Chapter 12

Oil-field Salinization Screening on the Edwards Plateau Using Airborne Geophysics

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Introduction

We conducted airborne and ground-based geophysical studies in Sterling County, Texas (Figure 12-1), to examine the extent and intensity of natural and oil-field salinization of groundwater in the shallow subsurface (Paine, 2002; Paine and Collins, 2003). The project area is located on the north margin of the Edwards Plateau west of Sterling City, where Cretaceous Edwards Group carbonates cap a plateau that has been dissected by the North Concho River, Lacy Creek, and several small tributaries (Figure 12-2).

The principal geophysical method employed in this study is electromagnetic (EM) induction in which surface, airborne, or borehole instruments measure the apparent electrical conductivity of the ground. Ground conductivity is influenced both by sediment type (clayey sediments are more conductive than sandy sediments) and by water quality (saline water is more conductive than fresh water). Salinized areas will have relatively high electrical conductivity, whereas nonsalinized areas will have relatively low conductivity. The Sterling County airborne geophysical survey covers an area that is about twice as large as that of the recent helicopter-based Runnels County survey (Paine and others, 1999), uses an instrument that explores to significantly greater depths, and produces images of apparent conductivity at depth.

Dense spatial data were obtained by mounting the instruments in an aircraft and flying at low altitude on a grid, allowing potential changes in groundwater quality to be interpreted. We verified the airborne geophysical data by (1) acquiring ground-based geophysical data at representative locations and comparing ground and airborne results and (2) comparing available water well data with conductivity patterns evident in the airborne data set.

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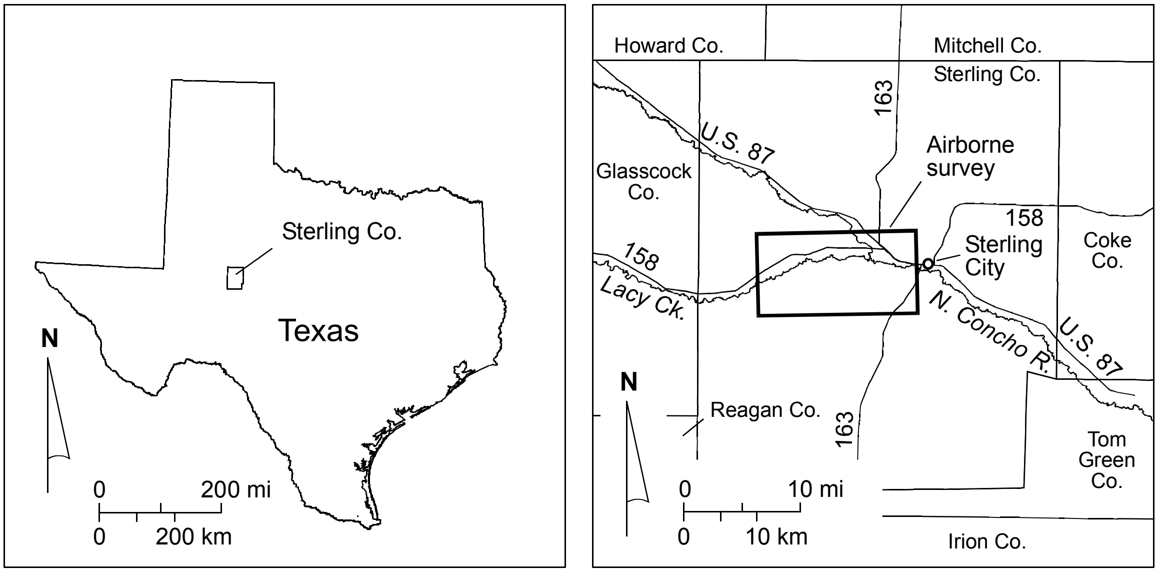

Figure 12-1: Location of the airborne survey area, Sterling County, Texas.

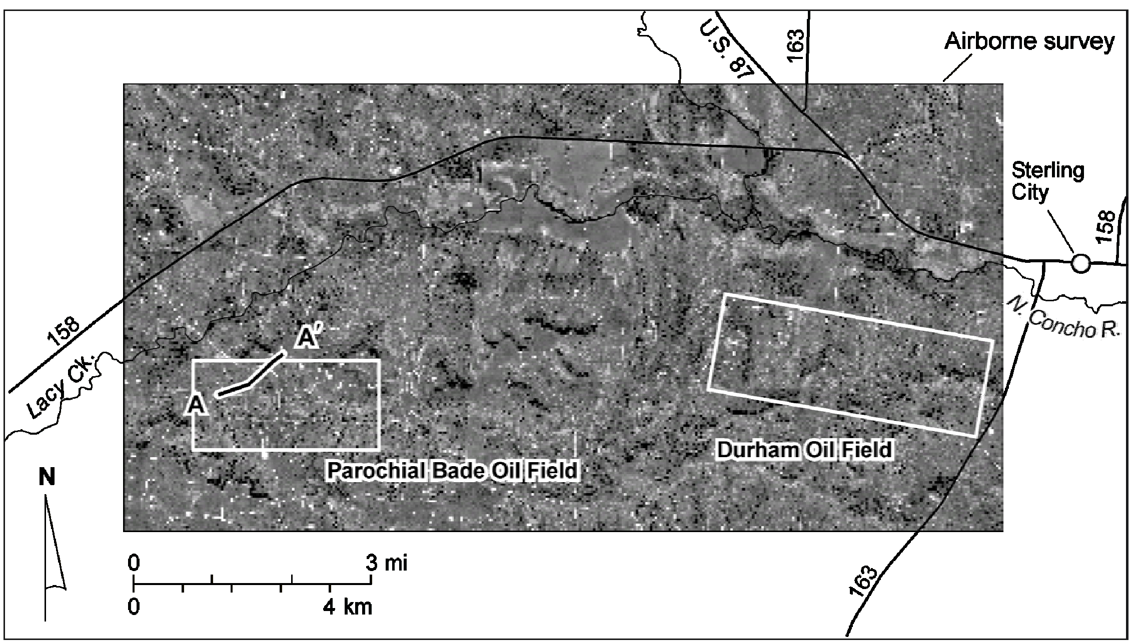

Figure 12-2: Aerial photographic mosaic of the airborne survey area and locations of Parochial Bade oil field, Durham oil field, and cross section A–A′. Aerial photograph taken in 1996 and modified from Texas Natural Resources Information System.

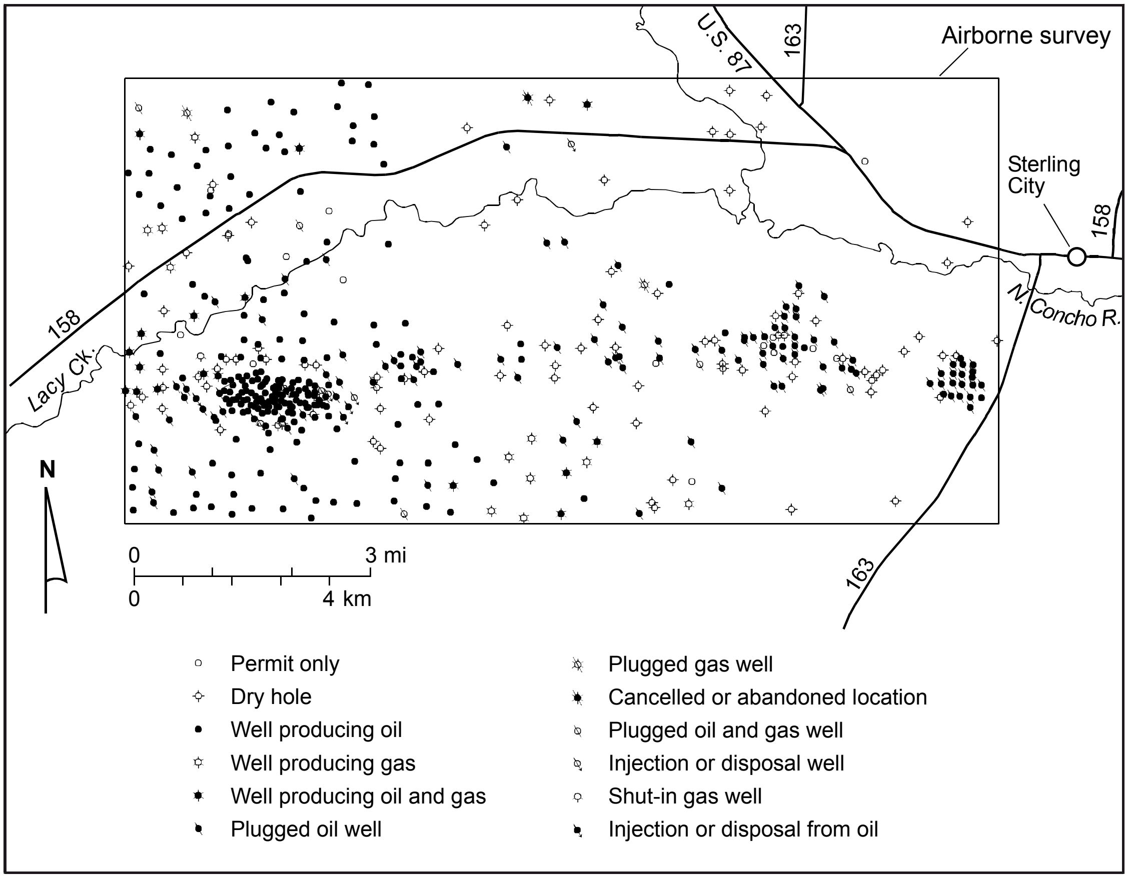

Figure 12-3: Locations of oil and gas wells within the airborne survey area (well data from the Railroad Commission of Texas).

Groundwater quality within the survey area, both from an alluvial aquifer along Lacy Creek and from the Cretaceous Antlers Sand aquifer, is generally good. Local salinization of Antlers groundwater related to oil and gas exploration and production has been documented in Parochial Bade oil field (Renfro, 1993). We obtained oil and gas well locations from the Railroad Commission of Texas (RRC) to examine the extent of this salinization and to delineate other areas of potential oil-field salinization. RRC records indicate that there are 475 known well locations within the survey area (Figure 12-3), with the densest concentrations in Parochial Bade field in the southwest part of the area and in Durham oil field in the southeast part of the area. Of these 475 locations, most are either producing (211) or plugged (109) oil wells. Less than 5 percent represent locations where no well exists, either as a permit only (15) or a cancelled or abandoned location (5). There are 12 documented injection or saltwater disposal wells. Potential salinization could be caused by past discharge of produced water into pits, migration of saline water from deeper formations into the shallow aquifers, or leakage of injected saline water into the shallow aquifers (Richter and others, 1990). In each case, significant salinization of the shallow aquifers should be accompanied by an increase in electrical conductivity of the ground near the leaking well or pit. Magnetic field data from airborne geophysical surveys can be used, along with known well locations, to verify well locations and locate either unknown or mislocated wells (Wilson and others, 1997). Conductivity data can be used to identify conductivity anomalies consistent with salinization. When combined, these data can help distinguish natural, oil-field, and agricultural sources of salinization (Paine and others, 1997, 1999; Smith and others, 1997).

Methods

We employed airborne and ground-based geophysical methods to rapidly and noninvasively delineate potentially salinized areas by measuring changes in electrical conductivity with depth. The principal geophysical method in the airborne and ground surveys is electromagnetic induction, or, simply, EM (Parasnis, 1973; Frischknecht and others, 1991; West and Macnae, 1991). This family of geophysical methods employs a changing primary magnetic field that is created around a current-carrying transmitter wire to induce a current to flow within the ground, which in turn creates a secondary magnetic field that is sensed by a receiver coil. In general, the strength of the secondary field is proportional to the conductivity of the ground.

We acquired ground-based conductivity data using a Geonics EM34 ground conductivity meter (McNeill, 1980). This instrument measures apparent electrical conductivity to multiple exploration depths. It consists of transmitter and receiver coils that are separated by distances of 10, 20, and 40 m, depending on the primary frequency and desired exploration depth. We collected data at either the 20- or 40-m coil separation along nine lines in the west part of the survey area.

Fugro Airborne Surveys flew an airborne geophysical survey covering about 162 km^2 west of Sterling City (Figure 12-4). The principal flight lines were 9.1-km long, oriented north-south, and spaced 100-m apart. The three tie lines were 17.8-km long, oriented east-west, and spaced 4,000-m apart. A total of 1,478 km of airborne data were acquired during 18 hours of flight time over a 9-day survey period in 2001 (Hefford, 2001). Instruments aboard the aircraft acquired time-domain EM (TDEM) and magnetic field data simultaneously.

The TDEM method (Kaufman and Keller, 1983; Spies and Frischknecht, 1991) measures decay of a transient, secondary magnetic field produced by termination of an alternating primary electric current in the transmitter loop. The receiving coil measures the strength of the secondary field that is generated by currents induced to flow in the ground when the transmitter current is terminated. Secondary field, or transient, strength at an early time gives information on conductivity in the shallow subsurface; transient strength at later times is influenced by conductivity at depth.

A DeHavilland Dash 7 aircraft (Figure 12-5) flying at a height of 120 m carried the MEGATEM II TDEM transmitter attached to the aircraft and towed a triaxial EM receiver about 131 m behind the transmitter at a height of 64 m above the ground. The

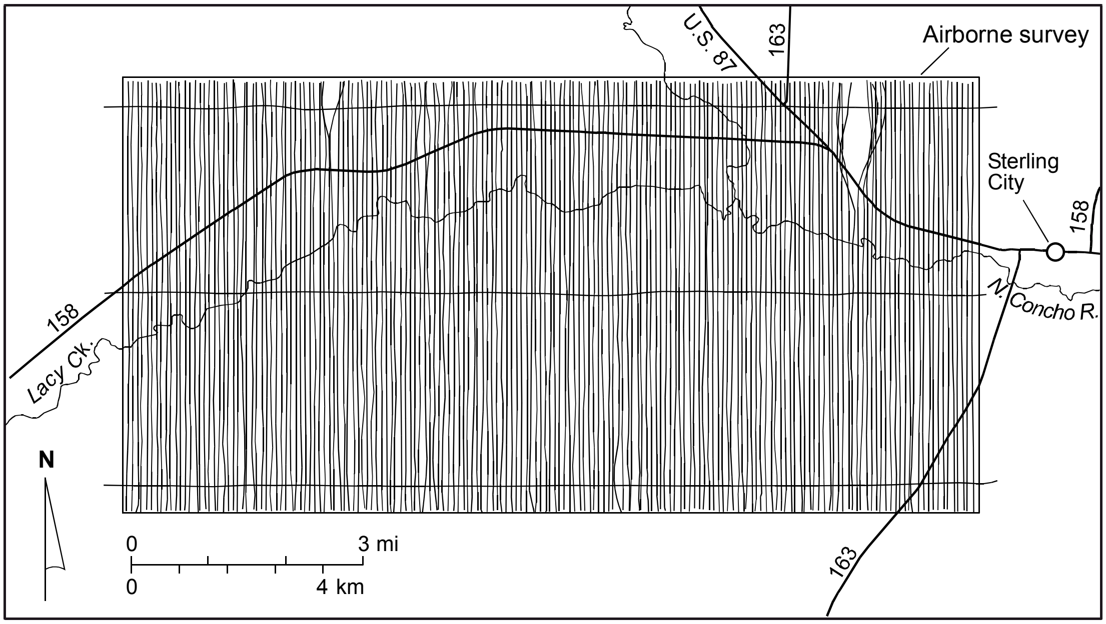

Figure 12-4: Flight lines flown by Fugro Airborne Surveys. Open areas are tower sites.

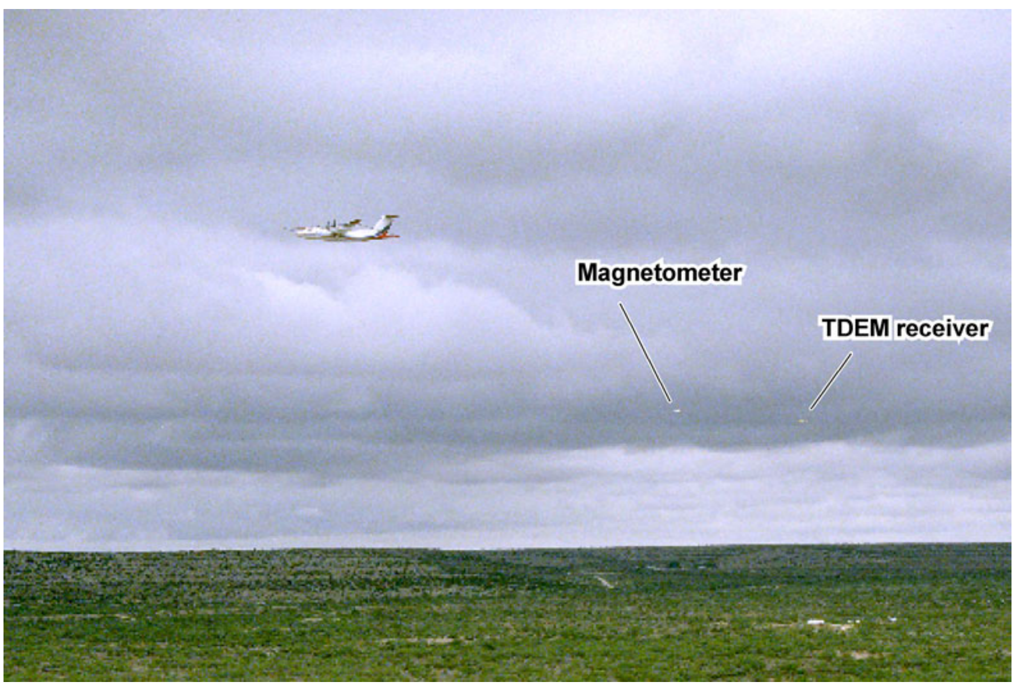

Figure 12-5: Survey aircraft acquiring TDEM and magnetic field data in Sterling County.

primary EM field was generated by a four-turn wire loop carrying a 1,331-ampere current at 30 Hz, resulting in a dipole moment of more than 2.1×10^6 A-m^2. Each transmitter current pulse lasted 3.9 milliseconds (ms). Transients were recorded during the 11.6-ms window following termination of the transmitter input pulse. EM diffusion depth, the depth below which currents will not have diffused during the measurement period, is commonly used as a proxy for exploration depth. It is calculated using the equation

$$d = k (t \rho)^{0.5}$$

where d = diffusion depth (in m), k = 503.3 $(m/ohm\text{-}s)^{0.5}$, t = latest time measured, and ρ = resistivity (in ohm-m) (Parasnis, 1986).

Assuming an average ground resistivity of 20 ohm-m and a latest measurement time of 11.6 ms, exploration depth for the study area is about 240 m. Measurement locations were determined from differential global-positioning-system (GPS) data by using a base station at the San Angelo airport and a roving receiver on the aircraft. At the 30-Hz transmitter frequency (60-Hz sample frequency) and an airspeed of about 70 m/s, transients were acquired at an along-line spacing of about 1 m. Adjacent transients were stacked to reduce noise and recorded at 4 Hz, resulting in 108,620 measurements at a final sample spacing of about 18 m. Fugro processed the data.

Along with the transients measured in the x (parallel to the flight path), y (horizontal and perpendicular to the flight path), and z (vertical) axes by the towed receiver coils, Fugro performed conductivity-depth transforms to produce relatively smooth conductivity models depicting a conductivity value at 10-m-depth intervals. Although these are not full, robust inversions of the TDEM data (Wolfgram and Karlik, 1995), they do produce pseudo-depth profiles from z-and x-axis data that reflect changes in signal strength with time and are thus useful in examining lateral and vertical changes in apparent conductivity.

We produced horizontal images of apparent subsurface conductivity by (1) extracting modeled conductivity values at 10-m-depth intervals, (2) gridding the values within the image processing software ERMapper, and (3) exporting the georeferenced images. Digital images were imported into a GIS database. Coverages used to analyze the relationship between the geophysical data and geological and hydrological characteristics included aerial photographs, water-well locations and depths, water-quality analyses, roads (and associated power lines), streams, oil and gas wells, and pipelines.

The aircraft also towed a cesium magnetometer at a height of 73 m above the ground (Figure 12-5) to measure changes in magnetic field strength caused by natural effects and local features, such as oil and gas wells that contain significant amounts of iron. Magnetometer data were acquired at 10 Hz, yielding a sample spacing of 7 m for magnetic field data.

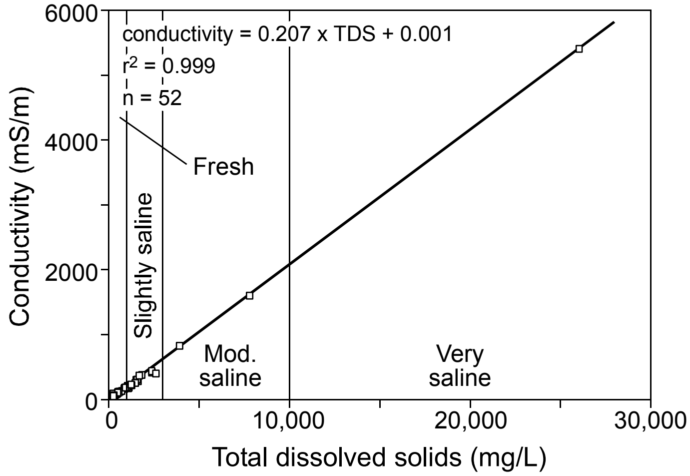

Figure 12-6. Relationship between total dissolved solids (TDS) concentration and specific conductivity of samples from 52 water wells within the airborne survey area (data from TWDB; water salinity classification from Robinove and others, 1958).

Groundwater Depth

To ensure that the exploration depth of the airborne and ground-based geophysical instruments was sufficient to reveal relevant information about groundwater salinization, we examined water depths reported from 75 wells within the survey area. These data indicate that depth to water ranges from about 4 to 94 m, averaging 26 m. Surface elevation also varies significantly across the study area, ranging from below 700 m in the Lacy Creek and North Concho River valleys to more than 800 m on the Edwards Plateau. There is a strong correlation between surface elevation and water depth: as elevation increases, depth to water also increases. In general, elevation of the water table mimics surface elevation. Well depths, reported for 69 wells in the survey area, range from 6 to 120 m. Calculated airborne geophysical exploration depths greater than 200 m exceed depths of the deepest water wells reported.

Groundwater Quality

Most of the water wells produce from an alluvial aquifer in near-surface, unconsolidated sediments or from the Antlers Sand, a Lower Cretaceous formation composed of sandstone, quartzite, conglomerate, and thin clay layers that underlie lower Cretaceous Edwards limestone (Ashworth and Coker, 1993; Renfro, 1993). Of the 75 study-area wells in the Texas Water Development Board (TWDB) database, 40 produce from the Antlers, 29 from alluvium, and 4 from combined alluvial and bedrock aquifers.

Groundwater is dominantly fresh to slightly saline (Figure 12-6). Reported total-dissolved-solids (TDS) concentrations range from fresh water at 238 mg/L to very saline water at 26,035 mg/L, but only four of the 53 analyses have TDS values higher than 3,000 mg/L and are classified as moderately to very saline. Chloride and bicarbonate are the most abundant anions in the reported analyses. Chloride has the highest average concentration in the 53 reported analyses at 878 mg/L and is the dominant anion in the 12 samples with TDS values higher than 1,600 mg/L. At least nine of these high TDS samples are from wells and test holes that have been impacted by oil-field activities (Renfro, 1993). At lower TDS values, typical of most water samples in this area, bicarbonate is the dominant anion at average concentrations of 336 mg/L.

Dominant cations by concentration are sodium (average concentration 515 mg/L) and calcium (139 mg/L). Extremely high sodium concentrations in a few samples raise average sodium concentrations well above the median concentration of only 94 mg/L. In all moderately to very saline samples, sodium is the most abundant cation. Calcium is the most abundant cation in 29 of the 33 fresh samples.

One of the keys to the potential success of airborne EM is the relationship between TDS concentration and electrical conductivity of water. The 52 water samples for which both specific conductance and TDS were measured show a good relationship between TDS and electrical conductivity. As TDS increases, measured conductivity of the water sample increases linearly at a rate of 0.2 mS/m per 1 mg/L increase in TDS concentration (Figure 12-6). Groundwater conductivity in the survey area is relatively low because TDS concentrations are relatively low. Only three water samples have conductivities that exceed 500 mS/m, suggesting that rock properties will have a strong relative influence on measured conductivities of the ground. Highly conductive ground (more than 200 mS/m) is expected only in areas where groundwater is moderately to very saline. Elsewhere, low TDS concentrations combined with relatively nonconductive soil, sediment, and rock should yield low apparent ground conductivities.

Magnetic Field Data

Magnetic field strength measured by the airborne magnetometer ranged from 49,464 to 49,660 nanoteslas (nT). To enhance local magnetic anomalies caused by significant iron-bearing materials such as wells, pipelines, and some structures, the regional gradient of gradually increasing magnetic-field strength to the northeast was removed. The resulting residual magnetic intensity map (Figure 12-7) shows a few linear anomalies corresponding to major pipelines and hundreds of small anomalies that are tens of meters across and a few to several tens of nT in magnitude. Most of these anomalies correspond to oil- and gas-well locations that have been obtained from RRC files, or, if a well location is erroneous, to visual evidence of a well location from aerial photographs (Figure 12-2). A few known wells, particularly those that are midway between adjacent flight lines, produce a magnetic-field anomaly that was not detected by the airborne magnetometer. The airborne magnetometer distinguishes individual wells best where they are spaced farther than about 100 m apart. At closer well spacing, such as in Parochial Bade field in the southwest part of the survey area, signatures of several adjacent wells can combine to form a single anomaly. Individual, densely clustered wells cannot be distinguished in these areas without tighter flight spacing or ground-based measurements.

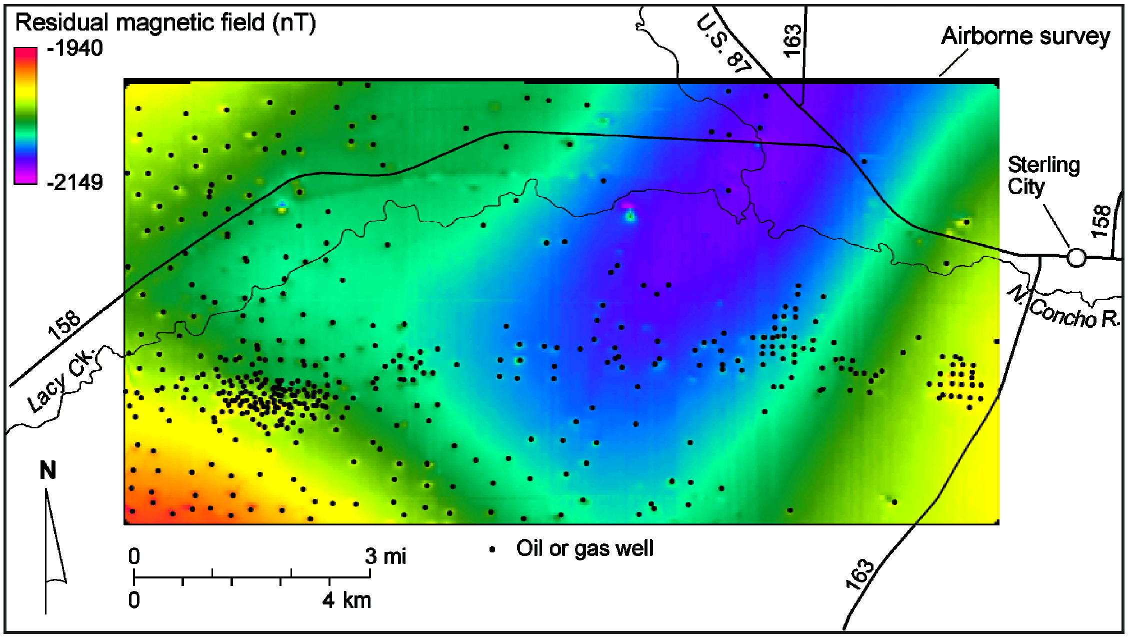

Figure 12-7: Residual magnetic field intensity measured during the airborne survey. Also shown are oil and gas well locations from RRC.

Airborne EM Data

The principal data recorded by the airborne EM instrument are decays of secondary fields generated by currents flowing in the ground as the transmitter loop flies overhead. These signals are recorded in the vertical and two horizontal directions and are proportional to the conductivity of the ground. Highly conductive bodies, such as metallic structures and strong fields generated by electrical power lines, can dominate or disrupt the secondary signal and can render conductivity models generated from the EM data invalid. Noise levels were low across most of the survey area, except near major power lines. High noise areas include a corridor through the middle part of Parochial Bade field, but most oil and gas wells are in low-noise areas.

Apparent Conductance

General conductivity trends are evident in the apparent conductance map (Figure 12-8). Apparent conductance represents the single value at a measurement point that best fits the observed transient decay at that point, without regard for vertical distribution of conductive material. Maps of apparent conductance help locate areas with differing ground conductivity. Most (99 percent) conductance values are between 253 and 3,691 mS and are highly correlated to surface elevation. At higher elevations, where poorly conductive Segovia and Fort Terrett Formation limestones cap the plateaus (Eifler and Barnes, 1974), apparent conductance values are relatively low. At lower elevations,

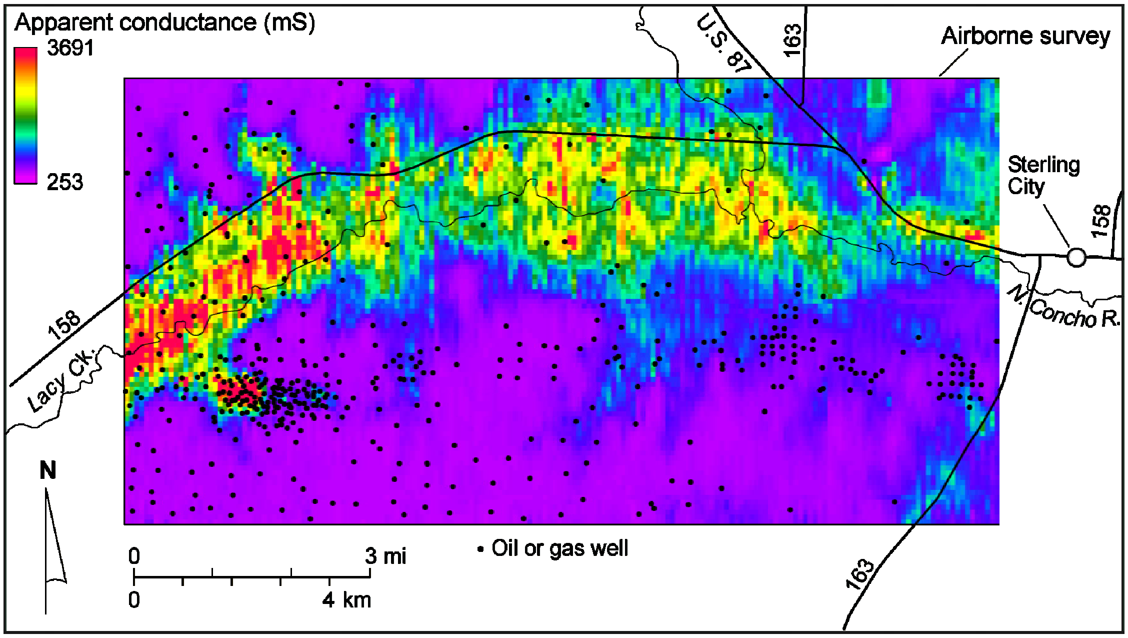

Figure 12-8: Apparent conductance calculated from TDEM data collected during the airborne survey. Also shown are oil and gas well locations from RRC.

where Edwards Group limestones are thin or absent and more conductive alluvium and underlying Cretaceous Antlers Sand and older strata are present, conductance values are relatively high. Highest conductances are located along Lacy Creek in the west part of the survey area and within parts of Parochial Bade field. Conductances within Parochial Bade field are higher than those in other valleys at similar elevations and are also associated with the locations of shallow water wells with high TDS values, suggesting that the elevated conductance is caused by salinization.

Conductivity-Depth Slices

Fugro processed raw airborne EM data to transform recorded EM field decays into models of conductivity change with depth at each measurement location. Conductivity values at common depths can be combined to form images of apparent conductivity at selected depths, which can then be used to interpret salinization extent and intensity by examining apparent conductivity patterns. Most of the 108,620 conductivity models generated from airborne data were valid to depths greater than 200 m. Because water wells in the area are shallow, conductivity slices at 10-m intervals between 10 and 100 m below the ground surface were most relevant to water quality.

In general, ground conductivity in the survey area is low. Highest apparent conductivity values are observed on depth slices from the upper few tens of meters. Conductivity

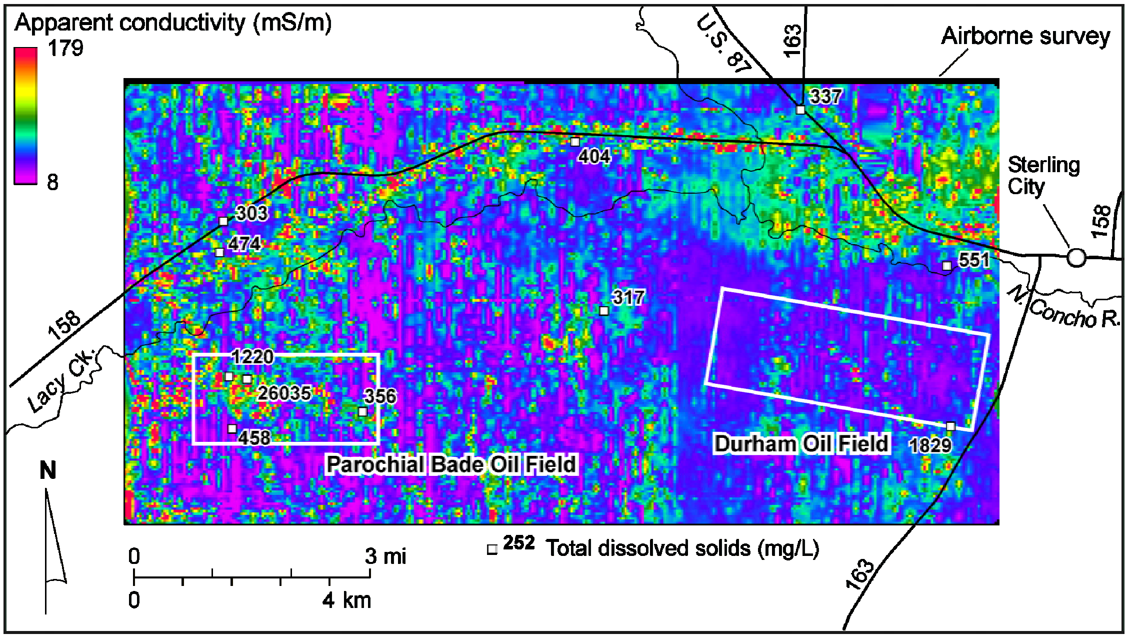

Figure 12-9. Apparent conductivity at a depth of 30 m. Also shown are locations of wells with TDS values from samples interpreted to be from this depth range.

slices at 10- to 30-m depths reveal two areas of relatively high conductivity (Figure 12-9). One is located in the west part of Parochial Bade field. The other is just downstream from the confluence of Lacy Creek and the North Concho River. Water samples of various vintages from nine wells that have depths greater than 10 m and water levels at or shallower than 10 m have fresh to slightly saline TDS values (254 to 1,242 mg/L). The two highest values are located within relatively conductive zones on the east side of the survey area on the 10-m depth slice. Water-quality data from the 20-m depth range include fresh to slightly saline TDS values from 11 wells, most of which are on the east side of the study area. Low TDS values (below 1,000 mg/L) tend to be from low-conductivity areas on the 20-m depth slice, whereas three of the highest TDS values (above 1,000 mg/L) are from the elevated conductivity area northwest of Sterling City. At 30-m depth (Figure 12-9), the highest TDS value reported for the area (26,035 mg/L) is from a test hole within the elevated conductivity area at Parochial Bade field. Lower TDS values characteristic of fresh water are reported in low-conductivity areas at this approximate depth.

At 40- to 60-m depths, apparent conductivities remain elevated in the Parochial Bade area and northwest of Sterling City. Three TDS values interpreted to be from the 40-m depth range all have low TDS values (249 to 273 mg/L) and are from areas depicting relatively low conductivity. Four water wells that have TDS values interpreted to be from the 50-m depth range show good agreement with apparent conductivity patterns at that depth. Slightly saline TDS values (1,621 and 2,379 mg/L) are located within areas of elevated conductivity in Parochial Bade field; fresh-water TDS values (244 to 557 mg/L) are located in areas of relatively low apparent conductivity within and around the perimeter of the field. One water well sample interpreted to be from the 60-m depth range has a moderately saline TDS value (3,927 mg/L) and is located within the area of elevated conductivity at Parochial Bade field.

Conductivity patterns in the 70- to 100-m depth range are similar to those at shallower depths. Conductivities in and near Parochial Bade field become less anomalous as depth increases, suggesting that the vertical extent of salinization is limited. Water samples interpreted to be from the 80- and 90-m depth range show slightly to moderately saline TDS values within the zone of elevated conductivity associated with Parochial Bade field.

All reported water wells are shallower than 110 m. Conductivity slices from deeper depths penetrate stratigraphic levels that are below the principal aquifer host, the Antlers Sand. These slices show elevated conductivity values in the northwest and southwest part of the survey area. Deeper than 130 m, a zone of elevated conductivity is evident southwest of Sterling City, in the approximate area of Durham oil field. These elevated conductivities appear to expand and migrate westward with increasing depth. No water well data are available that would distinguish among possible causes of high conductivity, but depth and lateral extent suggest the presence of naturally conductive strata.

Conductivity Cross Section

Another way to view the airborne EM data is to create vertical sections composed of apparent conductivity profiles. We constructed cross section A–A′ (Figures 12-2 and 12-10) using 14 conductivity profiles located near wells and boreholes that were used to make a geologic and hydrologic cross section near a salinized water well in Parochial Bade field (Renfro, 1993). Each profile is constructed from conductivity values at 10-m depth intervals that were the same as those used for the depth slices. These profiles lack the vertical resolution of borehole logs but can be helpful in depicting major lithologic units and identifying salinized zones.

The cross section depicts low (less than 100 mS/m) apparent conductivities in Edwards Group strata on the plateau above Parochial Bade field (Figure 12-10). Conductivity values increase within the Antlers Sand, particularly near wells such as Test Hole #4, where an elevated TDS value (4,878 mg/L) coincides with an apparent conductivity value higher than 100 mS/m in the nearest conductivity profile from the airborne geophysical survey. At lower elevations in Parochial Bade field, some profiles show highly elevated apparent conductivities above and within Antlers strata. These elevated apparent conductivities are more than 300 mS/m near Test Hole #6 and are corroborated by elevated conductivities measured using a borehole instrument during the salinized well investigation (Renfro, 1993).

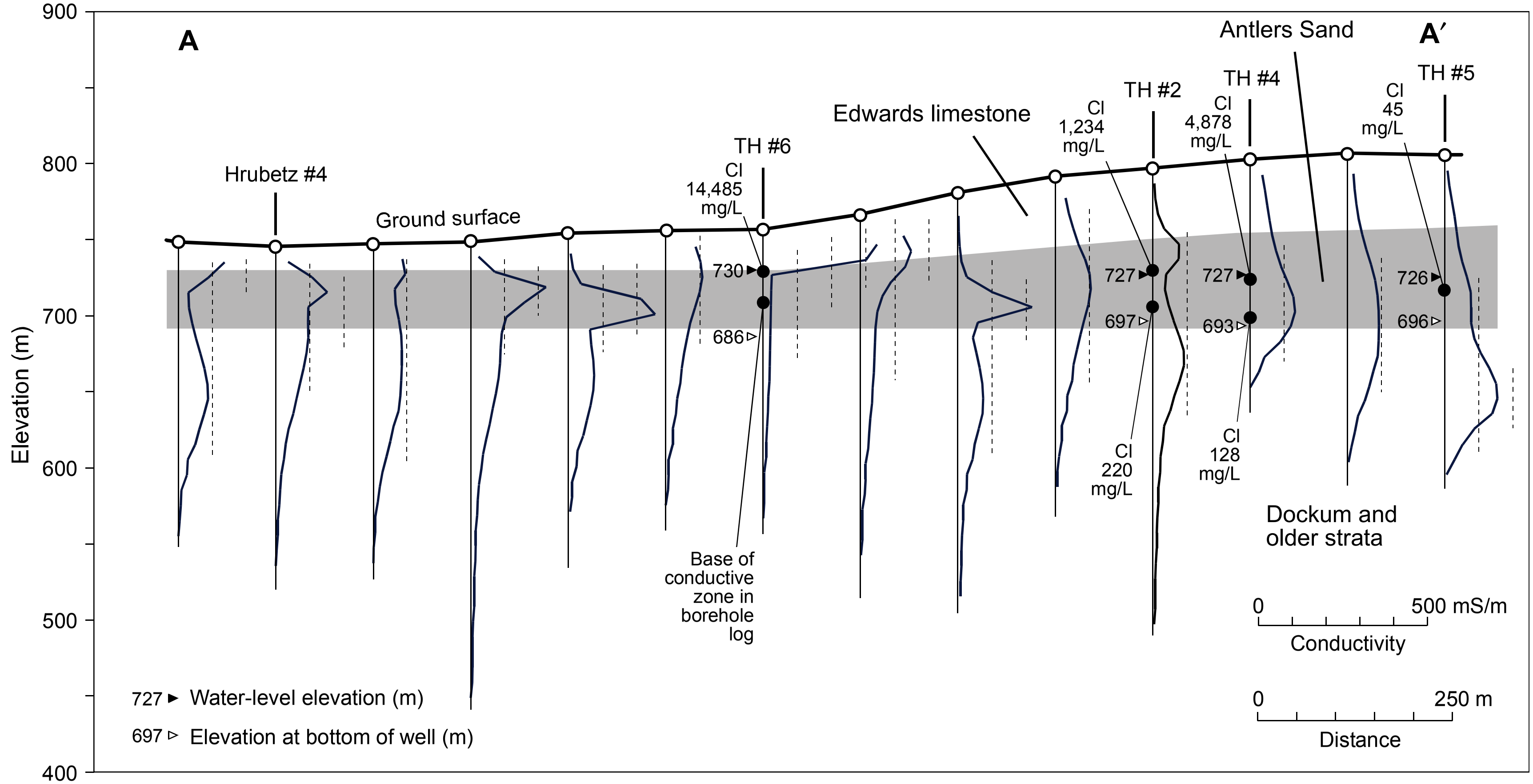

Figure 12-10: Cross section A–A′ of Parochial Bade field constructed from apparent conductivity profiles extracted from airborne geophysical data (includes stratigraphic and hydrologic data from Renfro [1993]).

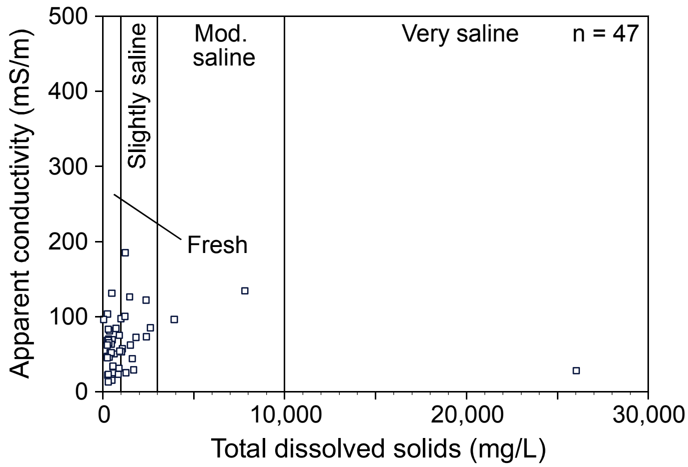

Figure 12-11: Relationship between TDS concentration in groundwater samples from the airborne survey area and apparent conductivities calculated from airborne data for depths below the water level and above the well depth (water data from TWDB).

Relationship Between Apparent Conductivity and Salinity

Qualitative comparisons of TDS values from water samples with apparent conductivities at various depths show reasonable spatial agreement (Figure 12-9). Areas with relatively high apparent conductivities at given depths tend to correlate to wells with relatively high TDS water at that depth, and areas with relatively low apparent conductivities at given depths tend to be near water wells producing relatively low TDS water at those depths. To better quantify this relationship, we extracted an apparent conductivity value at the location of the well and at a depth that was shallower than the well depth but deeper than the reported water level. We found 47 water wells in the TWDB database for which there was a well depth, a water level, and a TDS value. We used the reported locations of these wells to obtain an apparent conductivity at that location from the airborne geophysical data.

At this level of comparison, reported TDS values correlate moderately with apparent conductivities at the specific well location and interpreted sample depth (Figure 12-11). There are several possible explanations for the lack of a stronger relationship between TDS and apparent conductivity. First, most of the TDS values are for fresh to slightly saline water. At low TDS values, the conductivity of water-saturated sediments and rocks is more strongly influenced by sediment or rock type than it is at higher TDS values. Second, the airborne survey was flown in 2001, whereas chemical analyses of water samples were conducted between 1961 and 2001. Reported TDS values may not match actual TDS values on the airborne survey date. Third, locations of many of the water wells are less accurate than location of the conductivity profiles. If the wells are mislocated by more than about 25 m, comparison could be based on an apparent conductivity value near the wrong well location. Fourth, except for a few wells, it is difficult to assess the actual stratal depth that contributed the analyzed water sample. Fifth, apparent conductivity values were determined from gridded data rather than from the nearest actual measurement. Depending on the well distance from the original measurement, the apparent conductivity value may not represent the best estimate obtainable from airborne geophysical data at the actual well location. In surveys where these data have been used, correlation between TDS and apparent conductivity improves (Paine and Collins, 2003).

Extent and Intensity of salinization

Airborne and ground-based geophysical data from Sterling County show that ground conductivity is relatively low. This finding is consistent with the distribution and predominance of fresh to slightly saline water in the alluvial and Antlers aquifers. Although there have been significant oil and gas exploration and production in the area, particularly in Parochial Bade and Durham fields, oil-field salinization extent appears to be limited. Elevated conductivities consistent with shallow salinization that has impacted the alluvial and Antlers aquifers are present in Parochial Bade field, particularly near former saltwater disposal pits (Ashworth and Coker, 1993). Conductivities within the field, along the draw through the field, on the north perimeter of the field and along a segment of Lacy Creek below the field are relatively high compared with those of similar settings elsewhere in the survey area, suggesting that salinization related to oil-field development has occurred. An area of relatively low conductivity that persists from depths as shallow as 20 m to as deep as 120 m surrounds Durham oil field. There is little or no evidence of shallow salinization in or near this field.

Conclusions

Magnetic-field data acquired during a 2001 airborne geophysical survey west of Sterling City reveal accurate locations of most of the oil and gas wells. In some cases, aerial photographs confirm that the magnetic-field anomalies are more accurate representations of well position than the plotted locations from State records. Wells located nearly equidistant from the flight lines produce anomalies that can be missed by airborne instruments. Depending on the location relative to flight lines, magnetic anomalies caused by wells spaced closer than the flight-line spacing can appear as a single anomaly.

EM data acquired during the airborne survey show that ground conductivities in the survey area are relatively low, indicating that oil-field salinization is limited. Low conductivities in the shallow, water-bearing strata indicate that groundwater has low TDS concentrations typical of the fresh to slightly saline values reported from most water wells. Areas of elevated conductivity, particularly in and around Parochial Bade oil field, suggest that groundwater salinity has been increased locally by oil-field activities. Both airborne and ground-based geophysical surveys indicate that sites of former saltwater disposal pits have elevated conductivities indicating salinization. Conductivities measured in the shallow subsurface in and near Durham oil field are relatively low, suggesting that little or no salinization associated with this field remains in the shallow subsurface.

EM surveys are a valuable tool for rapidly assessing the extent and intensity of salinization over large areas because they are sensitive to groundwater salinization from any source. Data from airborne magnetometers and determinations of apparent-conductivity changes with depth help distinguish among possible natural, oil-field, and agricultural sources of groundwater salinization.

Acknowledgments

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