The Role of the Cedar Hills/Lyons Sandstone Aquifer in the Dissolution of Halite Cement from Siliciclastic Sediments of the Permian Nippewalla Group in the Syracuse Basin in Western Kansas and Eastern Colorado

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ABSTRACT

The Syracuse Basin presents a rare opportunity to study a salt- and salt-cement-dissolution system over an extremely large area. Abundant geophysical well-log control spanning the salt- bearing interior sediments and their lateral salt-dissolved equivalents is available to define and characterize this salt-dissolution phenomenon. Detailed regional mapping using this abundant well-log database reveals a broad salt-cement-dissolution halo around the entire perimeter of the Syracuse Basin in Nippewalla Group siliciclastic sediments radiating outward from the central salt-preserved interior of the basin.

Five areas around the perimeter of the basin were selected for detailed study to illustrate the dominant role of the Cedar Hills/Lyons Sandstone aquifer in the salt-dissolution system. The Cedar Hills/Lyons Sandstone stands out as the most prominent and regionally widespread aquifer within Permian sediments of the Syracuse Basin and surrounding region. Detailed regional subsurface mapping and cross sections presented in this paper clearly show that this high-quality confined aquifer delivered (and is still delivering) groundwater that is unsaturated with respect to sodium chloride and is responsible for this major regional phenomenon of dissolution of halite in salt-cemented siliciclastics.

We will show that water unsaturated with sodium chloride encroaches on salt-bearing siliciclastic units of the Nippewalla Group in the Syracuse Basin by first invading the Cedar Hills/Lyons Sandstone, where the water is under hydrostatic pressure. Unsaturated water then is forced down into the underlying Salt Plain Formation and Harper Sandstone, dissolving interstitial salt in those formations, and may then go deeper and dissolve the Stone Corral salt. Unsaturated water in the Cedar Hills/Lyons is locally forced upward to dissolve some or all of the overlying Flowerpot salt—mainly where the overlying Y-anhydrite aquitard is absent.

A preliminary semi-regional resistivity map is presented for the Cedar Hills/Lyons Sandstone aquifer. Dramatic resistivity contrasts between fresher unsaturated recharge groundwaters (with higher resistivity readings of 10 to 20+ ohm-meters) and highly saline brines (with ultra-low resistivity readings of less than 0.1

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to 0.5 ohm-meters) associated with salt-dissolution events can reveal clues about modern- and paleo-hydrologic history as well as about the dissolution and flushing history of the highly saline brines created by this process.

Semi-regional dissolution "halo" maps and resistivity (water-salinity) maps are herein generated by well-log studies of the Nippewalla Group evaporitic sediments in the Syracuse Basin region. Oil and gas regulatory agencies may use these maps in well permitting, plugging, and underground injection control (UIC) activities (saltwater-disposal permitting). Industry personnel can use these maps in well planning and design in the areas affected by salt and salt-cement dissolution. Additionally, oil and gas seismic surveys could benefit by consulting the regional dissolution "halo" maps to assist in avoiding seismic-velocity pitfalls that could interfere with data interpretation.

Although Permian aquifers in close association with evaporitic sediments are not typically developed for domestic use because of their poor water quality, hydrologists may be interested in mapping these saline aquifers to gain an understanding of their potential to cross contaminate nearby freshwater aquifers. This is particularly true when underlying highly saline confined aquifers could discharge upward into a shallower, overlying freshwater aquifer.

INTRODUCTION, GEOLOGIC BACKGROUND, AND REGIONAL PERMIAN STRATIGRAPHY

Introduction and Geologic Background

The Greater Permian Evaporite Basin (GPEB) of North America's midcontinent region spans an area of approximately 250,000 mi² (650,000 km²) underlying portions of Texas, New Mexico, Oklahoma, Kansas, and Colorado (Johnson, 2021a). Multiple sequences of Permian evaporitic sediments dominated by salt (halite), gypsum and/or anhydrite, and fine-grained siliciclastic sediments (commonly salt cemented) make this vast area one of the more dominant regions worldwide containing these particular lithotypes. Within the GPEB, the Syracuse Basin of western Kansas and eastern Colorado is the focus of this paper. The basin covers about 8,100 mi² (21,000 km²) and is underlain by bedded salts, displacive salts, and salt-cemented siliciclastic sediments in the Late Permian Nippewalla Group (Johnson and Timson, 2023). These salt-bearing formations are interbedded with anhydrite and gypsum and range in depth from approximately 1,100 ft (335 m) along the shallow southern rim to nearly 3,000 ft (915 m) at the northern edge of the basin. The entire perimeter of the Syracuse Basin is defined by salt-dissolution boundaries.

Although previously described by numerous researchers as a structural or depositional basin, the Syracuse Basin of western Kansas and eastern Colorado (fig. 1) has recently been redefined as a dissolutional remnant wherein displacive salts in the Blaine and Flowerpot Formations of the Permian-age Nippewalla Group are dissolved at all places around the basin's margins (Johnson, and Timson, 2023). Figure 1B shows the position of the Syracuse Basin within the North American GPEB, as defined by Johnson et al. (2021).

The current paper presents a more detailed look at dissolution of the Syracuse Basin's salt-cemented siliciclastic sediments and bedded salt in the Cedar Hills, Salt Plain, Harper, and Stone Corral Formations (descending order), located immediately below the Flowerpot Formation (table 1). All of these formations appear to be acting as a connected hydrologic unit with

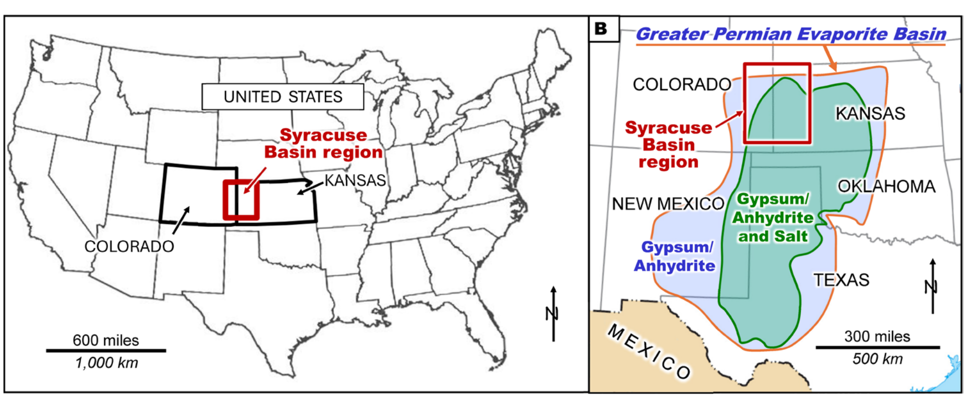

Figure 1. Location of the Syracuse Basin region. A) Map of United States. B) Greater Permian Evaporite Basin (after Johnson, 2021a).

respect to post-depositional salt dissolution. Additionally, where reference is made to the Cedar Hills Sandstone in parts of eastern Colorado, it also is meant to include the Lyons Sandstone.

Approximately 4,200 geophysical well logs were examined to produce a regional salt-cement-dissolution "halo" map for this study (fig. 2). Five areas were selected around the perimeter of the Syracuse Basin for detailed study to show that dissolution of salt cement occurs first in the Cedar Hills Sandstone and then migrates down through the Salt Plain and Harper Formations and ultimately the Stone Corral salt. Where the Y-anhydrite (an aquiclude at the top of the Cedar Hills Sandstone) is not present, unsaturated water in the Cedar Hills also can migrate up and dissolve some or all of the salt in the overlying Flowerpot Formation. Multiple lines of evidence presented in this study demonstrate that the Cedar Hills Sandstone aquifer played a dominant role in delivering unsaturated water to this dissolution process.

The current study will show that resistivity and potentiometric data for the Cedar Hills Sandstone are useful in tracing the post-Laramide hydrologic evolution of the central midcontinent/Hugoton Embayment region. Outcrops of the Lyons Sandstone in the Rocky Mountain Front Range in Colorado are at a much higher elevation than, but are hydrologically connected to, the stratigraphically equivalent Cedar Hills Sandstone in the Syracuse Basin. The Lyons therefore transmits groundwater to the east, where it encounters and dissolves the salt in the Nippewalla Group siliciclastics and the Stone Corral salt in the Syracuse Basin region. The Lyons/Cedar Hills Sandstone is the dominant groundwater aquifer in this process. Hypersaline brine generated by the salt-cement-dissolution process "flushes" to the east and northeast toward discharge subcrops and outcrops located across central Kansas and south-central Nebraska. Regional salinity variations resulting from this hydrologic system and its interaction with the Nippewalla Group salt-bearing strata are evident in this study.

This study is enhanced by the presence of two cores that recovered all or part of the Nippewalla Group sediments. Both core holes are located in the central part of the Syracuse Basin where no salt dissolution has occurred (fig. 2). In addition to the core data, the petroleum industry continues to add a significant amount of new well control throughout the Syracuse Basin region in the form of modern geophysical open-hole well-log suites run through the shallow Permian sediments. These new data points will allow for refinement of maps and cross sections as they pertain to ongoing geologic studies of the shallow salt-bearing Permian strata.

Regional Permian Stratigraphy

Included in this study are Permian siliciclastic and salt-bearing strata from the Cedar Hills Sandstone (youngest unit) down to the Stone Corral Formation (oldest) in the Syracuse Basin and surrounding region (table 1). Descriptions of these units in outcrops are given in West et al. (2010). Although the Kansas Geological Survey regards the Sumner and Nippewalla Groups

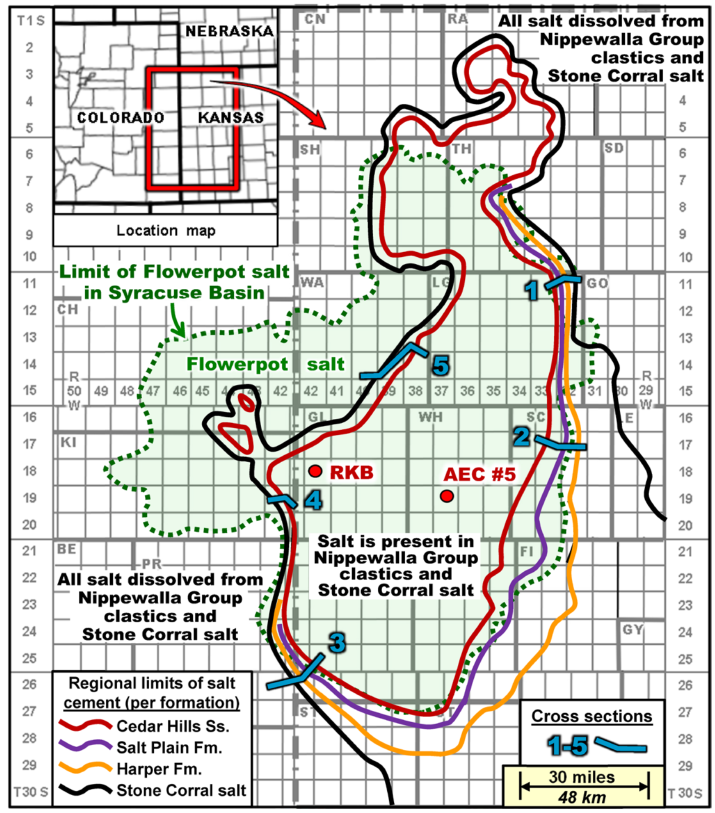

Figure 2. Regional limits of salt cement in siliciclastic formations in the Nippewalla Group and salt in the Stone Corral Formation in the Syracuse Basin region. Also shown, in green, are the areas underlain by the Flowerpot salt (from Johnson and Timson, 2023), the RKB and AEC #5 core locations, and five cross sections across salt-dissolution boundaries. Cross section areas: 1 = Oakley, 2 = Scott City, 3 = Bear Creek, 4 = Stateline, and 5 = Wallace. Fm = Formation; Ss = Sandstone.

Table 1. Permian stratigraphy of Nippewalla and Sumner Groups 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), Johnson (2021a), and Johnson and Timson (2023). Although the Stone Corral Formation is in the Sumner Group, it is combined with the Nippewalla Group for descriptive simplicity in most parts of this paper.

Series	Group	Formation
		Dog Creek Shale
		Blaine Formation
Guadalupian	**Nippewalla Group**	Flowerpot Formation
		Cedar Hills Sandstone
		Salt Plain Formation and Harper Sandstone
Leonardian	**Sumner Group**	Stone Corral Formation

to be Leonardian in age (Swineford, 1955; Zeller, 1968; West, 2010; Zambito et al., 2012), the Nippewalla Group formations are regarded as Guadalupian by others (Dunbar et al., 1960; Hills and Kottlowski, 1983; Johnson, 2021a; Johnson and Timson, 2023). The Cedar Hills Sandstone is correlative, at least in part, with the Lyons Sandstone of the Front Range (Maher, 1946, 1947; McKee et al., 1967; Mudge, 1967; Hagadorn et al., 2016). The Stone Corral Formation, the Y-anhydrite (at the top of the Cedar Hills Sandstone), and the Blaine Formation 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 (described below), 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).

METHODS AND APPROACH

This study presents the results of detailed regional mapping of a portion of the salt-bearing Nippewalla Group sediments (Cedar Hills, Salt Plain, and Harper Formations) and the Stone Corral Formation and their salt-dissolved equivalents using an extensive dataset of geophysical well logs. This mapping effort resulted in a regional halo map (fig. 2) showing regional limits of salt cement in each of the siliciclastic units of the Nippewalla Group and the Stone Corral as well as resistivity and potentiometric data for the Cedar Hills that show the direction of groundwater flow.

Additionally, five areas of detailed study were selected around the perimeter of the Syracuse Basin to demonstrate the salt- and salt-cement dissolution process (fig. 2). Each study area presents a detailed local map of each formation's salt-dissolution limit and a cross section illustrating the dissolution progression. Past publications have presented structure and isopach maps of the various Nippewalla Group formations; among them are Schumaker (1966), Holdoway (1978), and Macfarlane et al. (1993). The current study does not include structure and isopach maps of the various formations. Instead, the focus is on the presence or absence of salt and salt cement in each formation and implications that can be derived from the maps and cross sections relating to dissolution diagenesis and the hydrologic evolution of these sediments.

Geophysical well-log control is abundant throughout most of the Syracuse Basin region as a consequence of the petroleum industry's past and continuing exploration and development of numerous deeper oil- and natural-gas-bearing formations throughout the region, including the giant Hugoton natural-gas field.

Cores and Lithologic Descriptions

Two wells drilled in the middle part of the Syracuse Basin (fig. 2) were cored through all or part of the Nippewalla Group and Stone Corral Formation: 1) Amoco Production Co. drilled the Rebecca K. Bounds #1 (RKB well; fig. 3), and 2) Union Carbide Corporation drilled the AEC Test Hole #5 (AEC #5 well; fig. 4). Cores from these wells provide valuable information about the nature of the salts and salt-cemented siliciclastics far from the dissolution front that surrounds the Syracuse Basin. Lithologic logs of these cores are herein plotted along with the suite of geophysical logs from the same wells to calibrate the geophysical signatures to rock types.

The RKB core was described by Zambito et al. (2012) and Benison et al. (2013, 2015), and the AEC #5 core was described in AEC #5 Driller's Log (1972) and Holdoway (1978). These papers provide detailed descriptions of the petrography and related characteristics of the salt-bearing sediments. Figure 5 shows core photos of selected siliciclastic intervals from the RKB core, and fig. 6 shows two photomicrographs of thin sections of halite-cemented Cedar Hills Sandstone—one photo from each of the cored wells. Brief summaries of the lithologies of the major Nippewalla Group and Stone Corral salt-bearing formations from these core studies, and average thicknesses of the formations in the five areas of detailed study, are presented in table 2 and below.

Cedar Hills Sandstone: Core studies of the Cedar Hills describe a red-brown, fine- to medium-grained, massive sandstone (Holdoway, 1978; Zambito et al., 2012) (figs. 5A and 6). The sandstone has a pronounced bi-modal grain-size distribution and locally exhibits horizontal stratification or high-angle cross bedding. Holdoway's thin-section petrographic study of samples from the AEC #5 core described the sandstone as a quartz arenite with 5–10% of individual grains being feldspar, with minimal rock fragments. The thin-section study confirmed the presence of halite cement filling all pore spaces within the formation.

The Cedar Hills Sandstone extends across the entire Syracuse Basin region, ranging in thickness from less than 50 ft (15 m) to more than 200 ft (61 m). In the five areas of detailed study, the thickness of the Cedar Hills averages 89 ft (27 m) where it contains salt cement and averages 98 ft (30 m) where the salt has been dissolved (table 2). Outside of the salt-cemented area of the Syracuse Basin, the Cedar Hills and its equivalents (mainly the Lyons Sandstone) are predominantly a brine-filled aquifer extending into portions of states adjoining Kansas and

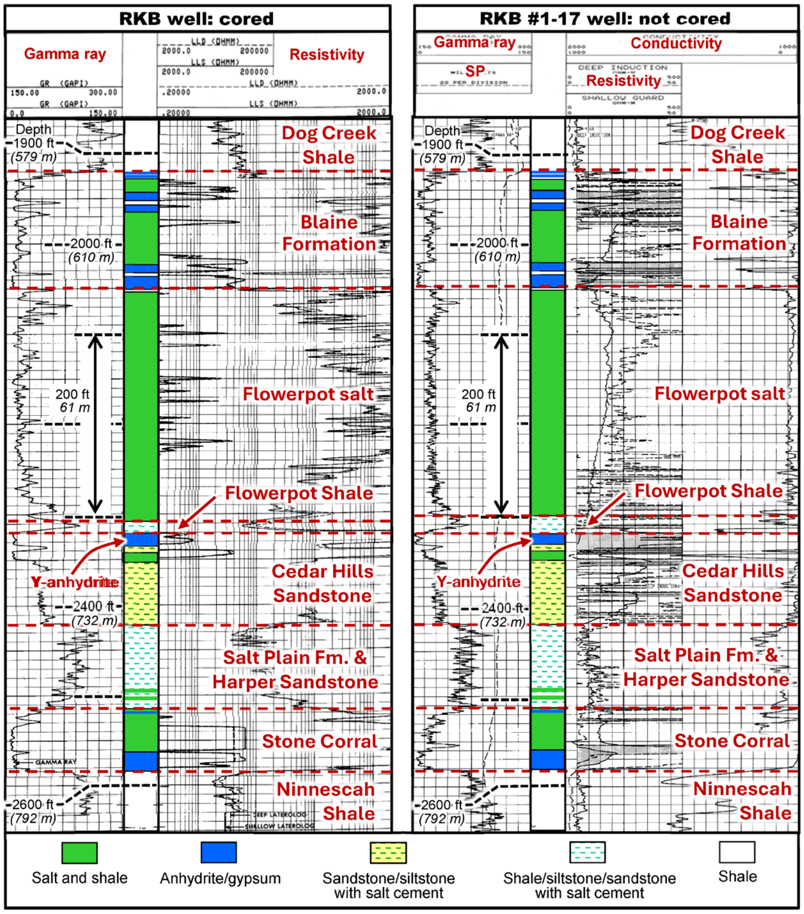

Figure 3. Geophysical logs and lithology based on core from the RKB well (on left); core descriptions from Zambito et al. (2012) and Benison et al. (2013). The RKB well was continuously cored through this entire section. The geophysical log of the RKB #1-17 well (on right), drilled only 100 ft (30 m) away from the cored RKB well, is included here to show the response on a different log (comparing a dual laterolog, left, with a dual induction log, right). Fm = Formation.

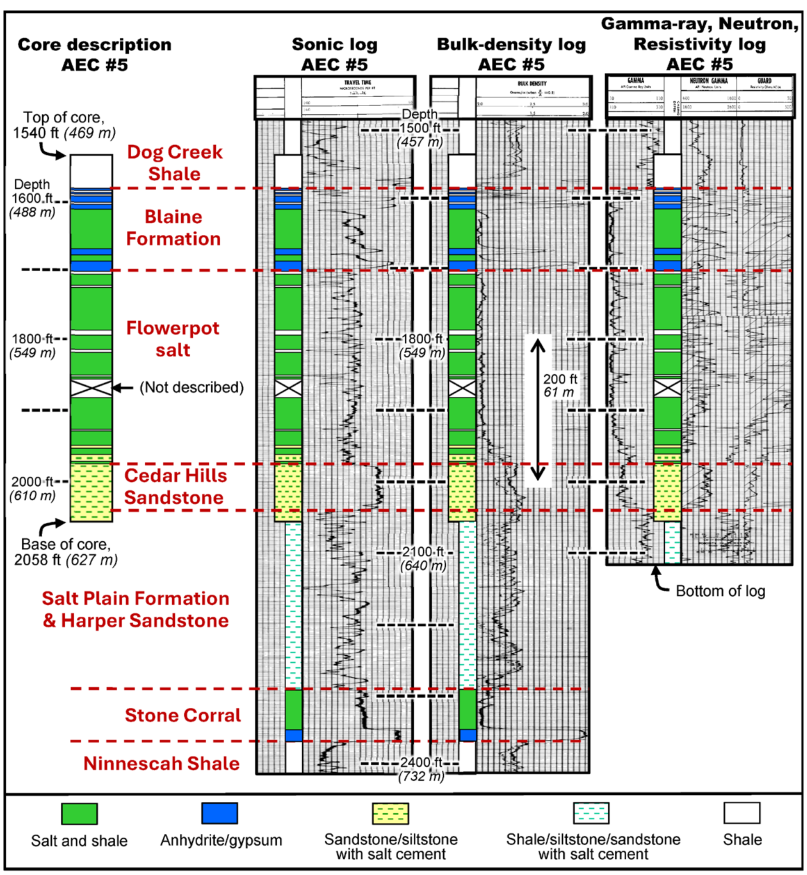

Figure 4. Geophysical logs and lithology based on core from the AEC #5 well; core descriptions from the AEC #5 Driller's Log (1972) and Holdoway (1978). The core, limited to depths of 1,540–2,058 ft (469–627 m), is shown on the three logs run on the well; lithologies above and below the core are interpreted from the logs.

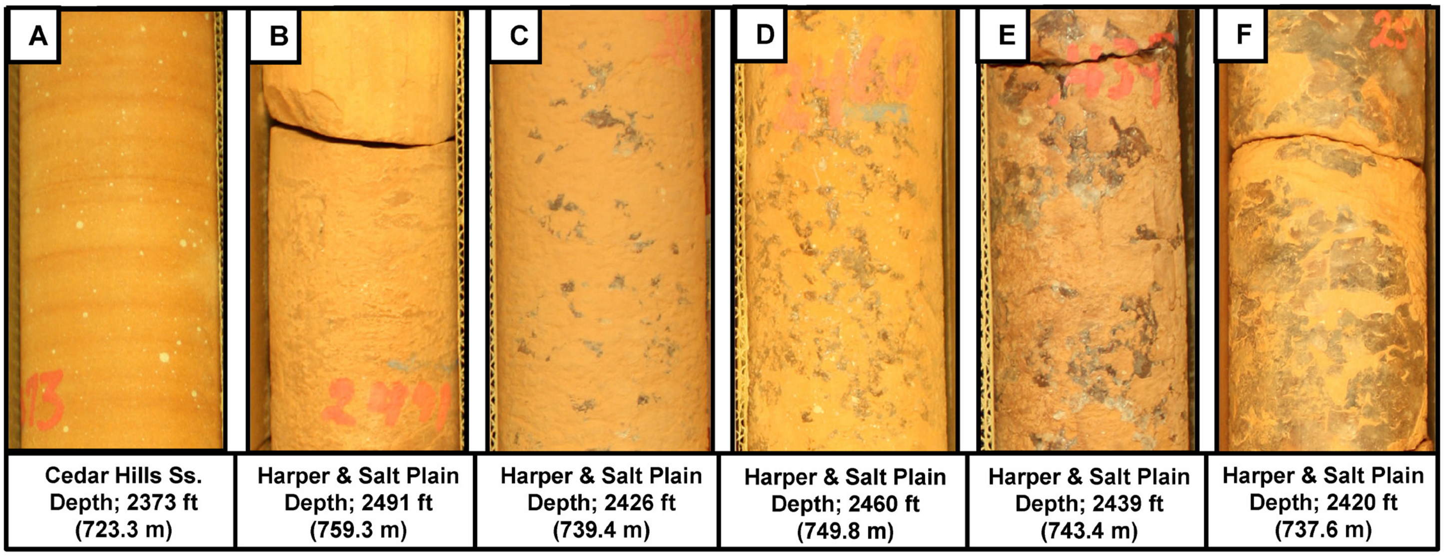

Figure 5. Photographs of cores from the Amoco Rebecca K. Bounds #1 (RKB) well, drilled in sec. 17, T. 18 S., R. 42 W., Greeley County, Kansas. All cores are about 3 in. (7.6 cm) wide. A) Typical Cedar Hills Sandstone with halite cement. B–F) Samples of Harper and Salt Plain Formations with increasing amounts of halite (from B to F) cementing the siliciclastics sediment. Photos C through F also show the salt occurring as displacive-salt masses. Photos of the entire RKB core are available through the Kansas Geological Survey list of wells with core images: https://chasm.kgs.ku.edu/ords/qualified.cimg2.CoreImages?f_well=1006067111 Ss = Sandstone.

Colorado, including Nebraska, Wyoming, Oklahoma, Texas Panhandle, and New Mexico (Glorietta Sandstone). Due to the sandstone's predominantly grain-supported fabric, its thickness remains relatively constant, whether halite is present or dissolved. The thickness and elevation of the top of the Cedar Hills is shown for the southern two-thirds of the Syracuse Basin in Macfarlane et al. (1993).

The Y-anhydrite comprises 10–20 ft (3–6 m) of anhydrite at the top of the Cedar Hills Sandstone in the northwest half of the Syracuse Basin, but it is generally absent in the southeast half of the basin. It is present in the RKB well (fig. 3) but is absent in the AEC #5 well (fig. 4). The Y-anhydrite is an excellent marker bed on geophysical logs for correlation purposes; it separates the sandstone in the Cedar Hills from the overlying Flowerpot Formation. The Y-anhydrite is an aquiclude that prevents, or at least inhibits, upward migration of unsaturated water from the Cedar Hills aquifer into the Flowerpot Formation. Where the Y-anhydrite is absent, water has moved up into the Flowerpot and has dissolved some or all of the Flowerpot salt.

Salt Plain Formation and Harper Sandstone: The Salt Plain and Harper Formations are generally undifferentiated in this paper because they are not readily separated on many of the geophysical logs. In cores, however, the Salt Plain Formation is described as predominantly a red-orange to red-brown shale and silty shale (Holdoway, 1978; Zambito et al., 2012). The shale is halite cemented within the Syracuse Basin and is composed of the finest grain sizes of all the siliciclastic sediments of the Nippewalla Group. Cores of the underlying Harper Sandstone

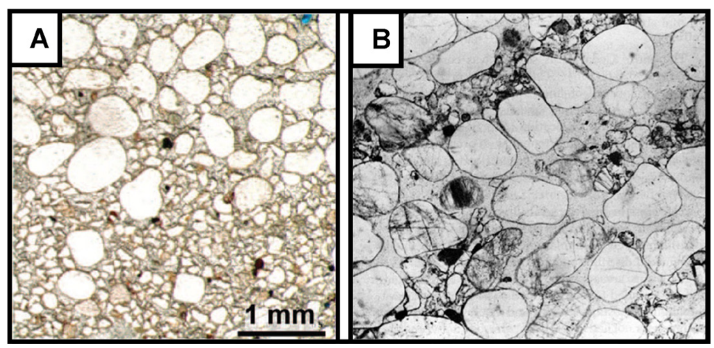

Figure 6. Photomicrographs of thin sections of halite-cemented Cedar Hills Sandstone consisting of well-rounded, medium-sized quartz grains, with a matrix of fine sand grains, all floating in halite cement. This shows that within the Syracuse Basin, the Cedar Hills Sandstone is tightly cemented with halite, in comparison to the non-cemented Cedar Hills where it is an aquifer outside of the Syracuse Basin. A) Sample from RKB core at a depth of 2,423 ft (738.5 m) (Benison et al., 2015). B) Sample from the AEC #5 core (Holdoway, 1978) at a depth 2,016.6 ft (614.7 m); magnified x 32.

are similar in lithology to the Salt Plain Formation, but they tend to be somewhat coarser grained with more silt-sized and fine-grained sand-sized components, especially toward the base of the formation. Halite cement is pervasive throughout the Harper Sandstone within the basin, and displacive halite may be present but not abundant. Figure 5B–F shows photographs of Salt Plain and Harper cores.

Precise geophysical well-log correlation differentiating the Salt Plain and Harper Formations is challenging in the Syracuse Basin region. This condition is particularly true around the outer perimeter of the basin where the salt cement has been dissolved.

Table 2. Thickness of lower Nippewalla Group formations and Stone Corral salt, with or without salt cement or bedded salt. Values here are average and range of thicknesses derived from the well logs shown in the five areas of detailed study included in this paper. Thicknesses outside of the five study areas may be lower or higher than what is shown here.

Formation	Thickness, with Salt (No Dissolution)		Thickness, without Salt (Dissolution)	
	Average	Range	Average	Range
Cedar Hills Sandstone	89 ft (27 m)	60–118 ft (18–36 m)	98 ft (30 m)	65–147 ft (20–45 m)
Salt Plain Formation	82 ft (25 m)	39–121 ft (12–37 m)	68 ft (21 m)	33–97 ft (10–30 m)
Harper Sandstone	89 ft (27 m)	38–123 ft (12–37 m)	72 ft (22 m)	32–97 ft (10–30 m)
Stone Corral salt	50 ft (15 m)	41–58 ft (12-18 m)	only insolubles; how much is from salt beds is unknown	only insolubles; how much is from salt beds is unknown

The five areas of detailed study illustrate our best efforts to carry geophysical well-log correlations across the Salt Plain–Harper boundary from the salt-cemented core area to the basin exterior where the salt cement is dissolved.

The average thickness of the Salt Plain Formation in the five areas of detailed study is 82 ft (25 m) where salt cement is present and is 68 ft (21 m) where the salt cement is dissolved. The Harper Sandstone averages 89 ft (27 m) where salt cemented and 72 ft (22 m) where salt cement is dissolved (table 2). The regional thickness and elevation of the top of the Salt Plain Formation/Harper Sandstone is shown for the southern two-thirds of the Syracuse Basin in Macfarlane et al. (1993).

Stone Corral Formation: The AEC #5 core did not reach the Stone Corral Formation and thus detailed petrographic descriptions of this formation are limited to the RKB core (Zambito et al., 2012). Zambito et al. (2012) considered only the basal anhydrite as the Stone Corral Formation (2,564–2,588 ft [782–780 m], fig. 3). The current authors place the top of the Stone Corral Formation at a depth of 2,515 ft (767 m), thus embracing the Stone Corral salt and a thin anhydrite at the top of the salt (fig. 3). This is consistent with other authors, such as Merriam (1963), Schumaker (1966), Rascoe and Baars (1972), Sorenson (1996), West et al. (2010), and Johnson and Timson (2023). Zambito et al. (2012) describe the basal Stone Corral anhydrite as predominantly a pale-blue anhydrite with purple-maroon mottling, halite pseudomorphs of bottom-growth gypsum, and rare thin mudstone beds.

The middle salt layer averages 50 ft (15 m) thick (table 2) in the five areas of detailed study and is present beneath the entire Syracuse Basin. The limit of the Stone Corral salt is a dissolutional limit around the majority of the Syracuse Basin (fig. 2). The basal Stone Corral anhydrite ranges from 8 to more than 40 ft (2.4 to more than 12 m) thick and extends far beyond the edges of the Syracuse Basin in every direction.

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) cement in the siliciclastic beds is critical in the current study because it shows the way that unsaturated groundwater in the Cedar Hills Sandstone has dissolved interstitial halite in the siliciclastic beds. This was discussed recently in Johnson and Timson (2023, p. 13–14), and the following two paragraphs are from that paper.

> 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. (p. 13–14)
>
> 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). (p. 14)

Several factors can play a role in the variation of resistivity and conductivity responses seen on the varying vintages of open-hole log suites found throughout the study area. The dominant factors affecting resistivity/conductivity log readings in the Cedar Hills/Lyons Sandstone are the sandstone's brine salinity (brine water chemistry) and the sandstone's porosity. Other factors to consider include the potential presence of non-salt cements or fine-grained clay minerals in the pores. In addition to the petrophysical properties of the sandstone, drilling-mud programs and drilling conditions and practices can influence resistivity and conductivity readings. However, the Cedar Hills/Lyons Sandstone is predominantly a blanket sandstone with reasonably uniform porosity across most of the study area. Non-salt cements and clay minerals are not prevalent (Holdoway, 1978: Zambito et al., 2012).

The marked changes in resistivity and conductivity in the Nippewalla siliciclastics on geophysical logs in the Syracuse Basin and surrounding areas of western Kansas and eastern Colorado enable identification of zones of salt-cement dissolution in each of the formations around the Syracuse Basin. Figure 7 shows two dual induction logs of wells where the resistivity and conductivity logs clearly show the presence or absence of salt cement in the Cedar Hills Sandstone and other siliciclastics. Where salt cement is present, the resistivity is moderately high to high (curve deflected to the right) and the conductivity is low (curve deflected to the right). Where salt cement has been dissolved and the pore spaces are replaced by brine, the resistivity is extremely low (curve deflected to the left) and the conductivity is moderately high to high (curve deflected to the left). The contrast between salt cement presence versus brine replacement is quite sharp in both of these logs: Salt cement is clearly absent and replaced by brine in the upper Cedar Hills Sandstone in fig. 7A, and brine has replaced salt cement down to the middle of the Salt Plain Formation in fig. 7B.

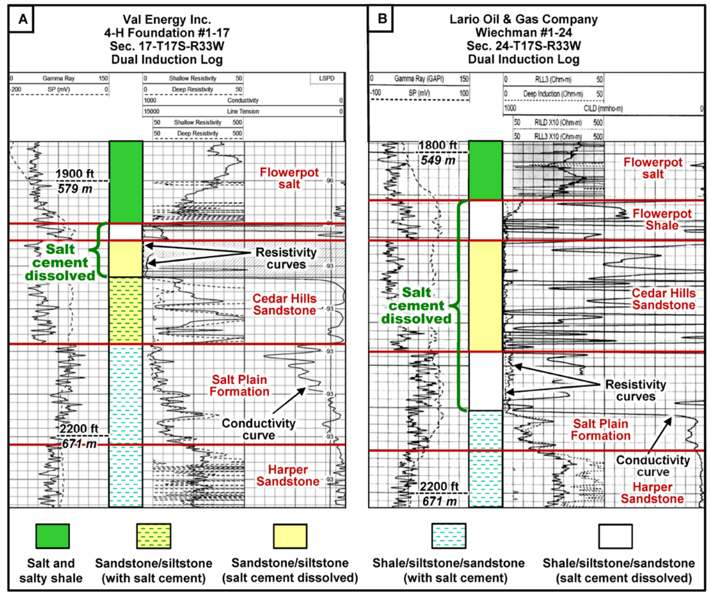

Figure 7. Dual induction logs showing results of dissolution of salt cement in siliciclastic rocks. The presence of salt cement results in moderate to high resistivity and low conductivity; dissolution of salt results in a brine with extremely low resistivity and high conductivity. Logs are for wells 2 and 3 in fig. 10 (Scott City area). A) Salt-cement-dissolution boundary located in Cedar Hills Sandstone. B) Salt-cement-dissolution boundary located in Salt Plain Formation. In this figure, and on most other logs in this paper, shallow resistivity is shown by a solid line, and deep resistivity is shown by a dashed line.

DISCUSSION

Areas For Detailed Study of Salt Dissolution

Five areas were selected to show details of salt-cement dissolution in siliciclastics of the Nippewalla Group and the Stone Corral salt around the perimeter of the Syracuse Basin (figs. 8–15). The study areas begin with the Oakley area (cross section 1 in the northeast part of the basin, fig. 2) and continue clockwise around the basin with the Scott City, Bear Creek, Stateline, and Wallace areas (cross sections 2–5 in fig. 2). In each area, cross sections and maps show how unsaturated groundwater in the Cedar Hills Sandstone moving toward the basin center causes dissolution of salt cement in the Cedar Hills first, and then the downward migration of that unsaturated water causes salt cement or salt to be dissolved in the underlying Salt Plain, Harper, and Stone Corral Formations, successively. Where the overlying Y-anhydrite aquitard is absent, unsaturated water also can migrate above the Cedar Hills and dissolve salt in the overlying Flowerpot and Blaine Formations. For each study area, we present 1) a map of the salt-dissolution halo boundaries for the Cedar Hills and the underlying salt-bearing formations in that area and 2) a cross section of geophysical well logs documenting the presence or absence of salt or salt cement in each of the formations. Table 3 gives the depth to the top and base of the salt-cement-dissolution zone in each of the wells shown on cross sections in the five areas of detailed study.

The stratigraphic datum for all five cross sections is the top of the Cedar Hills Sandstone. This helps demonstrate the top-down dissolution pattern beginning at the top of the uppermost Cedar Hills Sandstone. The caption for each of the figures for the detailed study areas gives a well-by-well description of the dissolution progression depicted by the geophysical well logs. Varying amounts of geophysical well-log control exist, depending on the location of each study area around the perimeter of the Syracuse Basin; however, sufficient regional control exists to define the position of the dissolution halo quite accurately around the entire basin, as shown in fig. 2.

Area 1—Oakley Area: The Oakley area, located just southwest of Oakley, in Logan County, Kansas (figs. 8–9), is near the northeast end of the Syracuse Basin. Unsaturated groundwater moving to the west and southwest in the Cedar Hills Sandstone has removed interstitial salt in the Cedar Hills in all wells, except for well 1. Unsaturated water has also moved down to remove salt cement in the underlying Salt Plain and Harper Formations, successively (wells 2, 3, and 4), and ultimately has even dissolved the Stone Corral salt (well 5). A previous study of the Oakley area (fig. 20 in Johnson and Timson, 2023) showed that the Flowerpot salt here was dissolved by descending water. Thus, the Y-anhydrite, an aquiclude that normally prevents upward movement of water from the Cedar Hills, is not a factor in dissolution of Flowerpot salt in wells 2–5. The length of cross section A–B–C is about 5 mi (8 km), and the dissolution zone—the distance between the limit of salt cement in the Cedar Hills Sandstone and the limit of Stone Corral salt—is about 2.5 mi (4 km) wide.

Table 3. Depth to top and base of halite-cement-dissolution zone in wells shown on cross sections in five areas of detailed study.

Area and Well	Depth to Top of Halite Dissolution	Depth to Base of Halite Dissolution
Area 1—Oakley		
Well 1	No dissolution	No dissolution
Well 2	Above Blaine Fm.	2,380 ft (725 m)
Well 3	Above Blaine Fm.	2,462 ft (750 m)
Well 4	Above Blaine Fm.	2,552 ft (778 m)
Well 5	Above Blaine Fm.	2,575 ft (785 m)
Area 2—Scott City		
Well 1	No dissolution	No dissolution
Well 2	1,955 ft (596 m)	2,012 ft (613 m)
Well 3	1,855 ft (565 m)	2,105 ft (642 m)
Well 4	Above Blaine Fm.	2,195 ft (669 m)
Well 5	Above Blaine Fm.	2,265 ft (690 m)
Area 3—Bear Creek		
Well 1	Above Blaine Fm.	1,770 ft (539 m)
Well 2	Above Blaine Fm.	1,703 ft (519 m)
Well 3	1,424 ft (434 m)	1,585 ft (483 m)
Well 4	No dissolution	No dissolution
Area 4—Stateline		
Well 1	2,339 ft (713 m)	2,465 ft (751 m)
Well 2	2,248 ft (685 m)	2,352 ft (717 m)
Well 3	2,220 ft (677 m)	2,255 ft (687 m)
Well 4	No dissolution	No dissolution
Area 5—Wallace		
Well 1	2,548 ft (777 m)	2,733 ft (833 m)
Well 2	2,503 ft (763 m)	2,693 ft (821 m)
Well 3	2,510 ft (765 m)	2,615 ft (797 m)
Well 4	2,135 ft (651 m)	2,195 ft (669 m)
Well 5	No dissolution	No dissolution

Area 2—Scott City Area: The Scott City area is located about 5 mi (about 8 km) north of Scott City, in Scott County, Kansas (figs. 10–11). Unsaturated groundwater moving to the west has dissolved all the salt cement in the Cedar Hills Sandstone in the three easternmost wells (wells 3, 4, and 5), starting with well 5. The unsaturated water, moving in the upper part of the Cedar Hills in well 2, has dissolved salt in the upper one-third of the Cedar Hills and also has migrated up and removed the lower part of the Flowerpot salt. Absence of the Y-anhydrite aquiclude at the top of the Cedar Hills Sandstone here enables water to move up more freely into overlying strata in wells 2, 3, 4, and 5. The length of cross section D–E–F is about 10.5 mi (17 km), and the dissolution zone—the distance between the limit of salt cement in the Cedar Hills Sandstone and the limit of salt cement in the Harper Sandstone—is about 8 mi (13 km) wide. The Stone Corral salt is ultimately dissolved about 15 mi (24 km) farther to the east of the Harper Sandstone salt-cement limit (fig. 2).

Area 3—Bear Creek Area: The Bear Creek area is in Prowers County, Colorado, and Hamilton County, Kansas, and is about 2–3 mi (3–5 km) northwest of North Bear Creek (fig. 12). Unsaturated groundwater has moved to the northeast, dissolving all the salt cement in the Cedar Hills Sandstone in wells 1, 2, and 3, but has not yet reached well 4. After removing salt cement from the Cedar Hills, unsaturated water has migrated down to successively remove salt cement in the Salt Plain and Harper Formations (wells 1, 2, and 3), and finally remove the Stone Corral salt (well 1). Unsaturated water also has moved up (the Y-anhydrite aquiclude is not present in this area to inhibit upward movement) and has dissolved all the Flowerpot salt in wells 1 and 2 and most of the Flowerpot salt in well 3. The length of cross section G–H is about 14 mi (23 km), and the dissolution zone—the distance between the limit of salt cement in the Cedar Hills Sandstone and the limit of Stone Corral salt—is about 5 mi (8 km) wide.

Area 4—Stateline Area: The Stateline area is in Kiowa County, Colorado, just west of the Colorado-Kansas border (fig. 13). Unsaturated groundwater moving to the east in the Cedar Hills Sandstone has removed interstitial salt in the Cedar Hills in wells 1 and 2 and only in the upper part of the Cedar Hills in well 3. Unsaturated water also has moved down to remove salt cement in the underlying Salt Plain and Harper Formations, successively (wells 1 and 2), and ultimately has even dissolved the Stone Corral salt (well 1). The Y-anhydrite aquiclude is quite thick

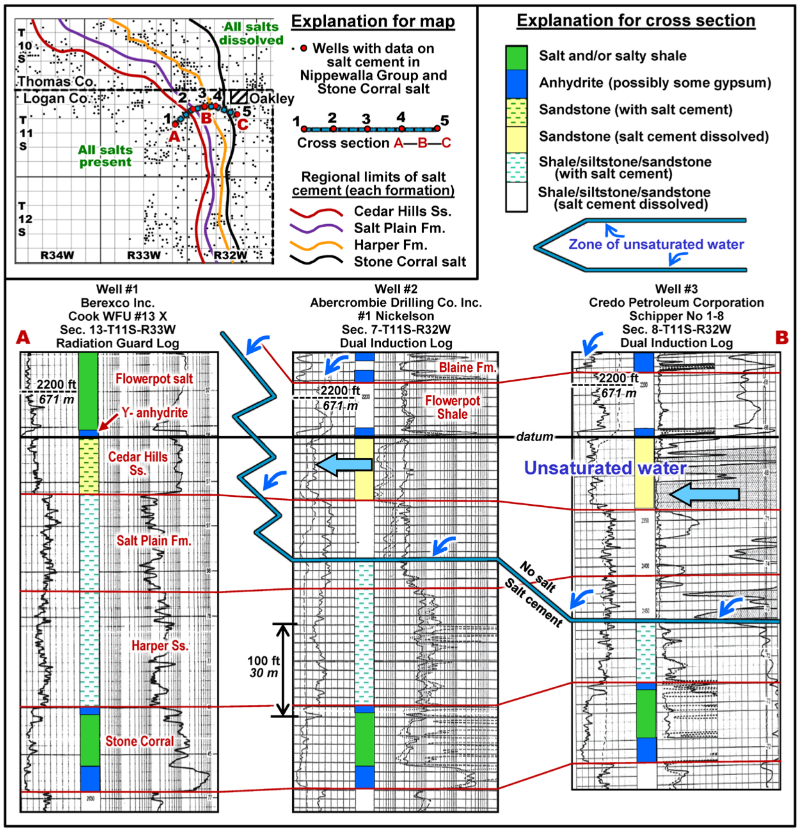

Figure 8. Stratigraphic cross section A–B shows dissolution of interstitial salt in the Nippewalla Group in the Oakley area, Logan County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Unsaturated water has not yet reached the siliciclastics in well 1. Fm = Formation; Ss = Sandstone.

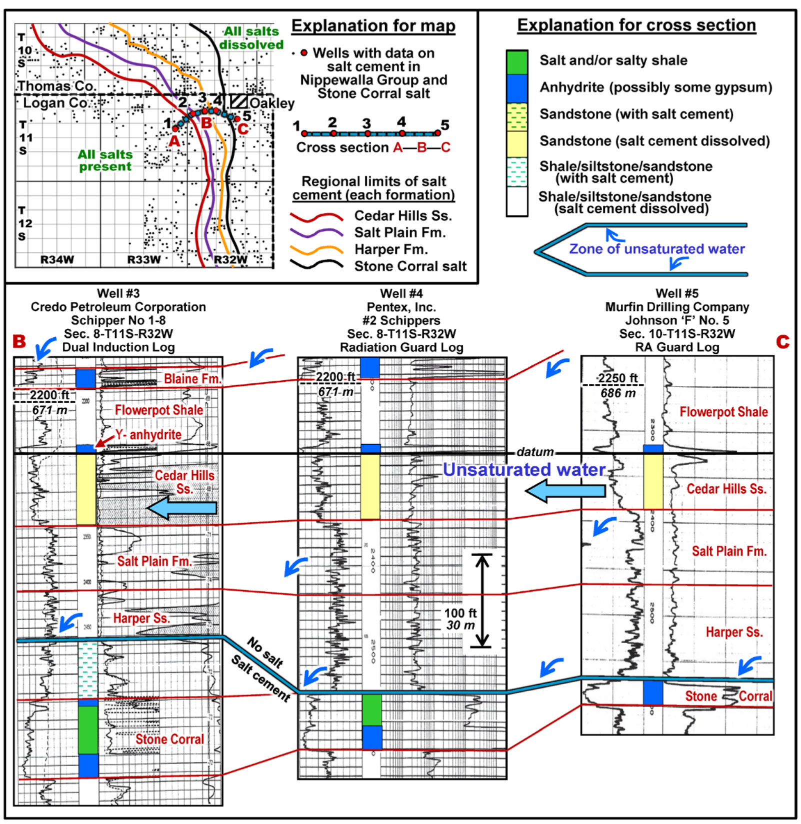

Figure 9. Stratigraphic cross section B–C shows dissolution of interstitial salt in the Nippewalla Group in the Oakley area, Logan County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Ultimately, bedded salt in the Stone Corral is also dissolved (well 5). Fm = Formation; Ss = Sandstone.

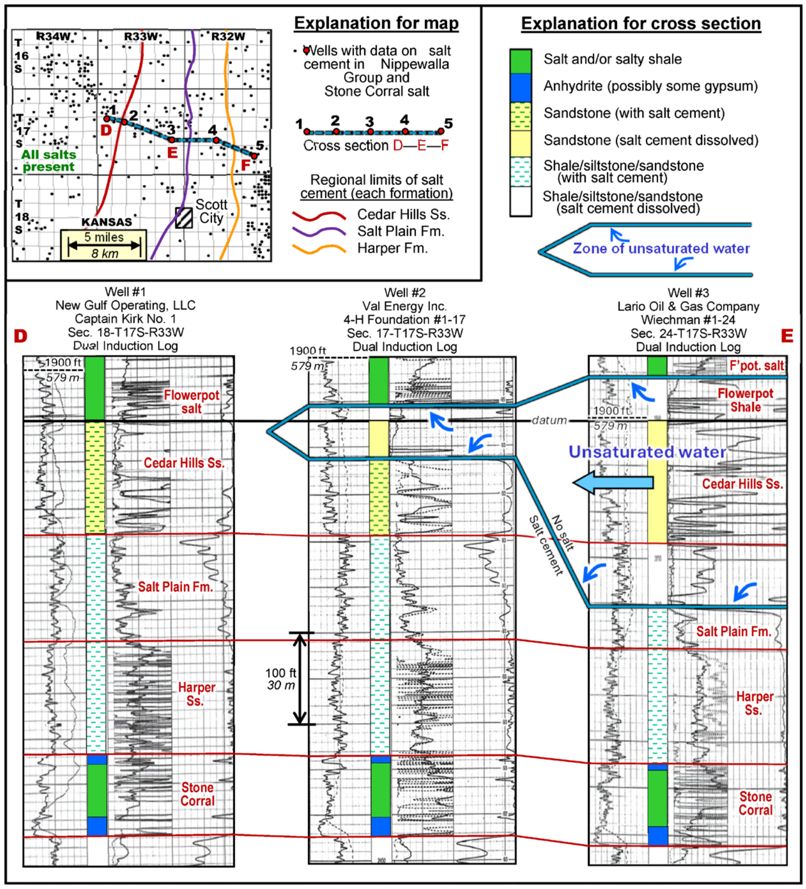

Figure 10. Stratigraphic cross section D–E shows dissolution of interstitial salt in the Nippewalla Group in the Scott City area, Scott County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Unsaturated water has not yet reached the siliciclastics in well 1. F'pot = Flowerpot; Fm = Formation; Ss = Sandstone.

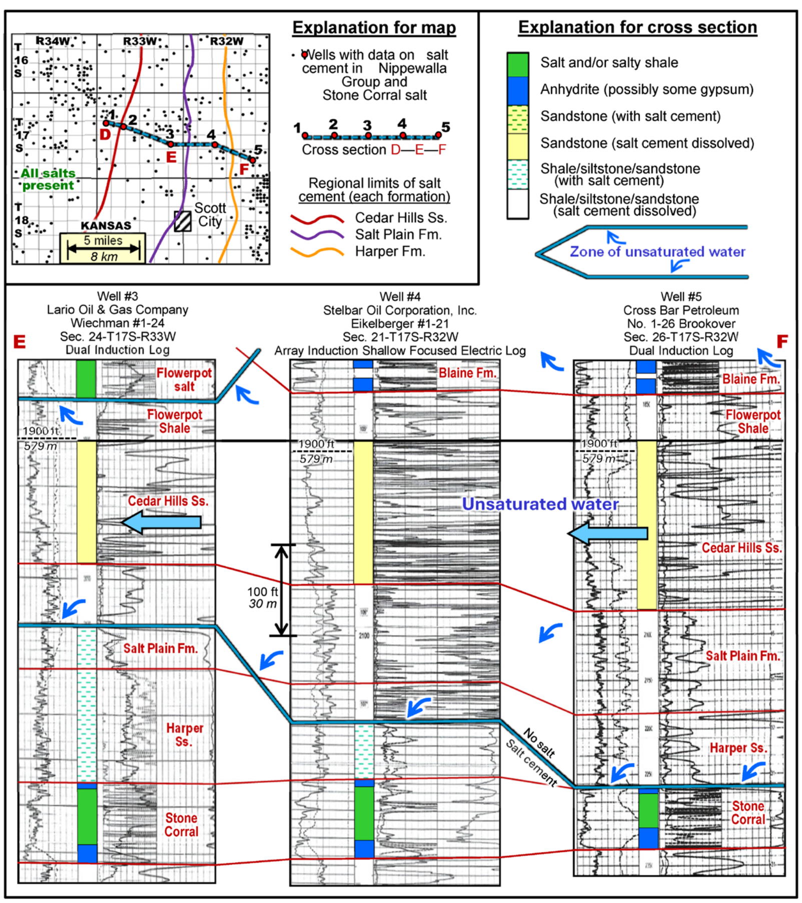

Figure 11. Stratigraphic cross section E–F shows dissolution of interstitial salt in the Nippewalla Group in the Scott City area, Scott County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Ultimately, some bedded salt in the upper part of the Stone Corral is also dissolved (well 5). Fm = Formation; Ss = Sandstone.

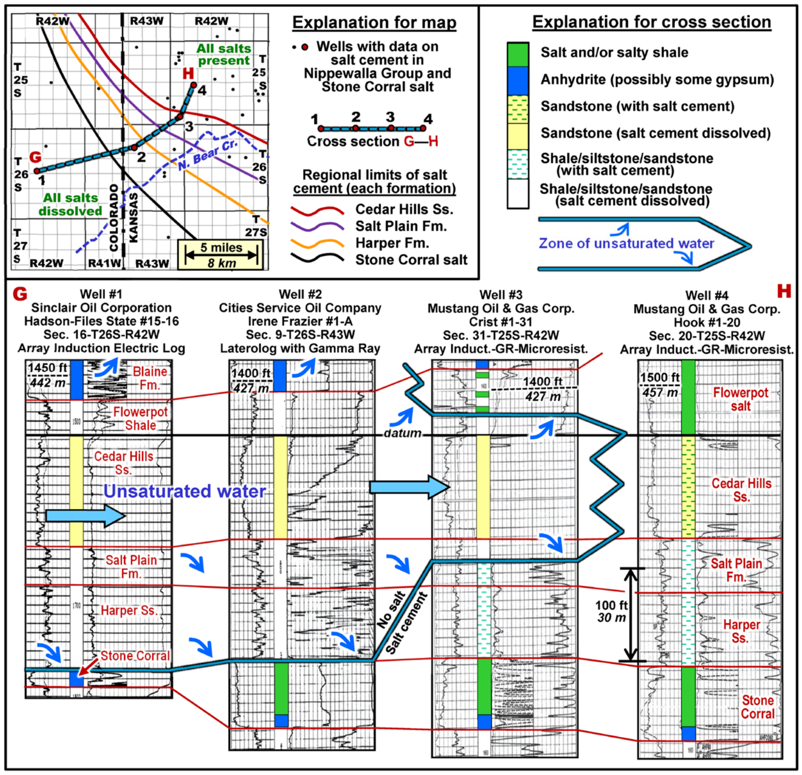

Figure 12. Stratigraphic cross section G–H shows dissolution of interstitial salt in the Nippewalla Group in the Bear Creek area, Prowers County, Colorado, and Hamilton County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Bedded salt in the Stone Corral also has been dissolved in well 1; unsaturated water has not yet reached the siliciclastics in well 4. Fm = Formation; Ss = Sandstone.

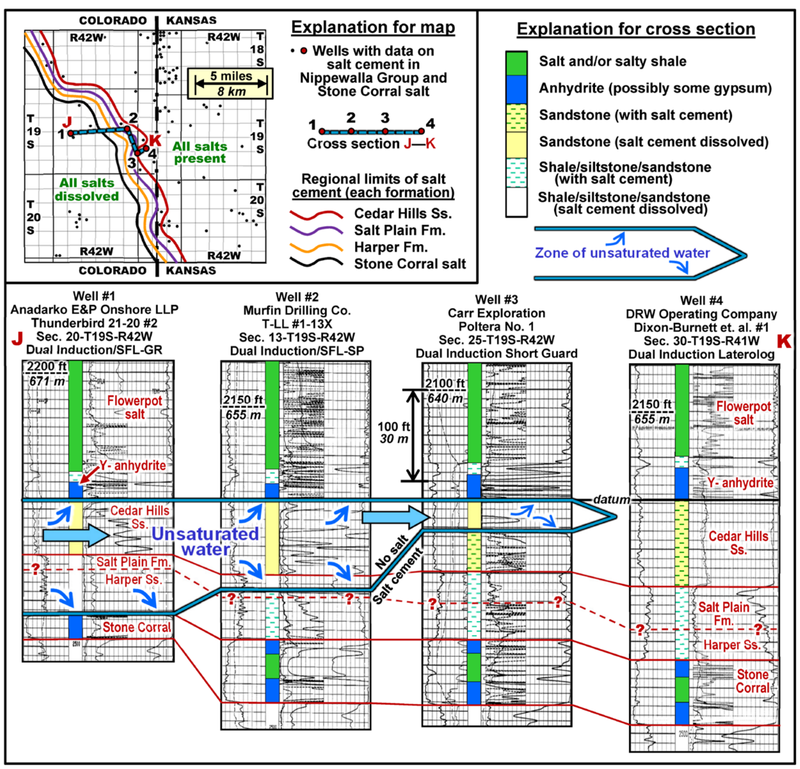

Figure 13. Stratigraphic cross section J–K shows dissolution of interstitial salt in the Nippewalla Group in the Stateline area, Kiowa County, Colorado. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Bedded salt in the Stone Corral also has been dissolved in well 1; unsaturated water has not yet reached the siliciclastics in well 4. Fm = Formation; Ss = Sandstone.

here and has effectively stopped the upward flow of water from the Cedar Hills. Therefore, the Flowerpot salt is not dissolved at all. The length of cross section J–K is about 5 mi (8 km), and the dissolution zone—the distance between the limit of salt cement in the Cedar Hills Sandstone and the limit of Stone Corral salt—is about 1.5 mi (2.4 km) wide.

Area 5—Wallace Area: The Wallace area is in Wallace County, Kansas, just south of the city of Wallace (figs. 14–15). Unsaturated groundwater moving to the east and southeast in the Cedar Hills Sandstone has dissolved salt cement in the Cedar Hills in wells 1–4 but has not yet reached well 5. The water also has moved down and dissolved salt cement in the underlying Salt

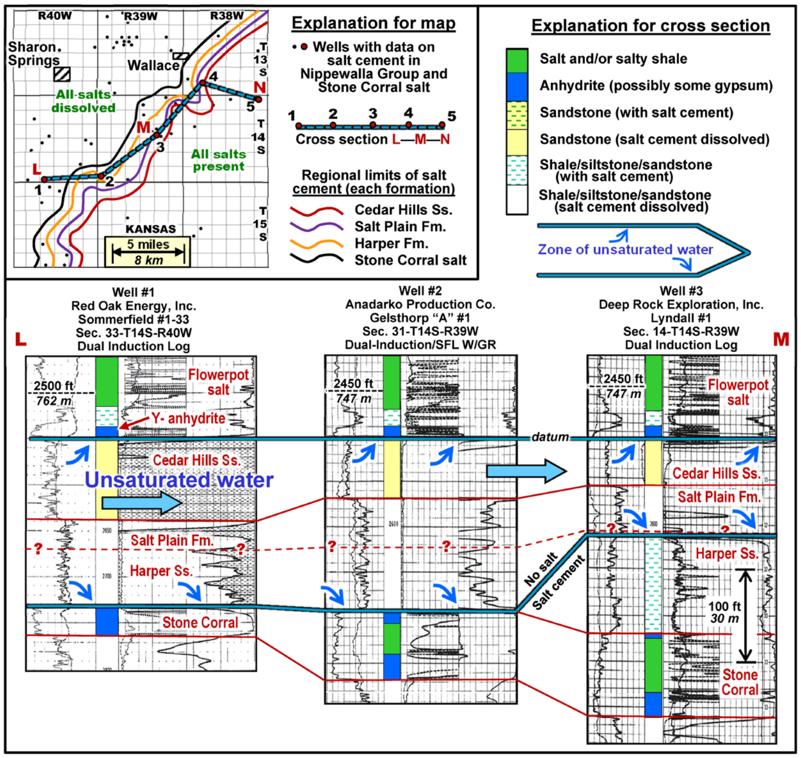

Figure 14. Stratigraphic cross section L–M shows dissolution of interstitial salt in the Nippewalla Group in the Wallace area, Wallace County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Ultimately, bedded salt in the Stone Corral is also dissolved (well 1). Fm = Formation; Ss = Sandstone.

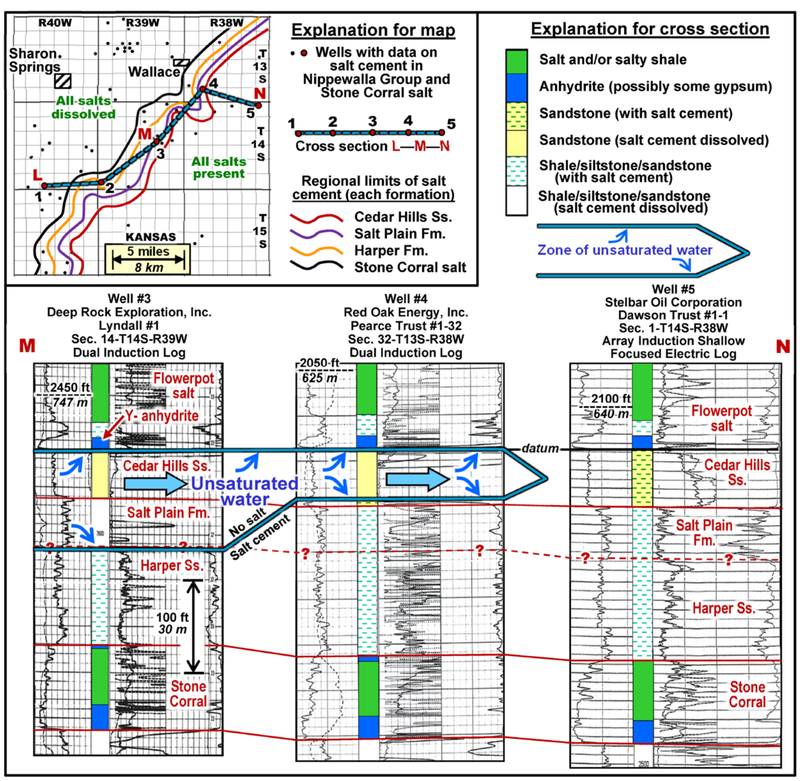

Figure 15. Stratigraphic cross section M–N shows dissolution of interstitial salt in the Nippewalla Group in the Wallace area, Wallace County, Kansas. Salt cement in the Cedar Hills is dissolved first, and then salt cement in siliciclastic strata below the Cedar Hills is dissolved from the top downward. Unsaturated water has not yet reached the siliciclastics in well 5. Fm = Formation; Ss = Sandstone.

Plain and Harper Formations, successively (wells 2 and 3) and also has dissolved the Stone Corral salt (well 1). The Y-anhydrite is present in this area, and as an aquiclude it has prevented water from rising above the Cedar Hills aquifer to dissolve the overlying Flowerpot salt. The length of cross section L–M–N is about 17 mi (27 km), and the dissolution zone—the distance between the limit of salt cement in the Cedar Hills Sandstone and the limit of Stone Corral salt—is about 1.5–2 mi (2.4–3.2 km) wide.

Regional Siliciclastic Salt-Cement-Dissolution Halo Map

The salt-cement-dissolution halo map (fig. 2) was created by examining approximately 4,200 geophysical well logs to determine the lateral extent of salt dissolution in each of the formations being examined—the Cedar Hills, Salt Plain, Harper, and Stone Corral Formations. Local maps and cross sections presented for each of the five areas of detailed study show how the limits of salt were determined. Also included on the halo map is the dissolution limit of the overlying Flowerpot salt in the Syracuse Basin from Johnson and Timson (2023).

Evidence exists in some areas of the Syracuse Basin that undersaturated groundwater has circulated downward (from above the Blaine Formation) and has dissolved Blaine and Flowerpot salts in a "top-down" fashion (figs. 11, 20, 23, and 27 in Johnson and Timson, 2023; figs. 8–9 in this paper). Elsewhere, however, the Cedar Hills Sandstone aquifer has introduced unsaturated water into the area, and it has caused dissolution of the salt and salt cement from underlying strata (figs. 15–16 in Johnson and Timson, 2023; figs. 10–15 in this paper).

Figure 16 is a regional map, similar to fig. 2, that also shows the location of 43 geophysical well logs of unique importance in demonstrating the dominant role that the Cedar Hills Sandstone plays in the salt-cement-dissolution process. These well logs all show that the dissolution boundary showing where salt cement is present or absent is within the Cedar Hills Sandstone and that none of the underlying salt or salt cement has been dissolved. Therefore, it is the Cedar Hills aquifer that is bringing the unsaturated water into the system. These well logs also indicate the location of the current subsurface dissolution front (boundary) of the salt cement in the Cedar Hills Sandstone. The salt-cement dissolution always begins at the top of the sandstone, as shown in fig. 7A (from the Scott City area, fig. 10, well 2). Other well logs showing the salt-dissolution front within the Cedar Hills are in the Stateline study area (fig. 13, well 3) and the Wallace study area (fig. 15, well 4). All these wells, as well as the remainder of the 43 unique wells, have the following characteristics in common:

1. The pore space in the upper sandstone, where salt cement is dissolved, is saturated with hypersaline brine, as shown by ultra-low resistivity readings averaging less than 0.1–0.2 ohm-meters. The lower portion of the sandstone, where salt cement is still present, exhibits readings of 15–20+ ohm-meters and shows that salt cement remains in the pore spaces.
2. The vertical relationship is ***always*** brine at the top of the Cedar Hills Sandstone with salt-cemented sandstone below. None of the 43 well logs deviate from this pattern.
3. No examples of these well-log phenomena are found at any other location throughout the region, other than the wells occurring at the Cedar Hills Sandstone salt-cement-dissolution boundary surrounding the Syracuse Basin (shown on fig. 16).
4. The boundary between 100% salt-cemented Cedar Hills Sandstone and 100% dissolved salt cement occurs along an extremely narrow fairway spanning a horizontal distance of only 1,200–1,500 ft (366–457 m).
5. Unfortunately, no water samples from the Cedar Hills Sandstone are available in this area (water is too salty for use as a water well, and the Cedar Hills is not drill-stem tested because it is not known to produce oil or gas

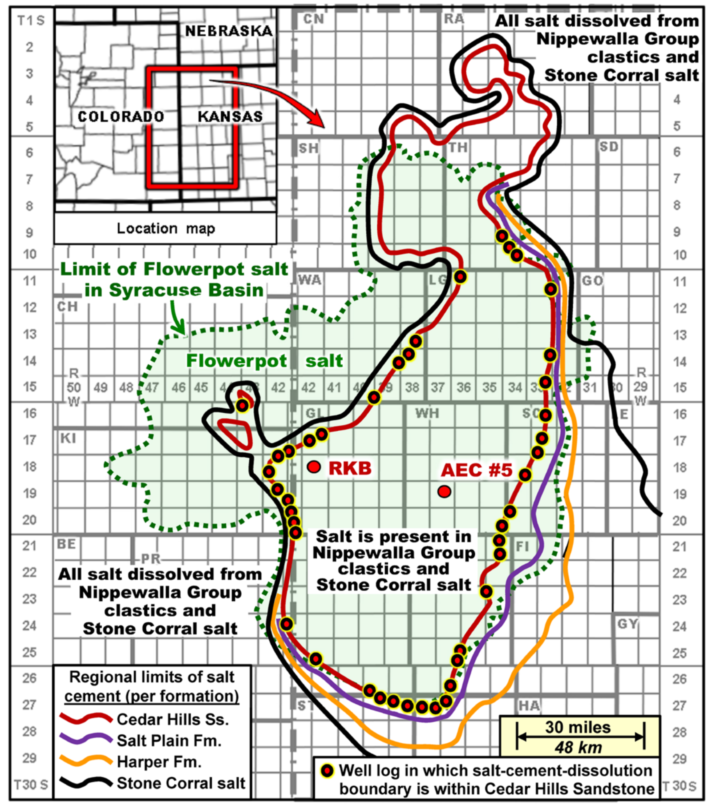

Figure 16. Map (same as fig. 2) also showing the location of 43 unique well logs in which the salt-cement-dissolution boundary occurs within the Cedar Hills Sandstone. These wells occur along a narrow fairway spanning a horizontal distance of only about 1,200–1,500 ft (366–457 m) and show the maximum penetration of the present-day dissolution front affecting salt cement in the Cedar Hills Sandstone around the entire perimeter of the Syracuse Basin. Area shown in green is underlain by the Flowerpot salt (from Johnson and Timson, 2023).

in the region), so we must rely on interpretation of the geophysical logs.

We offer the following processes to explain observations from resistivity logs in the evaporite succession. After dissolving all salt cement from the Cedar Hills Sandstone, dissolution of deeper siliciclastic salt cement then continues to progress downward through the underlying formations (Salt Plain Formation, Harper Sandstone, and Stone Corral salt), ultimately dissolving all salt cement and bedded salt down to the basal Stone Corral anhydrite. All of the unsaturated groundwater responsible for dissolving salt cement and displacive/bedded salts from the lower Nippewalla Group and Stone Corral arrived at the dissolution front via the Cedar Hills Sandstone aquifer, with dissolution progressing downward from the top of the Cedar Hills Sandstone until reaching the basal Stone Corral anhydrite.

The basal Stone Corral anhydrite is not dissolved throughout the study area and apparently acts as an aquiclude to prevent further downward movement of unsaturated groundwater from the Cedar Hills Sandstone. The regional limits of the basal Stone Corral anhydrite extend far beyond the area of the Syracuse Basin in all directions, a condition demonstrating that this anhydrite is the least soluble of all of the evaporite units in this salt-bearing sequence. This thin and widespread anhydrite bed is a significant regional aquiclude in comparison to all other strata in the midcontinent area.

Preliminary Regional Resistivity Map of Cedar Hills Sandstone

A resistivity map (fig. 17) is a "quick look" tool used by geologists and hydrologists to gain a regional overview of the salinity distribution in an aquifer. It is not intended to be an exhaustive or detailed petrophysical study. Using well-log resistivity as a proxy for formation-water salinity in a regionally deposited porous sandstone is based on the following assumptions: 1) a higher concentration of salts dissolved in a brine results in a higher salinity of the water, and this results in lower resistivities on standard well logs; 2) conversely, a lower concentration of salts in brine results in a lower salinity of the water and thus higher resistivity readings on logs. Therefore, the chemistry or salinity of the water is the major factor responsible for regional variation in resistivity values on the well logs, regardless of the log's vintage. Because we are interested in understanding the regional salinity distribution where brine flows within the aquifer, fig. 17 shows resistivity data only where the sandstone aquifer is brine saturated and not where the sandstone is salt cemented and lacks porosity and groundwater. Accordingly, the area comprising the Syracuse Basin, where the Cedar Hills/Lyons Sandstone is salt cemented, does not show regional resistivity data.

Freshwater enters the Lyons/Cedar Hills Sandstone aquifer through higher-elevation outcrops along the Rocky Mountain Front Range far to the west of the Syracuse Basin and then flows generally in an easterly direction toward the salt-cemented Lyons/Cedar Hills Sandstone in the Syracuse Basin area (figs.

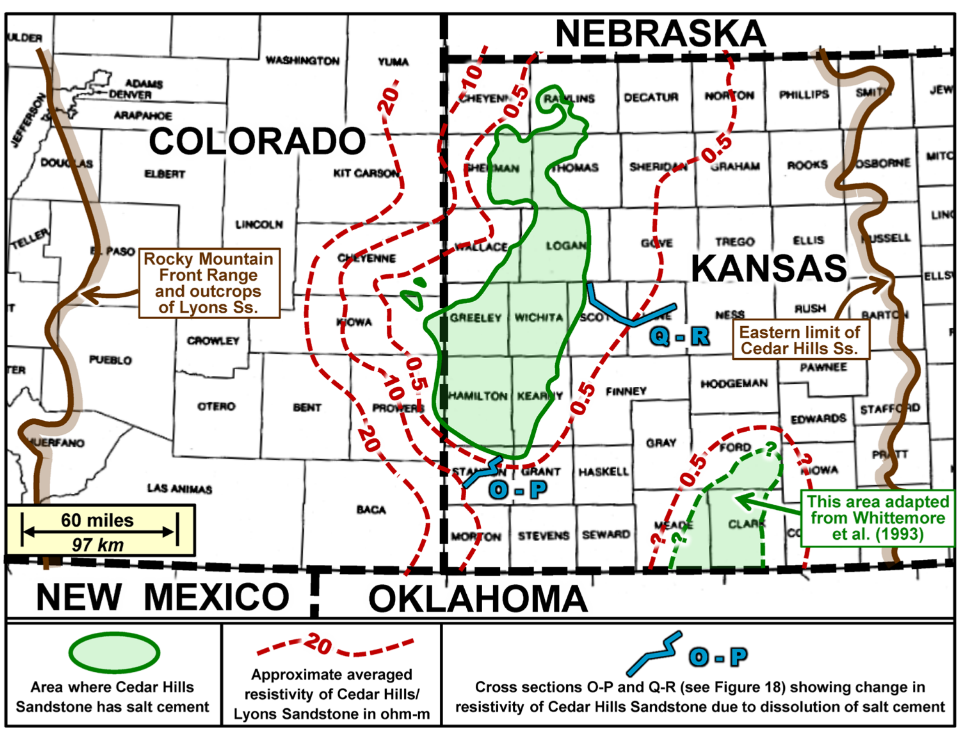

Figure 17. Approximate resistivity of the Cedar Hills/Lyons Sandstone aquifer in Kansas and Colorado, based on geophysical well logs. This map shows an increase in resistivity (a decrease in salinity of water in the aquifer) away from the Syracuse Basin region, where the Cedar Hills Sandstone is cemented by salt. Ss = Sandstone.

17–19). The longer this freshwater resides in the east-moving groundwater system, the more saline it becomes (lowering its resistivity). This eastward decrease in resistivity of the sandstone aquifer continues until the undersaturated brine encounters the salt-cemented sandstone at the salt-dissolution-boundary interface (figs. 17–18). Here a dramatic decrease in resistivity results from the abrupt creation of a hypersaline brine at the salt-dissolution boundary.

For this study, an average deep-resistivity reading over the entire thickness of the Cedar Hills Sandstone for each geophysical well log was recorded and contoured. The most porous sections of the Cedar Hills Sandstone typically dominate the log response and the shalier sections (usually minimal) are disregarded. Local anomalies in resistivity due to differing vintage logging tools and drilling-mud conditions tend to be smoothed out on a regional scale, and accordingly this map is a useful tool reflecting regional salinity trends within the aquifer. Calibrating the resistivity map with water-chemistry analyses was beyond the scope of this study but would be a worthwhile future project.

Figure 17 shows the results of the preliminary resistivity mapping of the Cedar Hills Sandstone aquifer, focusing on the Syracuse Basin region in the central midcontinent region. Cross sections O–P and Q–R (fig. 18) illustrate the well-log-resistivity characteristics used in constructing the regional map. The most conspicuous feature on the regional Cedar Hills Sandstone resistivity map is the hypersaline-brine halo (resistivity less than 0.5 ohm-meter) immediately surrounding the core area where the sandstone is entirely cemented by salt.

Although somewhat less saline than the hypersaline zone adjacent to the salt-cemented area, resistivity readings throughout the entire eastern discharge area in Kansas remain relatively low and are characteristic of a highly saline brine. From the Syracuse Basin to outcrops or subcrops at its eastern limits, the Cedar Hills groundwater maintains its hypersaline or highly saline condition. Resistivity readings rarely rise above 1.2–1.5 ohm-meters throughout this entire regional eastern discharge region. In stark contrast, resistivity readings to the west of the salt-cemented area demonstrate a rapid westward increase to 20+ ohm-meters, indicating a decrease in brine salinity, due to fresher, unsaturated water coming from the higher elevation recharge outcrops along the Rocky Mountain Front Range. This is the area delivering unsaturated groundwater to the present-day Syracuse Basin dissolution front.

Regional Hydrology

The region shown in figs. 17 and 19 is part of a still-larger regional hydrodynamic groundwater-flow system extending to the north and south and spanning most of the North American continent (Larson, 1971; Belitz and Bredehoeft, 1988; Jorgensen et al., 1993). This vast system is dominated now by topographically driven west-to-east groundwater flow from high-elevation recharge outcrops, located along the Rocky Mountain Front Range, to lower-elevation lowland-plains discharge areas located to the east. In Colorado and Kansas (figs. 17 and 19), the elevation of Lyons outcrops in Colorado's Front Range is generally 5,000–6,500 ft (1,500–2,000 m), and the elevation of equivalent Cedar Hills Sandstone in the Syracuse Basin region is 500–2,000 ft (150–600 m). This difference in elevation sets up the current west-to-east groundwater flow of unsaturated water that is dissolving salt in the lower Nippewalla Group and Stone Corral Formation along the western and southern flanks of the Syracuse Basin.

Figure 19 is a regional potentiometric-surface map of the Cedar Hills/Lyons Sandstone aquifer. Despite the sandstone's high-quality reservoir characteristics, the aquifer is of limited value for domestic use owing to its elevated salinities, a consequence of its close association with Permian-age evaporite (salt) formations. Accordingly, detailed hydrologic data are less abundant for the Cedar Hills/Lyons aquifer than other freshwater aquifers in the region (Irwin and Morton, 1969).

For this study, fig. 19 has been adapted from two published potentiometric-surface maps. The primary regional potentiometric-surface map used was compiled by the Gulf Coast Carbon Capture (GCCC) study group, an affiliate of the University of Texas at Austin, as a part of its study of the Lyons Sandstone in the Denver Basin region as a potential candidate for CO_2 sequestration into shallow saline brine formations (Hovorka et al., 2012). Additionally, the Kansas Geological Survey (KGS) published a potentiometric-surface map of the Cedar Hills Sandstone covering western Kansas as part of an in-depth study of the hydrology of the western Kansas region (Whittemore et al., 1992). Data from these two published potentiometric-surface maps are summarized in the regional map of groundwater in the Cedar Hills/Lyons aquifer (fig. 19).

The Cedar Hills/Lyons Sandstone is a confined aquifer that is under considerable hydrostatic pressure in the Syracuse Basin region. This helps drive its unsaturated water into adjacent strata. The potentiometric surface of water in the Cedar Hills ranges from 3,000 ft (900 m) at the south end of the Syracuse Basin to 1,500 ft (460 m) at the north end (fig. 19), whereas the elevation of the Cedar Hills is 2,000 ft (600 m) in the south and 500 ft (150 m) in the north. Therefore, the potentiometric surface of the aquifer is approximately 1,000 ft (300 m) above the top of the Cedar Hills aquifer.

The current west-to-east regional groundwater flow system did not begin until the onset of the Laramide Orogeny (66 mya), with uplift in the west throughout the Rocky Mountain region (Jorgensen et al., 1993). In contrast, from the time of deposition of the Nippewalla Group salt-bearing sediments until the onset

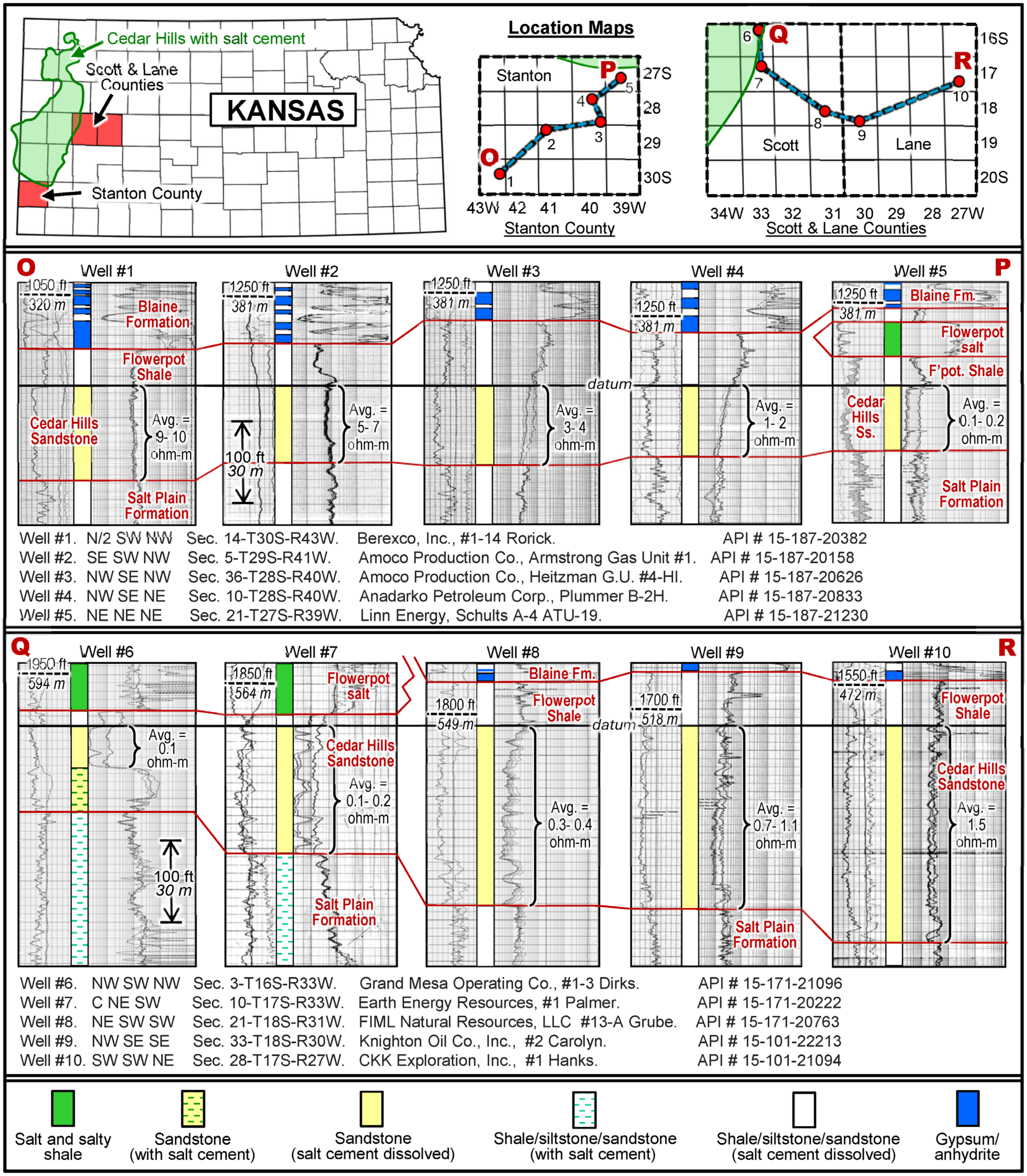

Figure 18. Cross sections O–P and Q–R showing resistivity increase in the Cedar Hills Sandstone aquifer as its brine becomes less saline away from the Syracuse Basin region. All 10 well logs are large-scale, detailed, dual induction or array induction logs; scale of original logs is 5 in. = 100 ft (12.7 cm = 30.5 m). F'pot = Flowerpot; Fm = Formation; Ss = Sandstone.

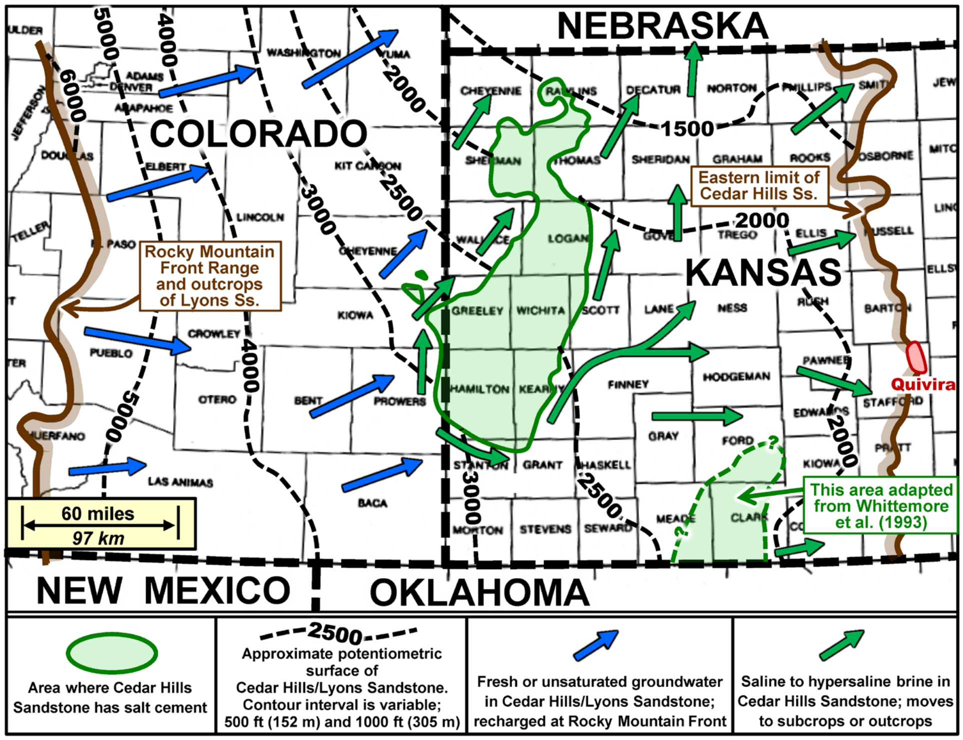

Figure 19. Approximate potentiometric surface and direction of regional groundwater flow in Cedar Hills/Lyons Sandstone aquifer. Blue arrows show flow of fresher, unsaturated groundwater that is recharged in outcrops of the Lyons Sandstone along the Rocky Mountain Front. Green arrows show flow of brine, resulting from dissolution of salt cement in Cedar Hills Sandstone, that flows to the north and east and is discharged where the Cedar Hills subcrops or crops out. Location of salt marshes at Quivira National Wildlife Refuge shown in Stafford County near east edge of map. Where the Cedar Hills has salt cement, it contains no water, and no potentiometric surface can be shown. Ss = Sandstone.

of the Laramide Orogeny, the dominant groundwater flow was generally in the opposite direction—from east to west (Jorgensen et al., 1993). These opposing groundwater-flow directions appear to be the primary reason that salt-dissolution boundaries occur around the entire perimeter of the Syracuse Basin (Johnson and Timson, 2023; and this paper).

Current-day regional groundwater directional-flow vectors are superimposed on the potentiometric-surface map (fig. 19). We suggest that freshwater recharge into high-elevation Permian outcrops along the Rocky Mountain Front Range to the west of the Syracuse Basin directs unsaturated groundwater (blue arrows) toward the still-preserved salt-cemented area centered in western Kansas. Unsaturated groundwater becomes totally saturated with respect to sodium and chlorine as this unsaturated brine encounters the salt-cemented Syracuse Basin strata, at which point dissolution progresses. At this point, the groundwater becomes a hypersaline brine at the dissolution interface, as seen in the well-log resistivity responses in fig. 18 and the cross sections of the five areas of detailed study.

Groundwater flows through the system moving downward through the Cedar Hills/Lyons aquifer into the deeper salt-cemented siliciclastics (dissolving more salt cement) and also laterally, predominantly through the Cedar Hills/Lyons Sandstone, along the regional salt-dissolution front, and ultimately flowing toward discharge outcrops and subcrops to the east and northeast. The green flow-vector arrows superimposed on the potentiometric-surface map (fig. 19) depict the likely path followed by hypersaline brine as it "flushes" from the salt-dissolution interface, working its way around the salt-cemented core of the Syracuse Basin. The brine remains highly saline to hypersaline from the current-day salt-cemented area all the way to the discharge outcrops and subcrops at the eastern limit of the Cedar Hills Sandstone.

One location for discharge of this brine in the east is at Big and Little Salt Marshes at Quivira National Wildlife Refuge in Stafford County (fig. 19) (Sawin and Buchanan, 2002). The land surface here is capped by a veneer of wind-blown dune sand, but the underlying Cedar Hills Sandstone is carrying saline water that is discharged into the salt marshes and is further concentrated by evaporation. The average salinity of Little Salt Marsh is about 2,500 parts per million (ppm) chloride, and that of Big Salt Marsh ranges from about 5,000 to 10,000 ppm chloride (Sawin and Buchanan, 2002).

The Cedar Hills/Lyons Sandstone is the dominant aquifer within the Nippewalla Group due to its significantly superior porosity, permeability, thickness, and regional continuity all the way to the elevated recharge outcrops along the Rocky Mountain Front Range to the west of the Syracuse Basin. Accordingly, it is highly unlikely that any unsaturated groundwater reaches the Nippewalla Group's salts or salt cements via lateral migration through the Blaine, Flowerpot, Salt Plain, Harper, or Stone Corral sediments before the Cedar Hills/Lyons Sandstone aquifer's unsaturated groundwater arrival has completely dissolved all salt in the manner described previously.

CONCLUSIONS

Because of a basin-wide abundance of geophysical well logs, the Syracuse Basin region of western Kansas and eastern Colorado presents an excellent opportunity to study salt-dissolution diagenesis patterns and the hydrologic conditions associated with that process in the salt-cemented siliciclastic sediments of the Permian Nippewalla Group. Numerous oil and natural-gas fields producing from deeper horizons, including the giant Permian-age Hugoton gas field, occur throughout the Syracuse Basin region, and this results in the abundance of well logs that also cover the shallower Nippewalla Group salt-bearing sediments.

Detailed mapping reveals a salt-dissolution-halo profile in siliciclastic sediments around the entire 460 mi (740 km) perimeter of the salt-cemented remnant in the interior of the Syracuse Basin. The unsaturated groundwater that causes this dissolution is delivered to the dissolution interface by the highly porous and permeable Cedar Hills/Lyons aquifer. We offer a model whereby freshwater recharge into higher elevation outcrops of the Lyons Sandstone along the Rocky Mountain Front to the west directs unsaturated groundwater toward the Syracuse Basin region where the fresher groundwater is converted to a hypersaline brine upon encountering the salt-cemented siliciclastic sediments.

As shown in five areas of detailed study, and by regional mapping, the Cedar Hills/Lyons Sandstone is the first siliciclastic formation in the Nippewalla Group to undergo salt-cement dissolution. Salt dissolution begins at the top of the formation, proceeds downward through the base of the sandstone, then continues down through the salt cement in the underlying Salt Plain and Harper Formations, and finally removes the Stone Corral salt. The basal Stone Corral anhydrite is highly insoluble and acts as a floor to this dissolution process. Likewise, the overlying Y-anhydrite aquitard prevents, or at least inhibits, upward movement of Cedar Hills water into the Flowerpot salt.

The hypersaline brine created by this regional dissolution process is “flushed” from the dissolution interface along the southern and western flanks of the current salt-cemented region and flows “around” the Syracuse Basin toward discharge outcrops and subcrops located to the east and northeast; i.e., the Salt Marshes at Quivira National Wildlife Refuge. Groundwater in the “flushed” portion of the system in Kansas is highly saline and has been the focus of studies to understand the potential for contamination of overlying freshwater aquifers through naturally occurring crossflow from the underlying Cedar Hills Sandstone (Whittemore et al., 1992). The porous Cedar Hills Sandstone and its equivalents have been used for saltwater disposal by the oil and gas industry for decades. This practice has been a continuing concern for state oil and gas regulatory agencies in their efforts to avoid introducing highly saline wastewater into shallower freshwater aquifers.

Regional resistivity mapping using geophysical well logs has proven to be an effective tool for evaluating large-scale salinity trends within the Cedar Hills/Lyons aquifer in the Syracuse Basin region. The distribution of brines of highly contrasting salinities can be mapped in detail using the abundant well control in and around the brine/salt interface surrounding the Syracuse Basin. The relatively narrow band of hypersaline brine surrounding the salt-cemented region’s core is the most prominent feature shown on the regional resistivity map. Although the Cedar Hills/Lyons Sandstone is obviously the dominant aquifer in the Permian section of the Syracuse Basin region, significant vertical permeability within the underlying evaporitic siliciclastic sediments of lesser reservoir quality is implied by the dissolution patterns documented in this study. Detailed cross sections in the five study areas clearly show the first arrival of unsaturated, salt-cement-dissolving groundwater in the Cedar Hills/Lyons aquifer, followed by downward progression of the groundwater through the shaly, fine-grained sediments of the Salt Plain and Harper Formations. This downward flow of groundwater implies that vertical permeability exists in these formations.

The semi-regional dissolution “halo” maps and resistivity (water-salinity) maps generated by well-log studies of the Nippewalla Group evaporitic sediments in the Syracuse Basin region may be useful tools for a variety of disciplines. The Kansas and Colorado oil and gas regulatory agencies could benefit in well permitting, plugging, and UIC activities (saltwater-disposal permitting). Oil and gas industry operators can use these maps in well planning and design when conducting drilling and completion operations in the areas affected by salt and salt-cement dissolution. Additionally, oil and gas exploration efforts involving seismic surveys could benefit from consulting the regional dissolution “halo” maps to assist in avoiding seismic-velocity pitfalls that could interfere with data interpretation.

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