Environmental impacts of oil production on soil, bedrock, and vegetation at the U.S. Geological Survey Osage–Skiatook Petroleum Environmental Research site A, Osage County, Oklahoma

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ABSTRACT

The U.S. Geological Survey is investigating the impacts of oil and gas production on soils, groundwater, surface water, and ecosystems in the United States. Two sites in northeastern Oklahoma (sites A and B) are presently being investigated under the Osage–Skiatook Petroleum Environmental Research project. Oil wells on the lease surrounding site A in Osage County, Oklahoma, produced about 100,000 bbl of oil between 1913 and 1981. Prominent production features on the 1.5-ha (3.7-ac) site A include a tank battery, an oil-filled trench, pipelines, storage pits for both produced water and oil, and an old power unit. Site activities and historic releases have left open areas in the local oak forest adjacent to these features and a deeply eroded salt scar downslope from the pits that extends to nearby Skiatook Lake. The site is underlain by surficial sediments comprised of very fine-grained eolian sand and colluvium as much as 1.4 m (4.6 ft) thick, which, in turn, overlie flat-lying, fractured bedrock comprised of sandstone, clayey sandstone, mudstone, and shale. A geophysical survey of ground conductance and concentration measurements of aqueous extracts (1:1 by weight) of core samples taken in the salt scar and adjacent areas indicate that unusual concentrations of NaCl-rich salt are present at depths to at least 8 m (26 ft) in the bedrock; however, little salt occurs in the eolian sand. Historic aerial photographs, anecdotal reports from oil-lease operators, and tree-ring records indicate that the surrounding oak forest was largely established after 1935 and thus postdates the majority of surface damage at the site. Blackjack oaks adjacent to the salt scar have anomalously

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elevated chloride (>400 ppm) in their leaves and record the presence of NaCl-rich salt or salty water in the shallow subsurface. The geophysical measurements also indicate moderately elevated conductance beneath the oak forest adjoining the salt scar.

INTRODUCTION

The U.S. Geological Survey is investigating the impacts of oil and gas production on soils, groundwater, surface water, and ecosystems at selected sites in the United States. In September 2000, two sites in northeastern Oklahoma (A and B), about 30 km (18 mi) northwest of Tulsa, were selected for in-depth, multidisciplinary studies. Early results of investigations at these two sites are described in several papers in a report edited by Kharaka and Otton (2003). This report describes additional results from site A and focuses on geologic, solid-phase geochemical, geophysical, ecological, and biogeochemical data. These results indicate the impact of produced water releases on the salinity of bedrock across the site and the impact of these releases and other site activities on the growth of the local oak forest. The aqueous geochemistry of groundwaters encountered in the wells drilled at site A over the past 2 yr are discussed in a companion paper (Kharaka et al., this volume).

Site A is adjacent to Skiatook Lake in southeastern Osage County about 30 km (18 mi) northwest of downtown Tulsa, Oklahoma (Figure 1). The lake, a U.S. Army Corps of Engineers project, was completed in the mid-1980s and was designed for flood control, water supply, and recreation. A major recreational fishery has been developed in the lake. The normal conservation pool elevation of the lake is 217.6 m (714 ft). During the course of this study (started March 2001), the lake level has varied from about 215.8 to 219.2 m (708 to 719 ft).

Petroleum production in Osage County started in the late 1800s, and more than 38,000 wells have been drilled across the county during the last 100 yr. Production activities at site A began about 1913 and continued to about 1973, when the tank battery, pits, and a central power unit fell into disuse. Sometime after 1973, another tank battery was constructed to the southeast, wells were powered individually, and production continued through the early 1980s. The U.S. Geological Survey began multidisciplinary studies at the site in March 2001. In March 2002, the first of several investigative drilling programs was completed. Most wells have been completed with one or two screened intervals depending on depth and have been monitored and sampled periodically since.

Site investigations have included cultural and geologic mapping, soil geochemistry and mineralogy, coring and bedrock geochemistry, groundwater geochemistry including stable isotopes, organic geochemistry, water-level monitoring, drill-hole geophysical logging, surface electromagnetic (EM) geophysics, direct current soundings, oak tree leaf biogeochemistry, oak tree ring dating, plant surveys,

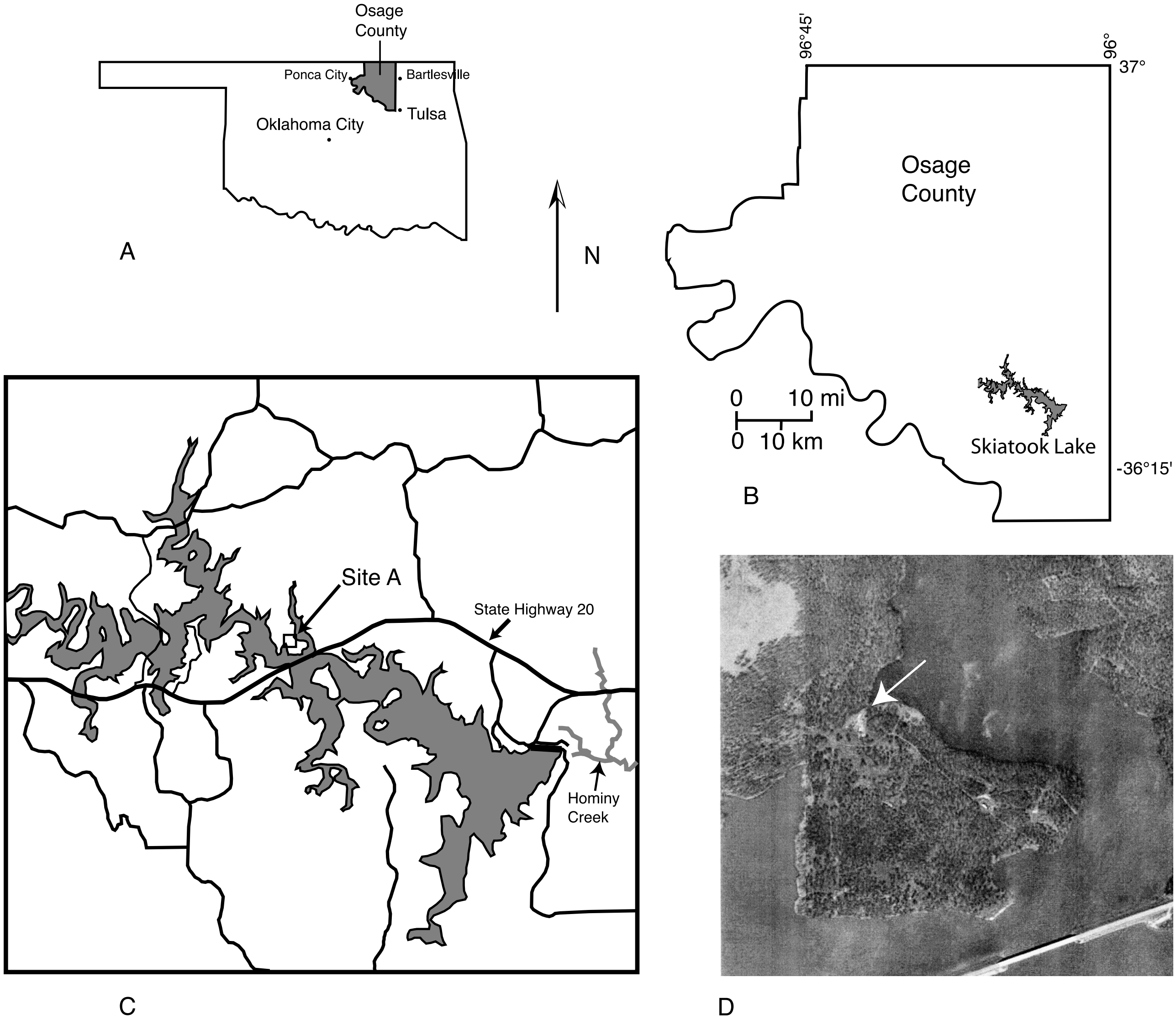


Figure 1. Location map and aerial photo for site A. (A) County location map. (B) Skiatook Lake location map. (C) A site location on Skiatook Lake. (D) Aerial photo of the peninsula that includes site A; the arrow points to the prominent salt scar at the north end of site A. The lines on the image are quarter section lines for section 13. Note the Highway 20 bridge across Skiatook Lake in the lower right corner.

and microbial population studies. Nearby, active oil wells on other leases have been sampled for crude oil and produced waters, and these fluids have been characterized.

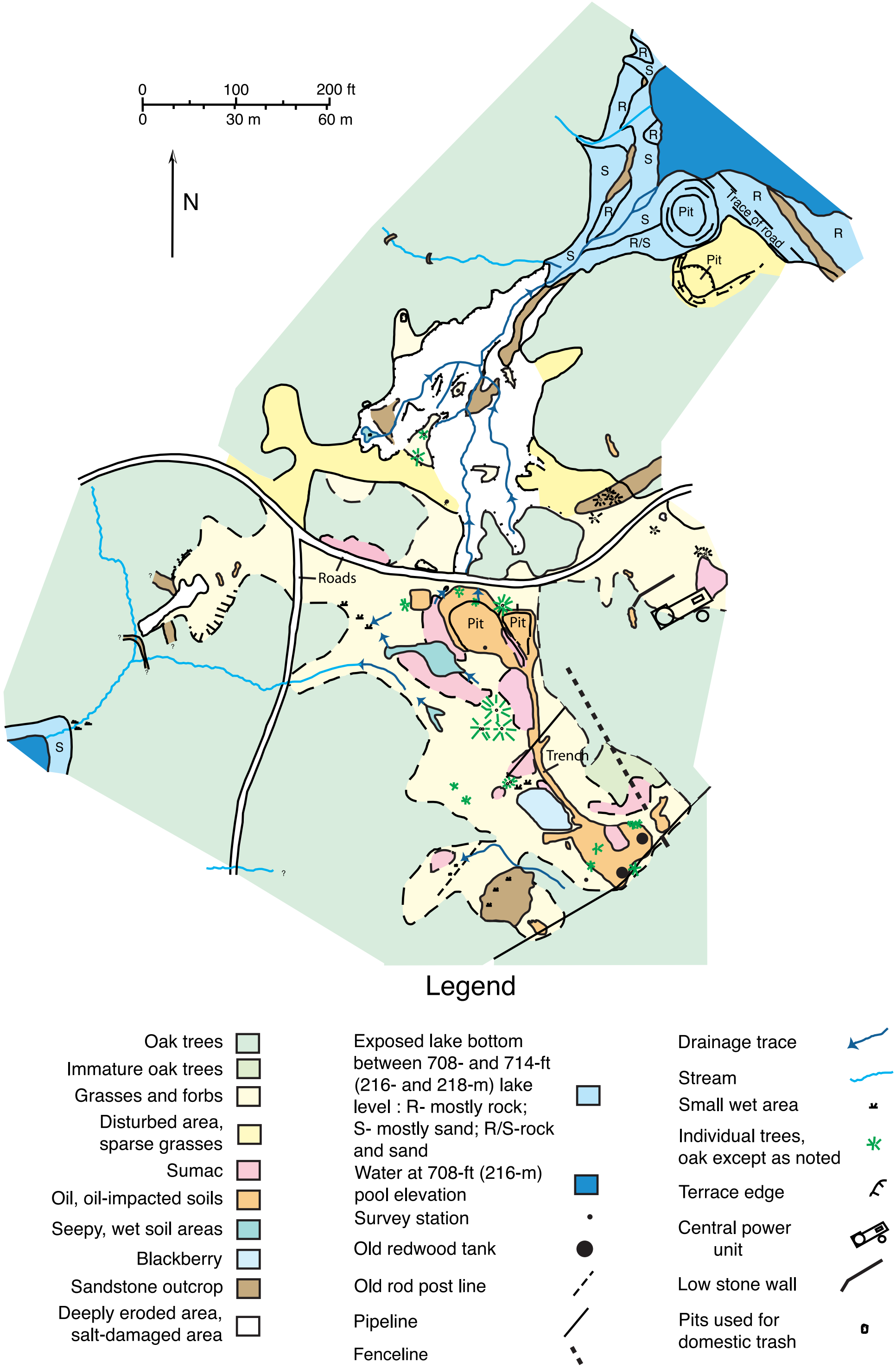
Site Vegetation

The site consists of about 1.5 ha (3.7 ac) of irregular, open, grassy areas and a partly revegetated salt scar surrounded by an oak forest comprised mostly of post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*) (Figure 2). Isolated oak and patches of sumac trees occur in the open area south of the east-west access road that divides the site into north and south parts. Three large clumps of trees occur just north of the road between it and the deeply eroded, salt-scarred area that extends down to the lake. The deeply eroded area is partly delineated by a terrace edge. Four isolated soil pedestals on which the original soil profile is preserved occur in the eroded area. Another road extends from the east-west access road southward.

Cultural Features

Two redwood tanks surrounded by an area of oil-stained thin sandy soil and patchy sandstone bedrock exposures occur in the southern part of the open area

Figure 2. Cultural and vegetation map for site A from mapping in 2001 and 2002. Small open areas within the oak trees are not mapped.



(Figure 2). A trench filled with weathered hydrocarbon extends from the tank area northward to two pits just south of the east-west access road. It appears that product and produced water from the tank battery were drained into these two pits via the trench. The western pit is a significant depression surrounded by a prominent berm. It has a low point along the northern edge of the berm that probably served as an outlet for fluids in the pit. A gully extends northward from this outlet into the deeply eroded area. The eastern pit contains a thick layer of fresh hydrocarbon (possibly asphaltic tank bottoms) that nearly fills the pit. The pit berm surrounding this fresh asphalt layer is very weathered, like the asphalt to the west, suggesting that

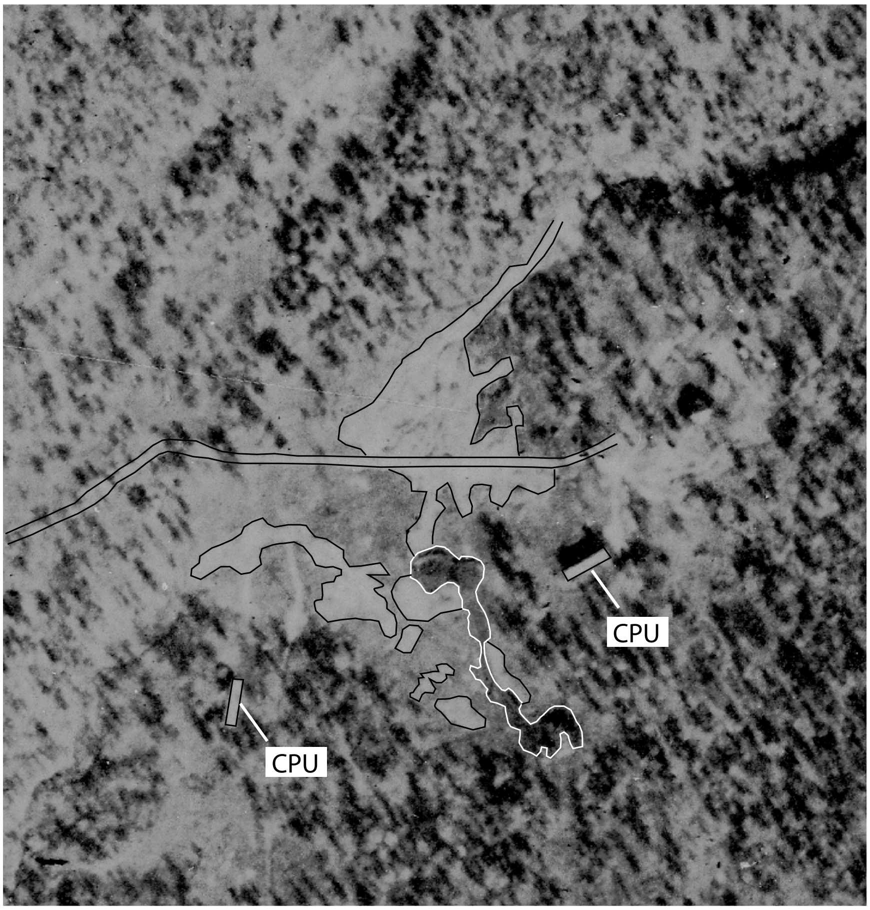


Figure 3. A 1936 aerial photo of the site. The tank battery area, trench, and pits are outlined in white. Salt-damaged areas related to the tank battery, trench, and pits are outlined in black; however, other salt-damaged areas are likely present. The location of the road as configured in 1936 is shown. CPU = central power units; only their foundations remain presently.

the eastern pit is as old as the western pit. Both pits can be seen in a 1936 aerial photo of the site (Figure 3). A pipe protrudes from the northern berm of the eastern pit, and a corroded valve lies nearby. We conclude that the eastern pit was used to temporarily store products prior to pickup by a tank truck, whereas the western pit temporarily stored produced water that was either allowed to evaporate, seep into the ground, or flow out of the pit to the north.

Remnants of an old power unit (stone wall, concrete foundations, bullwheel, and pump rods) occur at the head of an open area on the east edge of the map area. This power unit can also be seen on the east side of Figure 3. Two pits, traces of an old road, a wellhead, and other pieces of pipe and fencing occur on the exposed lake bottom and above the normal conservation pool shoreline at the north part of site A. Remnants of a pit berm and walls and associated salt-scarred area are in a clearing along the west edge of site A. Sections of fence, pipelines, and rod post lines, old trash pits, and isolated oil spills are scattered across the site. Two low depressional areas, now seasonally wet and occupied by wetland vegetation, occur southwest of the two pits. The 1936 aerial photo (Figure 3) suggests that these depressions were small salt scars. This same aerial photo shows that the deeply eroded, salt-scarred area north of the pits reached about 80% of its present surface area as early as 1936.

GEOLOGIC SETTING

Site A is underlain by (1) a surface layer of eolian sand or mixed eolian and slopewash sand of varying thickness (0 cm to 1 m; 0 in. to 3.28 ft); (2) colluvium that ranges from a thin layer of granule-pebble, weathered, sandstone-clast conglomerate to large boulders of sandstone in a sandy to clayey matrix (a few centimeters to 0.5 m [1.6 ft] thick); and (3) shale, mudstone, siltstone, clayey sandstone, and sandstone bedrock, weathered in its upper parts. South of the drainage divide, the surficial units are thin, a few tens of centimeters maximum, and they are thickest north of the drainage divide (combined thicknesses of as much as 1.4 m [4.6 ft]).

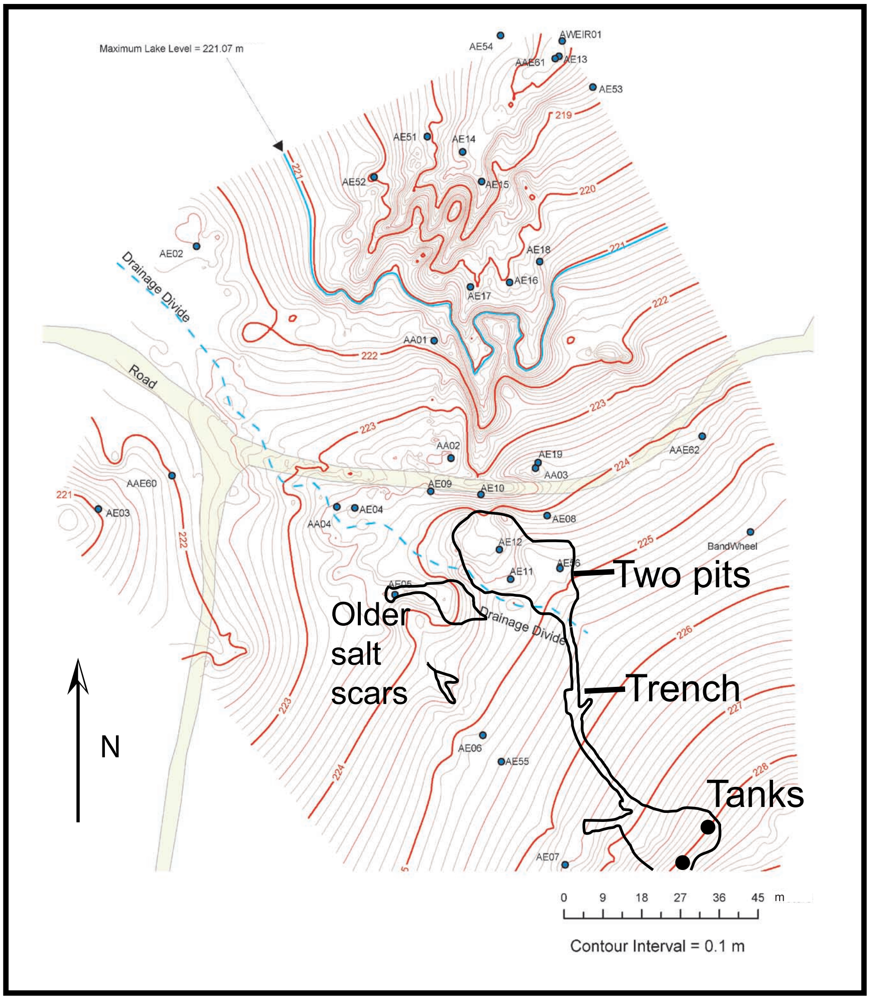


Figure 4. Topographic map of site A developed from a GPS survey and a Geographic Information System (GIS) software (Abbott, 2003) with locations of selected wells.

A thick sandstone unit crops out in the southernmost part of the open area (Figure 2), and the patches of sandstone around the nearby redwood tanks are outcrops of the same unit. The basal contact between this thick sandstone and the underlying interbedded shale, mudstone, clayey sandstone, and thin sandstone to the north can be recognized by a gentle break in slope at the north edge of laterally discontinuous exposures of the thick sandstone. North of this contact, the bedrock is only well exposed in the deeply eroded area, where clayey sandstone, mudstone, siltstone, and thin sandstone crop out, although sandstone ledges crop out on the exposed lake bottom to the north and in stream cuts on the west side of the site.

All units in the deeply eroded area are weathered, and most units form poor exposures except in some of the deeper gullies. Resistant sandstone ledges crop out in three areas: the west edge, the center, and the north part of the deeply eroded area (Figure 2). The outcrop at the west edge consists of cross-bedded channel sandstone, whereas the other sandstones are sheetlike. Drilling at this site (15 holes, 4–23 m [13–75 ft] deep; 26 holes, 0.5–4 m [1.6–13 ft] deep) shows that the section is characterized by stacked, intertonguing sheets of sandstone, mudstone, and shale cut by at least one sandstone channel. Thin coaly horizons are present in some of the shale. The section dips gently westward to northwestward at 1–2°.

Site Topography

Site A has been mapped using the global positioning system (GPS) (Abbott, 2003) to generate a topographic map with a 0.1-m (0.3-ft) contour interval (Figure 4). The upper, southerly part of site A drains northwest, then west, then southwest into an arm of Lake Skiatook that is located west of the site (Figure 2). A low drainage divide separates this southern section from a northern section that drains northward into the Cedar

Creek arm of Skiatook Lake. The tank battery is located in the southern section. The trench moved fluids from the tank battery area across the low drainage divide to the two pits that lie just to the north of the drainage divide.

North of the two pits, the irregular topographic surface shows the extent of erosion related to the salt water movement downslope to the north from the two pits. The deepest erosion, about 2.0 m (6.6 ft), occurs near the soil pedestal in the north-central part of the deeply eroded area. Southwest of the two pits, just across the drainage divide, topographic contours delineate two shallow depressions that were formerly salt scars and are seasonally wet (compare Figures 2, 4).

The Oak Forest

The open area delineating the site is surrounded by an oak forest dominated by blackjack and post oaks with minor hickory. The age of these trees has been determined in a detailed tree-ring survey along four transects across the site (Figure 5) (Keeland and McCoy, 2003). Most trees are younger than 90 yr of age (the start of production at the site), and these are dominantly blackjack oak. Only the post oak trees predate production. Anecdotal reports state that in the early 1900s, the site was occupied by grasses with scattered post oak trees. Blackjack became the dominant tree to colonize the map area because fires were suppressed by residents and oil field workers; however, colonization by oak trees was only locally successful in the open area (isolated trees and clumps of trees in the grassy areas of Figure 2). Present-day traces of former residents on this site are limited to two trash pits (Figure 2). Notable among these local trees is a single blackjack oak tree about 12 m (39 ft) high growing at the north edge of the east pit berm and a group of three trees about 15–20 m (49–66 ft) high in the open area about 15 m (49 ft) south of the pits. These four trees are 45–55 yr of age.

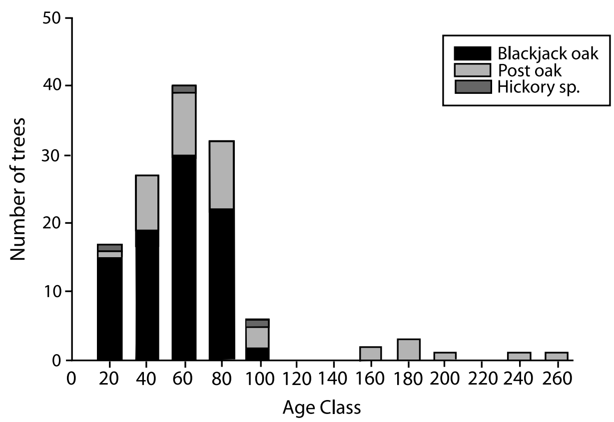


Figure 5. Age (in years) of oak and hickory trees along four traverses at site A (Keeland and McCoy, 2003).

Dispersion of Salt at Site A

Long-term seepage and overflow from the two pits and from other lesser sources has permitted saline-produced water to move northward and westward following topography and westward to northwestward following bedrock dip. Bedrock has become saline by the passage of this water. We have investigated the extent of salt dispersion by leaching bedrock core shortly after its retrieval and analyzing the leachate for salt content, measuring ground conductivity using surface EM techniques; conducting borehole conductivity measurements and comparing the data to salt leachates of core samples; and analyzing oak tree leaves for salt components. The extent of movement of produced water salts in groundwater is reported in a companion paper (Kharaka et al., this volume).

Salt in Bedrock Core

Chloride concentrations in leachates of core from several wells along north-south and east-west transects at site A document the extent of saline bedrock in the subsurface. Figure 6 shows the location of the two transects. Figure 7A and B shows the pit position (projected into the line of section in each case), well locations, topography, lithologies, and saline zones in bedrock along these two transects (the vertical red lines adjacent to the columnar sections). The methods used are documented in Zielinski et al. (2002).

The north-south cross section (Figure 7A) suggests that saline water from the pits moved downward into a sandstone layer immediately below the surface eolian sand and colluvium, then down the topographic slope, and down the apparent bedrock dip to the north above an underlying shale bed. However, the salt water also moved into a lower sandstone sequence (probably two stacked sheets of sandstone) and moved similarly down the topographic slope and down the apparent dip to the north above a second, underlying shaly interval. The pathway through the first shale to the lower sandstones is not known at this point. In addition, the two shales are saline, suggesting salt penetration through time of these fine-grained units. In well AA02, salt

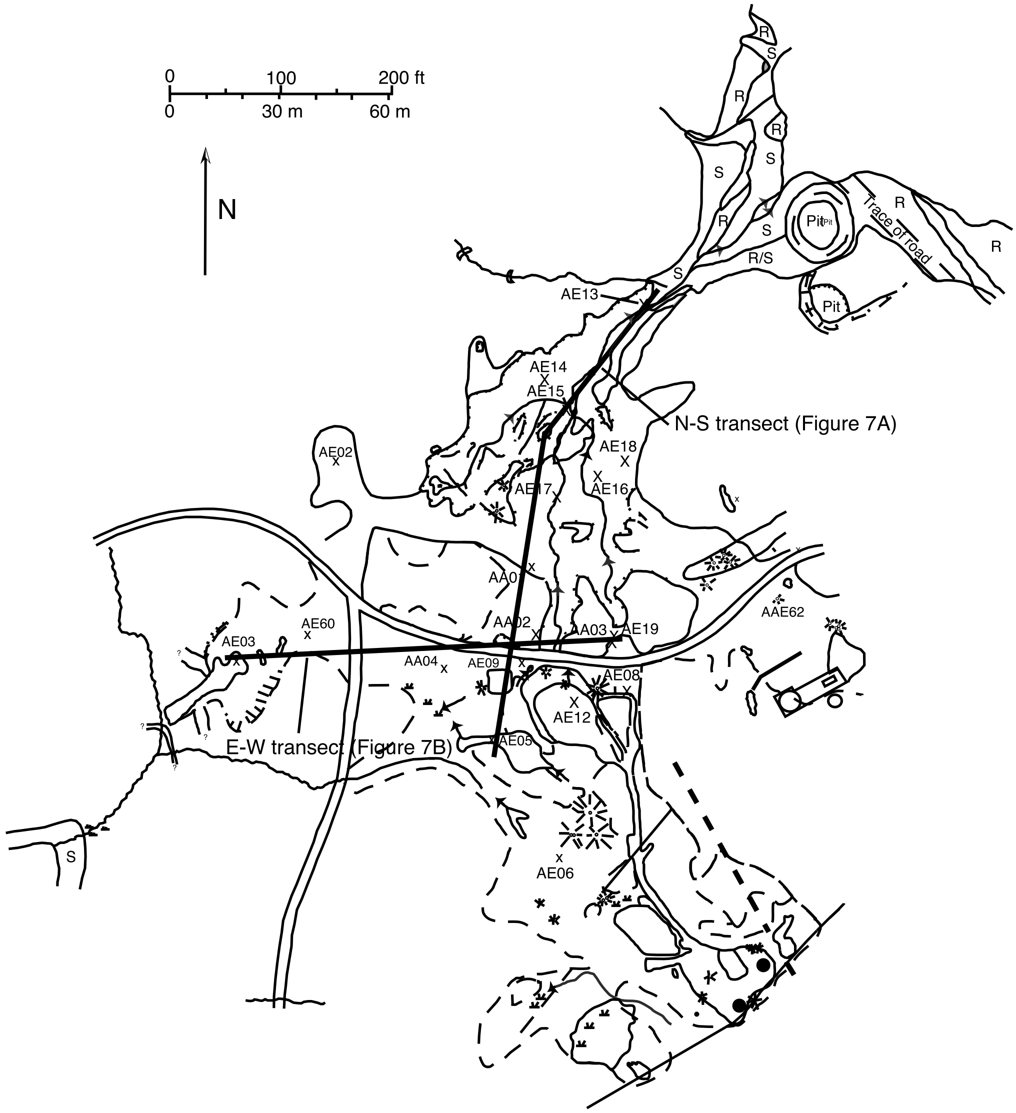


Figure 6. Site A showing the location of two transects (Figure 7A, B) and selected site wells. Line work derived from Figure 2.

does not appear to have penetrated below the second shale into the thick underlying sandstone unit as this sandstone shows background chloride concentrations in leachates all the way down to a lower shale sequence (see further discussion of this hole below). Downslope to the north in AA01, AE15, and AE13, the full thickness of the core is saline, and the depth of salt penetration is unknown and needs further investigation. Note that the salt scar (the deeply eroded area in Figure 7A) heads near the point where saline water following the uppermost sandstone-shale contact is forced to the surface because the topographic slope is greater than the apparent dip.

Saline zones in the east-west cross section (Figure 7B) suggest that saline water from the pits has moved down the topographic slope and downdip to the west. The section in hole AA03, which is just north of the pits, is fully saturated with salt, and the depth of salt penetration here is not known. To the west in hole AA02, salt penetrates two sand-shale sequences but stops just below the lower shale. In hole AA04, salt has penetrated the full thickness of the surface sandstone unit and several meters into underlying weathered (green) and unweathered (dark gray) shale. In AE60, salt occurs above and within a thin shale layer, then in the basal part of an underlying sand, and in the thick section of underlying weathered and unweathered shale.

An apparent strong permeablility contrast exists between the unconsolidated eolian sand-colluvium surface layer and the underlying variably weathered sandstone. The pattern of salinity in AE60 suggests that saline water moved through the basal eolian sand and

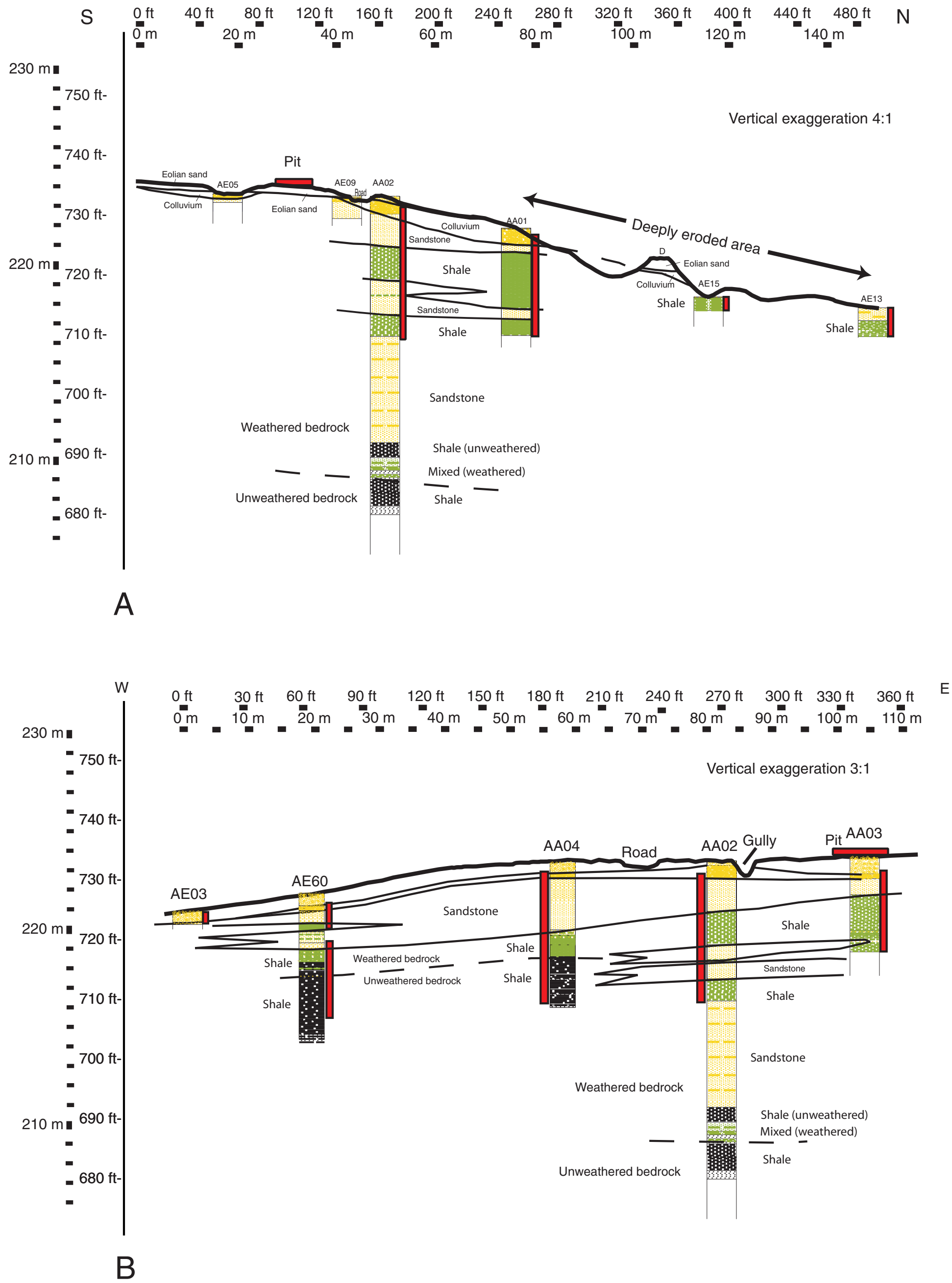


Figure 7. Cross sections. (A) North-south cross section showing pit location (projected into the section from the east), topography, well locations, lithology, lithologic correlations, and saline bedrock intervals (vertical red bars) as indicated by leachates of bedrock core. See Figure 6 for location. Yellow and green colors represent sandstone and fine-grained lithologies, respectively. The fine-grained units include shale, siltstone, and mudstone. The gray colors represent unweathered units. The distance from the pits to the lake (just to the north of the section) is about 120 m (393 ft). (B) East-west cross section showing pit location (projected into the section from the south), topography, well locations, lithology, lithologic correlations, and saline bedrock intervals (vertical red bars) as indicated by leachates of bedrock core. Note the horizontal scale change and change in vertical exaggeration in (B).

colluvium along the contact with the underlying sandstone and slowly penetrated the underlying sandstone from the top down to an underlying shale bed, where it would move laterally downdip along the sandstone-shale contact. In addition, saline water seeping directly from the bottom of the pit may have moved downward into the underlying weathered sandstone, then, where a shale bed was encountered, it would move laterally downdip through the sandstone along the sandstone-shale contact.

Ground Conductivity Geophysical Surveys

Apparent conductivity (millisiemens per meter, mS/m) measurements are shown in Figure 8. Warmer colors indicate high conductivity. The effective depth of investigation of the instrument is 4.5 m (15 ft). Figure 8 shows the survey superimposed on a 1960 aerial photograph of the site. Red dots are selected rotary and auger holes and direct-push well locations. The location of two drill holes (AA02 and AA04) that were

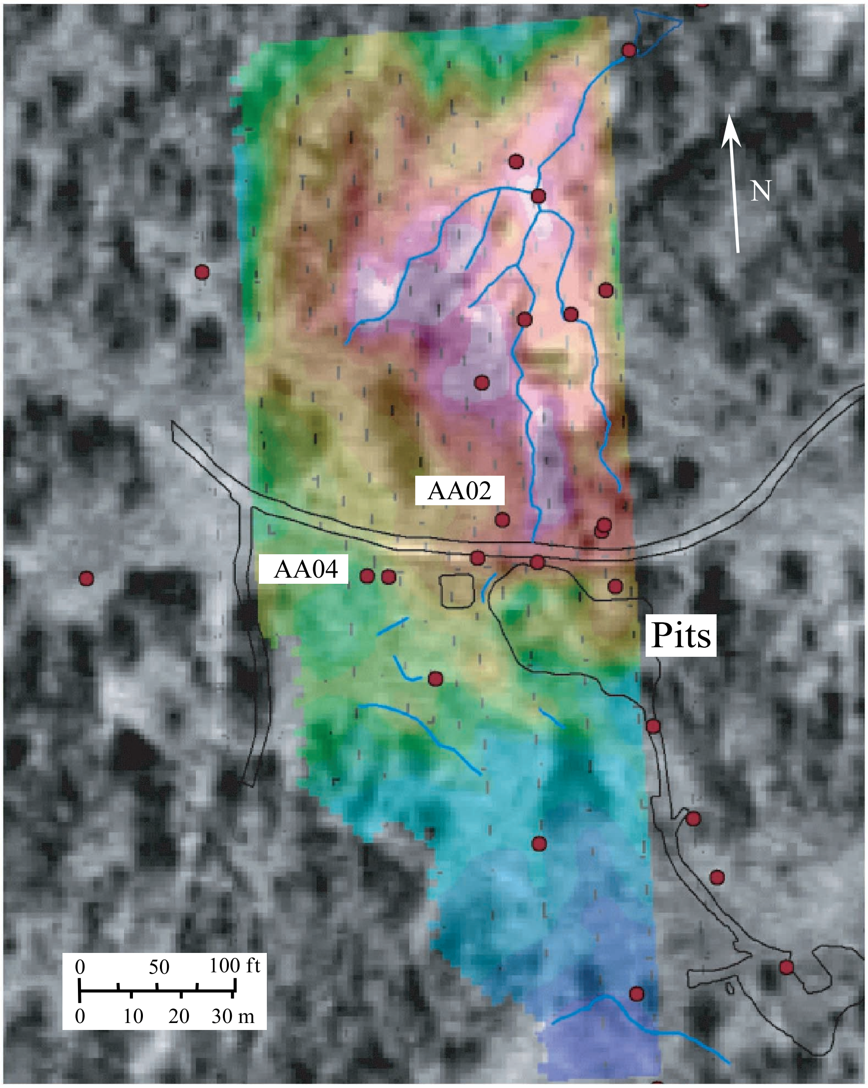


Figure 8. Apparent conductivity measurements from an EM survey of the central part of site A using an EM-31 instrument along traverse lines about 10 m (33 ft) apart. Warmer colors represent higher conductivity. Color image superposed on a 1960 aerial photo of the site. Red dots represent selected wells. Blue lines represent traces of surface drainage ways. The site roads, pits, oil trench, and related oil-saturated soils are shown in line work. The dashed lines represent the EM survey lines. Note the location of drill holes AA02 and AA04.

drilled and sampled in March 2002 and logged in August 2003 are shown.

The area of highest conductivity is downslope to the north from the two pits. It starts just north of the western pit close to the low point on the north berm and extends northward to low parts of the salt-scarred area. Highest conductivities seem to occur in the western part of the salt-scarred area. Produced water released from the west pit may have followed a northwest-trending channel in the colluvium-sandstone contact filled with permeable colluvium (J. K. Otton, 2003, unpublished detailed mapping). The area of high conductivity extends beyond the surface scar northwest into the oak forest.

West of the two pits, the apparent conductivities are lower, possibly because salt movement in that direction was dominated by relatively slow seepage from the pits instead of overflow that occurred only to the north. Modestly elevated conductivities are associated with the topographically low marshy area just southwest of the pits.

Detailed Drill-Hole Logging and Geochemistry

Figure 9 shows lithologic and geophysical logs and chloride analyses for drill hole AA02. The full length of hole AA02 was not logged geophysically because of the limitations of probe geometry (the measuring points are some distance from the upper and lower ends of the gamma and conductivity probes). Conductivity readings (Figure 9) show the influence of salt saturation of the sandstone and shale units in the upper part of the section. Highest conductivity readings occur in the lower part of the upper sandstone and the upper part of the immediately underlying shale unit.

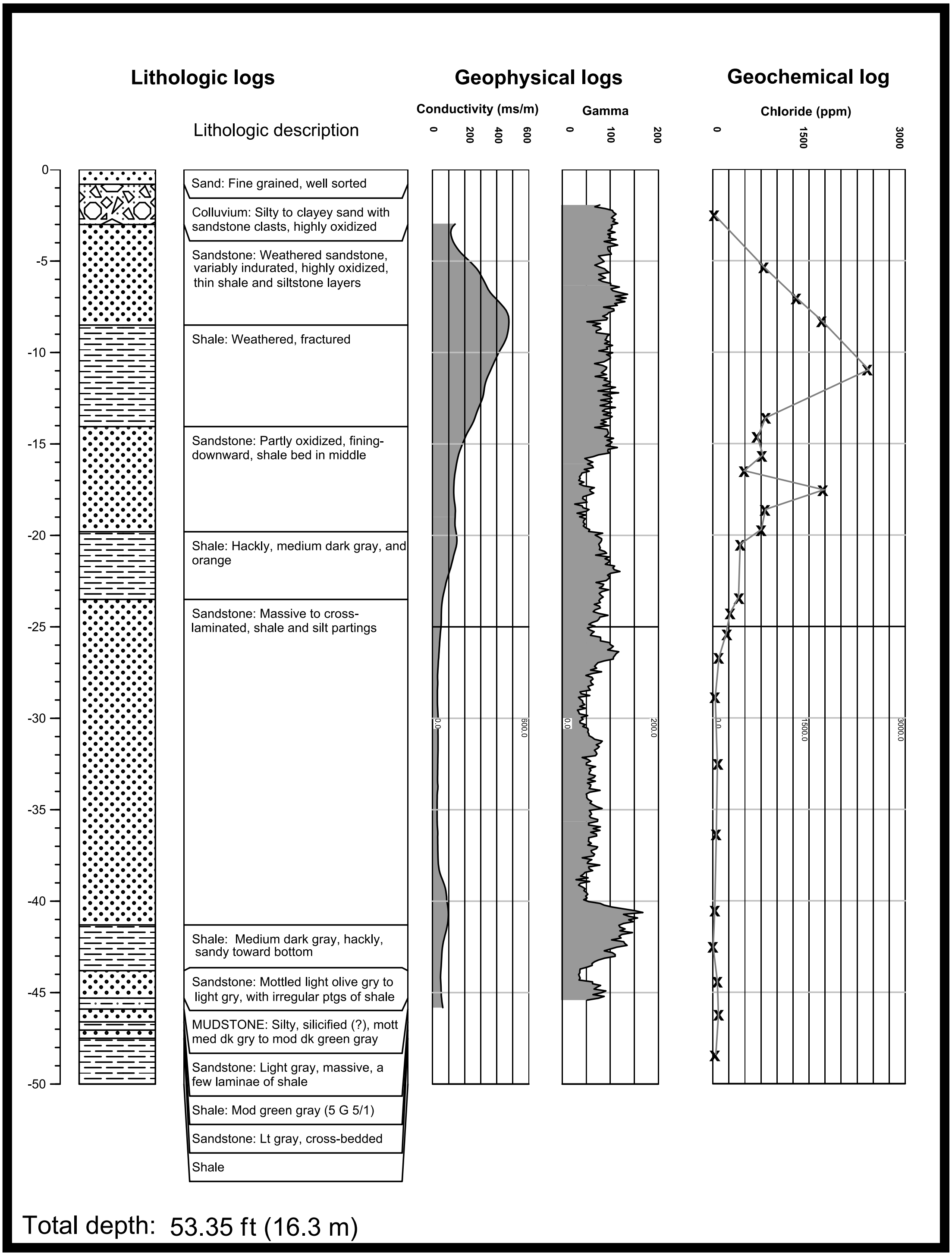


Figure 9. Lithologic, geophysical, and geochemical logs for drill hole AA02. See Figures 6 and 8 for location and Figure 7A and B for cross sections that include this well.

The next sandstone down has a conductivity signature lower than the upper sandstone but higher than the thick lower sandstone, which is largely unaffected by salt. The shale underlying this sandstone is most conductive in its upper parts. Conductivities decrease to what are probably local background values in the upper part of the thick lower sand. Modest conductivity increases occur near the base of the thick lower sandstone and in the lower mixed sandstone-mudstone-shale sequence in the section.

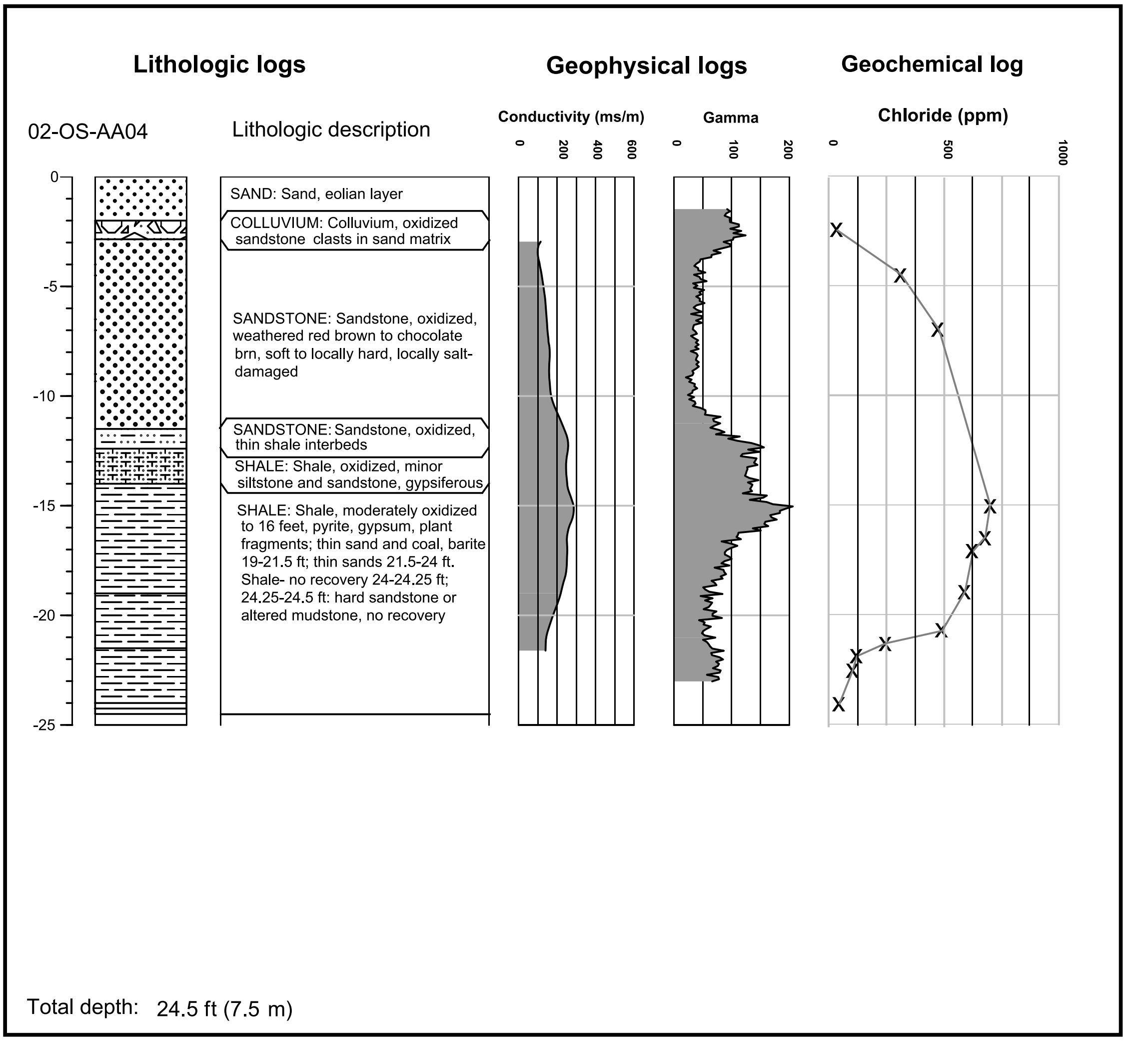


Figure 10. Detailed lithologic, geophysical, and geochemical logs for drill hole AA04. See Figures 6 and 8 for the location and Figure 7B for the cross section that includes this well. Note the scale change for the chloride concentrations.

The gamma log for the upper sandstone and shale sequence does not show the contrast seen in most logs for these rock types elsewhere and seen in the lower part of this hole (sandstone low, shale high). Modest amounts of radium derived from the brine may be precipitated in the salt-saturated upper sandstone in this hole, raising the gamma signature to levels similar to the underlying shale. Although the radium activity concentration of the saline groundwater at site A has not been measured, radium contamination of oil field operations producing from the same units nearby has been documented (Otton et al., 1997).

The chloride content of leachates from AA02 core samples is elevated (as much as 2500 ppm) in the upper part of the section, with highest chloride concentrations in the basal upper sandstone and the upper shale. The induction geophysical log shows highest conductivity values (200–500 mS/m) in the same zone, but the peak is offset from the highest chloride sample. The next sandstone-shale sequence has more modestly elevated chloride levels. Chloride concentrations drop to apparent background levels in the thick lower sandstone at depths below 8.2 m (27 ft). Near the base of the thick lower sandstone, chloride concentrations do not increase in the zone where the conductivity is slightly elevated, suggesting that produced water salt is not the cause of this elevated conductivity.

Figure 10 shows lithologic and geophysical logs and chloride analyses for drill hole AA04. The upper half of the hole is dominated by the eolian sand, colluvium, and sandstone, whereas the lower half is dominated by shale. Conductivities in the sandstone are elevated above apparent background values (see

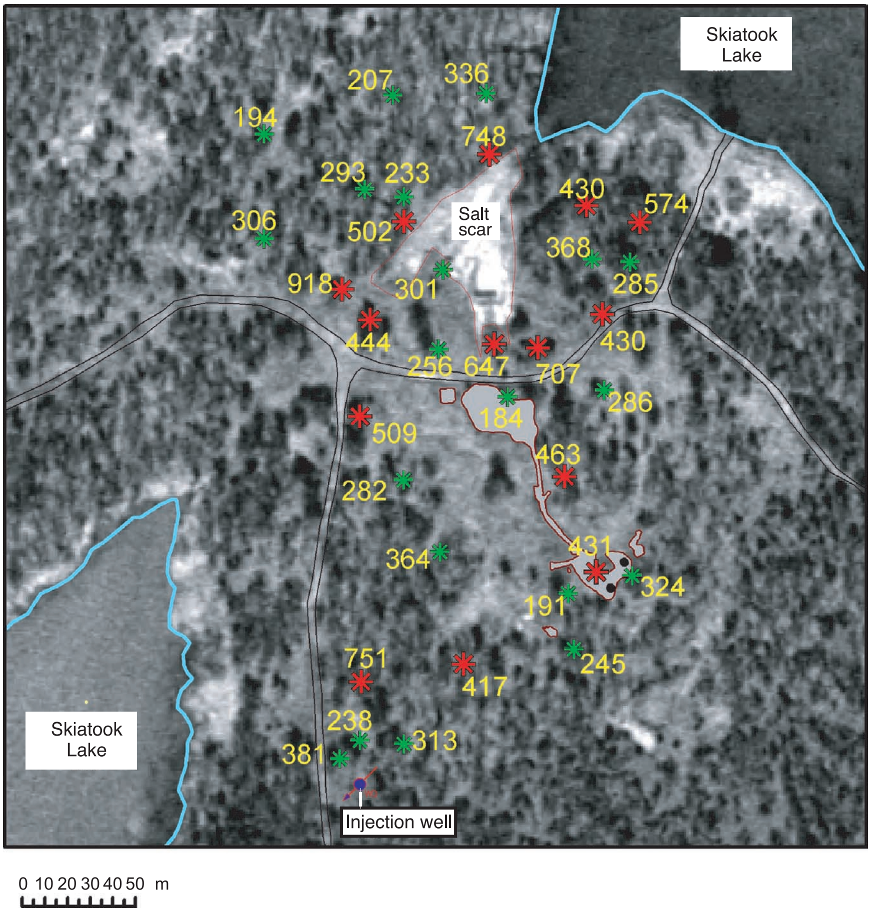


Figure 11. Aerial photo (1995) of site A showing locations of sampled blackjack oak trees and chloride concentrations of leaves. Trees with chloride concentrations greater than 400 ppm are shown in red.

lower sandstone in AA02) and gradually increase downward to sandstone-shale contact, where they increase significantly then drop gradually. These data suggest that the sandstone section and most of the shale is salty. The gamma log shows a near-surface elevated zone that may be associated with iron-rich colluvium and weathered sandstone. Highest gamma values occur in the upper part of the shale. The upper elevated gamma zone may reflect sorption of radium from the brine by hydrous ferric oxides in the colluvium and rusty-weathered sandstone (Langmuir, 1997). The elevated gamma in the upper part of the shale may represent uranium or potassium enrichment in the upper shale beds or sorption of radium from the brine or both.

The chloride content of leachates of core samples is low just below the colluvium-sandstone contact but increases steadily to high values (500–700 ppm) in the middle and lower parts of the underlying shale. The basal shale appears to have background chloride values suggesting that the limit of salt penetration was reached.

Hole AA04 is in a location with much lower surface conductivity values than hole AA02 (Figure 8). The drill-hole logging shows that maximum conductivity values are lower and deeper in hole AA04 than in AA02. Much of the elevated conductivity in hole AA04 occurs below the effective depth of investigation of the EM instrument (4.5 m; 15 ft), whereas the reverse is true for AA02. Both holes have a comparable thickness of relatively salt-poor eolian sand and colluvium (about 0.9 m [2.9 ft]).

Chloride Levels in Oak Tree Leaves

Leaves of blackjack oak (Q. *marilandica*) were collected in late 2002 and analyzed in early 2003. Methods used to collect and analyze leaf material are documented in Zielinski et al. (2003). The objective was to investigate the response of native oak trees to known NaCl contamination in the shallow (1–8 m; 3.3–26 ft) subsurface. Trees were sampled from a 225 × 300-m (738 × 984-ft) area that included sites variably removed (10–200 m; 33–660 ft) from the open grassy and salt-scarred areas of site A (Figure 11). Trees within about 30 m (100 ft) of the salt scar are subject to subsurface contamination by NaCl as indicated by ground-based geophysics

(Figure 8) and anomalous chloride contents of aqueous extracts of core samples (for example, AA02 and AA04). The chloride content of dried oak leaves was determined by ion chromatography and varied from 170 to 920 ppm (Figure 11). Of the 14 samples with more than 400 ppm Cl (the apparent threshold for anomalous values), 8 plotted within 30 m (100 ft) of the salt scar and open areas, and 10 plotted within 45 m (147 ft) of the scar and open areas. The location of these trees confirmed and also suggested an expansion of the area affected by subsurface salt. Cl-enriched trees more removed from the salt scar may be spatially associated with a small tank site, an injection-well lolcation, and pipeline breaks. The single tree at the north edge of the east pit contains 184 ppm chloride in its leaves despite the presence of a shallow, thin saline water layer below the hydrocarbon in the east pit, which contains 120,000 ppm total dissolved solids.

CONCLUSIONS

Salt from produced-water releases from two pits and other lesser sources at site A have penetrated as much as 7.5 m (24 ft) into the underlying bedrock, although the maximum depth has not been fully evaluated in parts of the site. The saline bedrock extends westward and northward from the two pits. The position of the west pit outlet, topography, pit location at the drainage divide, channels in the contact between the permeable surficial sediment and the less permeable underlying bedrock, and bedrock dip are the major factors controlling the direction of dispersion of salt. Shales and mudstones in the upper part of the bedrock section may have served as aquitards but became salt saturated themselves with time. The upper shale unit beneath the pits diverted saline water in the upper sandstone downdip to the north and to the west. An underlying sandstone unit also became salt saturated, but the pathway for salt water from the pit to this unit is not obvious in the present data.

Produced water releases and suppression of fire by residents and workers converted the predevelopment post oak savannah to an area of blackjack-post oak forest with openings caused by production activity disturbances. Locally within the disturbed area, oak trees have found sites where they have become established.

Surface conductivity surveys with an EM instrument define the limits of the shallow parts of the saline bedrock (to 4.5-m [14.7-ft] depth) and show that the most intensely saline bedrock occurs to the north under the salt-scarred area downslope from the outlet at the north edge of the west pit. Some salt moved westward from the pits. The data suggest that the tank battery area in the southeast part of the site was a limited source of salt.

The high salinity has modified the conductivity of the salt-saturated sandstone and the shale observed in borehole logs. Good concurrence exists between the conductivity logging and the salt levels measured in sandstone and shale core sample leachates. Minor radium accumulation probably has occurred in the sandstone and shale impacted by salt water, and the gamma-log pattern has been modified.

Oak trees near the northwest edge of the salt scar have extracted chloride from shallow parts of the plume. Other oak trees still over the plume but farther to the northwest of the salt scar (compare Figures 8, 11) did not absorb anomalous levels of chloride, probably because the salt is below their root zone. Other oak trees near the salt scar, the open area to the south, and in specific locations where other produced water releases were likely also show elevated chloride levels. Biogeochemical sampling of this type may provide a less costly alternative to geophysics or drilling when assessing NaCl salt dispersion in the shallow subsurface.

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