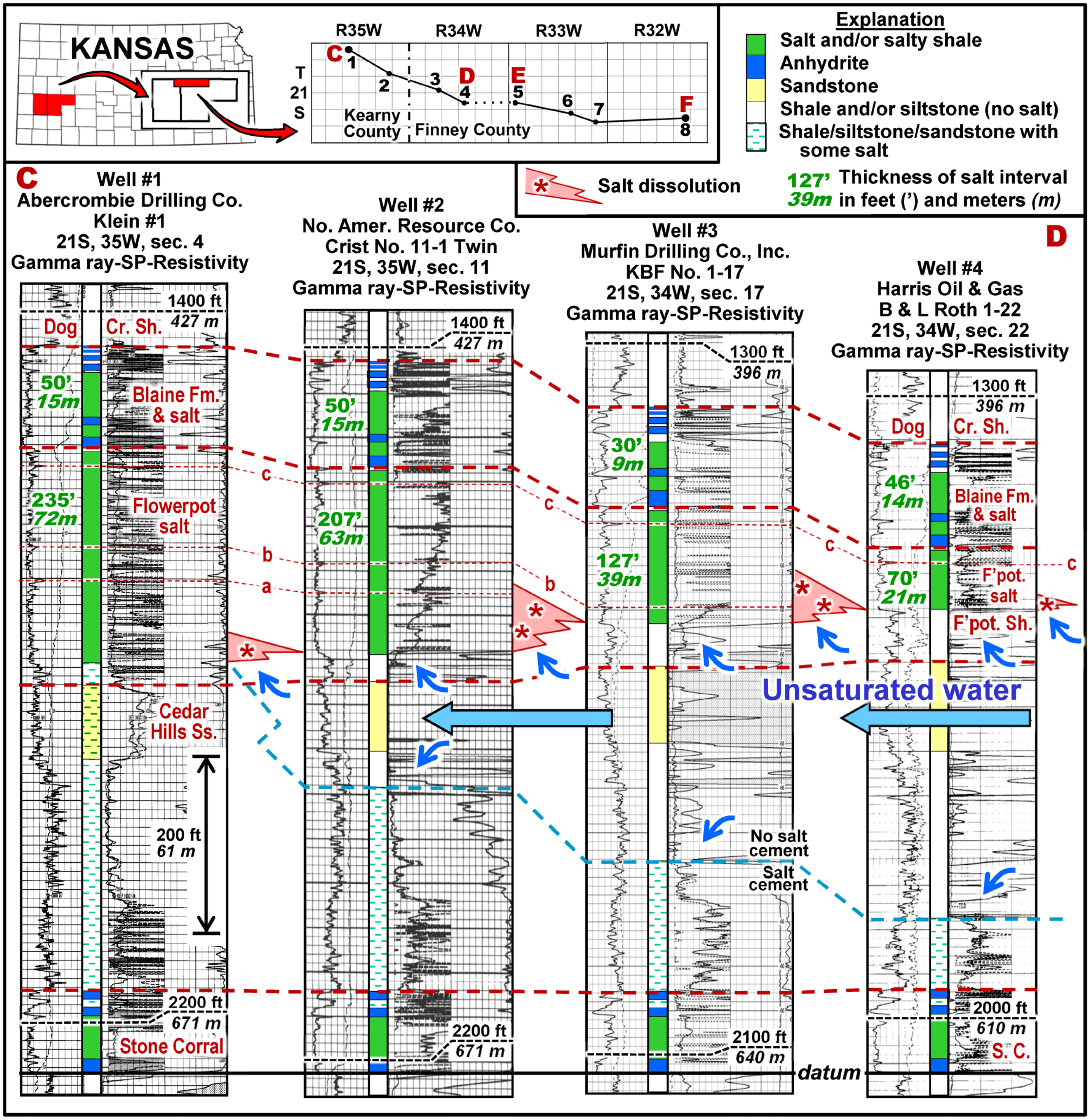

Figure 15. Stratigraphic cross section C–D shows that dissolution of salt in the Finney-Kearny County Area results from westward movement of unsaturated water in the Cedar Hills Sandstone. Salt-dissolving water reached well #4 first and then wells #3 and #2; it has not yet reached well #1 in the west. Salt beds in the lower Flowerpot are dissolved before Blaine salts, and salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Shale marker beds denoted by "a," "b," "c," and thin red dashed line. Location of cross section C–D shown in fig. 14.

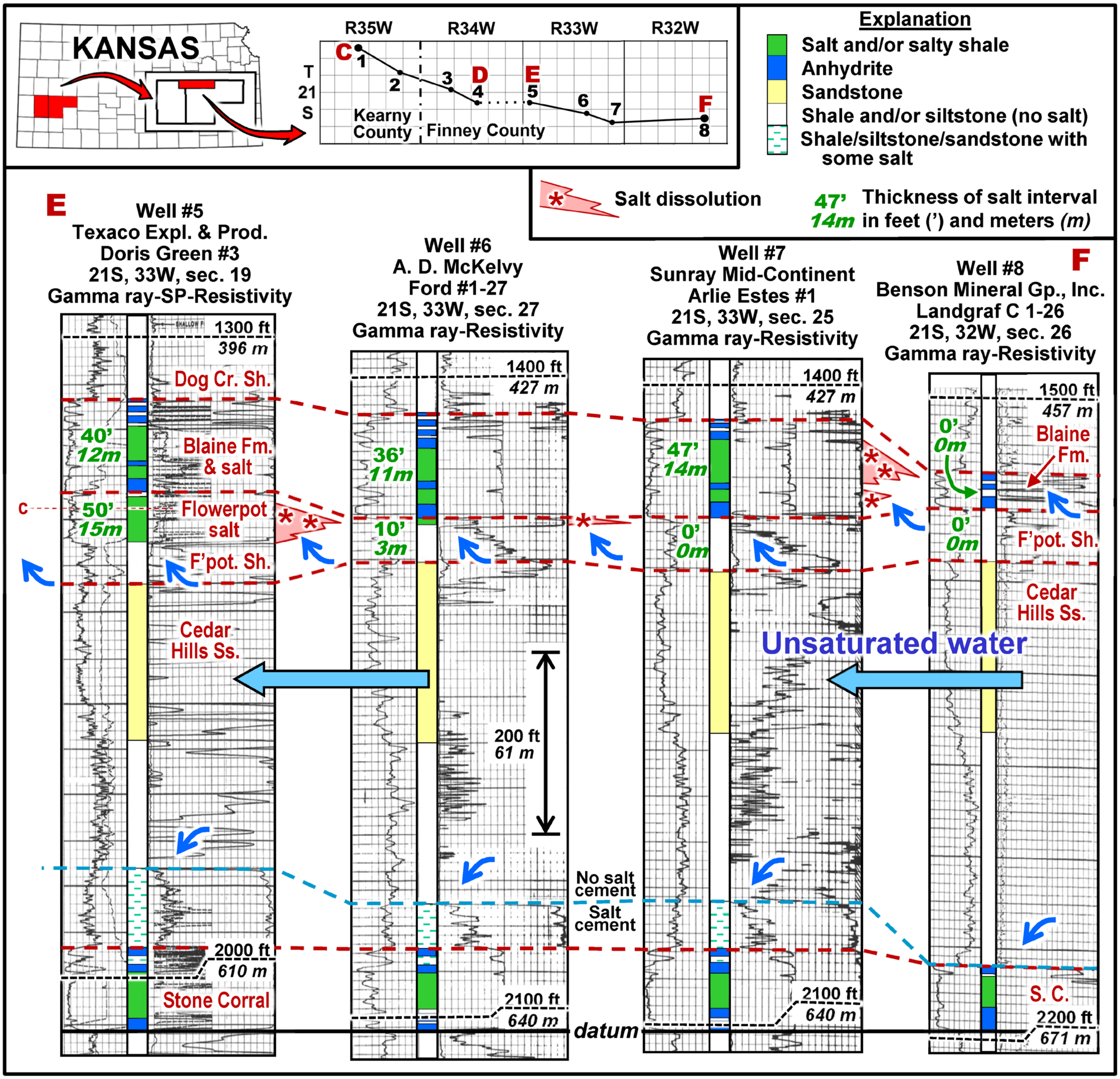

Figure 16. Stratigraphic cross section E–F shows that dissolution of salt in the Finney-Kearny County area results from westward movement of unsaturated water in the Cedar Hills Sandstone. Salt-dissolving water entered well #8 first and then wells #7, #6, and #5, successively. It then continued westward to dissolve salts as shown in cross section C–D (fig. 15). Salt beds in the Flowerpot are dissolved first (wells #8 and #7), and then salts in the Blaine are finally dissolved (well #8). Salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Shale marker bed denoted by "c" and thin red dashed line in well #5. Location of cross section E–F shown in fig. 14.

(figs. 2, 18). It is located along the northeast edge of the Syracuse Basin and locally shows an impressive amount of salt dissolution of the Flowerpot salt over a short horizontal distance. The only Permian salts currently present in the area are the Flowerpot and Stone Corral salts. The Flowerpot salt ranges from 200 to 250 ft (61–76 m) thick where it is not dissolved in the southern and western parts of the North Oakley area, but elsewhere in the area it is partly or totally dissolved (fig. 18). In the northeast part of the area, the thickness of Flowerpot strata (Flowerpot Shale and residual Flowerpot salt) is generally 50–150 ft (15–46 m).

In secs. 29–32, T. 10 S., R. 32 W., the abundance of boreholes and well logs shows that Flowerpot salt is dissolved within a very short distance (fig. 19). In the southwest half of this small area, the Flowerpot strata (from the base of the Blaine Formation to the top of the Y-anhydrite) are 223–264 ft (68–80 m) thick, whereas just to the northeast this same sequence is mostly only 48–89 ft (15–27 m) thick. Along the line of cross section G–H (figs. 20, 21), there is a loss of 163 ft (50 m) of salt within a horizontal distance of only 930 ft (283 m). Flowerpot strata here are reduced in thickness from 249 ft to 86 ft (76 m to 26 m). This is a remarkable loss of salt within a short distance, and as a result the overlying strata arch over the dissolution zone in a sharp flexure (fig. 21).

The deeper Stone Corral salt is 60–65 ft (18–20 m) thick in T. 10 S., R. 34 W. of the North Oakley area. It thins to the east from the middle of R. 33 W. and is completely missing in the east half of R. 32 W. The assumption is that the Stone Corral salt is being dissolved in the east by unsaturated water that is also removing halite cement and displacive salt from siliciclastic strata below the Cedar Hills Sandstone (fig. 20). Evidence that the Cedar Hills is an aquifer here derives from the resistivity logs in siliciclastic strata between the Stone Corral and the Flowerpot salt. The high-resistivity salt in the siliciclastics is being dissolved, and the resultant brine in these strata has a low resistivity.

The middle Blaine salt—present in the four other areas studied—is missing here; it is uncertain whether the middle Blaine salt was originally deposited in the area. The nearest middle Blaine salt is about 16 mi (26 km) southwest of this study area, in sec. 7, T. 12 S., R. 37 W. In that area, the middle Blaine salt is 30 ft (9 m) thick, but it is absent in sec. 34, T. 11 S., R. 37 W., a distance of 4 mi (6.4 km). This is probably a dissolutional limit for the middle Blaine salt, but the data are too sparse to be certain.

Structure mapping at the base of the Stone Corral anhydrite (fig. 18B) shows a gentle dip toward the north and northeast. The highest elevations of the Stone Corral in the area, 501–503 ft (152.7–153.3 m), are in the southeast

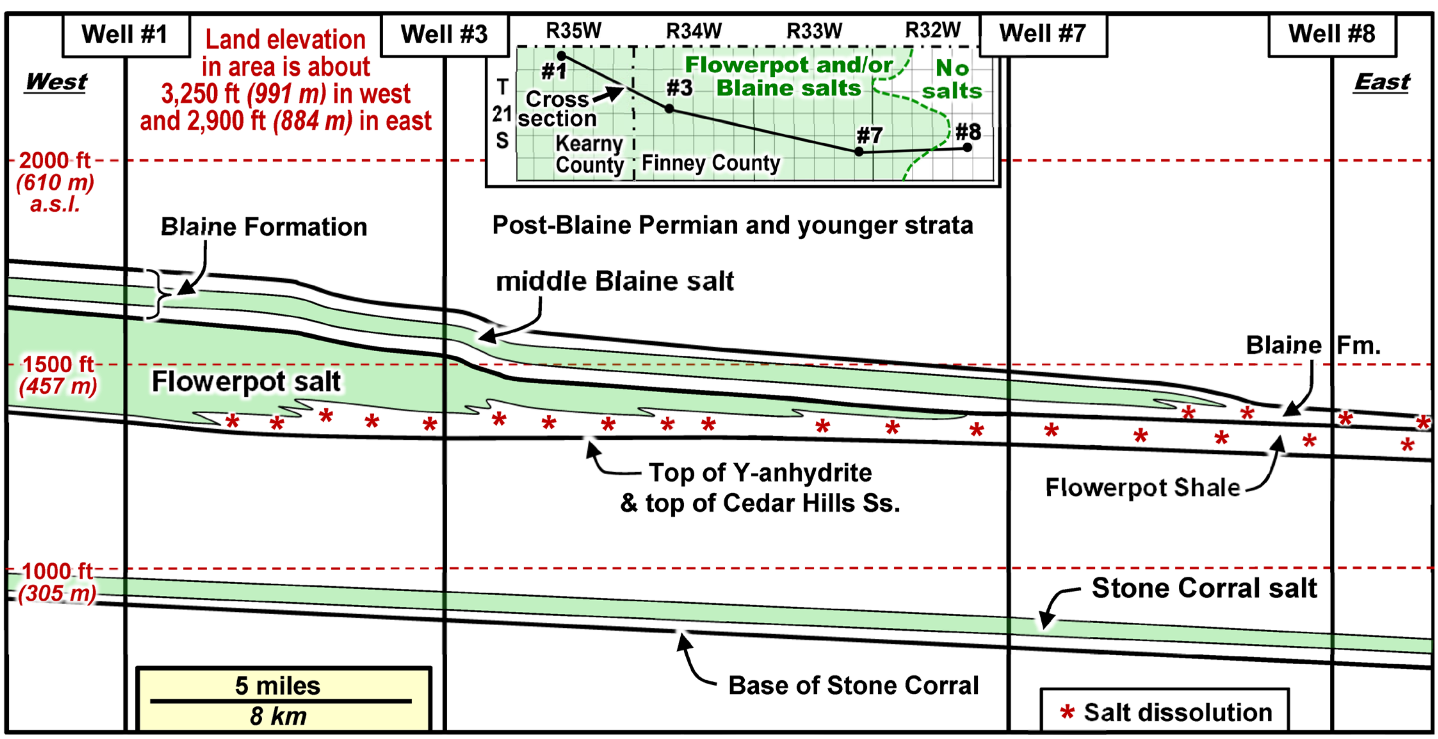

Figure 17. Schematic east-west structural cross section in the Finney-Kearny County area showing dissolution of Flowerpot and middle Blaine salt beds and subsidence of overlying strata. Based on well data in figs. 15 and 16. Elevations are in feet *(meters)* above sea level.

corner of R. 34 W., and the lowest elevation is 415 ft (126 m) in the northeast corner of R. 32 W.

Area 4: Sharon Springs Area

The Sharon Springs study area is in the central part of Wallace County, northwest Kansas (figs. 2, 22). Salt deposits and salt dissolution in the area were studied recently by Johnson (2021d), and much of the current discussion of this area is based on that earlier work. Both the Flowerpot salt and the middle Blaine salt are present in most of the south part of the Sharon Springs area. Where neither salt is affected by dissolution, the Flowerpot salt ranges from about 200 to 240 ft (61–73 m) thick, and the middle Blaine salt is about 40–45 ft (12–14 m) thick. To the north and northwest, however, these salts are partly dissolved, and in the far northwest of the Sharon Springs area both salts are totally missing (figs. 22–24). The dissolution zone for these salts is generally about 1–5 mi (1.6–8.1 km) wide.

Dissolution of salt here results from unsaturated water descending from above, moving laterally toward the south and east, or both. Descending (rather than ascending) unsaturated water is affirmed by dissolution of the middle Blaine salt first (fig. 23, wells #1, #2), and then the Flowerpot salt is removed (fig. 23, well #1). These salts originally extended far to the west and northwest, extending to the similar-aged salt units in northeastern Colorado and beyond (Oldham 1996, 1997). Figure 6 shows extension of the Flowerpot salt to the west and its dissolution to the north.

The structural geology of the area is not complex, except for the Ruggles Draw Fault Zone in the north, the Sharon Springs Fault in the south, and the results of salt

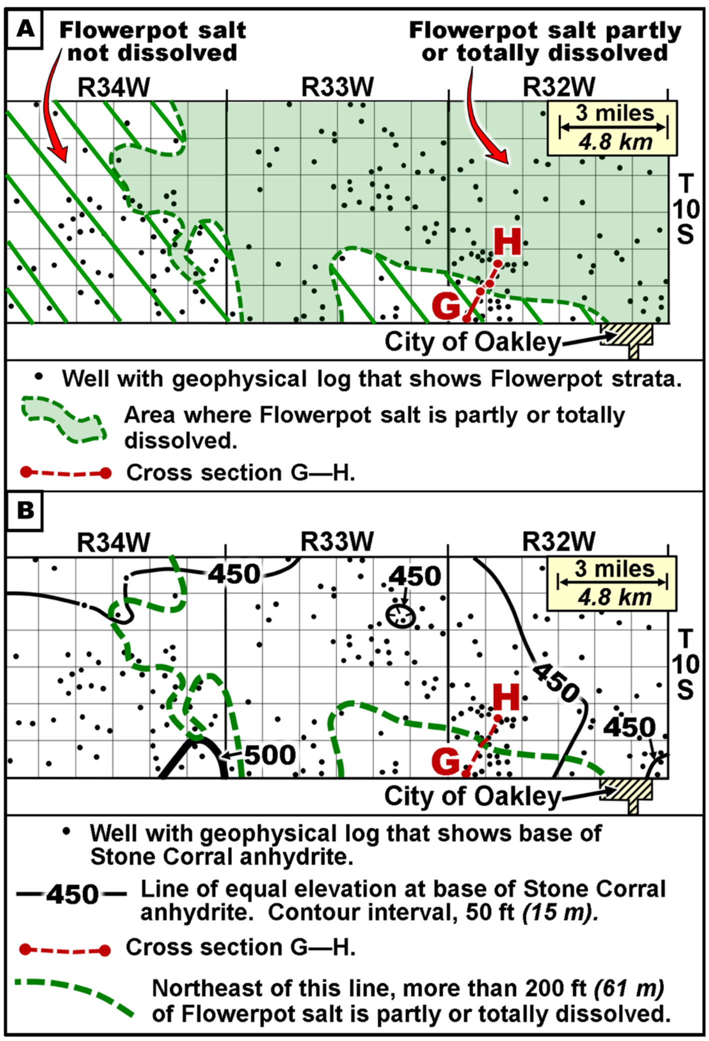

Figure 18. Maps of the North Oakley area in Thomas County, northwest Kansas. A) Map shows where Flowerpot salt is more than 200 ft (61 m) thick (white with green stripes) and where Flowerpot salt is partly or totally dissolved (green). There is no middle Blaine salt in this area. B) Elevation of base of the Stone Corral anhydrite. Cross section G–H shown in figs. 20 and 21.

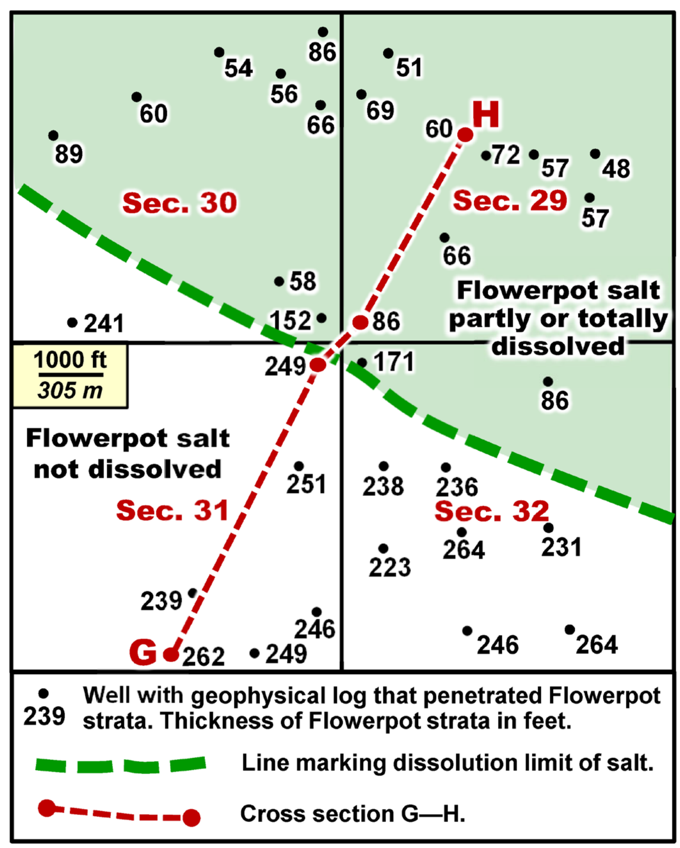

Figure 19. Map showing sharp decrease in thickness of Flowerpot strata (strata from base of Blaine Formation to top of Y-anhydrite) northeast of dissolution limit in secs. 29–32, T. 10 S., R. 32 W., just northwest of Oakley, in the southern part of Thomas County, northwest Kansas. Cross section G–H shown in figs. 20 and 21.

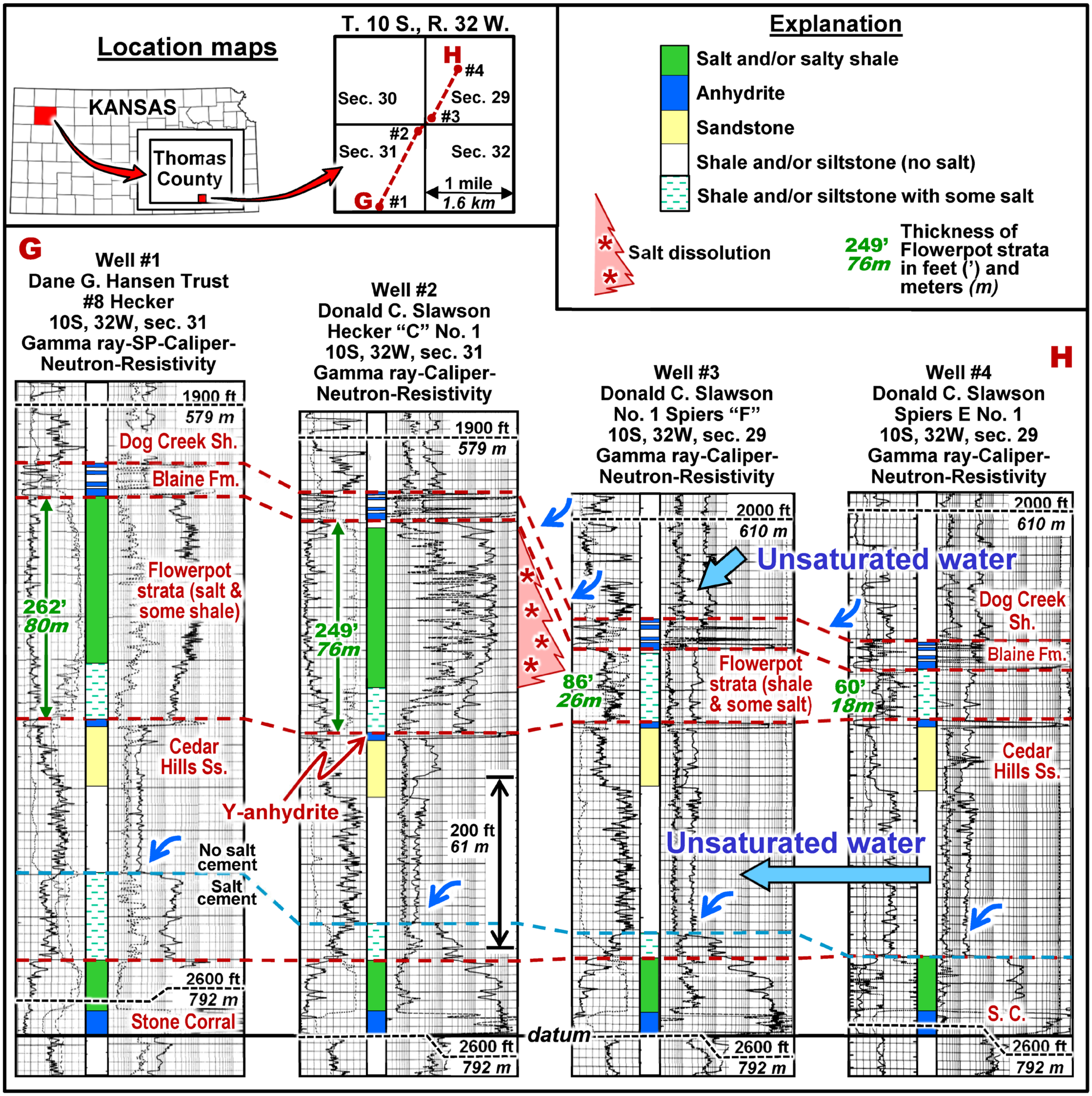

Figure 20. Stratigraphic cross section G–H in North Oakley area shows that dissolution of salt progresses from northeast to southwest. Unsaturated water has dissolved most of the salt from Flowerpot strata in wells #3 and #4 but has not yet reached wells #1 and #2. Middle Blaine salt is missing in the area. Salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Location of cross section G–H shown in figs. 18 and 19.

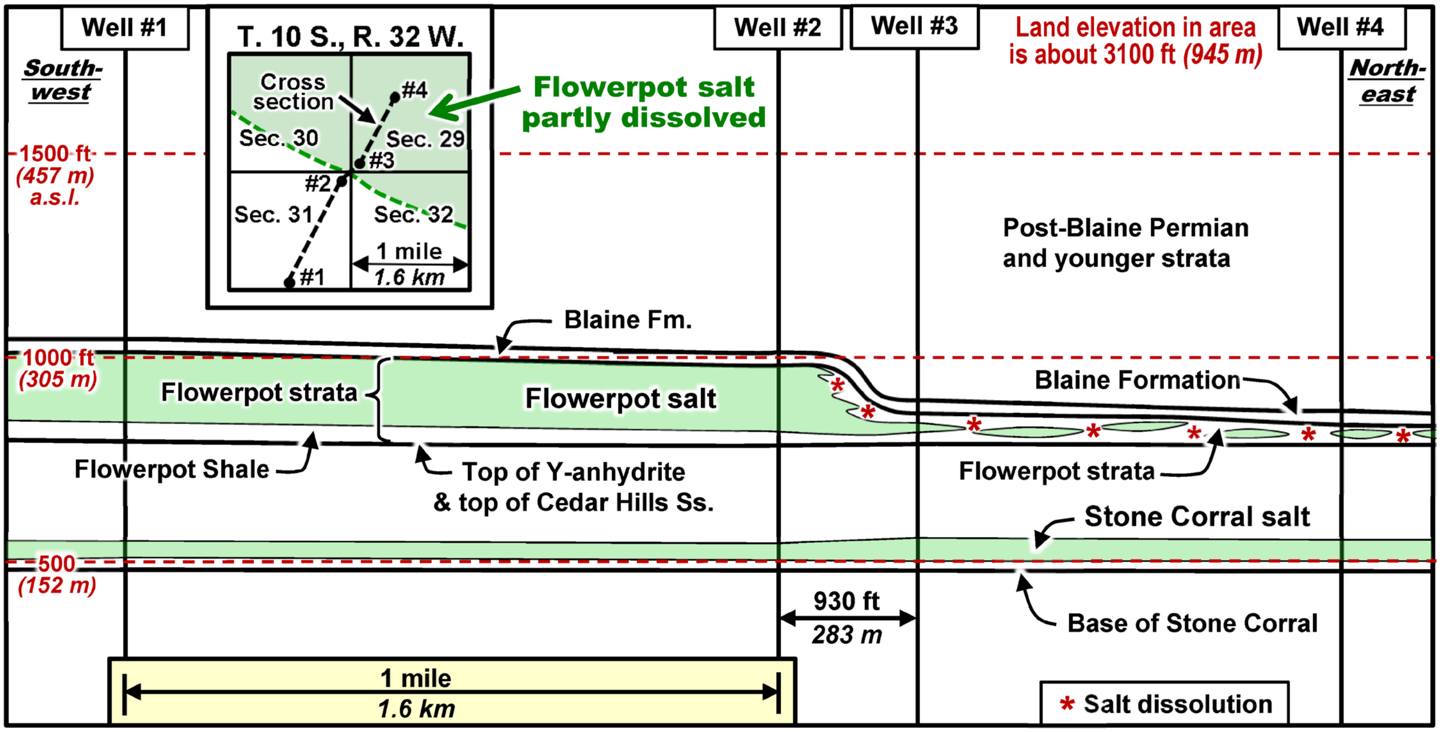

Figure 21. Schematic northeast–southwest structural cross section in the North Oakley area showing dissolution of Flowerpot salt to the northeast and subsidence of overlying strata. Based on well data in fig. 20. Elevations are in feet *(meters)* above sea level.

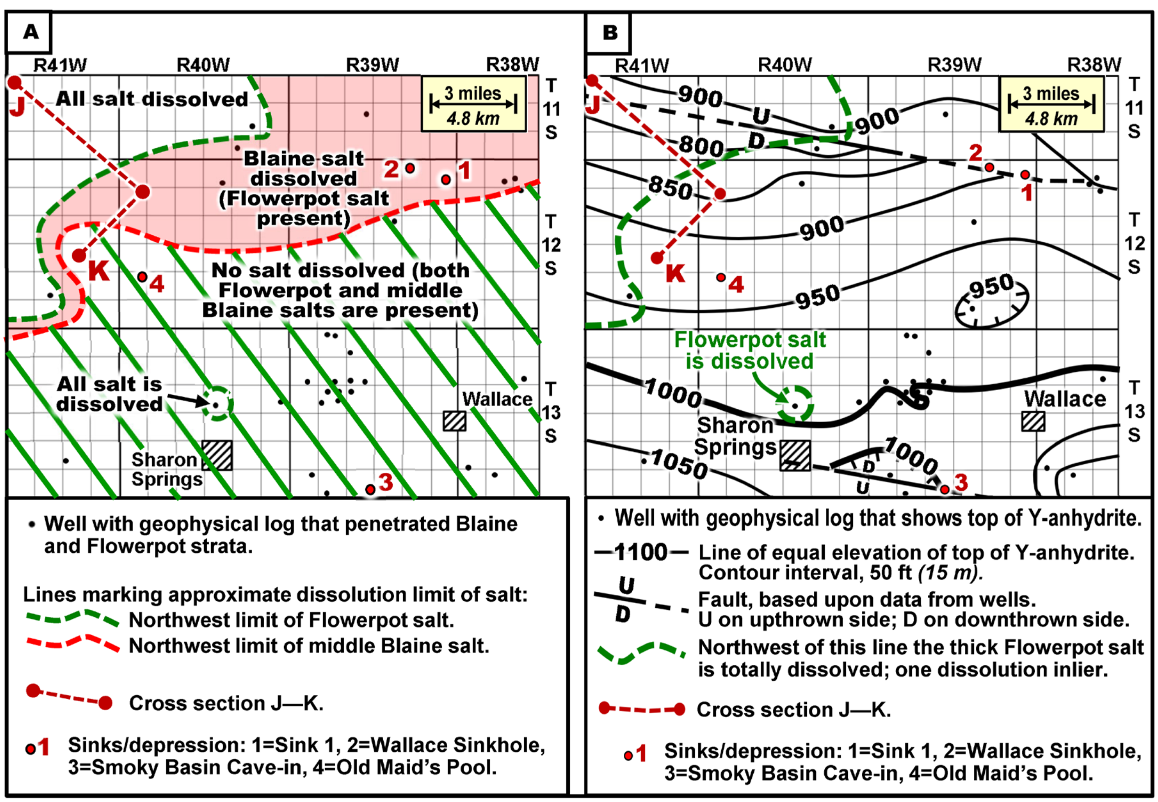

Figure 22. Maps of the Sharon Springs area in Wallace County, northwest Kansas (modified from Johnson, 2021d). A) Dissolution limits of the Flowerpot and middle Blaine salts. B) Elevation of base of the Stone Corral anhydrite. Cross section J–K shown in figs. 23 and 24.

dissolution on Blaine and younger strata above the salt-dissolution zones (Johnson, 2021d). The Y-anhydrite and other strata immediately below the Flowerpot dip gently to the north (fig. 22B) at 12–25 ft/mi (2.3–5 m/km), or about 0.1–0.3 degree. Structure at the top of the Blaine Formation, however, is more complicated. The top of the Blaine dips to the north at about the same rate as the Y-anhydrite in most of the area, but this simple structure is disrupted at many places by subsidence and collapse into dissolution zones in the underlying Flowerpot and middle Blaine salts (Johnson, 2021d). The most conspicuous structural feature in the Blaine Formation is a major monoclinal flexure in the west, where the Blaine and younger formations drop about 150–200 ft (46–61 m) across the Flowerpot salt-dissolution zone (fig. 24).

Three natural sinkholes have formed in the Sharon Springs area (figs. 22, 25) since about 1900 (Johnson, 2021d). Fortunately, all three sinks opened in pastureland and caused no injuries or infrastructure damage. The earliest historic sinkhole, Sink 1, about 9 mi (14 km) north of Wallace, originated about 1900 and now is about 200 ft (61 m) wide (figs. 22, 25D,E). The next sinkhole, the Smoky Basin Cave-in, formed on March 9, 1926, about 5 mi (8 km) east of Sharon Springs (figs. 22, 25F). It was originally described as being 250 by 350 ft (76 by 107 m) wide, and its depth was estimated by early visitors to be at least 300 ft (91 m); however, this depth seems extreme and unreasonable. Early soundings of water depth in the sinkhole showed the middle part of the depression was about 165 ft (50 m) deep, and the volume of the depression

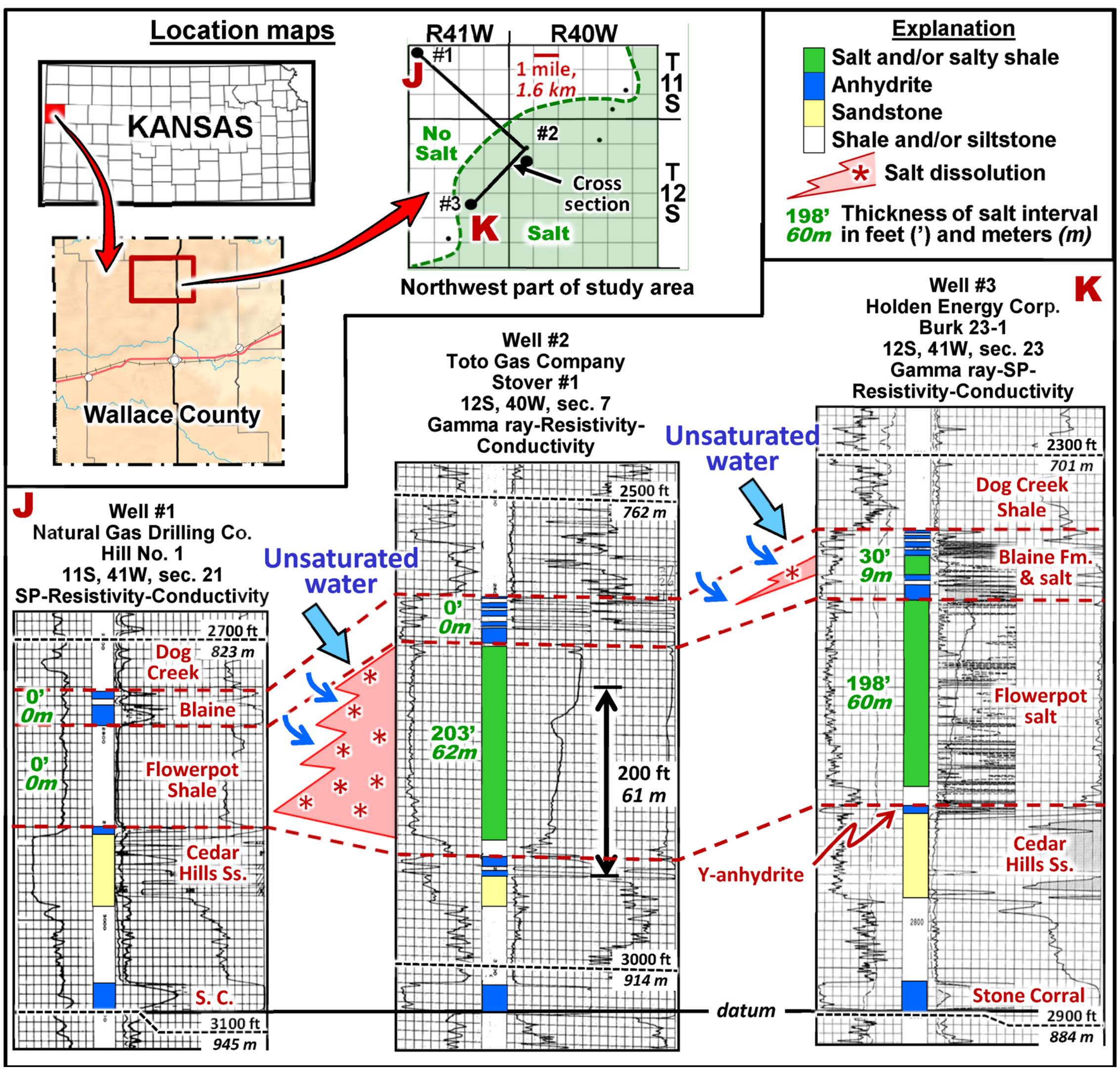

Figure 23. Stratigraphic cross section J–K shows that dissolution of salt in the Sharon Springs area progresses toward the southeast and downward. Unsaturated water first dissolves all the middle Blaine salt (wells #1 and #2) and then all the Flowerpot salt (well #1). Location of cross section shown in fig. 22.

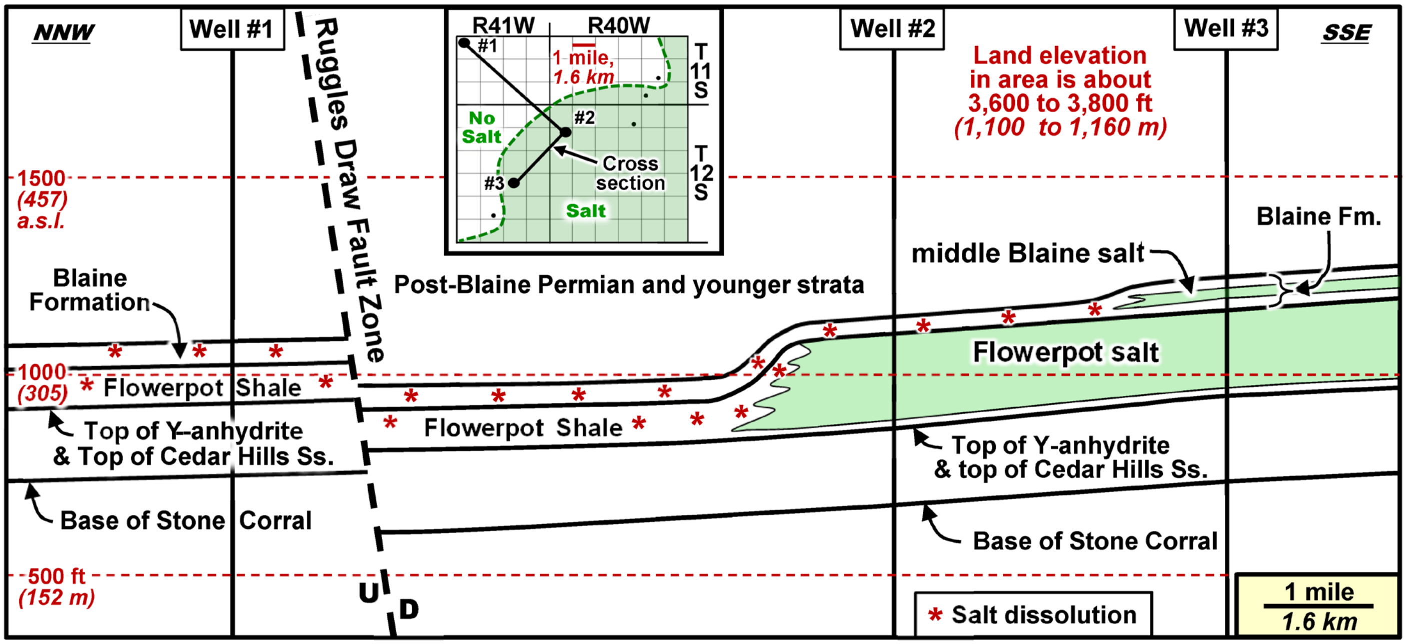

Figure 24. Schematic north-northwest to south-southeast structural cross section in Sharon Springs area showing dissolution of Flowerpot and middle Blaine salts and subsidence of overlying strata. Based on well data in fig. 23. Elevations are in feet *(meters)* above sea level.

was estimated at 1.5 million ft^3 (42,475 m^3). The last historic sinkhole, the Wallace Sinkhole, is about 9 mi (14 km) north of Wallace and about 7,000 ft (2,134 m) west-northwest of Sink 1 (figs. 22, 25A,B). It formed on July 31, 2013, and is now about 200 ft (61 m) in diameter and 90 ft (27 m) deep. A series of concentric fractures around the south side of this sink indicate that the hole could become larger by sloughing off of the sides.

All three historic sinkholes formed along two faults with an orientation of S 80° E (fig. 22B), and it is likely that unsaturated groundwater seeped down in the fault zones and caused salt dissolution. The middle Blaine salt is generally 35–50 ft (11–15 m) thick in the vicinity of these three sinkholes, and the Flowerpot salt is generally 200–225 ft (61–69 m) thick (Johnson, 2021d). Because of the size and depth of these sinks, it is likely that not only is the shallower middle Blaine salt dissolved beneath these three sinkholes, but some (or all?) of the deeper, thick Flowerpot salt is also dissolved.

A large, nearly circular depression, Old Maid's Pool, is present in the western part of the area (figs. 22, 25C). This feature is about 1,000 by 1,500 ft (305 by 457 m) wide and is at least 60 ft (18 m) from the rim to a permanent pool of water (Johnson, 2021d). It probably results from dissolution of all the middle Blaine salt and a significant part (or all?) of the Flowerpot salt from beneath the depression. Two additional natural sinkholes are present in the northeast between Sink 1 and the Wallace Sinkhole. These two sinkholes and the Old Maid's Pool all formed prior to European settlement and cannot be dated (Johnson, 2021d).

Area 5: Great Plains Reservoirs Area

The Great Plains Reservoirs study area is in the south-central part of Kiowa County, southeast Colorado (figs. 2, 26). Johnson (2021e) recently studied the salt deposits and dissolution in this area, and much of the following discussion is based on that study. Both the Flowerpot and middle Blaine salts are present in the northeast part of the area. Where neither salt is dissolved, the Flowerpot salt is 206–245 ft (63–75 m) thick, and the middle Blaine salt is mostly 15–40 ft (5–12 m) thick. Both these salts are dissolved to the southwest, and they are missing entirely in most of the southwest half of the map area. There are, however, at least two outliers of Flowerpot salt that have (so far) escaped dissolution (fig. 26). The dissolution zone appears to vary from about 1 mi (1.6 km) wide in the southeast to 5–6 mi (8–10 km) wide in the north-central part of the area.

Surface evidence of salt dissolution consists of large, natural depressions now used to impound water in four major artificial reservoirs, and several smaller ones, that comprise the Great Plains Reservoirs (Johnson, 2021e) (fig. 26). Dissolution, mainly of the thick Flowerpot salt, caused foundering and collapse of overlying strata, and the collapse

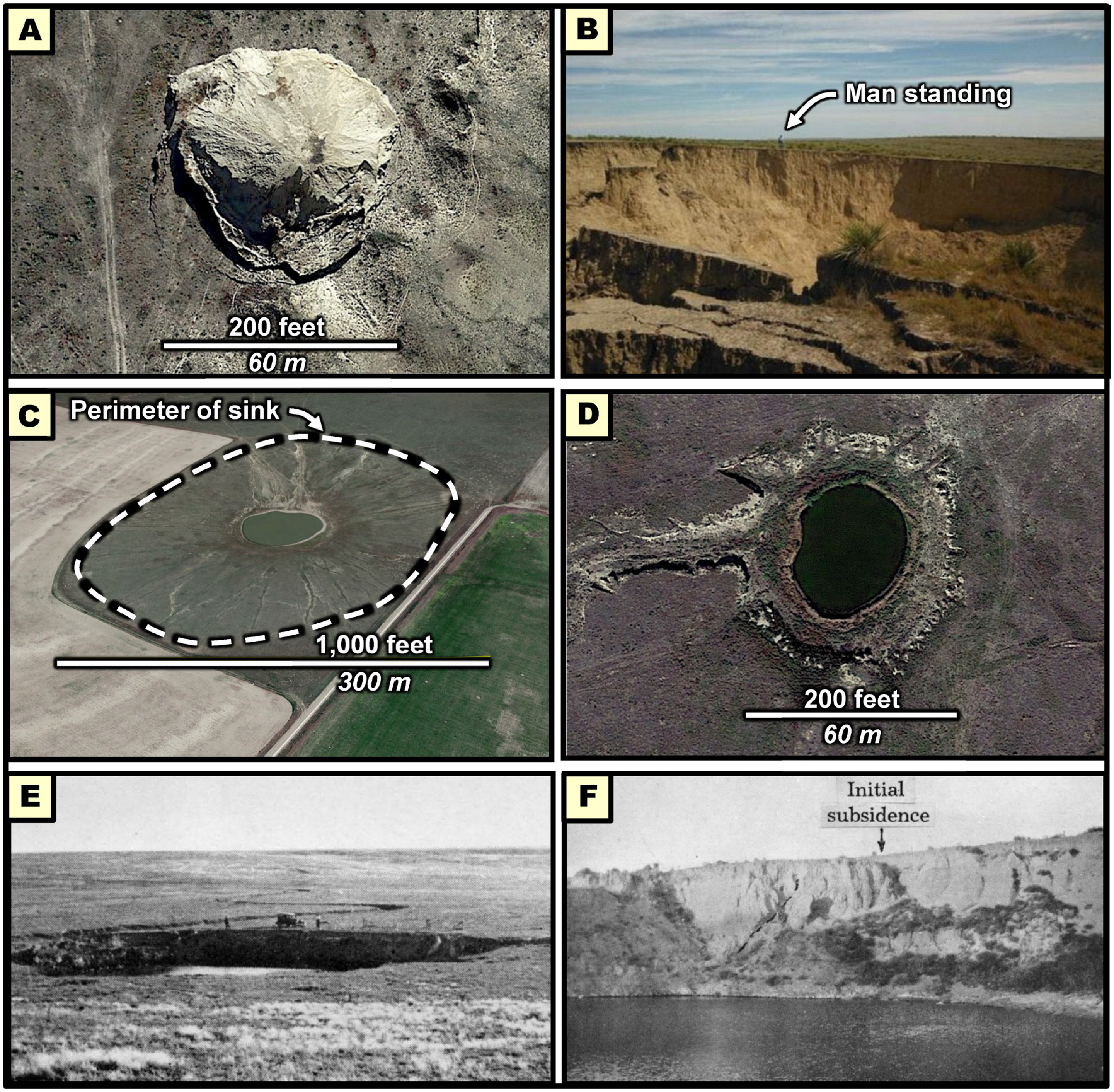

Figure 25. Photos of sinkholes and depressions in the Sharon Springs area (Johnson, 2021d). A) Google Earth vertical view of Wallace Sinkhole, dated October 6, 2014. B) Ground view of Wallace Sinkhole, courtesy Larry Townsend, Wallace County sheriff. C) Google Earth oblique view of Old Maid's Pool, dated July 10, 2016. D) Google Earth vertical view of Sink 1 in Bradford Draw, dated October 6, 2014. E) Ground view of Sink 1, taken about 1930, some 30 years after the sinkhole formed (Elias, 1931, plate XL-B). F) View of Smoky Basin Cave-in, taken about 1930, some four years after the sinkhole formed (Elias, 1931, plate XL-A). Locations of all photos shown on fig. 22.

eventually reached the land surface to form these subsidence features. Dissolution and collapse were not uniform across the area, and the result is that these natural depressions, as well as several smaller depressions, are scattered and localized just beyond the salt-dissolution front.

Salt dissolution in the area is a result of unsaturated water descending from above or moving laterally to the east or northeast (figs. 27, 28). This direction of movement of salt-dissolving water is affirmed by dissolution of the middle Blaine salt first followed by removal of the stratigraphically lower Flowerpot salt. The original westward extent of these salts is unknown, but Ege (1985) mapped a subsurface patch of Flowerpot/Blaine(?) salt about 50 mi (80 km) farther west in Crowley County.

The structural geology of the Great Plains Reservoirs area is fairly simple (fig. 26B), except for the results of salt dissolution on strata above the salt-dissolution zones (Johnson, 2021e). The Y-anhydrite, just below the Flowerpot salt, dips gently to the northeast throughout the area at 10–30 ft/mi (2–6 m/km), or about 0.1–0.3 degree. In contrast, the top of the Blaine Formation presents a more complicated situation. The Blaine Formation has collapsed some 200–245 ft (61–75 m) where the Flowerpot salt is dissolved. Northeast of the Flowerpot salt dissolution front, the Blaine dips gently to the north at 10–30 ft/mi (2–6 m/km). However, the top of the Blaine drops sharply to the southwest, across the underlying dissolution front, and southwest of the front the formation again dips gently to the northeast at 10–30 ft/mi (2–6 m/km). This dramatic drop in elevation of the Blaine across the dissolution front shows up as a monoclinal flexure in cross section (fig. 28).

TIMING OF SALT DISSOLUTION IN THE SYRACUSE BASIN

Dissolution has occurred at different times in different parts of the Syracuse Basin. In most areas, dissolution is well documented to have occurred mainly during the Pliocene–Pleistocene–Holocene Epochs, but locally it is reported to have started before deposition of the Cretaceous or even from Late Permian through Early Cretaceous time (as described below). Inasmuch as the Flowerpot salt is the thickest salt in the Syracuse Basin (thickness generally 200–300 ft [61–91 m]), the timing of its dissolution is more significant than dissolution of the middle Blaine salt (thickness generally 45–60 ft [14–18 m]).

The timing of Flowerpot salt dissolution in the South Syracuse area is documented by accumulation of thick deposits of the Ogallala Formation (Pliocene–Pleistocene) and alluvium (Pleistocene–Holocene) in the resulting depression caused by subsidence (Latta, 1941; McLaughlin, 1943; Fader et al., 1964; Gutentag et al., 1972; Lobmeyer and Sauer, 1974; Macfarlane and Wilson, 2006). The area south of the Bear Creek flexure subsided as salt was being removed, and the Ogallala through Holocene sediments filled this topographic depression as it was being formed. The presence of numerous depressions (small ponds and ephemeral ponds) and the Coolidge Sinkhole (formed in 1929) immediately south of the Bear

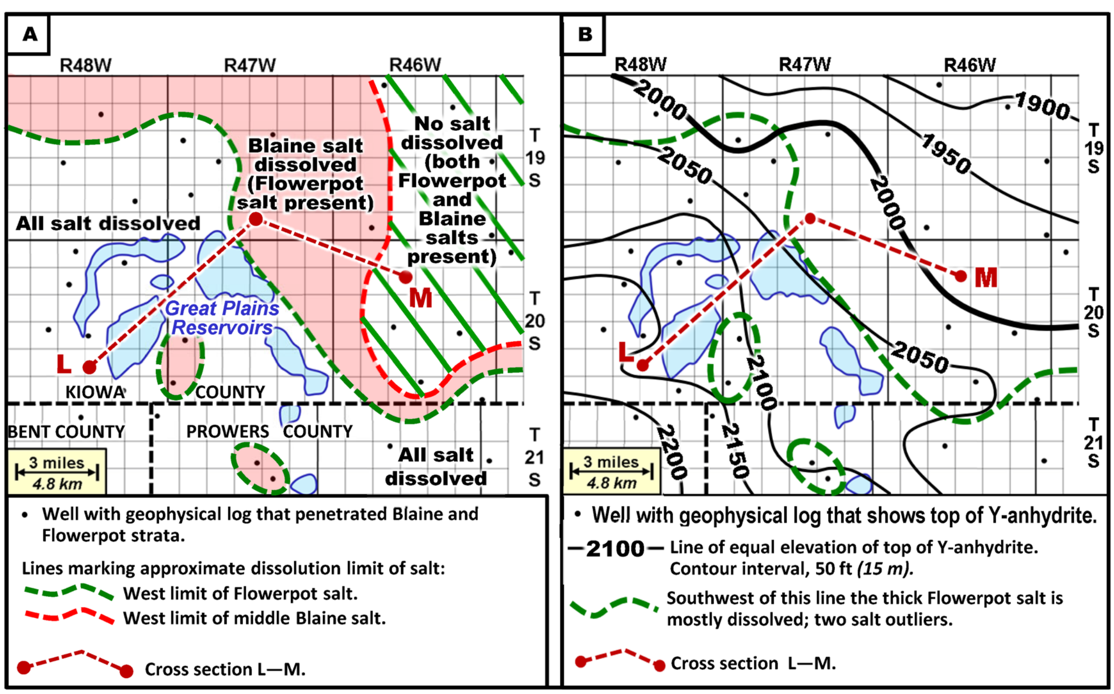

Figure 26. Maps of the Great Plains Reservoirs area in Kiowa, Prowers, and Bent counties, southeast Colorado (modified from Johnson, 2021e). A) Dissolution limits of the Flowerpot and middle Blaine salts. B) Elevation of base of the Stone Corral anhydrite. Cross section L–M shown in figs. 27 and 28.

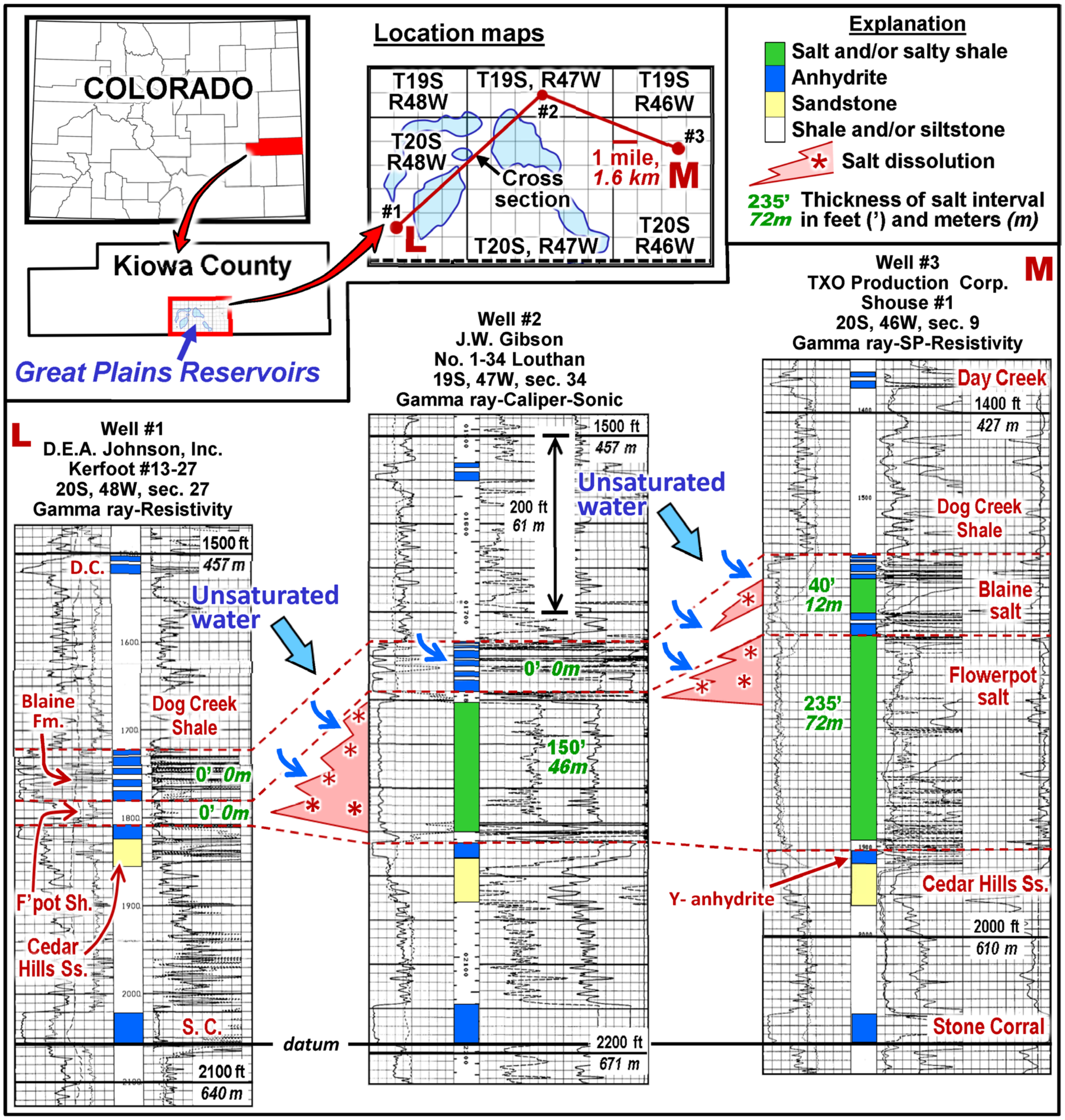

Figure 27. Stratigraphic cross section L–M shows that dissolution of salt in the Great Plains Reservoirs area progresses toward the east and downward. Unsaturated water first dissolves all the middle Blaine salt (wells #1 and #2) and then all the Flowerpot salt (well #1). Location of cross section shown in fig. 26.

Creek flexure show that dissolution is still occurring in the South Syracuse area.

The Finney-Kearny County area is at the south end of the Scott-Finney depression, which coincides with the Flowerpot salt-dissolution zone along much of the east side of the Syracuse Basin (Fig. 5C). Development of this dissolution zone started in Ogallala or pre-Ogallala times, according to Smith (1940). Macfarlane et al. (1993) note that thickening of Cretaceous formations above the dissolution zone suggests that dissolution has been going on here at least since before deposition of the Cretaceous. Waite (1947) shows that up to 200 ft (61 m) of undifferentiated Pleistocene sediments are present in test holes drilled in the Scott-Finney depression.

No data are available on the timing of salt dissolution in the North Oakley area. Studies of Thomas County by Frye (1945) and of adjacent Logan County by Johnson (1958) did not report any conspicuous features that are due to dissolution of salt in the subsurface. Just to the south of the North Oakley area, in northern Logan County, Johnson (1958) shows that the Ogallala thickness locally reaches about 200 ft (61 m) in a wide, buried valley cut into the underlying Cretaceous strata (Pierre Shale) during pre-Pliocene time. However, the buried valley cannot be related

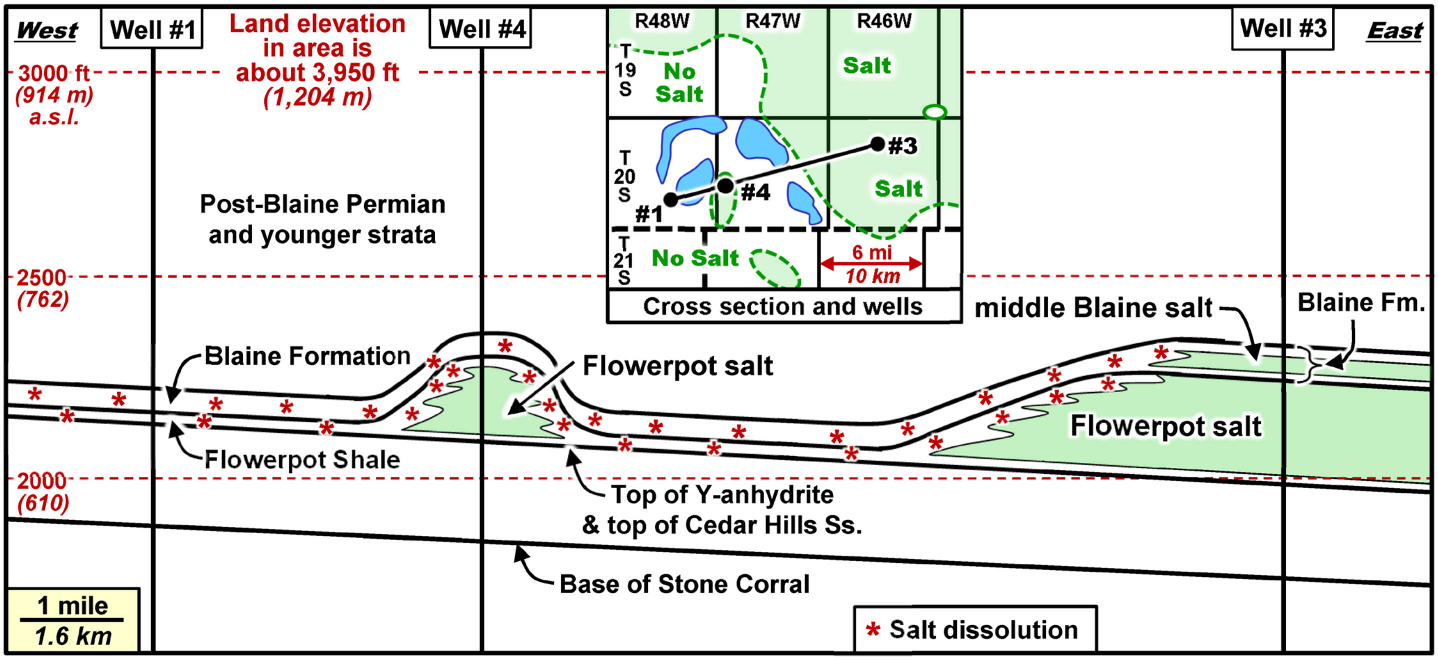

Figure 28. Schematic east–west structural cross section in Great Plains Reservoirs area showing dissolution of Flowerpot and middle Blaine salt beds and subsidence of overlying strata. Based on well data in fig. 27. Elevations are in feet *(meters)* above sea level. Wells #1 and #3 are identified in fig. 27; well #4 is the D. D. Harrington, Baughman "A" #1, sec. 19, T. 20 S., R. 47 W.

to Flowerpot salt dissolution because it extends from Oakley to the west-southwest for about 25 mi (40 km). This paleovalley does not parallel the dissolution front but is oriented at an angle about 60 degrees from the dissolution front in the area.

The Sharon Springs area contains three historic sinkholes (Johnson, 2021d), thus affirming that salt dissolution is still going on here. These historic sinks — Wallace Sinkhole, Smoky Basin Cave-in, and Sink 1 (figs. 22, 25) — formed between about 1900 and 2013 and are structurally controlled. That is, they line up along two fault zones that have an orientation of S 80° E. In addition, three other sinks of earlier but unknown age are present in the area (Johnson, 2021d): Sinks 2 and 3, each about 150–200 ft (46–61 m) wide, are located between the Wallace Sink and Sink 1; Old Maid's Pool is a large depression located about 3 mi (4.8 km) east of the present Flowerpot salt dissolution front. Wallace County studies by Elias (1931) and Hodson (1963) noted the historic and prehistoric sinks (except for the Wallace Sinkhole, which formed in 2013) but did not recognize the significance of salt dissolution in forming the sinkholes. The common view at those times was that they resulted from dissolution of the Late Cretaceous Niobrara chalk along fault lines. Contours on the base of the Ogallala present a fairly complex surface, particularly in the northwest part of the Sharon Springs area (plate 1 in Hodson, 1963). This probably results from salt dissolution and irregular collapse of overlying strata, including the base of the Ogallala, but it does not indicate when salt dissolution may have started in the area.

The timing of salt dissolution in the Great Plains Reservoirs area is not known, but it may have started during or after Late Cretaceous time and persisted until the Late Pleistocene or Holocene Epochs (Johnson, 2021e). It certainly was prior to European settlement of the area in the late 1800s, as there are no historic reports of subsidence or collapse in the area. The artificial reservoirs here were created in the late 1800s by channeling water from the nearby Arkansas River into large, natural depressions caused by salt dissolution (Johnson, 2021e). The depressions were probably continuing to form during the Late Pleistocene or Holocene. They would likely have been filled and covered by windblown or sheetwash sediment if the current depressions had stopped subsiding at a much earlier time. It is likely that salt is still being dissolved here today. Data on salt dissolution are available in two areas near the Great Plains Reservoirs. About 20 mi (32 km) to the north, in Cheyenne and Kiowa counties, Colorado, Berry (2018) concluded that dissolution of the Flowerpot salt on the west side of the Syracuse Basin occurred in post-Taloga time (Late Permian) but before deposition of the early Late Cretaceous Dakota Formation. Also, three fossil sinkholes in Prowers County, about 20 mi (32 km) southeast of Great Plains Reservoirs, are about 100 ft (30 m) in diameter and contain brecciated blocks of the Late Cretaceous Niobrara Formation. Their collapse was assumed to have occurred sometime in the Pleistocene (Dane and Pierce, 1934).

ORIGINAL EXTENT OF FLOWERPOT AND BLAINE SALTS BEYOND THE SYRACUSE BASIN

The Flowerpot and middle Blaine salts have dissolution boundaries around the perimeter of the Syracuse Basin, but the original extent of both these salt bodies went far beyond the present boundaries. Remnants of both these salts are still present in several large, separate regions that extend from northeast Colorado and western Nebraska on the north to western Oklahoma, Texas Panhandle, and northeast New Mexico on the south (fig. 29).

Original Extent of Flowerpot salt

The original extent of the Flowerpot salt went far beyond the Syracuse Basin. The Flowerpot salt is recognizable below the Blaine Formation and can be traced discontinuously from the Palo Duro and Anadarko basins on the south (fig. 4 in Hovorka and Granger, 1988; fig. 8 in Johnson, 2021c), through the Syracuse Basin (this study), and at least to the northern part of the Denver Basin in western Nebraska and southeast Wyoming (fig. 8–10 in Oldham, 1996, 1997). And it can be traced from Washita and Custer counties, Oklahoma, in the east (fig. 7 in Johnson, 1967: plate III in Jordan and Vosburg, 1963), to Guadalupe County, New Mexico, in the west (plate 19 in McKee, Oriel, et al., 1967; plates D–F in McGookey et al., 1988). This area, originally underlain continuously by the Flowerpot salt, is at least 590 mi (950 km) from south to north and as much as 310 mi (500 km) from east to west, a total area of about 115,800 mi^2 (300,000 km^2) (fig. 29).

Flowerpot and Blaine evaporites north of the Matador arch in north-central Texas are the lateral equivalents of San Andres carbonates in the back-reef area of the Delaware and Midland basins, located farther to the south and west (Presley, 1981; McGookey et al., 1988; Hovorka et al., 1993). Lateral gradation of the San Andres carbonates into the Flowerpot and Blaine evaporites from the south to the north and northeast is as follows: 1) from the Midland Basin, thick San Andres back-reef carbonates grade into the thick San Andres evaporite sequence of the Palo Duro Basin; 2) farther north, salt and gypsum/anhydrite units in part of the San Andres grade into the Flowerpot and Blaine Formations of the Anadarko Basin; and 3) still farther north, in the Syracuse Basin and beyond, the Blaine Formation and the Flowerpot and middle Blaine salts were originally deposited over a vast area, but the salts now have a more limited distribution due to dissolution (fig. 29).

Flowerpot salt west and northwest of the Syracuse Basin (in the Denver Basin) is referred to as "salt 7" by Oldham (1996, 1997) and as "lower Blaine halite" by Berry (2018). South of the Syracuse Basin, the term Flowerpot salt is used in the Anadarko Basin of Oklahoma and the Texas Panhandle (Jordan and Vosburg, 1963; Johnson, 1976). Still farther south, in the Palo Duro Basin, it is part of "lower San Andres Formation unit 4" (Presley, 1981; Hovorka et al., 1993; Johnson, 2021c).

Current limits of the Flowerpot salt are dissolutional limits in almost all areas from the Palo Duro Basin to the Denver Basin (fig. 29). Invariably, at and beyond these dissolutional limits, overlying Permian and younger strata are disrupted with chaotic structures, collapse features, breccia pipes, or sinkholes, thus showing that the dissolution is not syndepositional, or shortly after

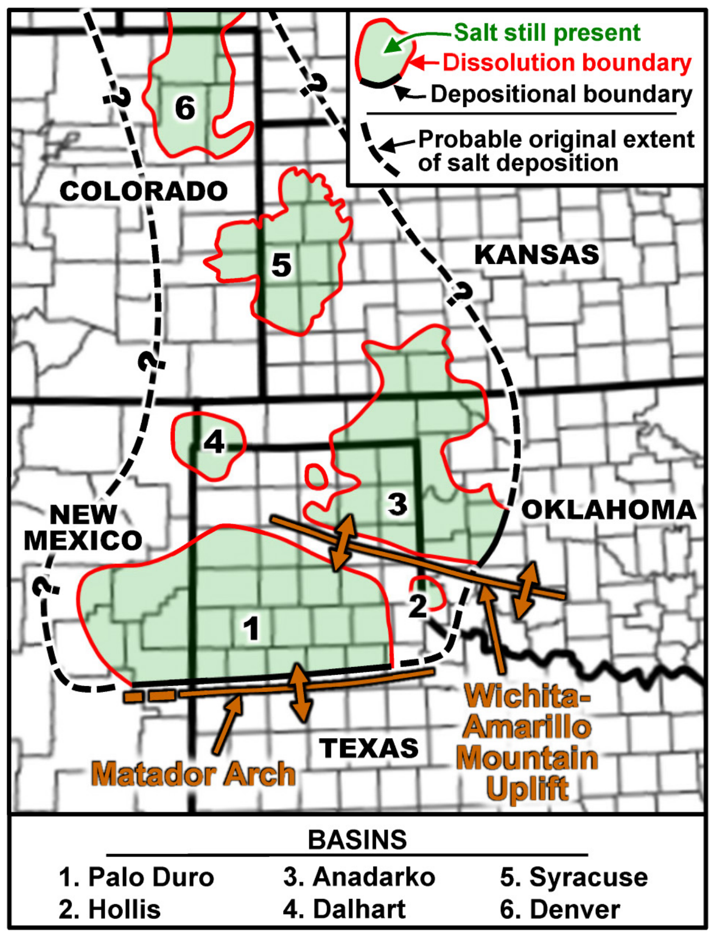

Figure 29. Map showing Flowerpot salt that remains in the Greater Permian Evaporite Basin and an estimate of the probable original area of Flowerpot salt deposition. The current limits of the Flowerpot salt are dissolutional boundaries in all areas, except at the Matador arch in the south and the eastern area of the Anadarko Basin.

deposition, but is Late Permian or post Permian, and in some areas is even going on today. In most parts of the GPEB, the Flowerpot salt is preserved in the deeper part of structural basins (fig. 29), but it is dissolved on the flanks of the basins where the salt was at shallower depths and more likely to encounter unsaturated groundwater. This is well illustrated in the northern part of the Palo Duro Basin and southern part of the Anadarko Basin, where the Flowerpot salt is dissolved as it rises in elevation on the flanks of the Wichita–Amarillo Mountain uplift (Johnson, 1976; Presley, 1981; McGookey et al., 1988).

Dissolutional limits of the Flowerpot salt have been shown in the following studies: in the Palo Duro, Hollis, Anadarko, and Dalhart basins, studies by Johnson (1976), Gustavson et al. (1980), Presley (1981), and McGookey et al. (1988); in the Syracuse Basin, by Smith (1940), Moore (1954), Schumaker (1966), Holdoway (1978), Macfarlane et al. (1993), Macfarlane and Wilson (2006), and the current study; and in the Denver Basin, by Oldham (1996, 1997) and Berry (2018). Original depositional limits of the Flowerpot salt are preserved only at the Matador arch in Texas and in part of the Anadarko Basin of Oklahoma. At the Matador arch, the Flowerpot salt, labeled as part of unit 4 in the lower San Andres Formation in the Palo Duro Basin, grades laterally to the south into a back-reef facies of dolomite, anhydrite, and limestone on the north side of the Midland Basin (Presley, 1981; McGookey et al., 1988; Hovorka et al., 1993). In the Anadarko Basin, the Flowerpot salt grades laterally to the east into red-bed mudstones of the Flowerpot Shale (Jordan and Vosburg, 1963; Johnson, 1963, 1967).

Original Extent of Middle Blaine Salt

The middle Blaine salt may have been nearly as widespread as the Flowerpot salt in the GPEB, and, like the Flowerpot salt, it now occurs as regional, dissolutional remnants in most parts of the GPEB. This salt has been unnamed or given different names in different regions of the GPEB. On the south side of the Palo Duro Basin, at the Matador arch, a back-reef facies of dolomite, anhydrite, and limestone grades northward into the middle Blaine salt, which here is an unnamed salt in the upper part of the "lower San Andres Formation unit 5" (Presley, 1981; McGookey et al., 1988; Hovorka and Granger, 1988; Hovorka et al., 1993; Johnson, 2021c). Farther northeast, in the deep Anadarko Basin in Oklahoma, it is an unnamed salt in the middle of the Blaine Formation, just above the Collingsworth Bed (which is equivalent to the Nescatunga Bed) (Johnson, 1963, 1967, 2021c). In Baca County, southeast Colorado, midway between the Dalhart and Syracuse basins, Askew (2013) calls it the "middle Blaine salt." And in the Denver Basin, it is referred to as "salt 5" by Oldham (1996, 1997) and as "upper Blaine halite" by Berry (2018).

PROBLEMS ASSOCIATED WITH SALT DISSOLUTION

Underground cavities formed by salt dissolution can become too large for the roof to be self-supporting, leading to roof collapse. Successive roof failures may cause the collapse to migrate upward and perhaps reach the land surface. Therefore, dissolution of salt can cause serious problems by generating sinkholes and subsidence features at the land surface. Salt deposits and salt dissolution can also cause problems in exploration for petroleum: 1) seismic-reflection surveys across a dissolution boundary can lead to false images (phantom structures) in strata below the dissolution zone; and 2) drilling through salt beds may require special drilling muds, as well as special casing and casing-cement programs, to isolate the salt from unsaturated water that could cause cavity development in the salt and ultimate collapse.

Sinkholes and Subsidence Features

Sinkholes and subsidence features can easily form above sites or zones where the Flowerpot or Blaine salts are undergoing current dissolution, and when such collapse features reach the land surface, they can cause disruption of local infrastructure (houses, roads, etc.) and can even cause human injury or death. Several historic natural sinkholes that formed within the Syracuse Basin are described elsewhere in this study: 1) the Coolidge Sinkhole in the South Syracuse area (fig. 13) and 2) the Wallace Sinkhole, Smoky Basin Cave-in, and Sink 1 in the Sharon Springs area (fig. 25). Another historic sinkhole in western Kansas is the Meade Salt Sink, located about 1.5 mi (2.4 km) southeast of Meade, in Meade County, southeast of the Syracuse Basin. It formed in 1879, is about 200 ft (61 m) wide, and is located just east of the Crooked Creek–Fowler dissolution zone (Smith, 1940; Merriam and Mann, 1957; Merriam, 1963; Macfarlane and Wilson, 2006).

Several prehistoric sinkholes and subsidence features are present in western Kansas and eastern Colorado. Two areas of large, natural-subsidence topographic features located above dissolution zones are described elsewhere in this paper: 1) a series of natural subsidence- and sinkhole-related streams, lakes, and ponds (the "string of pearls") are present in the South Syracuse area and 2) major subsidence features are now being used to store water in the Great Plains Reservoirs area. Other prehistoric sinks in the Syracuse Basin, located in the Sharon Springs area, are the Old Maid's Pool (fig. 25C) as well as two more sinks in the vicinity of the Wallace Sinkhole and Sink 1 (Johnson, 2021d). Prehistoric sinkholes or depressions located southeast of the Syracuse Basin in Meade and Clark counties, Kansas, include Jones Ranch Sink, Big Basin, Little Basin, Jacob's Well, and Ashland Basin (Smith, 1940; Merriam and Mann, 1957; Appendix D in Merriam, 1963; Macfarlane and Wilson, 2006). Also, three roughly circular breccia pipes, about 100–200 ft (30–61 m) in diameter and containing collapsed Cretaceous strata, are exposed in northeast Prowers County, Colorado (Dane and Pierce, 1934). A general discussion and examples of sinkholes and subsidence features due to dissolution of evaporite rocks throughout the GPEB is given in Johnson (2021a).

Petroleum Exploration

Salt-dissolution boundaries, or salt outliers or inliers, can cause acoustic anomalies in seismic-reflection data (Widess, 1952; Moore, 1954; Jordan and Vosburg, 1963; Rummerfield and Rummerfield, 1989; Anderson et al., 1995; Oldham, 1996, 1997). Where Flowerpot or Blaine salts are dissolved in the GPEB, their stratigraphic positions are replaced by shales or mudstones—the residue after halite is removed from the displacive salt (Benison et al., 2015). Because salt has a much higher seismic velocity (faster wave propagation, or lower transit time in microseconds per foot) than shale or mudstone and because the thickness of a salt unit can change abruptly across a dissolution boundary, seismic indications of the depth to sub-salt horizons may be in error on maps or cross sections that cross a dissolution zone. Therefore, if the lateral transition from salt to residual shale or mudstone across a dissolution zone is not recognized or taken into consideration, anomalous phantom structures (faults or folds) may be mapped in sub-salt strata.

Widess (1952) and Moore (1954) discussed the seismic-velocity problem and the results of an extensive core-drill program that examined salt-bearing strata (the Flowerpot salt) between the Blaine Formation and the Stone Corral (Cimarron) anhydrite in southwestern Kansas and the Oklahoma Panhandle. Their study area included most of the Syracuse Basin and part of another large residual mass of Flowerpot salt to the southeast that extends into the Anadarko Basin (the northern part of area 3 in fig. 29). Their study noted that the thickness of the salt-bearing zone in the Blaine–Stone Corral interval decreased sharply at the boundaries of these regions from about 350 ft to 100 ft (107 m to 30 m), generally within a lateral distance of about 2–4 mi (3.2–6.4 km).

Widess (1952) and Moore (1954) concluded that the salt originally extended between the Syracuse and Anadarko basins but has been dissolved in the area between the two basins. Both authors made the following observations: 1) The thick Flowerpot salt is present in both the basins but is absent in the intervening 68 mi (109 km); 2) the lateral extent of salt is terminated abruptly at the edges of both regions; and 3) surface depressions, sinks, and basins are present at and near both salt-termination zones. In addition, whereas strata above the Flowerpot, including the Blaine Formation through Pliocene–Pleistocene sediments, are dropped down (flexed or faulted) across the salt-termination zones, the Stone Corral maintains a normal, unbroken regional dip beneath the dissolution zones. They also noted abrupt changes in seismic velocity in seismic surveys across these salt-dissolution boundaries, and this falsely suggested similar amounts of structural relief in deeper strata. Therefore, knowing the location of these salt-dissolution zones is critical in interpretation of seismic data.

Rummerfield and Rummerfield (1989) summarized the seismic-velocity problem in an area of salt dissolution in the Stone Corral, Flowerpot, and Blaine salts in part of the Anadarko Basin to the southeast of the Syracuse Basin, mainly in Meade, Clark, Gray, and Ford counties, Kansas. The dissolution zone here is similar to the South Syracuse area dissolution zone. The authors show that poor seismic reflections and velocity problems are due in part to dissolution of the Permian salts and the subsequent collapse of overlying strata. These dissolution-related phenomena distort, absorb, and disperse seismic energy and distort the accuracy of sub-salt seismic reflections by causing errors of more than 300 ft (91 m) in seismic depths in less than 3 mi (4.8 km), horizontally.

Anderson et al. (1995) summarized the difficulty of interpreting sub-salt seismic data beneath dissolution zones in the Hutchinson Salt in central and south-central Kansas. They pointed out that with seismic data, one must differentiate real structures from apparent structures in sub-salt strata to avoid drilling into non-existent structures, such as phantom folds and faults. Although their study was of the Hutchinson Salt, they caution that geologists working in any part of Kansas—and that includes the Syracuse Basin region—need to be aware of the presence and distribution of salt and of the location and magnitude of salt-dissolution features.

Jordan and Vosburg (1963) point out that the thickness and depth of salt units are also needed during the drilling of boreholes. Knowing the depth to salt can ensure that surface casing is set before drilling into the salt, so shallow aquifers are not contaminated by brine that could result from dissolving the salt. Engineers also can use depth-of-salt data in planning the drilling-mud program for drilling a well: 1) a salt-based drilling mud can be used while drilling through the salt, so there is little or no dissolution or hole enlargement in the salt section; 2) in drilling below the salt, mud characteristics can be radically altered by dissolved salt entering the drilling fluid, so a casing program should be designed to seal off the salt interval and prevent further contamination of the mud; and 3) casing programs, and injection of cement into salt cavities behind the casing, can also seal off the salt from any unsaturated fluids in the borehole that might dissolve the salt, as that could result in forming or enlarging a cavern in the salt and perhaps causing ultimate collapse of overlying strata (and even the land surface) into the solution cavity. Examples of sinkholes inadvertently created by boreholes drilled through salt deposits in Kansas are given in Walters (1978, 1991) and Johnson (2021a).

On the beneficial side, salt dissolution can be an aid in petroleum occurrence by creating structural traps for oil or gas in strata overlying areas of dissolution. Oldham (1996, 1997) points out that variations in salt thickness due to dissolution in the Denver Basin have created hydrocarbon-productive, closed structural highs in overlying Cretaceous strata. If anticlines or domes are created above irregular salt-dissolution zones, they can become favorable sites for trapping oil or gas that might later migrate through the area. Examples cited in the Denver Basin are the shallow Niobrara gas trend in eastern Colorado and the D and J sandstone fields of Colorado and Nebraska (Oldham, 1996, 1997).

SUMMARY

The Syracuse Basin is a large region of about 8,100 mi^2 (21,000 km^2) in western Kansas and eastern Colorado where the Permian-age Flowerpot and middle Blaine salts are isolated due to dissolution of those same salts around the entire perimeter of the basin. It is not a structural or depositional basin but is a salt-dissolutional remnant of what were, at one time, much more extensive salt deposits. The two main salt units, the Flowerpot salt and the middle Blaine salt, consist mainly of displacive halite in red-brown shales and siltstones (mudstones). The Flowerpot salt is generally 200–300 ft (61–91 m) thick within the basin, but outside the basin the salt is partially or totally dissolved and equivalent strata are 50–150 ft (15–46 m) thick. The middle Blaine salt is typically 45–60 ft (14–18 m) thick in the basin, but equivalent strata are 5–10 ft (1.5–3 m) thick outside the basin where all the salt is dissolved.

In the five areas selected for detailed study around the perimeter of the basin, about 250 ft (76 m) of Flowerpot salt is dissolved over various horizontal distances, ranging from about 930 ft (283 m) to as much as 14 mi (23 km). Three features show that the Syracuse Basin is a dissolutional remnant and not a structural or depositional basin: 1) Sub-salt strata dip gently and uninterrupted beneath the dissolution zone around the perimeter of the basin; 2) strata above the salt are disrupted and are flexed down by an amount roughly equal to the amount of dissolved salt; and 3) outliers or patches of undissolved salt are present at several places outside the perimeter of the basin. In four of the five detailed-study areas, unsaturated groundwater descended and moved toward the center of the basin to first dissolve the middle Blaine salt and then the deeper Flowerpot salt. But in the Finney-Kearny County area, unsaturated groundwater in the sub-salt Cedar Hills Sandstone aquifer moved upward, first dissolving the Flowerpot salt and then moving to the shallower middle Blaine salt.

Salt dissolution occurred at different times in different parts of the Syracuse Basin. Although in most areas it occurred mainly during the Pliocene–Pleistocene–Holocene Epochs, in some areas it started before deposition of the Cretaceous or even from Late Permian through Early Cretaceous time.

Originally, the Flowerpot and middle Blaine salts extended far beyond the Syracuse Basin and reached large regions as far north as the Denver Basin in northeast Colorado and western Nebraska and as far south as the Anadarko and Palo Duro basins in Oklahoma, Texas, and New Mexico, a total area of about 115,800 mi^2 (300,000 km^2). In all these regions, the two salt units have dissolutional boundaries, just like those around the perimeter of the Syracuse Basin.

Both natural and human-induced salt dissolution can cause problems if an underground cavity in salt becomes so large that its roof can no longer support the overlying strata. In such a case, the roof may collapse, and stoping of overlying rocks could eventually lead to ground subsidence or a catastrophic sinkhole. Interpreting the structure of sub-salt strata in seismic-reflection surveys that cross a salt-dissolution boundary can also be a problem: False images, such as phantom folds or faults, may be created in strata below the dissolution zone.

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