IDENTIFYING AND ASSESSING GROUND WATER IN THE LOWER RIO GRANDE VALLEY, TEXAS, USING AIRBORNE ELECTROMAGNETIC INDUCTION

by

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ABSTRACT

We applied airborne geophysical methods to identify potential ground-water resources and assess their quality in two 260-km^2 areas in the Lower Rio Grande Valley, Texas. In this drought-prone and rapidly growing region, heavy agricultural, municipal, and industrial demand for fresh water overburdens limited surface water supplied by the Rio Grande. Primary data for this study are two electromagnetic induction (EM) surveys flown using time-domain instruments carried by fixed-wing aircraft. Supporting data used to interpret the geophysical data include water-quality data from existing wells, geophysical well logs, and geologic maps and cross sections showing the lateral and vertical distribution of hydrologic and stratigraphic units in this coastal-plain setting. We analyzed these data within a geographic information system to (a) examine the relationship between water quality, sediment texture, and ground conductivity, (b) display subsurface images showing likely availability and suitability of ground water at various depths, and (c) help interpret late Cenozoic geologic environments.

The airborne EM systems achieved exploration depths of 150 to 300 m in the Faysville and Stockholm survey areas. Depth inversions of the EM data show that average conductivity generally increases downward in both areas to a maximum at 30-m depth then decreases to minimum values at the deepest depths explored. Average conductivities are higher in the Stockholm area than in the more inland Faysville area, suggesting either greater surface deposition and infiltration of windblown salt in the Stockholm area or saltwater intrusion into the Stockholm area from the Gulf of Mexico. General conductivity trends indicate that water quality should be better in the Faysville area than in the Stockholm area and that water quality should improve with depth within the upper 200 m in both areas. Below depths of about 600 m, well logs show that water quality generally deteriorates.

Comparisons of water-well data, including total dissolved solids (TDS) concentrations and sediment textures, with conductivity determined from the airborne survey indicate that the fresh to moderately saline ground water in these areas has a larger effect on measured conductivity than

does sediment texture. Nevertheless, conductivity patterns on horizontal slices through the Faysville and Stockholm conductivity volumes show a geologic influence. This apparent influence implies that differences in texture, mineral species, porosity, or permeability accompanying changes in depositional environment produce secondary conductivity influences than can be detected by the airborne instruments. Combining patterns evident on conductivity slices at various depths with conductivity values allows us to identify favorable targets for ground-water exploration, estimate depths to these targets, and predict water quality. The most favorable targets in this coastal-plain environment are those that are sinuous in plan view (suggesting channel or channel-complex environments) and are less conductive than adjacent areas (implying relatively coarse deposits saturated with relatively fresh water). We identified nine fresh to slightly saline targets in the Faysville area and five fresh to moderately saline targets in the Stockholm area within the upper 200 m.

Comparisons of ground-based EM measurements at representative sites within the two study areas showed that there is relative agreement in conductivity trends and magnitudes determined by the airborne and ground-based systems. Absolute conductivities at specific depths and locations determined from airborne and ground measurements commonly differed, suggesting that neither method reveals an absolutely accurate depiction of conductivity in the subsurface. Nevertheless, conductivity trends and spatial patterns discerned within areas flown by a common instrument should be sufficiently accurate to interpret relationships among water quality, sediment type, and water saturation.

Before the methods developed in this study are applied to similar coastal-plain environments in Texas and elsewhere, the water-resource predictions made from the geophysical data and the limited amount of available water-quality and sediment-texture data should be tested. These tests should include detailed logging and sampling of either new or existing wells within the surveyed areas.

INTRODUCTION

The Lower Rio Grande Valley (fig. 1) is a rapidly growing region subject to severe water shortages during droughts, and it needs new ground-water resources to ensure adequate water supplies for municipal, agricultural, and industrial uses. Applications of airborne or ground-based geophysical methods may rapidly and cost-effectively assist in delineating promising water-bearing subsurface units, estimating depth to water, and assessing the quality of potential water resources.

Water prospecting in the Lower Rio Grande Valley using electromagnetic induction (EM) exploits several known relationships. The EM method detects changes in the electrical conductivity of the ground that are caused by variations in rock or sediment type, water saturation, and water chemistry (McNeill, 1980; Rhoades, 1981; Paine and others, 1998). In this part of the Gulf Coastal Plain, near-surface sediments consist of Pliocene to Holocene interbedded sand, silt, and clay deposited in the ancestral Rio Grande delta and associated coastal depositional systems. The most abundant water resources are found in the sand-rich units. These sand bodies and the adjacent clay-rich units are likely to have different electrical conductivities, potentially enabling major water-bearing strata to be delineated laterally and vertically using EM. Additionally, because water high in total dissolved solids (TDS) has high electrical conductivity and fresh water has low electrical conductivity, measured electrical conductivities can be used to estimate water quality. In a water-saturated environment, the relative influence of water quality and sediment type on conductivity will depend largely on water quality. At high TDS, water quality will dominate the conductivity signal; at low TDS, sediment texture, porosity, and mineral composition will increase in importance.

Several steps are required to optimize the approach and determine the applicability of this method to ground-water prospecting in coastal-plain environments. We selected two test areas (the Faysville and Stockholm areas, fig. 1) in the Lower Rio Grande Valley; designed and conducted the airborne geophysical surveys; produced conductivity images at depths of 10 to 200 m

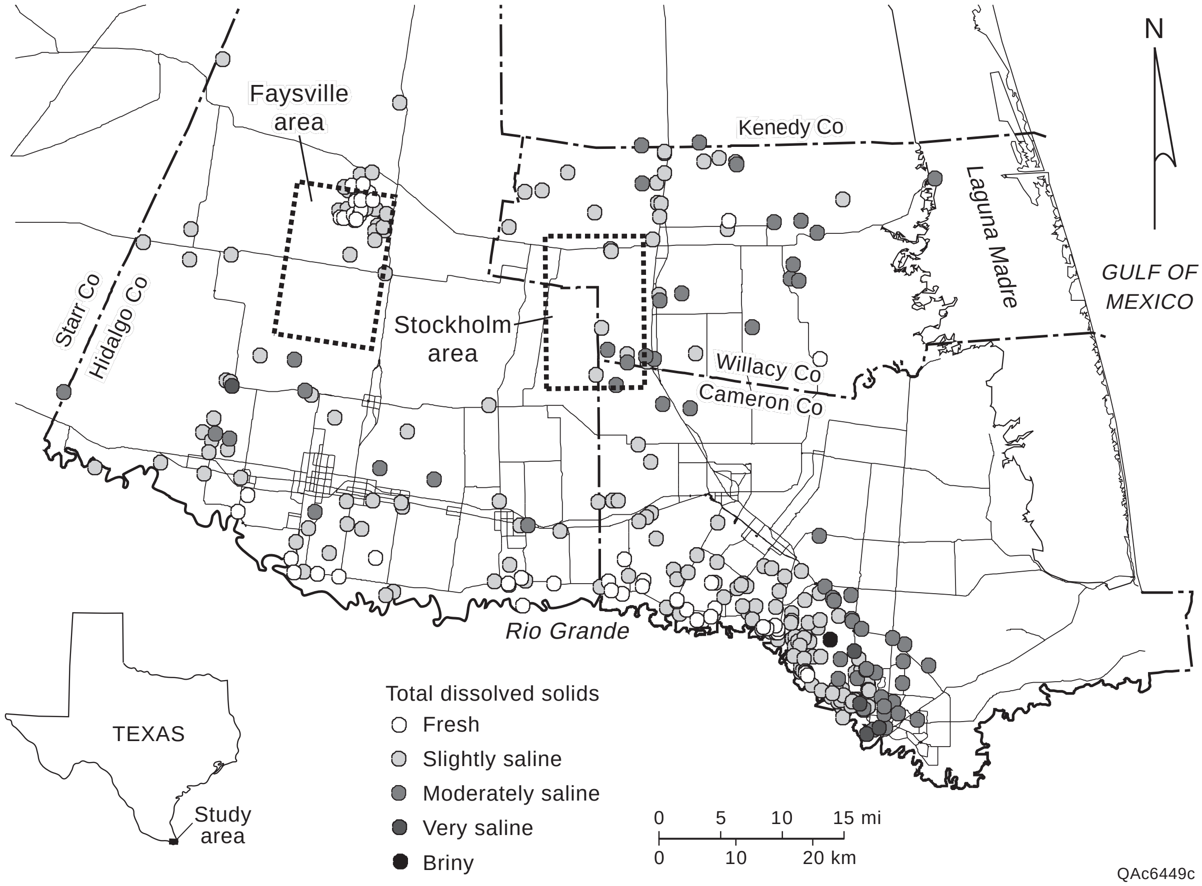

Figure 1. Location of the Faysville and Stockholm survey areas and water wells in the Lower Rio Grande Valley, Texas. Well symbols indicate salinity of ground water measured as total dissolved solids (TDS) concentration. Well locations and salinity data from Texas Water Development Board.

in each area from airborne survey data; integrated surficial geology, water-well data, and conductivity maps into a geographic information system (GIS) data base; compared airborne and ground-based EM data; analyzed the relationship between airborne EM data and existing data on sediment type and water quality; and interpreted target zones of favorable water quality. Future work should include verifying results through drilling and, if the method proves successful, applying the techniques to other suitable parts of the Rio Grande Valley and the Texas Coastal Plain that need additional ground water.

Water Demand in the Lower Rio Grande Valley

The Rio Grande is the primary source of water for the 850,000 inhabitants of Cameron, Hidalgo, and Willacy Counties, supplying more than 97 percent of the amount used for municipal, agricultural, and industrial purposes (McCoy, 1990). Municipalities in the Lower Rio Grande Valley, which includes five additional south Texas counties, consume about 18 percent of all surface and ground water used in the region. There is a trend toward increased reliance on ground water to meet municipal demand (fig. 2). Population of the major cities (McAllen, Brownsville, and Harlingen) is projected to increase 100 percent from an estimated 280,000 in 1995 to 560,000 in 2050. The impact on water resources is significant; municipal water use is projected to

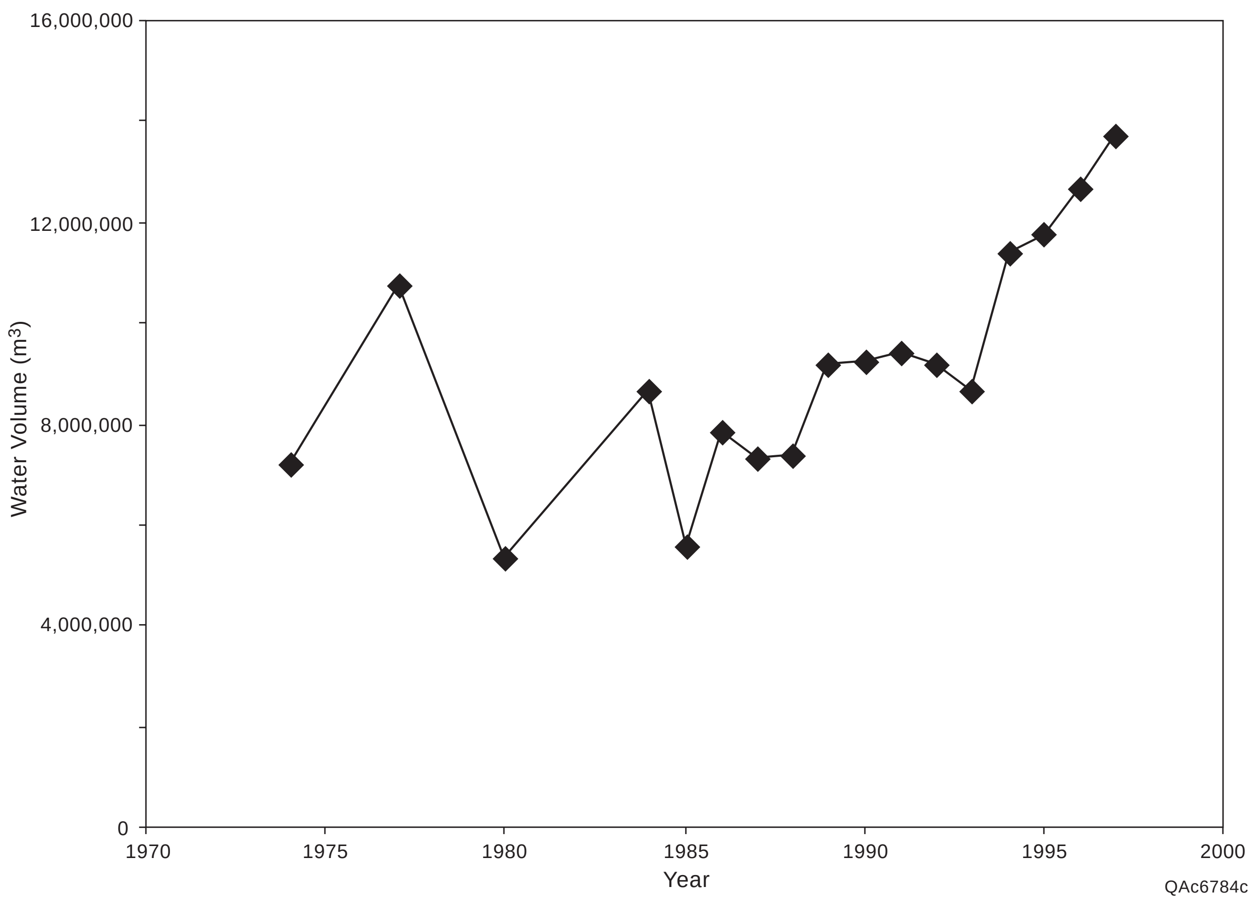

Figure 2. Municipal ground-water usage in the Lower Rio Grande Valley, 1974–1997. Data from Texas Water Development Board.

rise 51 percent from 89×10^6 m^3 in 2000 to 134×10^6 m^3 in 2050 (Texas Water Development Board, 1997). Currently, the Rio Grande and its reservoirs meet the demands of all three cities. Harlingen and McAllen needs will be met through 2050, but Brownsville will need supplemental water beginning in 2010. Possible long-term solutions include purchasing irrigation water rights, using Rio Grande floodwater, adding ground-water sources, enhancing aquifer storage and recovery, and desalinizing marginal surface and ground water. For municipalities located inland from the Rio Grande that rely on surface water, the development of additional ground-water resources will be vital to meet demand during droughts.

Surface- and Ground-Water Quality

Surface-water quality ranges from fresh (less than 100 mg/L TDS) during times of high flow to slightly saline (about 1,400 mg/L TDS) during low flow (Texas Water Commission, 1990). During and before a severe drought in the 1950's and the construction of Falcon and Amistad Reservoirs, the region relied heavily on ground water. There are records of more than 600 water wells in Cameron, Hidalgo, and Willacy Counties (fig. 1) producing from shallow aquifers hosted by Pliocene- to Holocene-age fluvial and deltaic deposits. Ground-water quality is generally poorer and more variable than surface-water quality (McCoy, 1990), with most samples ranging from fresh (less than 1,000 mg/L; figs. 1, 3; table 1) to moderately saline (about 5,000 mg/L). A few samples from Cameron and Hidalgo Counties are classified as very saline to briny at TDS values between 10,000 and 40,000 mg/L (fig. 3).

In this study, ground-water TDS concentration is important because it directly correlates with both the water quality (table 1) and the electrical conductivity of the water (fig. 3). In general, as the TDS and electrical conductivity of ground water increase, the conductivity of the ground saturated with that water also increases. If the TDS values are low, variations in ground conductivity may be measured that are related to changes in host-sediment minerals, porosity, and permeability (McNeill, 1980). At high TDS values, measured ground conductivity is largely a

Table 1. Salinity classifications based on TDS concentration. The Robinove and others (1958) classification is used in this report because it has more subdivisions within the 0 to 10,000 mg/L TDS range that encompasses most Lower Rio Grande Valley ground-water samples.

From Robinove and others (1958):

Classification	**TDS range (mg/L)**
Fresh	0 - 1,000
Slightly saline	1,000 - 3,000
Moderately saline	3,000 - 10,000
Very saline	10,000 - 35,000
Briny	35,000

From Freeze and Cherry (1979):

Classification	**TDS range (mg/L)**
Fresh	0 - 1,000
Brackish	1,000 - 10,000
Saline	10,000 - 100,000
Brine	100,000

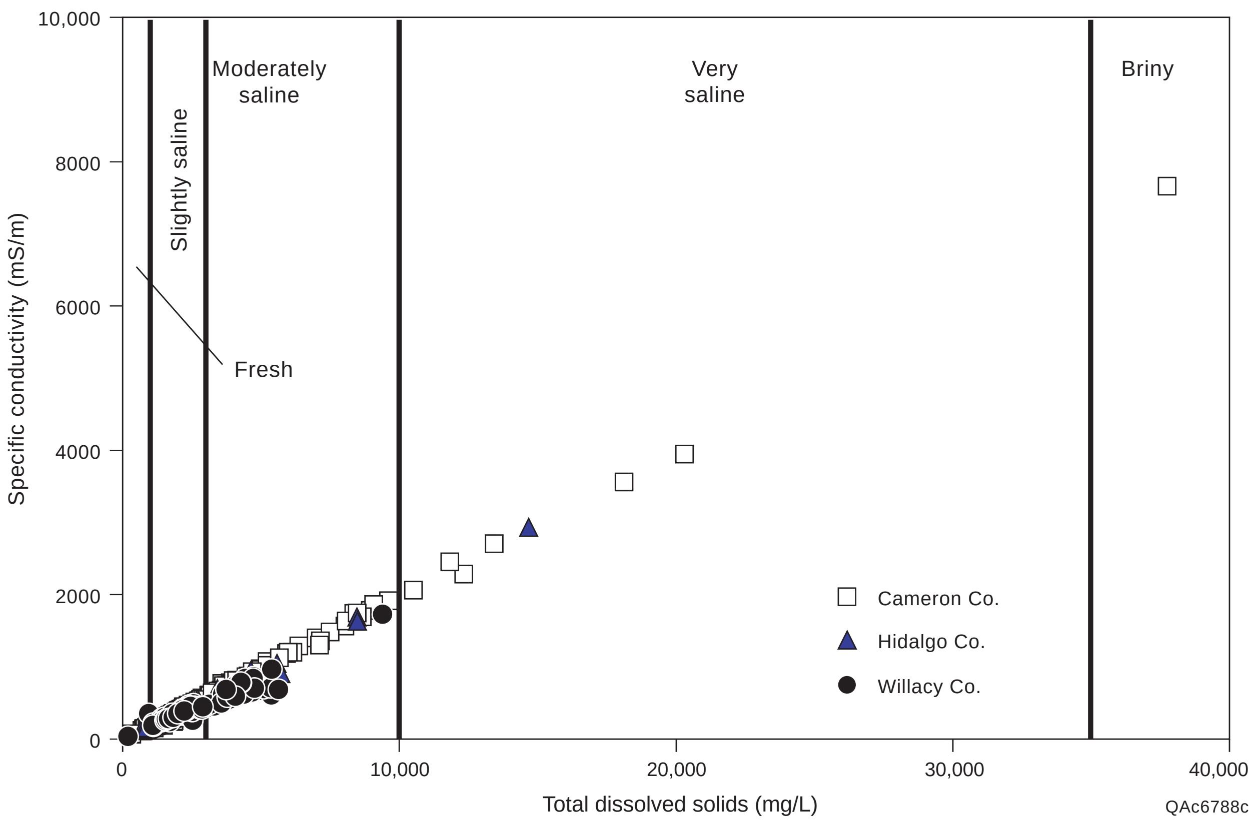

Figure 3. Relationship between measured TDS concentration and conductivity in ground-water samples from Cameron, Hidalgo, and Willacy Counties. Salinity classification from Robinove and others (1958).

function of the conductivity of the pore fluid, with relatively little effect from the host sediment. Commonly reported ground conductivities for unsaturated sediments and sediments saturated with fresh water range from a few to a few hundred mS/m; conductivities typically increase with increasing clay content. Most ground-water samples from Cameron, Hidalgo, and Willacy Counties have conductivities between several hundred and a few thousand mS/m (fig. 3), causing sediments saturated with this water to be significantly more conductive than sediments saturated with fresh water.

TDS concentration correlates with measured conductivity because minerals dissociate into anions and cations upon dissolution. The most abundant cation in ground water from Cameron, Hidalgo, and Willacy Counties is sodium, having an average concentration of more than 700 mg/L (table 2; fig. 4). Other abundant cations include calcium, magnesium, and silica, but their concen-

Table 2. Water-quality statistics for samples from Lower Rio Grande Valley water wells. Data from Texas Water Development Board.

		Combined		**Cameron Co.**		**Hidalgo Co.**		**Willacy Co.**	
Parameter	**Units**	**n**	**average**	**n**	**average**	**n**	**average**	**n**	**average**
Temperature	ºC	279	27	180	26	71	27	28	29
Silica	mg/L	545	32	341	30	136	44	68	21
Calcium	mg/L	586	106	351	102	159	115	76	104
Magnesium	mg/L	587	53	352	62	159	47	76	104
Sodium	mg/L	585	710	352	787	159	445	74	913
Potassium	mg/L	156	10.7	56	8.5	72	12.7	28	9.9
Strontium	mg/L	41	4.4	7	3.2	29	4.8	5	4.1
Carbonate	mg/L	600	1.6	353	2.3	169	0.1	78	1.7
Bicarbonate	mg/L	593	385	353	457	162	324	78	187
Sulfate	mg/L	590	699	355	747	161	359	74	1204
Chloride	mg/L	600	698	355	758	168	584	77	670
Fluoride	mg/L	470	1.6	323	1.4	106	2.0	41	2.5
Nitrate	mg/L	590	5.8	352	1.8	162	13.3	76	8.4
pH		532	7.82	340	7.82	116	7.66	76	8.09
TDS	mg/L	585	2506	353	2724	157	1766	75	3025
Alkalinity	mg/L	593	318	353	378	162	266	78	156
Hardness	mg/L	586	481	351	506	159	479	76	371
Sodium	%	584	74	351	75	159	65	74	85
SAR		586	17	351	17	159	10	76	26
Specific conductivity	mS/m	546	459	327	520	147	315	72	478

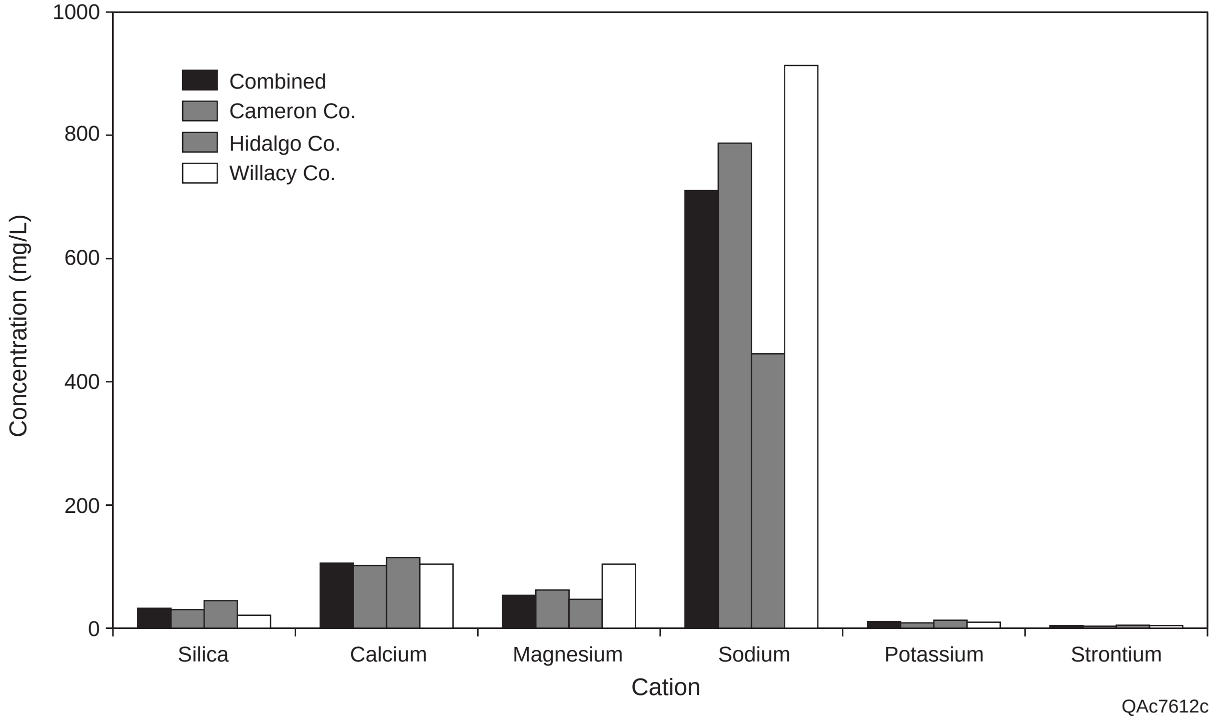

Figure 4. Average concentrations of analyzed cations in ground-water samples from Cameron, Hidalgo, and Willacy Counties. Data from Texas Water Development Board.

trations are much lower, averaging between 21 and 115 mg/L (table 2). Chloride, sulfate, and bicarbonate are the most abundant anions (fig. 5). Average chloride concentrations are higher in the coastal counties (758 mg/L in Cameron County and 670 mg/L in Willacy County, table 2) than they are in Hidalgo County (584 mg/L), perhaps reflecting migration of windblown salt into shallow inland aquifers or saltwater intrusion from the Gulf of Mexico.

Depths of Existing Water Wells

The exploration depth of geophysical methods such as EM depends on frequency, ground conductivity, and the strength of the EM field. Lower EM frequencies, lower ground conductivity, and higher EM field strength all increase exploration depth. We examined depths of existing wells in the Lower Rio Grande Valley to (1) determine whether EM methods might yield useful information at those depths and (2) help choose survey parameters and airborne instrument configurations.

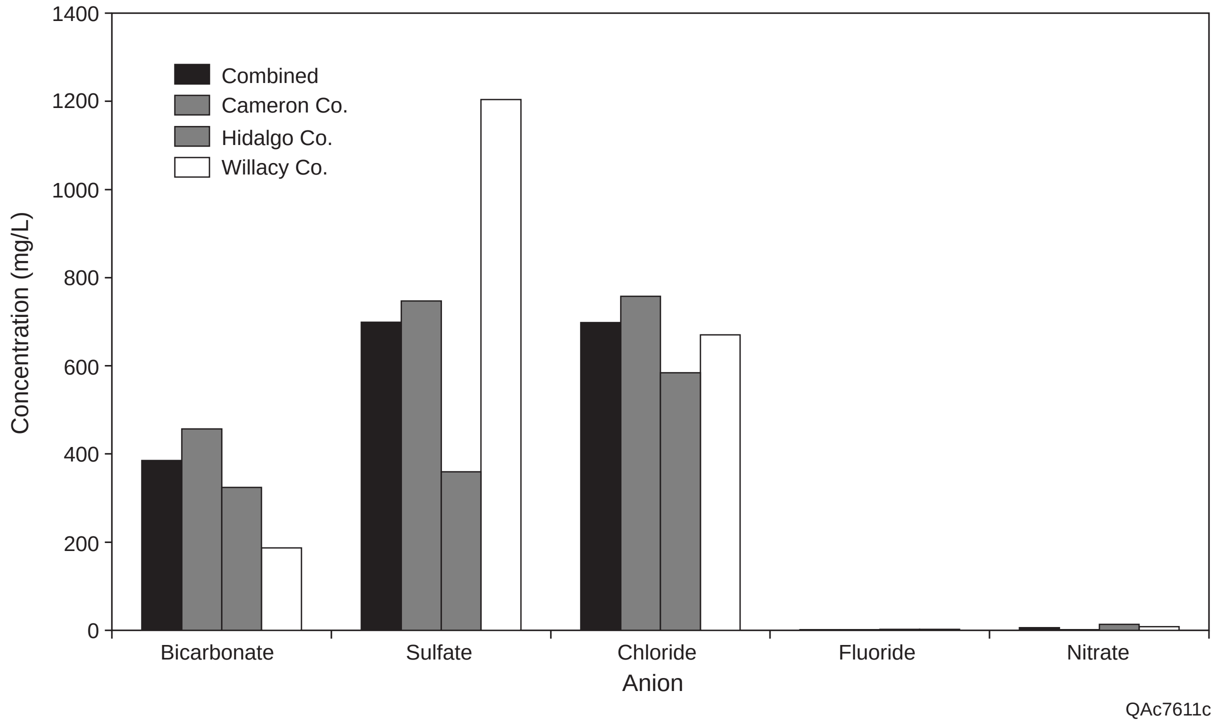

Figure 5. Average concentrations of analyzed anions in ground-water samples from Cameron, Hidalgo, and Willacy Counties. Data from Texas Water Development Board.

As of July 1999, the Texas Water Development Board water-well data base contained depth records for 537 wells in Cameron, Hidalgo, and Willacy Counties. These records indicate that the two most common well-depth ranges are 60 to 75 m and 30 to 45 m (fig. 6a) and that 85 percent of the wells in these counties are less than 135 m deep. In Cameron County, the county with the most wells reported, the most common well depth is between 60 and 75 m (fig. 6b), and 98 percent of the wells are less than 165 m deep. Depths are reported for nearly as many wells in Hidalgo County, where the most common depth is slightly shallower at 30 to 45 m (fig. 6c), and 90 percent of the wells are less than 195 m deep. Very few wells are reported for Willacy County, where only 19 percent of the depths are less than 195 m (fig. 6d). Many of the deep wells in Willacy County are oil and gas wells that have been converted to supply water.

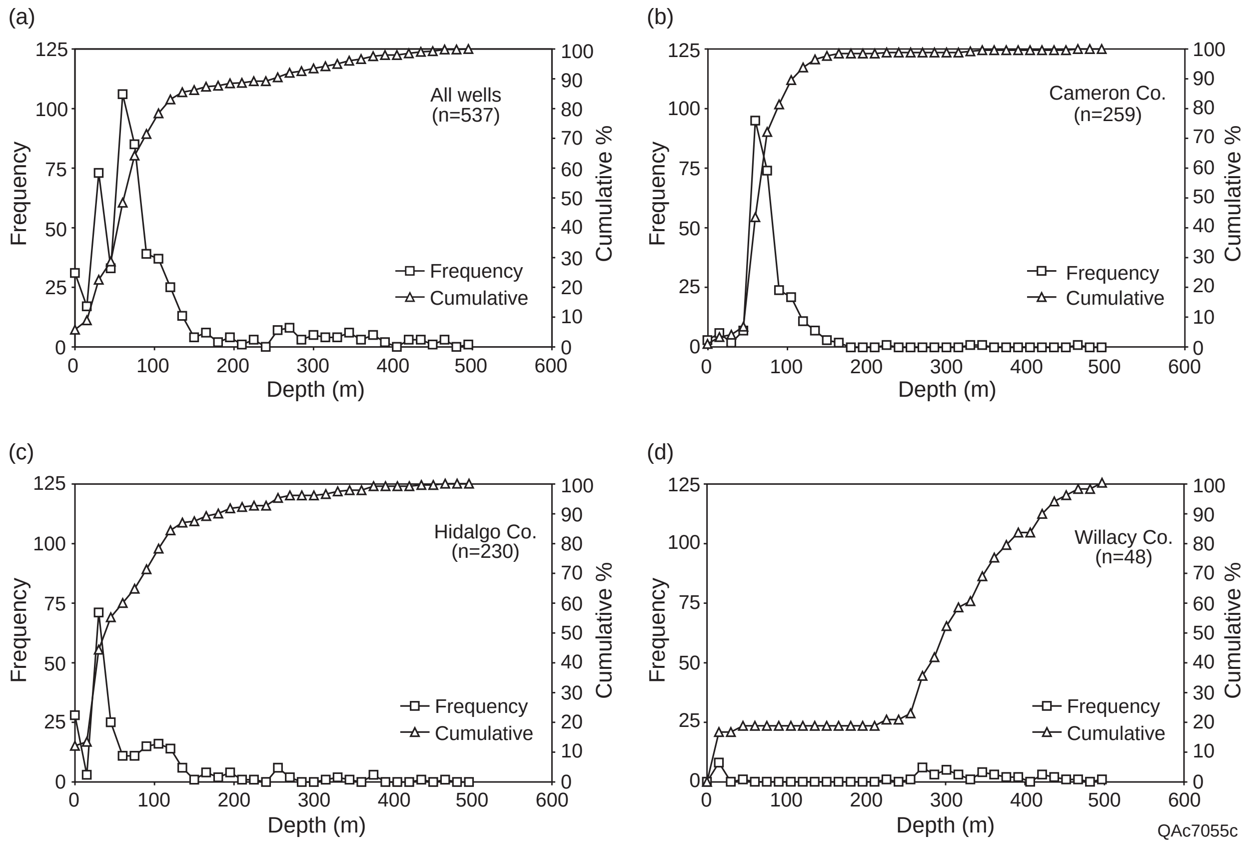

Figure 6. Distribution of water-well depths in (a) combined counties, (b) Cameron County, (c) Hidalgo County, and (d) Willacy County. Data from Texas Water Development Board.

Faysville and Stockholm Sites

The Faysville and Stockholm areas (fig. 1) were chosen for study on the basis of proximity to communities, degree of development, and hydrogeological characteristics. The Faysville area, located north of Edinburg and McAllen in central Hidalgo County, is mapped as an outcrop area of the Pliocene Goliad Formation (Brewton and others, 1976) covered in places by Quaternary sand dunes and sheets. Stratigraphic and hydrogeologic cross sections through this area show the base of the relatively coarse grained Goliad deepening eastward from 250 to 400 m in the Faysville area (Baker, 1979), below the exploration depth of the airborne EM instruments. Ground water in this depth range is within the Evangeline aquifer (Baker, 1979). The Evangeline aquifer in the Faysville area is mapped as fresh to slightly saline (McCoy, 1990). The Faysville survey area includes the southern, shallower part of the Linn-Faysville water-well district, which has produced large amounts of fresh to slightly saline water from depths of 30 m or less since the 1920's (George, 1947; Follett and others, 1949). Water levels in Linn-Faysville wells are 6 to 16 m below surface (Follett and others, 1949).

The Stockholm area is located west of the towns of Raymondville, Lyford, and Sebastian in parts Cameron, Hidalgo, and Willacy Counties. Geologic maps depict the Quaternary Beaumont Formation in the east half of the study area, grading westward into older deposits of the Lissie (Quaternary) and Goliad Formations (Brewton and others, 1976). Common depositional environments include meanderbelt sands, abandoned mud-filled channels, distributary and fluvial sands and silts, interdistributary muds, and floodplain and overbank muds (Brown and others, 1980). Hydrogeologic cross sections show abundant, relatively fine grained deposits surrounding coarser deposits of the Chicot aquifer that extend from the surface to a depth of 150 to 180 m in the Stockholm area (Baker, 1979). These units are underlain by the Evangeline aquifer and the host Goliad Formation sands to depths of 500 m or more. The Chicot and Evangeline aquifers within the Stockholm survey area are mapped as slightly saline (McCoy, 1990). Water levels are generally 2 to 7 m below the land surface (Baker and Dale, 1961).

Both the Faysville and Stockholm areas have water wells being used for domestic supply or irrigation (fig. 1). Both areas exhibit a range of reported water-well depths and water quality (fig. 7). Wells in the Stockholm area are fewer (13 known wells within the footprint of the airborne survey), are better distributed in depth (5 to more than 300 m), and are generally higher in TDS values (1,000 to 5,000 mg/L) than wells in the Faysville area (47 known wells, most wells less than 50 m deep, and TDS values between 800 and 2,500 mg/L).

TDS concentrations in Stockholm-area wells are generally lower in the deeper wells than they are in the shallow wells (fig. 7), but both the lowest and highest reported salinity values are from shallow wells (less than 50 m deep). Similarly, the lowest and highest reported salinity values from Faysville wells are from wells less than 40 m deep, but perhaps this is an artifact of the few

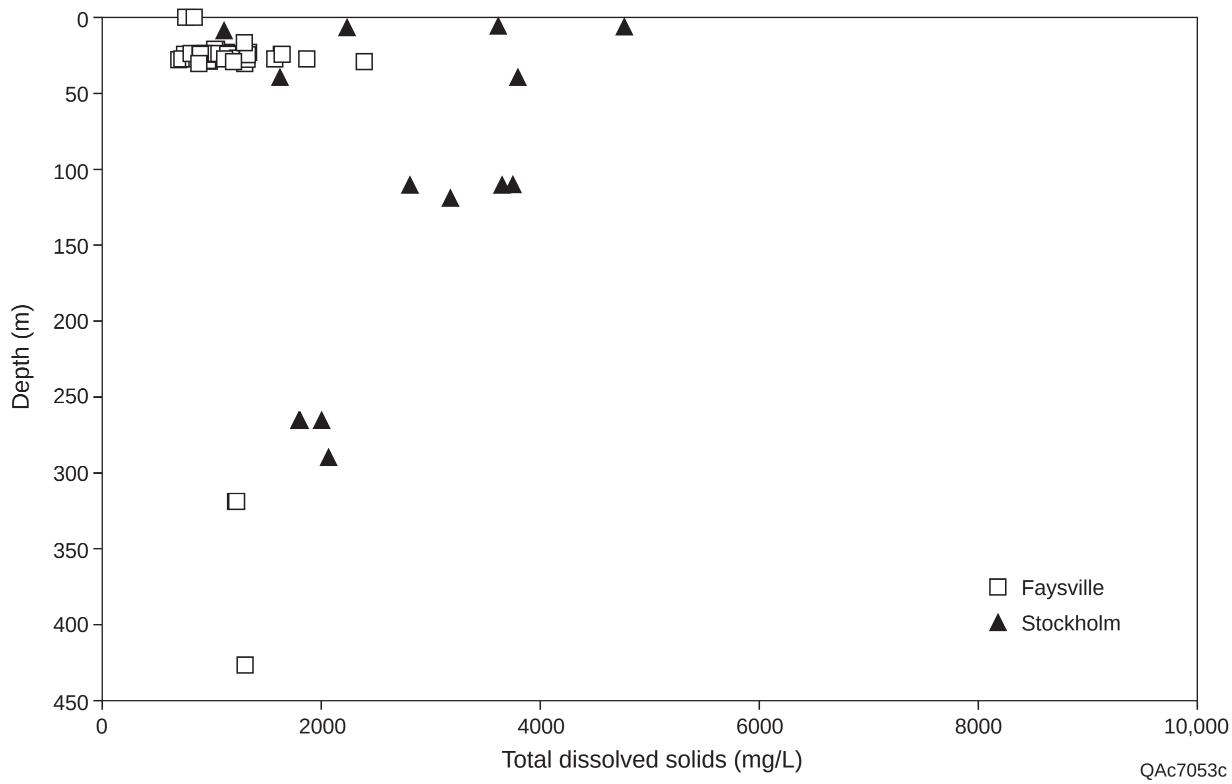

Figure 7. Relationship between TDS concentration and well depth for Faysville- and Stockholm-area water wells. Data from Texas Water Development Board.

deeper Faysville wells. Shallow wells in the Faysville area tend to have lower TDS values than Stockholm wells of similar depths. Wells in both areas that are deeper than 250 m appear to have similar TDS values. Geophysical well logs extending several hundred meters into the subsurface show that the improvement in water quality with depth in the upper few hundred meters is reversed by an increase in conductivity and a general degradation of water quality below depths of 600 to 700 m (Baker, 1979).

No clear long-term trend in salinity is discernible from water samples taken from Faysville and Stockholm water wells between the 1940's and late 1980's (fig. 8), suggesting that water quality has not been degraded by the production levels in these wells. All but one of the Faysville wells show very little change in TDS over the sampling period (fig. 8a). Of the three wells in the Stockholm area with multiple analyses, one shows a significant increase in TDS over time, one a significant decrease, and the third a slight decrease (fig. 8b).

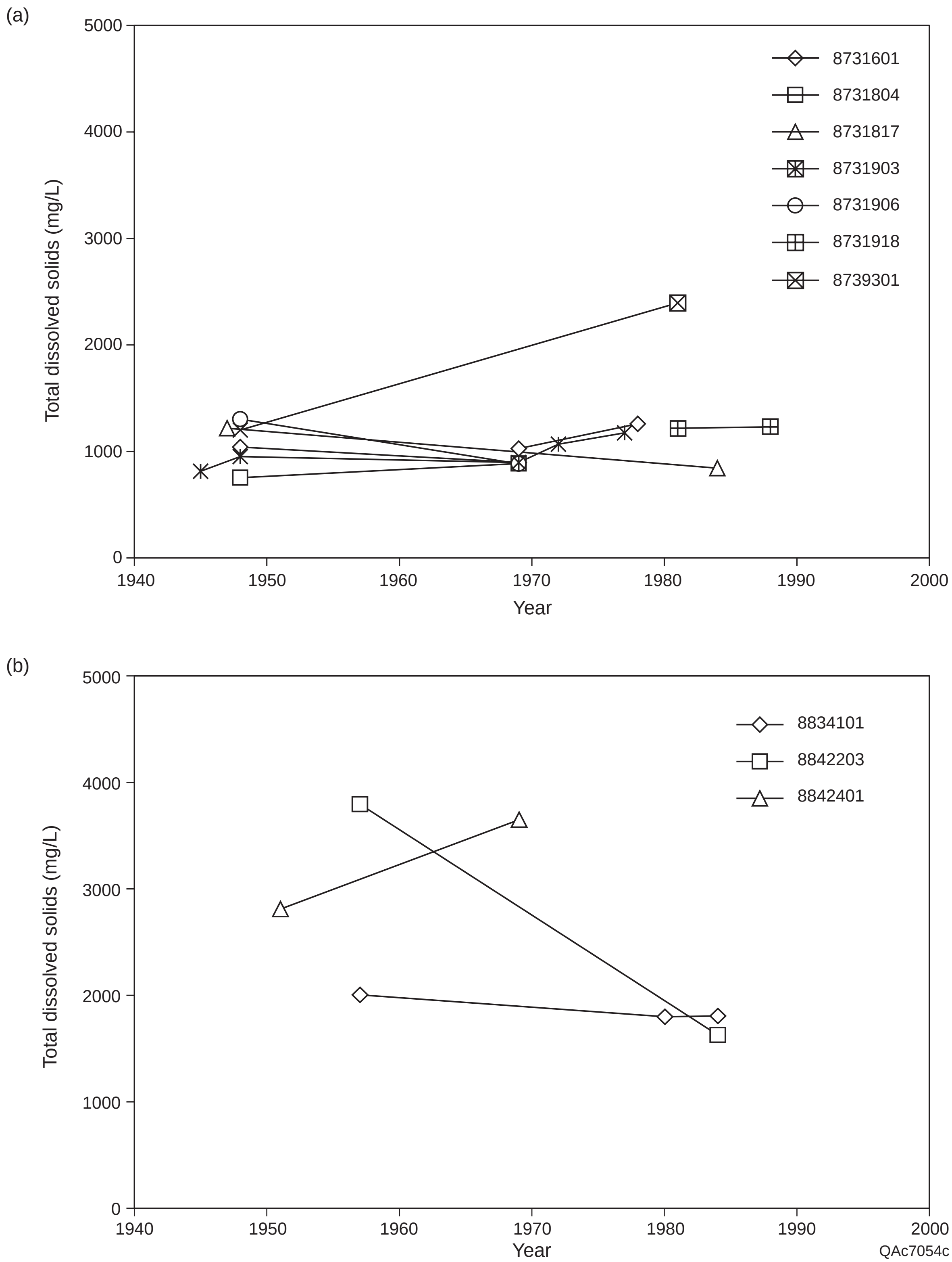

Figure 8. Changes in TDS over time in samples from (a) seven wells in the Faysville area and (b) three wells in the Stockholm area. Data from Texas Water Development Board.

METHODS

We employed airborne and ground-based geophysical methods to rapidly and noninvasively explore for ground water in the Faysville and Stockholm areas by measuring changes in electrical conductivity with depth. The principal geophysical method in the airborne and ground surveys is 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.

Time-domain EM methods (Kaufman and Keller, 1983; Spies and Frischknecht, 1991), used in both the airborne and ground-based surveys, measure the decay of a transient, secondary magnetic field produced by the termination of an alternating primary electric current in the transmitter loop (fig. 9). The secondary field, generated by current induced to flow in the ground, is measured by the receiving coil following transmitter current shutoff. Secondary field, or transient,

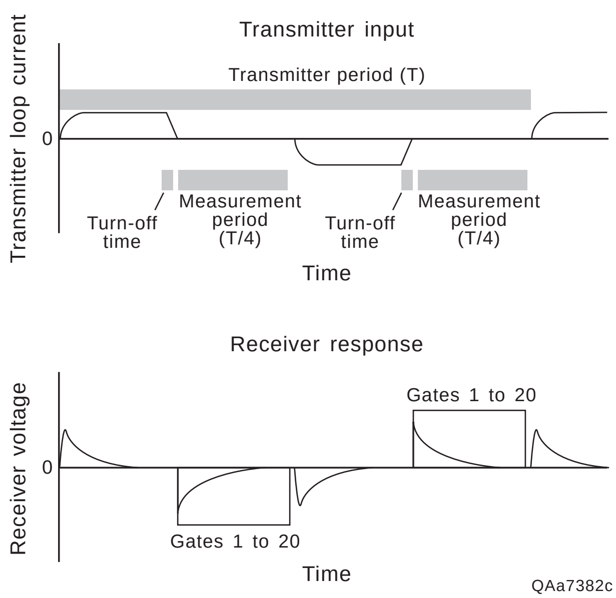

Figure 9. Time-domain EM transmitter input (upper graphic) and receiver response (lower graphic). Adapted from Geonics Limited (1992).

strength at an early time gives information on conductivity in the shallow subsurface; transient strength at later times is influenced by conductivity at depth.

Airborne Geophysical Surveys

Airborne geophysical data, including time-domain EM (TDEM) and magnetic-field data, were acquired over the Stockholm area in August 1999 by World Geoscience Corporation and over the Faysville area in October 1999 by Geoterrex-Dighem (both companies were subsequently acquired by Fugro).

Acquisition parameters were similar for both areas (table 3). In the Stockholm survey, the 260-km^2 area was covered by flying north-south lines spaced at 400 m and east-west tie lines spaced at 4 km (fig. 10). A Shorts Skyvan flying at a height of 120 m carried the cesium magnetometer and the QUESTEM TDEM transmitter attached to the aircraft and towed the EM receiver about 120 m behind the transmitter at a height of 50 m above the ground (fig. 11). The primary EM field was generated by a six-turn wire loop carrying a 450-ampere current at 25 Hz, resulting in a dipole moment of 5×10^5 A-m^2 (table 4). Each transmitter current pulse lasted 4.6 milliseconds (ms). The secondary field generated by current induced to flow in the ground

Table 3. Survey and flight parameters for the airborne geophysical surveys of the Faysville and Stockholm areas.

Parameter	**Faysville**	**Stockholm**
Company	Geoterrex	World Geoscience
Acquisition date	October 1999	August 1999
Aircraft	CASA C212 (twin engine)	Shorts Skyvan (twin engine)
Principal line spacing	400 m	400 m
Tie-line spacing	4,000 m	4,000 m
Principal line direction	9° and 189°	0° and 180°
Tie-line direction	99° and 279°	90° and 270°
Aircraft and transmitter height	120 m	120 m
Location	Differential GPS	Differential GPS
Flight speed	235 km/hr	240 km/hr
Area surveyed	260 km^2	260 km^2

Figure 10. Flight lines flown by World Geoscience over the Stockholm area in August 1999. Also shown are ground TDEM sites.

was measured at 20 time windows between 0.2 and 15.4 ms after current shutoff. EM skin depth, the depth at which the signal amplitude has decreased to 1/e, or 0.368 times its original value, is commonly used as a proxy for exploration depth. It is calculated using the equation

$$d = k\,(r / f)^{0.5}$$

where d = skin depth (in m), k = 504 (m/ohm-s)$^{0.5}$, r = resistivity (in ohm-m), and f = primary EM frequency.

Figure 11. World Geoscience's QUESTEM airborne TDEM system operating above the Stockholm area, August 5, 1999. The receiver trails the aircraft. Photograph by David M. Stephens.

Table 4. Acquisition parameters for the airborne TDEM surveys of the Faysville and Stockholm areas.

Parameter	**Faysville**	**Stockholm**
System	GEOTEM	QUESTEM 450
Transmitter-loop area	232 m^2	186 m^2
Transmitter-loop turns	6	6
Transmitter-loop current	500 A	450 A
Transmitter dipole moment	696,000 A-m^2	502,200 A-m^2
Transmitter frequency	30 Hz	25 Hz
Transmitter on time	4.1 ms	4.6 ms
Receiver type	Towed 3 axis	Towed 3 axis
Receiver height	70 m	50 m
Receiver trailing distance	125 m	~120 m
Number of recording windows	20	20
Recording time (from end of pulse)	–3.9 to 11.3 ms	0.2 to 15.4 ms
Sample rate	4 Hz	5 Hz
Sample interval	~16 m	~13 m

Assuming an average ground resistivity of 5 ohm-m obtained from nearby borehole resistivity logs and a primary EM frequency of 25 Hz, skin depth for the Stockholm area is 225 m. Measurement locations were determined from differential global-positioning-system (GPS) data by using a base station at the Harlingen airport and a roving receiver on the aircraft. At the 25-Hz transmitter frequency (50-Hz sample frequency) and an airspeed of about 240 km/hr, transients were acquired at an along-line spacing of 1 to 1.5 m. Adjacent transients were stacked to reduce noise and recorded at 5 Hz, resulting in the final sample spacing of 10 to 15 m. World Geoscience processed the data.

Flight-line spacings for the 260-km^2 Faysville area (figs. 1, 12) were 400 m for the north-south lines and 4 km for the east-west tie lines. Two of the tie lines extended eastward to the Gulf of Mexico shoreline to tie the Faysville and Stockholm surveys together and to examine the inland extent of saltwater encroachment from the gulf. Geoterrex collected EM and magnetic-field data using its GEOTEM TDEM system and a cesium magnetometer towed behind a CASA twin-engine aircraft (fig. 13). Flight height was 120 m; the three-axis EM receiver was towed 125 m behind the transmitter at a height of 70 m above the ground (table 3). The primary EM field was generated by a six-turn wire loop fixed to the aircraft carrying a 30-Hz, discontinuous sinusoidal current of 505 amperes, resulting in a dipole moment of 7×10^5 A-m^2 (table 4). Transients were recorded during the 11-ms window following termination of the 4-ms input pulse. Skin depth, assuming a ground resistivity of 10 ohm-m and an EM transmitter frequency of 30 Hz, is 290 m. Measurement locations were determined using differential GPS. At the 30-Hz transmitter frequency (60-Hz sample frequency) and a nominal airspeed of 235 km/hr, transients were acquired every 1.1 m along the flight line. Recording stacked transients at 4 Hz resulted in a sample spacing of about 16 m. Geoterrex 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, World Geoscience and Geoterrex also delivered layered-earth inversions of the *z*-axis data. For the Stockholm area, World Geoscience constructed a three-layer conductivity model for the stacked

Figure 12. Flight lines flown by Geoterrex over the Faysville area in October 1999. Also shown are ground TDEM sites.

transients. These models, spaced at about 60 m along each flight path, included thicknesses for layers 1 and 2 and conductivities for layers 1, 2, and 3. For the Faysville area, Geoterrex performed conductivity-depth transforms to produce relatively smooth conductivity models depicting

Figure 13. Geoterrex's GEOTEM airborne TDEM system operating over the Faysville study area, October 21, 1999. The six-turn transmitter loop is attached to the wing tips and booms at the front and rear of the aircraft. Cables trailing the aircraft tow the EM receiver and magnetometer (not shown). Photograph by David M. Stephens.

a conductivity value at 10-m-depth intervals. These transforms, spaced at 13-m intervals along the flight path, were performed for every stacked transient.

At the Bureau, we produced horizontal images of subsurface conductivity for each survey area by (1) extracting modeled conductivity values at 10-m-depth intervals; (2) gridding the values within the image processing software ERMapper using a cell size of 50 m; (3) smoothing the grids using either a 3 × 3- or 5 × 5-cell average; (4) rescaling the color bar to cover 99 percent of the data range (cutting off 0.5 percent of the values at the low and high "tails" of the data spectra), and (5) exporting the georeferenced images using the Universal Transverse Mercator (UTM) zone 14 north projection and the 1983 North American Datum.

Digital images from the Faysville and Stockholm surveys were imported into a GIS data base. Coverages used to analyze the relationship between the geophysical data and geological and hydrological characteristics of the region included maps of the distribution of geologic units, water-well locations and depths, water-quality analyses, roads (and associated power lines), surface-water bodies (streams, irrigation canals, and lakes), and oil- and gas-well locations.

Ground Geophysical Survey

Before the airborne geophysical data can be analyzed and interpreted, it is important to verify that the data are reasonably accurate. In other words, do the conductivity models derived from the airborne geophysical data accurately portray generalized conductivity variations in the subsurface? At the most rigorous level, borehole geophysical logs can be compared with vertical conductivity profiles constructed from the airborne data. This comparison is commonly futile because TDEM systems have far less vertical resolution than can be obtained using borehole logs, few wells are logged at the depths investigated in this study, and few borehole logs are calibrated for absolute conductivity measurements. The most that can be done to verify the airborne data is to compare those data with similar data acquired using ground-based instruments. At several representative sites in the Faysville and Stockholm areas, we examined the transients measured using airborne and ground instruments and compared conductivity models derived from both data sets.

Ground-based TDEM systems, such as the Geonics Protem 57 used in this study, operate on the same principles as the airborne systems (fig. 9). Compared with airborne systems, ground systems have fewer problems with EM noise and it is easier to keep the transmitter and receiver geometry constant, but data are more difficult to acquire. For example, an airborne system can acquire tens of thousands of measurements (soundings) per day, whereas a ground system might optimally acquire tens of soundings per day. Airborne systems make it possible to produce high-resolution images of subsurface conductivity over large areas that cannot be practically surveyed on the ground.

We acquired 14 TDEM soundings in the Faysville and Stockholm areas in May 2000. We selected seven sites (F, G, H, I, L, M, and N, fig. 12) in the Faysville area to represent a variety of environments based on the airborne survey results. We chose the seven Stockholm sites (A, B, C, D, E, J, and K, fig. 10) to represent the range of environments present in that area. In both areas, we acquired soundings in high- and low-conductivity environments as inferred from the airborne surveys. The location of each TDEM sounding was determined using a GPS receiver and high-resolution aerial photographs and was imported into the GIS data base to allow us to identify nearby soundings collected with the airborne systems.

For the airborne soundings, the receiver was towed behind the aircraft and was outside the transmitter loop. In the ground-based soundings, we used a larger transmitter loop (40 × 40 m) and placed the receiver in the center of the transmitter loop (fig. 14). The area of the transmitter loop was 1,600 m^2, and the effective area of the receiver coil was 100 m^2. At typical transmitter current of about 20 amperes, the transmitter dipole moment is 32,000 A-m^2, more than an order

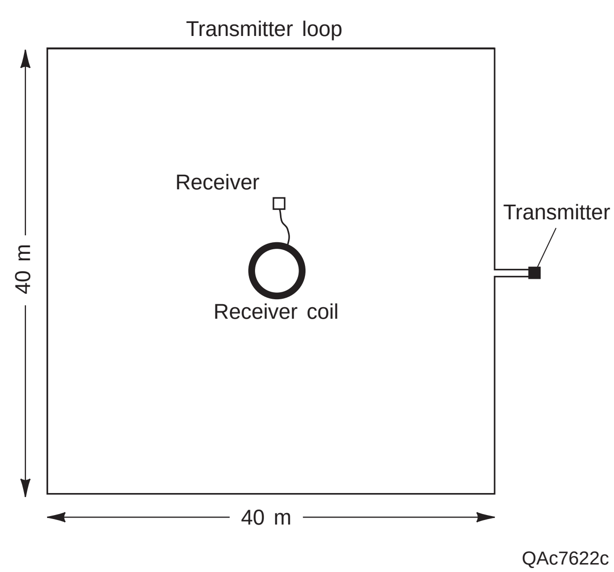

Figure 14. Central loop instrument configuration for ground-based TDEM soundings in the Faysville and Stockholm areas.

of magnitude smaller than the moment calculated for the airborne systems (table 4). The airborne transmitters operated at 25 or 30 Hz; we operated the ground transmitters at 30, 7.5, and 3 Hz at each location. Current shutoff times ranged from 35 to 50 μs. The resulting transients were measured at 20 time gates ranging from 0.0881 to 6.97 ms after current shutoff at 30 Hz, 0.352 to 27.9 ms after shutoff at 7.5 Hz, and 0.881 to 70 ms after shutoff at 3 Hz (fig. 9). Lower transmitter frequencies (and later measuring times) allow the ground-based systems to explore deeper than airborne systems if the transient is strong enough.

Ground-based data were processed using TEMIX, a software package published by Interpex. Beginning with one-layer conductivity models, we increased the number of layers at each site until there was no significant decrease in the fitting error (the difference between the observed transient and the transient predicted from the model and the acquisition parameters) when an additional layer was added. Three- or four-layer models were sufficient to produce fitting errors ranging from 0.7 to 6.1 percent. Because more than one model can produce a similar transient, we used TEMIX to analyze models that produced equivalent fits to the observed data.

AIRBORNE-SURVEY RESULTS

Results from the airborne geophysical surveys of the Faysville and Stockholm areas allow us to examine the usefulness of airborne EM in identifying and assessing additional sources of ground water. Primary data for this analysis are the layered-earth inversions and conductivity-depth transforms of the EM data, which enable us to associate an electrical conductivity with a location and depth within the survey areas. A technically successful airborne survey is one that accurately portrays the conductivity magnitude and distribution in the subsurface. For the project to be a success, the geophysical data must additionally correlate to hydrological or geological parameters that can be used to predict ground-water quality and availability within the survey areas.

Investigation Depth

A primary criterion in assessing the usefulness of airborne EM in ground-water resource investigation is exploration depth. In most cases, the deeper the exploration depth, the more useful the survey will be. Presurvey modeling suggested an exploration depth of 200 to 300 m could be achieved with the airborne systems used in this study, which was sufficient to exceed the depth of most water wells in the Lower Rio Grande Valley (fig. 6a). Upon completion of the surveys and inversions, we examined actual exploration depths achieved by determining the number of valid conductivity values at each 10-m-depth interval between the surface and a depth of 200 m (fig. 15).

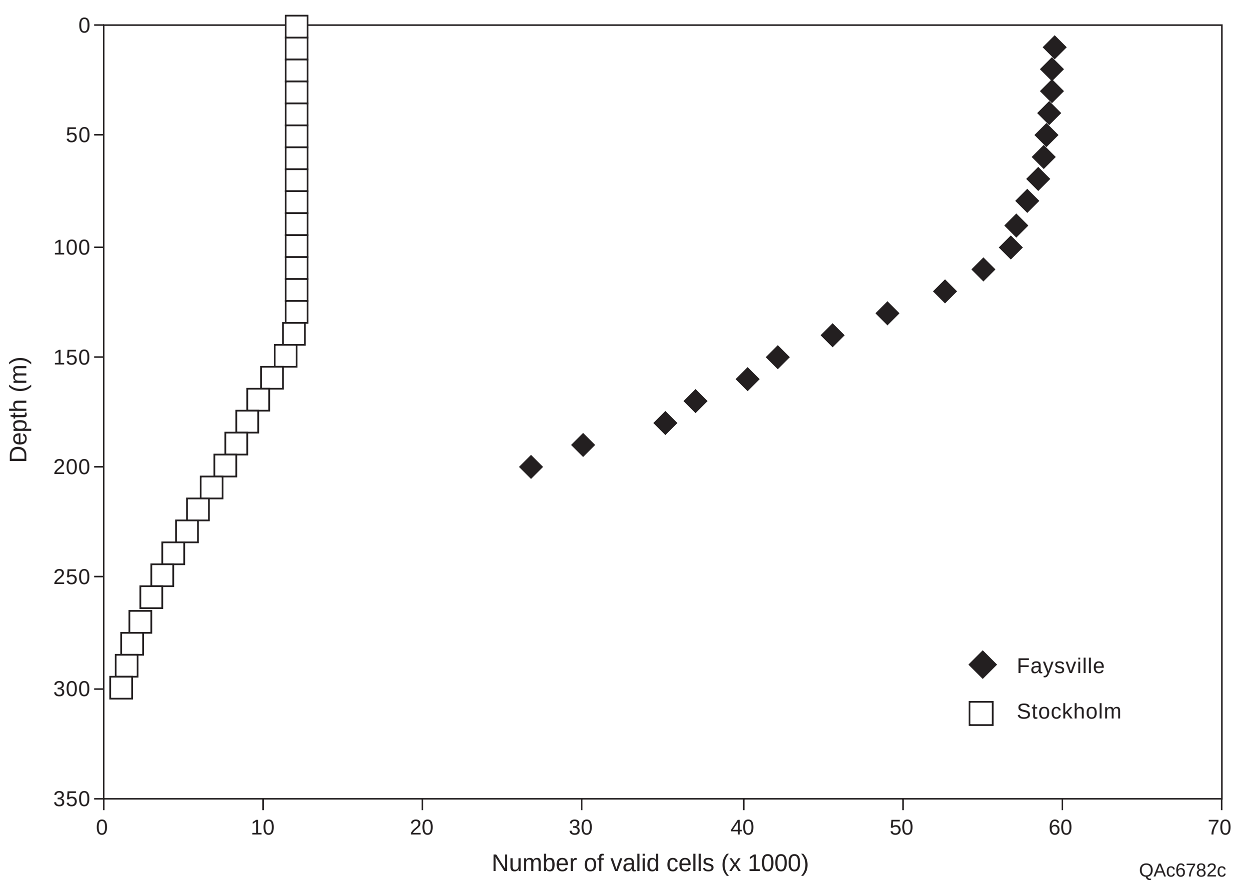

Figure 15. Number of valid conductivity values at 10-m-depth increments for the Faysville and Stockholm conductivity volumes.

As delivered by Geoterrex, the Faysville conductivity-depth transforms of the EM data consisted of 60,472 conductivity models at a spacing of about 13 m along the flight lines (fig. 12). Virtually all Faysville conductivity values were valid to a depth of 130 m (fig. 15); more than 50 percent remained valid to a depth of 210 m.

World Geoscience's layered-earth inversion of the Stockholm EM data consisted of 12,107 three-layer conductivity models spaced at about 60 m along the flight lines (fig. 10), reflecting along-line stacking of more transients than in the Faysville data set. Skin depths calculated using conductivities derived from the inversions were mostly between 140 and 320 m, averaging 218 m. Nearly all of the conductivity models had valid conductivities to a depth of 130 m (fig. 15). More than 50 percent of the models contained conductivity values at a depth of 210 m.

Conductivity Trends

We examined how ground conductivity varies with depth in the Faysville and Stockholm areas by determining conductivity averages at 10-m-depth intervals from the conductivity volumes (fig. 16). These data show that (a) both areas have similar conductivity trends (conductivities increase downward in the upper few tens of meters, then decrease downward to at least the 200-m depth), (b) highest conductivities are observed at about the 30-m depth, and (c) the lowest conductivities are found at the deepest depths.

In the Faysville area, average conductivity increases from 99 mS/m at 10-m depth to a maximum of 110 mS/m at a depth of 30 m (fig. 16). Conductivities decrease downward from that depth to a minimum average of 15 mS/m at 200 m. In the Stockholm area, average conductivity increases from 401 mS/m at 10 m to 721 mS/m at 30 m then decreases downward to 168 mS/m at 200 m and 94 mS/m at 270 to 280 m depth. Average conductivity increases slightly below the 290-m depth in the Stockholm area, mirroring the regional increase in conductivity with depth observed in geophysical logs of deep wells (Baker, 1979). This trend is based on a relatively small number of data points available at that depth (figs. 15, 16).

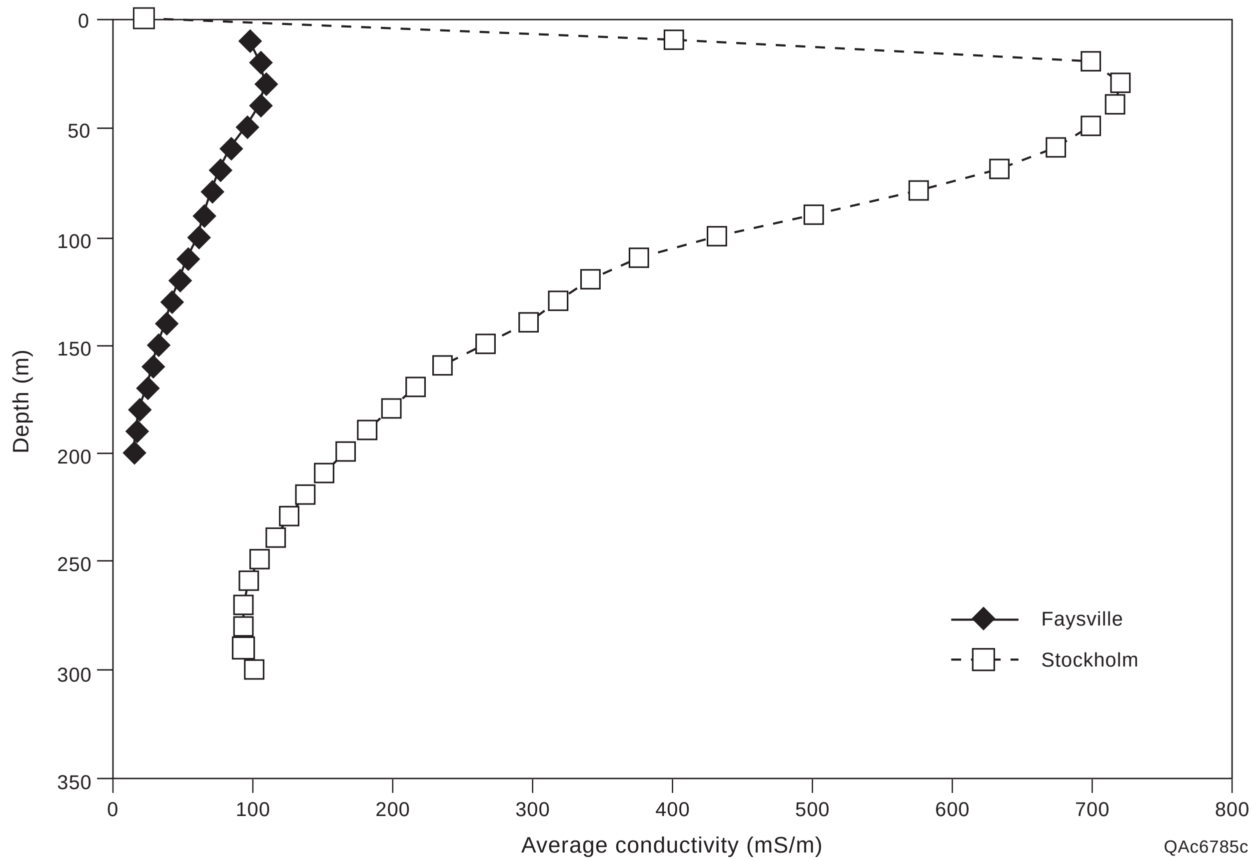

Figure 16. Average of all valid conductivity values at 10-m-depth increments for the Faysville and Stockholm conductivity volumes.

Conductivities are significantly higher in the Stockholm area than in the Faysville area at each depth, about four times higher at the 10-m depth, almost seven times higher at the 30-m depth, and more than 11 times higher at the 200-m depth. Because differing airborne instruments and processing algorithms were employed in each area, the large conductivity difference might be due to actual conductivity differences or it might be a system artifact. We made ground measurements using the same TDEM instrument in both areas to address this ambiguity.

Faysville Conductivity Data

Because one of the principal goals of the project is to identify potential ground-water resources by making hydrological and geological interpretations from the conductivity volumes, one of the most useful means of viewing the conductivity data is to "slice" the conductivity volume horizontally. Horizontal slices through the volume at various depths should reveal spatial patterns that allow us to estimate water quality and perhaps interpret likely geological environments. For the Faysville volume, we made 20 slices at 10-m-depth increments between 10- and 200-m depth. We have reproduced selected depth slices as figures, but all slices can be viewed as a digital animation, as web images, or in the GIS data set on the accompanying CD-ROM. To make conductivity patterns more apparent, the slices are displayed according to a linear color range that is rescaled for each image, not to the data range for the entire conductivity volume. For example, on these images red indicates conductivities that are high relative to other conductivities at the same depth, not necessarily to conductivities observed at other depths.

On images depicting conductivities at shallow depths (10 to 40 m), the lowest conductivities are found in the northern part of the Faysville area and the highest values are found in the south part of the area (fig. 17; CD-ROM). A network of sinuous, low-conductivity zones is visible throughout the northeast part of the volume at these depths that includes the dense concentration of shallow water wells in the Linn-Faysville district. A highly conductive zone extending about 4 km north-south and about 7 km east-west is located near the southern boundary of the Faysville survey area.

At deeper depths (greater than 70 m), conductivities in the north part of the survey area (north of FM 490) are generally higher than those to the south. Sinuous features that are 200 to 500 m wide and as much as 10 to 15 km long and are more conductive than their surroundings are visible in the north and northwest parts of the area, particularly at depths of 110 m or greater. Sinuous features that are less conductive than their surroundings are common in the south half of the survey area from depths of 50 m to more than 130 m, below which the number of cells having no data increases rapidly with increasing depth. The sinuous features in both areas are visible across several adjacent depth slices. The y-shaped zone of no data that crosses the east part of the survey area, particularly evident at depths of 90 m or greater, marks the location of major electrical power lines that disrupt the EM signal at relatively late times.

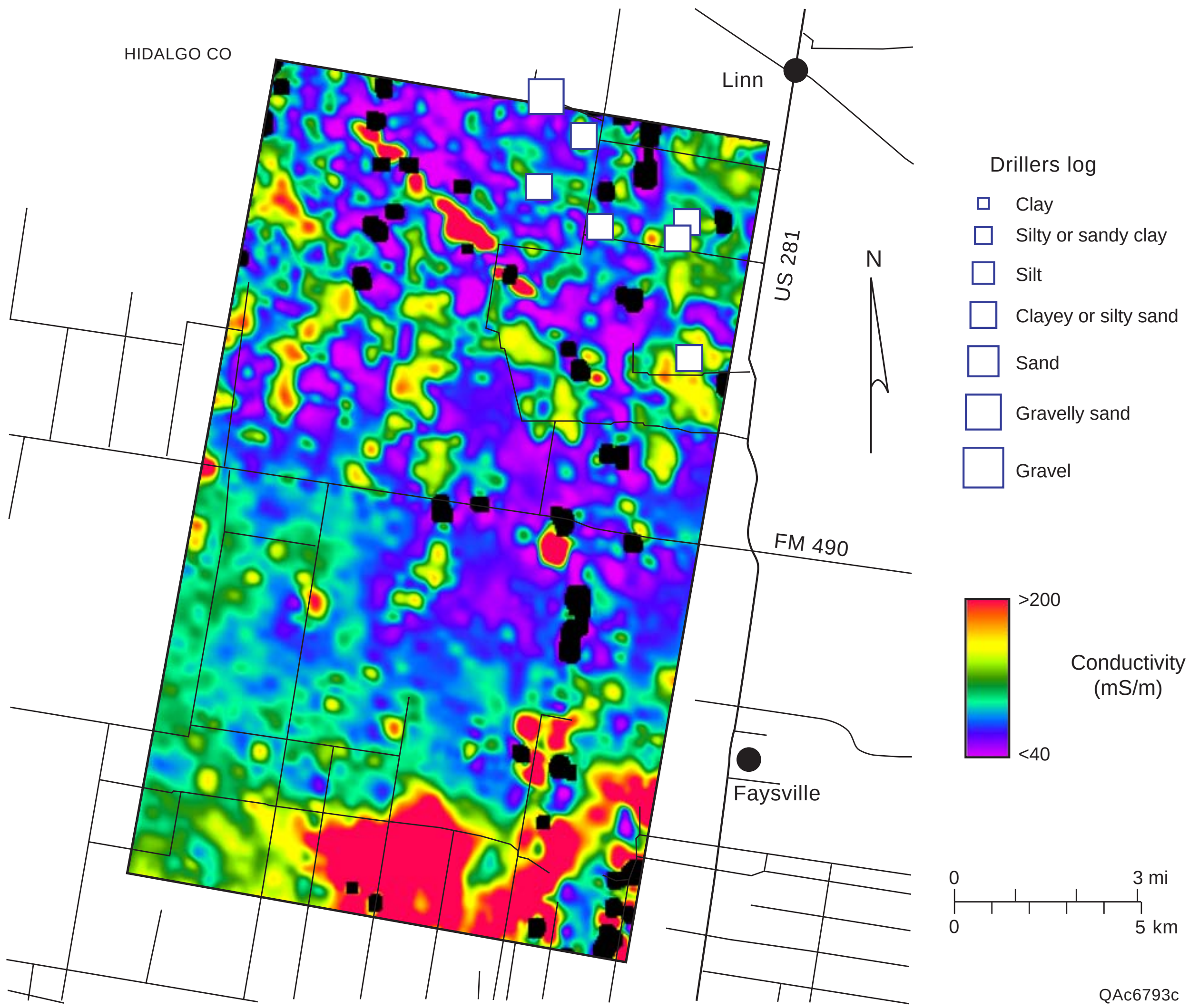

Figure 17. Apparent conductivity and sediment texture 20 m below the surface in the Faysville area. Texture is that reported in driller's logs at 20 m (Baker and Dale, 1961).

Changes in conductivity throughout the sampled volume are related to changes in sediment type and water quality. Although few geophysical logs exist in the survey area, some reports of the sediment encountered at various depths do exist in water-well driller's logs. We can use these logs to qualitatively compare conductivity patterns at a given depth with sediments encountered at the same depth during drilling, and we can use published analyses of water quality from wells in the survey area to examine how the conductivity patterns relate to changes in water quality.

There are driller's logs for seven wells in the northeast part of the Faysville survey area that report sediment type at a depth of 20 m (fig. 17). Six of these logs indicate sand as the dominant texture at 20 m depth; gravelly sand is reported to be the dominant texture at the remaining well at the north edge of the survey area. As is evident from the conductivity patterns, the well with the coarsest reported texture at 20-m depth coincides with an area of low conductivity depicted on the 20-m conductivity slice (fig. 17). Other than being located in an area of generally low conductivity, the sandy texture reported for the remaining six wells shows no rigorous relationship to conductivity, falling within local areas of low to moderate conductivity.

We can examine whether water quality influences ground conductivity measured by airborne instruments by comparing TDS concentrations in water samples from a specific depth with ground conductivity calculated for that same depth from data collected by the airborne instrument. The depth range contributing water might not be known for a well, but wells as deep or slightly deeper than a given conductivity slice are likely to produce water from near the same depth as the conductivity slice.

Most of the water-quality data in the Faysville area comes from wells that are 20 to 30 m deep. We can compare TDS values from the fresh to slightly saline water (699 to 1,870 mg/L) produced from 26 wells within this depth range with conductivity values depicted on the conductivity image calculated for the 20-m depth (fig. 18). Although the geographical extent of water-quality data is limited, it does appear that TDS values in wells that are 20 to 30 m deep correlate to conductivity at 20-m depth measured by using the airborne instruments. Wells producing water relatively high in TDS concentration tend to be associated with areas depicting relatively high

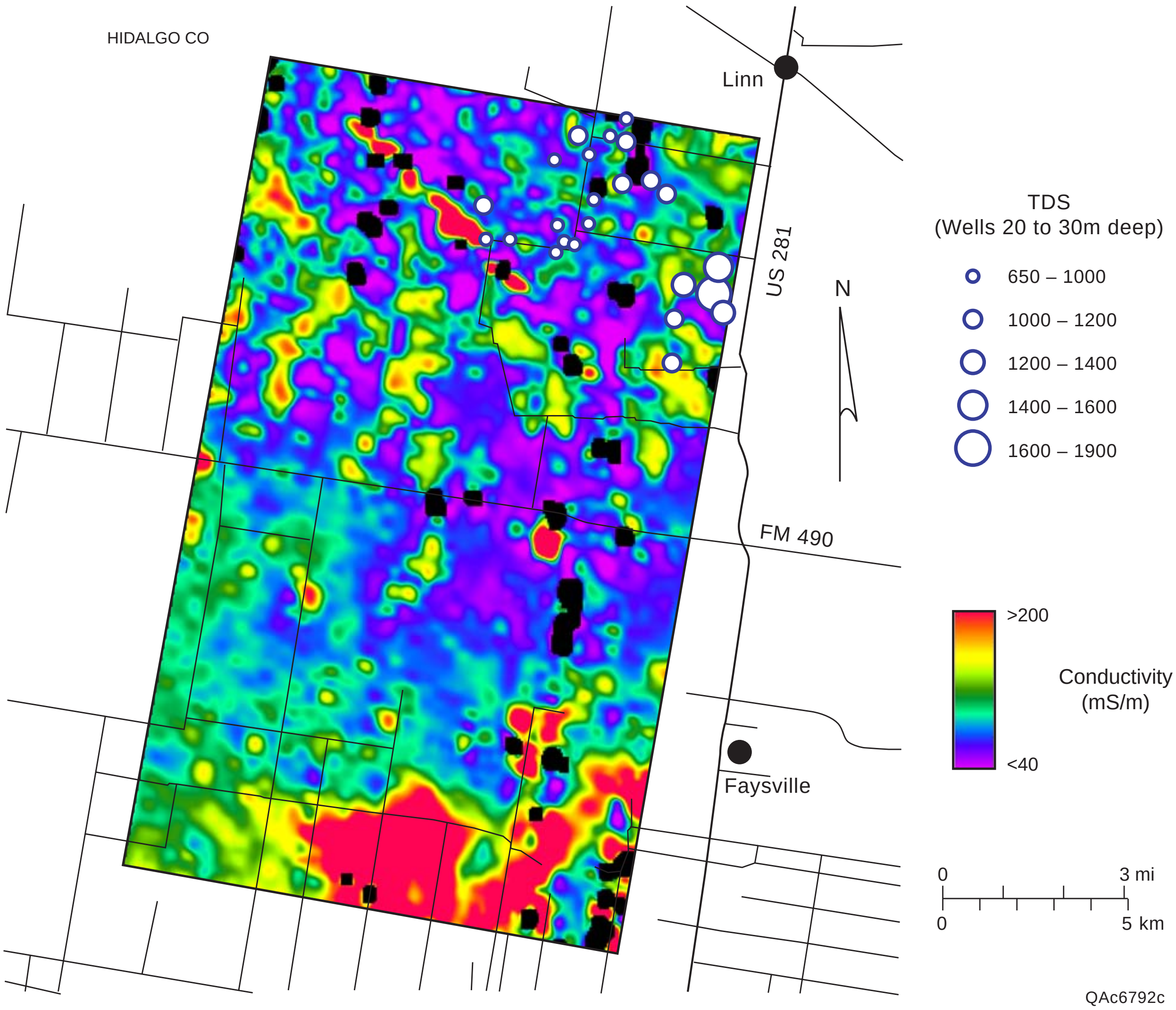

Figure 18. Apparent conductivity and water quality 20 m below the surface in the Faysville area. Water quality reported as TDS concentration (mg/L) in water wells with depths equal to or slightly greater than the depth of the conductivity image. Well data from Texas Water Development Board.

conductivity; conversely, wells producing water with relatively low TDS values tend to be associated with areas depicting relatively low conductivity.

To quantify this relationship, we compared reported TDS values with conductivity values measured by the airborne instruments at the well location and approximate well depth (fig. 19). Despite the likelihood of imprecise well locations, unknown depths of zones contributing water, and a relatively small range in TDS concentration reported for the Faysville area, conductivities measured using airborne instruments do tend to be higher at locations and depths corresponding to water wells with relatively high TDS values and lower at well locations and depths producing water with lower TDS values.

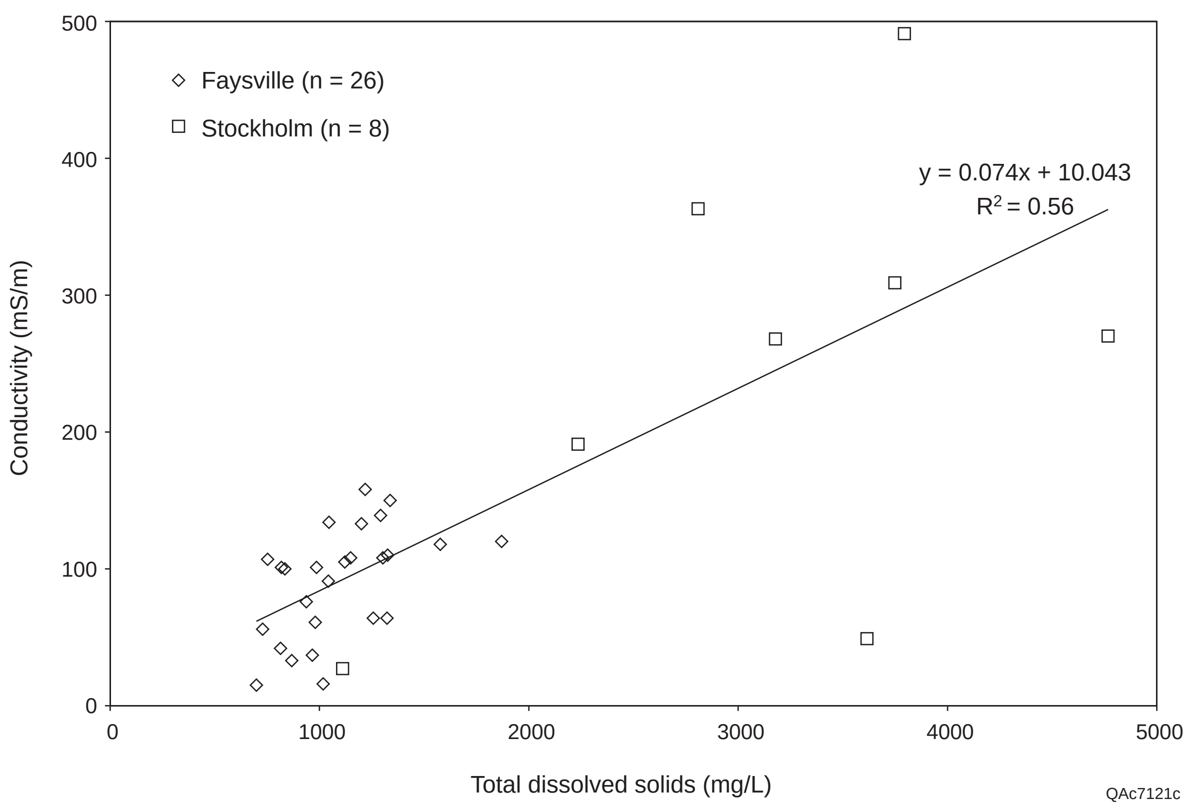

Figure 19. Relationship between TDS concentration in ground-water samples from the Faysville and Stockholm areas and conductivities calculated from airborne data for depths at or slightly above the depth of the water wells.

Stockholm Conductivity Data

EM data from the Stockholm airborne survey, processed by World Geoscience, allowed us to construct surveywide images of conductivity at early, middle, and late times during the transient, as well as a series of horizontal slices through conductivity volume at 20 depths between 10 and 200 m. Examples of these data are reproduced in this report, but the complete set of images can be viewed as static images or animations on the accompanying CD-ROM.

Because the transient electrical currents induced in the ground by the airborne transmitter propagate downward and outward with time, the conductivity image produced using data recorded at the earliest times after transmitter shutoff (fig. 20) depicts shallow-subsurface patterns better than images constructed from data acquired at later times. On this image, a sharp, arcuate boundary separates a large area of low conductivity in the southeast corner of the Stockholm area from an area of higher conductivity trending northeast across the image. A second, smaller, low-conductivity zone is located at the western margin. Arcuate zones of high and low conductivity several hundred meters to more than 1 km wide are common in the image.

Early-time (shallow-depth) patterns (fig. 20) reflect soil and geological features common to the late Cenozoic depositional environment in the Lower Rio Grande Valley. Relatively low conductivities in the northwest part of the image coincide with areas mapped as the Pliocene Goliad Formation (Brewton and others, 1976), a fluvial-deltaic unit consisting of gravel, sandstone, and clay beds. Soils in this area are mapped as deep, moderately permeable sandy loam (Jacobs, 1981). Lowest conductivities in this zone are adjacent to Delta Lake, located near the western boundary of the study area. This zone extends as much as 2 km east of the lake.

Narrow, arcuate patterns are visible in the conductive band that crosses the image from southwest to northeast. The conductive band is within an area mapped as Beaumont Formation, a Pleistocene fluvial-deltaic unit (Brewton and others, 1976). Soils within this band are loamy to clayey (Jacobs, 1981; Turner, 1982), having generally higher clay content than surrounding units. The arcs within this band are similar in size, shape, and location to units within the Beaumont,

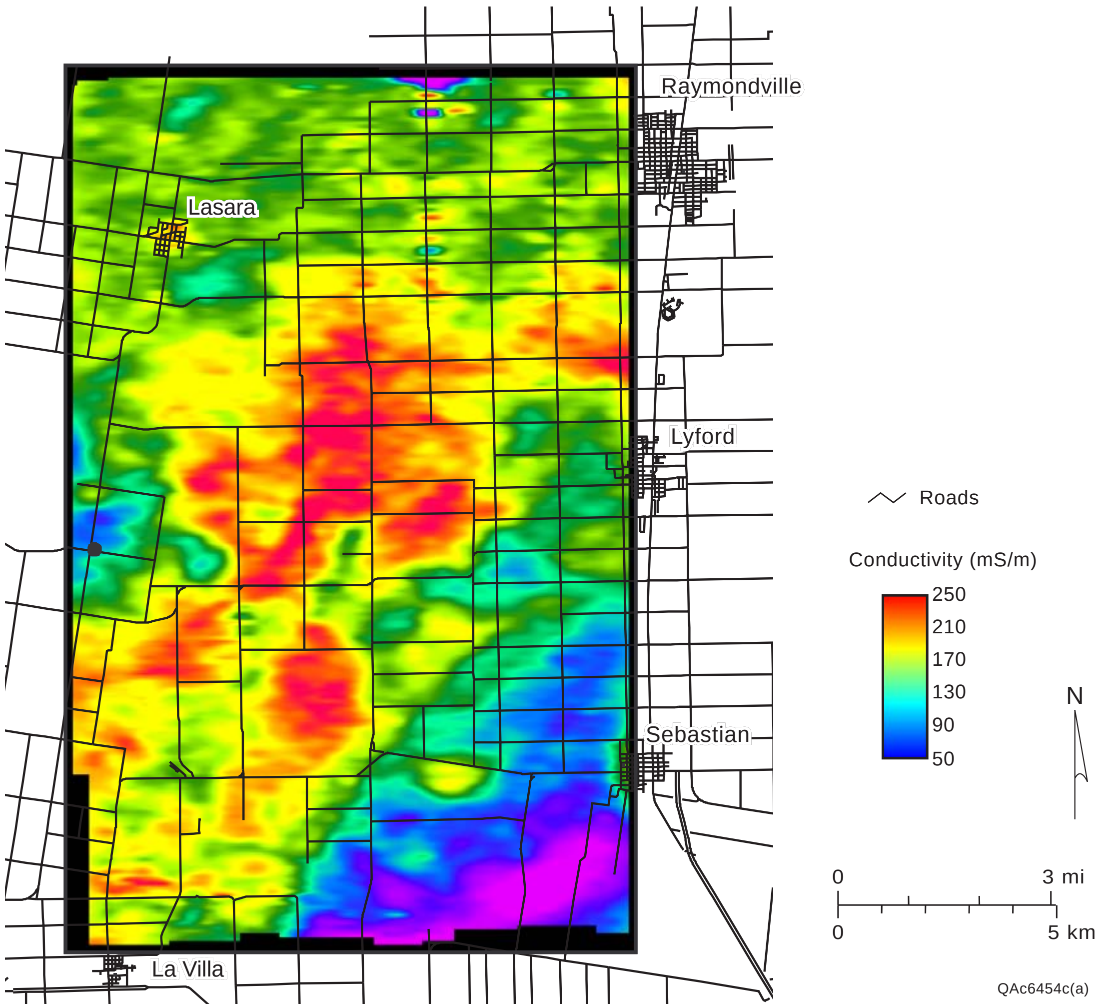

Figure 20. Apparent conductivity at early time (0.2 to 0.5 ms after current shutoff) in the Stockholm area.

described as dominantly clay and mud deposited in abandoned channels. These fine-grained, low-permeability units have higher conductivities than surrounding sediments.

The prominent curved boundary between low conductivities in the southeast corner of the image and the conductive central band (fig. 20) coincides with a change in depositional character within the Beaumont Formation (Brewton and others, 1976). The low-conductivity zone has more mapped channels, smaller channel radii, and narrower channel widths than the more conductive zone to the northwest. Soils are sandy to clay loams (Williams and others, 1977; Turner, 1982). The boundary may represent an unmapped valley margin between an older episode of Beaumont deposition to the northwest and a younger episode to the southeast.

Slices through the depth-converted Stockholm conductivity volume are much more conductive than equivalent Faysville slices (fig. 16). At shallow depths (fig. 21; CD-ROM), prominent features include a low-conductivity area between the surface and about 100-m depth that is as much as 8 km across in the southeast corner of the Stockholm area and a low-conductivity zone adjacent to the western edge of the survey area that is 3 to 4 km across and visible on slices at depths of 10 to 80 m.

At moderate depths of 50 to 140 m (fig. 22; CD-ROM), a relatively conductive zone is visible on the northern 7 km of the survey area that contains numerous sinuous, conductive features that are 200 to 600 m wide and several kilometers long. These features, particularly evident at depths of 90 to 120 m, persist vertically across several adjacent depth slices. They are similar in size and shape to channels mapped at the surface. Spatial patterns are difficult to discern as data density progressively decreases in the north part of the survey area at depths greater than 140 m.

Between 100 and 200 m, the most prominent feature is an elongate area of low conductivity that trends northeast–southwest and measures about 8 km in width and more than 15 km in length (fig. 22). This feature contains numerous sinuous elements similar in size to those in the slightly shallower conductive area to the north and to mapped channels at the surface. Some sinuous

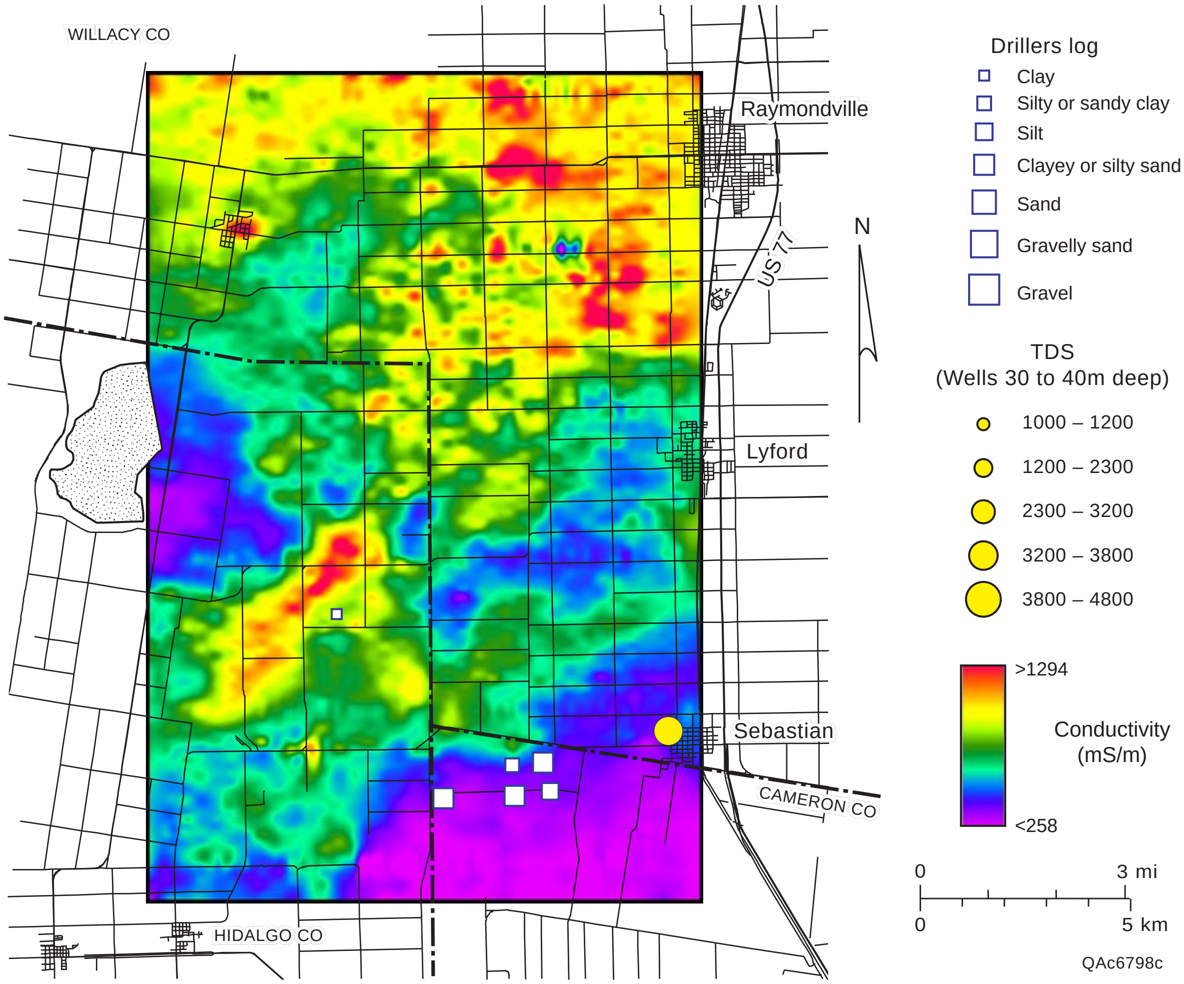

Figure 21. Apparent conductivity, sediment texture, and water quality 30 m below the surface in the Stockholm area. Texture is that reported in driller's logs at the depth indicated (Baker and Dale, 1961). Water quality reported as TDS concentration (mg/L) in water wells with depths equal to or slightly greater than the depth of the conductivity image. Well data from Texas Water Development Board.

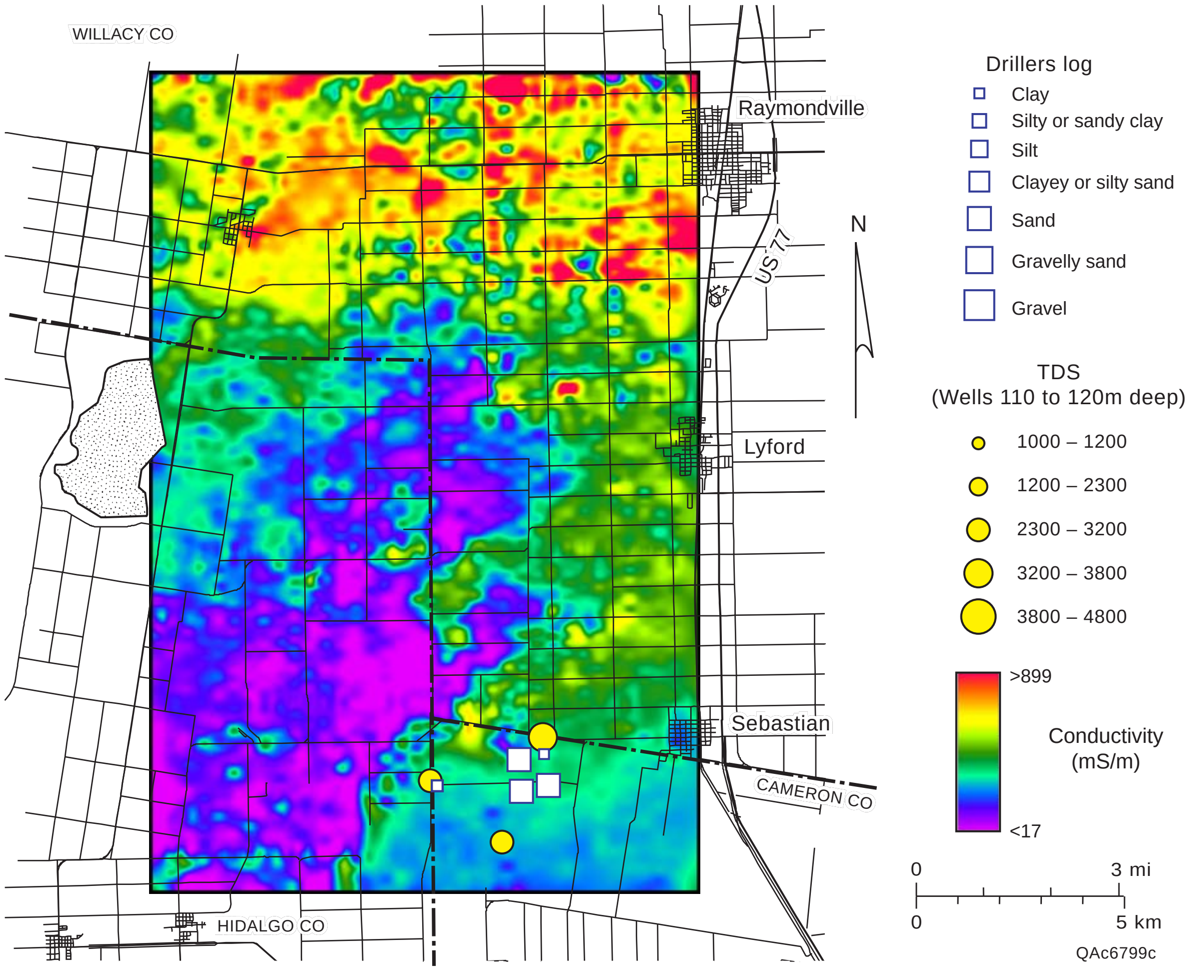

Figure 22. Apparent conductivity and water quality 110 m below the surface in the Stockholm area. Texture is that reported in driller's logs at the depth indicated (Baker and Dale, 1961). Water quality reported as TDS concentration (mg/L) in water wells with depths equal to or slightly greater than the depth of the conductivity image. Well data from Texas Water Development Board.

elements in the low-conductivity zone are slightly more conductive than their surroundings and others are slightly less conductive.

Textural data are available in driller's logs from eight water wells within the Stockholm survey area, although only one log extends deeper than 120 m. Assuming the texture reported on the logs accurately represents the sediment encountered during drilling, there is no reliable primary correlation between texture as reported in the logs and patterns visible in the conductivity data. At some depth levels, such as 30, 50, and 100 m (fig. 21), finer grained sediments such as clay and sandy clay are found in areas of elevated conductivity, whereas coarser grained sediments such as sand and clayey sand are found in areas of relatively low conductivity. At other depths, such as 20, 70, and 80 m, clays and silty clays are reported for wells in areas that are moderately to highly conductive and in areas having low conductivity. Sands are reported in logs from wells within highly conductive zones on the 40-, 90-, and 110-m conductivity slices. On the conductivity slice at a depth of 110 m (fig. 22), driller's logs show sediments ranging from clay to sand in five wells within an area of low conductivity in the southeast part of the survey area and sand in an area of high conductivity near the northern border of the survey.

There is a more consistent relationship in the Stockholm area between conductivity measured by the airborne instruments and water quality as determined by TDS concentration than there is between conductivity and sediment type. TDS concentrations in samples from eight water wells in the Stockholm survey area, when compared with conductivities determined for depths that are equal to or slightly shallower than the reported depth of the well, suggest that higher TDS values correlate to higher conductivity values. For example, if we assume that wells that are 110 to 120 m deep are producing the most water from that depth or slightly shallower, we can compare TDS values for those wells with conductivity determined for the 110-m depth (fig. 22). Three wells within this depth range in the Stockholm survey area have slightly to moderately saline TDS values ranging from 2,800 to 3,750 mg/L. The two wells with the lower TDS values are within areas of relatively low conductivity. The well with the highest TDS concentration is also associated with the highest conductivity.

Stockholm-area ground water, generally more saline than water from the Faysville area, also has a wider salinity range (fig. 7). Adding the Stockholm water-quality data and associated conductivities to the more limited-salinity Faysville data allows a better relationship to be determined between TDS values in water and conductivities determined by airborne instruments (fig. 19). Despite the uncertainties in well location, well depth, contributing zones, and time lag between sample dates and the airborne survey, high-conductivity measurements tend to be associated with high TDS values in the Faysville and Stockholm areas.

GROUND-BASED VERIFICATION OF AIRBORNE SURVEYS

Ground-based TDEM measurements were acquired at 14 sites in the Faysville and Stockholm areas (figs. 10, 12) to help validate the conductivity data collected during the airborne surveys. Ground measurements enable us to compare transients measured with airborne and ground instruments at specific locations and to compare conductivity models constructed to fit the transients observed with both systems. Further, using the same ground system in both the Faysville and Stockholm areas allows us to examine whether large differences in conductivity that are apparent from the Faysville and Stockholm airborne surveys are caused by actual conductivity differences between the two areas or are an artifact of differing airborne systems and processing algorithms.

Ground Measurements

Unprocessed data from the seven ground-based TDEM soundings in the Faysville area and seven soundings in the Stockholm area consist of measurements of secondary field strength (transients) at time increments following transmitter current shutoff (fig. 9). These transients, measured in several relatively conductive and resistive environments in each area, were measured by the instrument between 0.8 and 70 ms after current shutoff. The transients decay very rapidly, weakening more than five orders of magnitude in less than 10 ms and exhibiting linear trends on plots of logarithmic time and signal strength (fig. 23). Transients later than 8 to 30 ms were too weak to be measured.

The strongest and longest lasting transients occur over relatively conductive ground such as that at sounding J in the north part of the Stockholm area. Sounding A, in the more resistive south part of the Stockholm area, exhibits lower signal strength, shorter transient length, and a log-log decay slope similar to that shown for sounding J.

Faysville transients are weak and relatively short compared with those measured in most Stockholm soundings (fig. 23). Despite the generally lower signal strength of the Faysville tran-

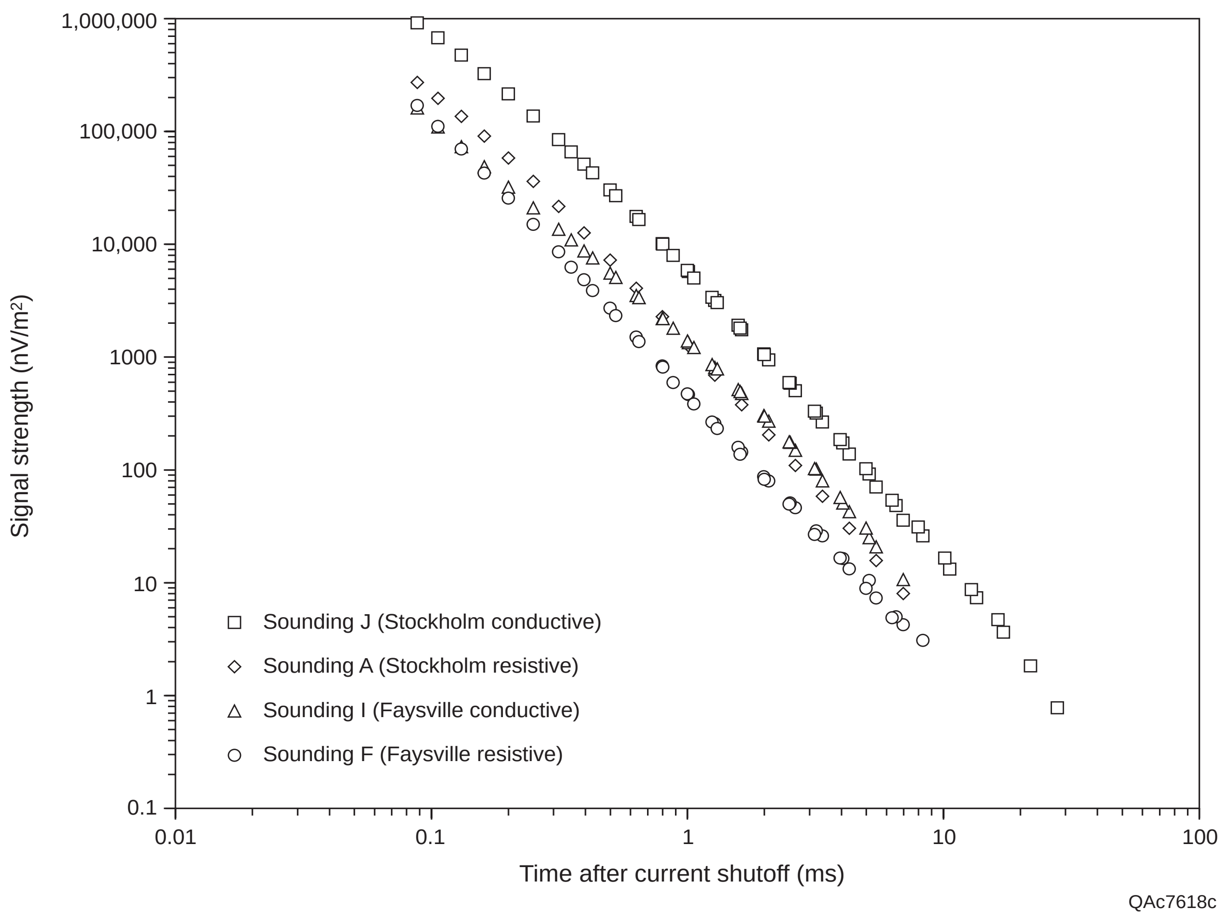

Figure 23. Transients recorded using a ground-based TDEM instrument that represent relatively resistive (sounding F) and conductive (sounding I) sites within the Faysville area and relatively resistive (sounding A) and conductive (sounding J) sites within the Stockholm area. Locations on figures 10 and 12.

sients, they retain a decay slope that is similar to that observed for Stockholm soundings. Soundings F and I, representing relatively resistive and conductive parts of the Faysville area, have similar transient signal strengths in the early part of the decay (earlier than 0.2 ms) that are lower than signal strengths from soundings in even the most resistive parts of the Stockholm area. At later times (0.2 to 10 ms), signal strength is higher for Faysville sounding I, located in a relatively conductive area, than it is for sounding F, located in an area that is relatively resistive. The stronger signal for sounding I is similar to that measured for Stockholm sounding J, located in a relatively resistive part of that area.

Raw transients can be recalculated as apparent electrical conductivity at each time gate. Because the secondary currents induced to flow in the ground travel outward and downward with time, apparent conductivity at early time reflects relatively shallow conditions and apparent conductivity at later time reflects relatively deep conditions. Apparent conductivities calculated for sounding F, located in a relatively resistive part of the Faysville area, are near 100 mS/m at all measured times (fig. 24a, left panel). Minor inflections in the conductivity data reveal clues about changes in conductivity with depth. Apparent conductivity rises at the earliest times, suggesting a relatively resistive surface layer underlain by a more conductive layer. Between about 0.3 and 1 ms, apparent conductivity is constant or decreasing slightly, suggesting a third layer that is more resistive than the second layer. Apparent conductivities begin rising again at times later than 1 ms, suggesting a fourth layer that is more conductive than the third.

Conductivity models can be constructed and tested using the program TEMIX (fig. 24a, right panel) to examine how closely apparent conductivities calculated from the model match those calculated from the transient. For Faysville sounding F, a four-layer model replicates the observed transient with a fitting error of about 6.1 percent (fig. 24a; table 5). Models that produce nearly equivalent results can also be constructed to show how much the thickness and conductivity of each layer might vary and still produce a similar transient.

Faysville sounding I, located in a relatively conductive part of the area, has similar apparent conductivity to sounding F at the earliest times (fig. 24b, left panel). Apparent conductivity rises

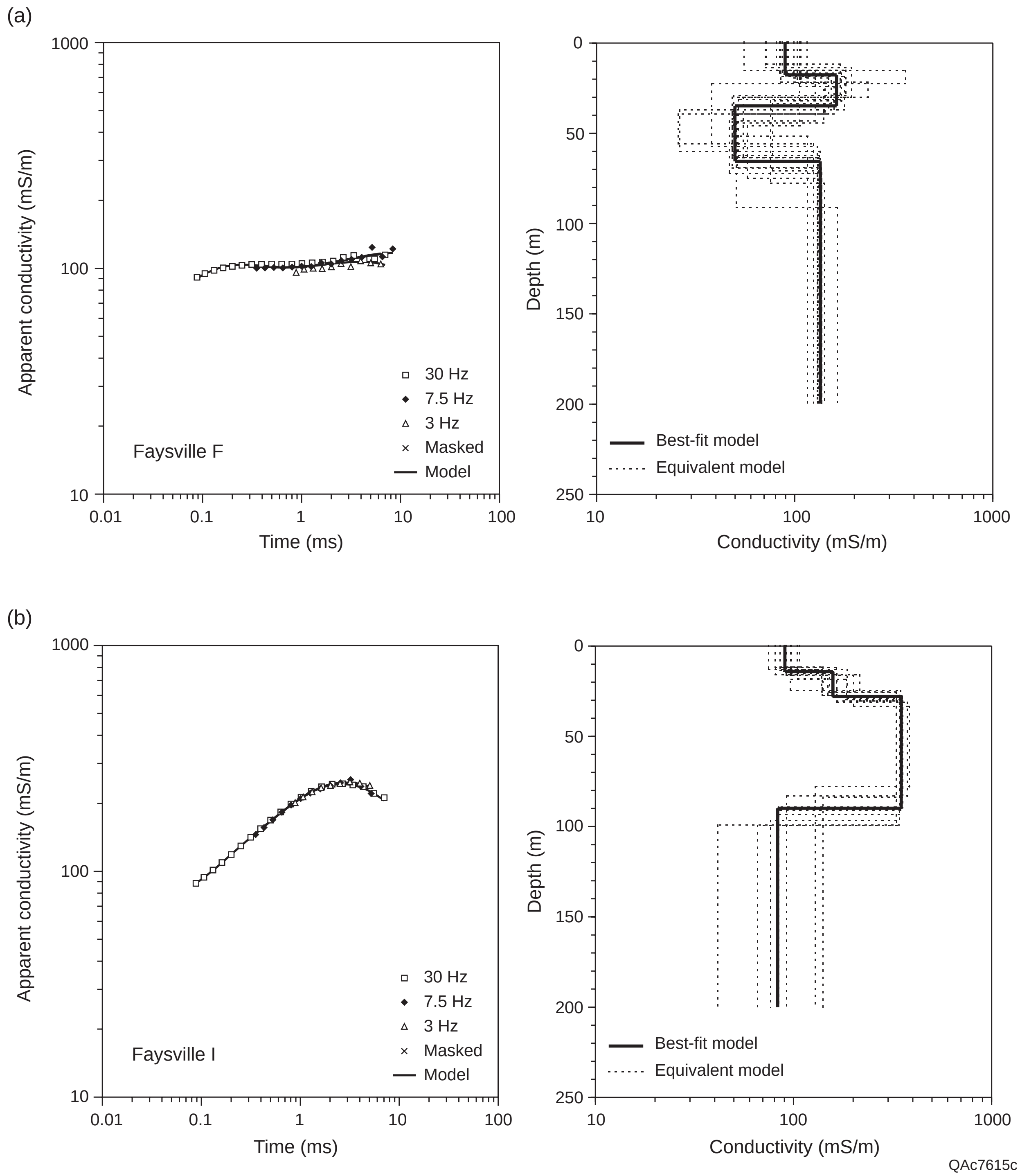

Figure 24. (left) Apparent conductivity and (right) conductivity models at ground-based TDEM soundings (a) Faysville F in a relatively resistive area and (b) Faysville I in a relatively conductive area (locations on figure 12). Symbols in the apparent-conductivity curve at left represent field measurements; the solid line through the data points at left represents the apparent conductivity calculated from the best-fit conductivity model at right. The conductivity model at right that has the solid line represents the model fitting the field data best; the dashed lines at right represent models that fit the field data nearly as well.

Table 5. Best-fit conductivity models for ground-based TDEM soundings in the Faysville area (fig. 12).

Sounding	Location (°)	Fitting error (%)	Layer	Conductivity (mS/m)	Thickness (m)	Depth to top (m)
F	Lat 26.4736	6.1	1	90	18.1	0
	Lon -98.1847		2	163	17.2	18.1
			3	50	30.8	35.3
			4	135	—	66.1
G	Lat 26.4211	3.5	1	58	16.2	0
	Lon -98.2378		2	234	11.7	16.2
			3	156	—	27.8
H	Lat 26.4589	4.6	1	117	10.8	0
	Lon -98.2392		2	238	45.1	10.8
			3	99	—	55.9
I	Lat 26.3878	2.1	1	90	14.5	0
	Lon -98.1997		2	158	13.8	14.5
			3	350	61.8	28.3
			4	83	—	90.1
L	Lat 26.5186	4.1	1	45	27.8	0
	Lon -98.1558		2	125	40.8	27.8
			3	206	—	68.6
M	Lat 26.5175	5.5	1	48	54.4	0
	Lon -98.1836		2	178	83.8	54.4
			3	122	—	138.2
N	Lat 26.3903	3.6	1	118	23.4	0
	Lon -98.1617		2	351	17.9	23.4
			3	248	—	41.3

steadily to a peak of more than 200 mS/m at about 3 ms, a much higher apparent conductivity than those calculated for sounding F. Apparent conductivity begins falling at the latest times measured. At a minimum, these trends suggest a relatively resistive surface layer underlain by a relatively conductive layer, which is in turn underlain by a relatively resistive layer. Models constructed to fit the transient (table 5; fig. 24b, right panel) support these general observations.

Similar relationships are present in two representative soundings from the Stockholm area (fig. 25). Sounding A, located in a relatively resistive part of the Stockholm area, exhibits relatively low apparent conductivity at early times that rises slightly before falling at later times

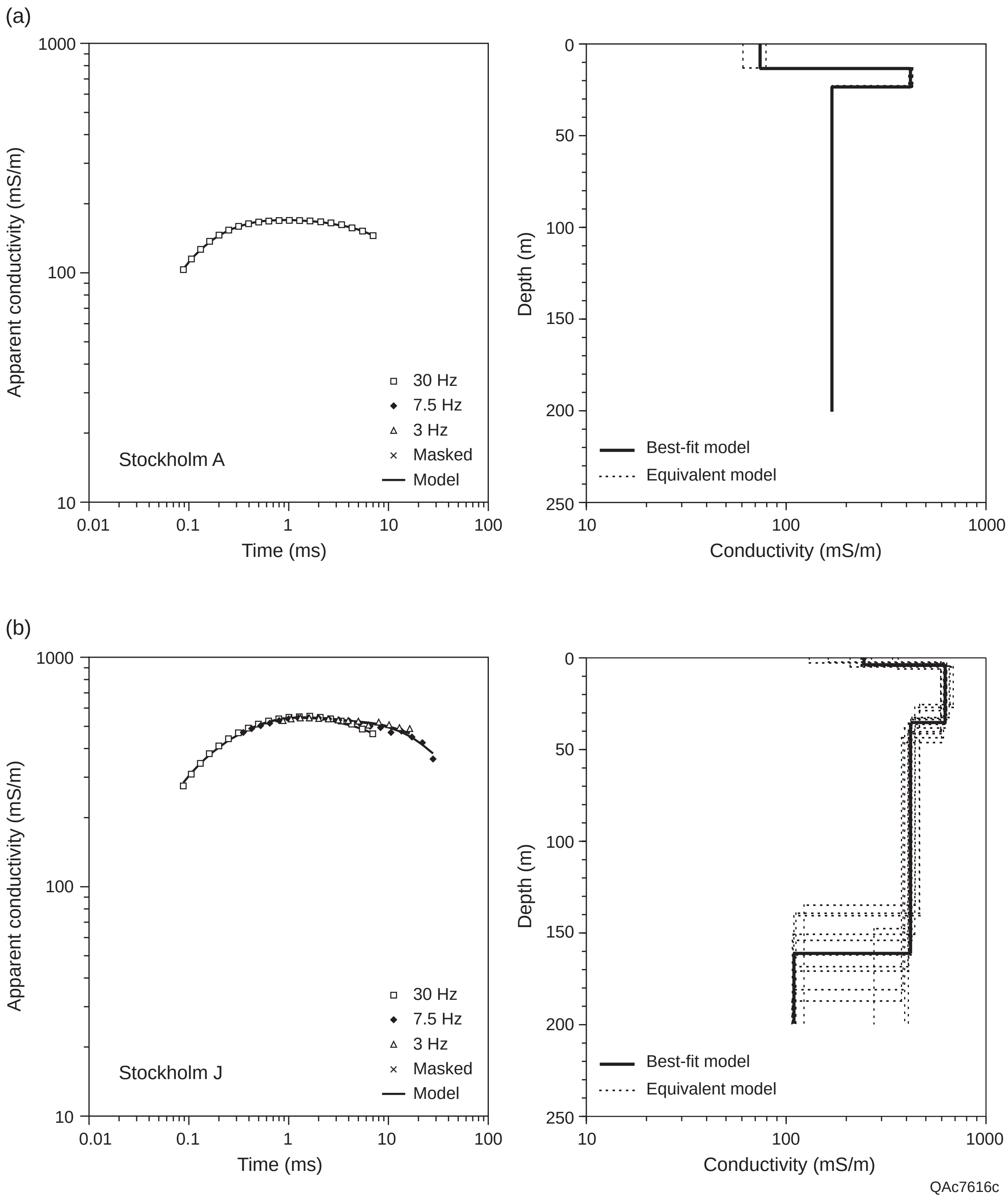

Figure 25. (left) Apparent conductivity and (right) conductivity models at ground-based TDEM soundings (a) Stockholm A in a relatively resistive area and (b) Stockholm J in a relatively conductive area (locations on figure 10).

(fig. 25a, left panel). A three-layer model (table 6; fig. 25a, right panel) produces a calculated transient that fits the observed transient with an error of less than 1 percent. Apparent conductivities from a transient indicating much more conductive ground are found at sounding J (fig. 25b, left panel), where again the highest apparent conductivities are calculated for the middle part of the transient. Models constructed to fit the sounding J transient (fig. 25b, right panel) have thick conductive layers overlain and underlain by more resistive layers.

These examples indicate that there are detectable differences in the electrical conductivity of the ground within and between each study area. The relatively conductive Faysville I sound-

Table 6. Best-fit conductivity models for ground-based TDEM soundings in the Stockholm area (fig. 10).

Sounding	**Location (°)**	**Fitting error (%)**	**Layer**	**Conductivity (mS/m)**	**Thickness (m)**	**Depth to top (m)**
A	Lat 26.3158	0.7	1	67	13.4	0
	Lon -97.8481		2	379	10.0	13.4
			3	153	—	23.4
B	Lat 26.3419	2.5	1	108	12.3	0
	Lon -97.8793		2	331	38.9	12.3
			3	168	—	51.2
C	Lat 26.4064	3.3	1	187	7.4	0
	Lon -97.9144		2	457	12.3	7.4
			3	193	—	19.7
D	Lat 26.3861	0.7	1	93	9.0	0
	Lon -97.8164		2	397	17.4	9.0
			3	258	—	26.4
E	Lat 26.4886	2.7	1	53	9.5	0
	Lon -97.8444		2	690	62.3	9.5
			3	319	—	71.8
J	Lat 26.4561	2.6	1	246	3.8	0
	Lon -97.8306		2	629	31.6	3.8
			3	422	126.2	35.3
			4	110	—	161.5
K	Lat 26.4794	3.2	1	288	4.8	0
	Lon -97.8733		2	568	17.3	4.8
			3	426	—	22.0

ing differs significantly from the relatively resistive Faysville F sounding in the observed transients, in the calculated apparent conductivities, and in the models constructed to fit the transients (figs. 23, 26a). Similarly, transients, apparent conductivities, and models of the Stockholm J sounding indicate far higher ground conductivities than are observed in the Stockholm A sounding (figs. 23, 26b).

As was the case in the airborne surveys, ground TDEM soundings indicate that conductivity is generally higher in the Stockholm area than it is in the Faysville area (tables 5, 6; fig. 26). Peak modeled conductivities in the Stockholm area reach nearly 700 mS/m; the highest conductivity layer modeled for Faysville-area soundings was about 350 mS/m.

Apparent conductivities and conductivity models for all ground-based TDEM soundings can be viewed in the web on the accompanying CD-ROM.

Comparisons of Airborne and Ground-Based Measurements

In addition to the general comparisons of airborne and ground-based results mentioned earlier, we used the GIS to identify all airborne measurements acquired within 250 m of each ground-based TDEM sounding. Although all ground locations were analyzed, the findings are adequately summarized by examining transients from the four representative locations (relatively conductive and resistive end-members in the Faysville and Stockholm areas) already considered.

Transients from the Faysville and Stockholm airborne systems cannot be directly compared with each other because they each have slightly different acquisition parameters (table 4). For example, the larger transmitter area and higher loop current used in the Faysville area translated to a nearly 40 percent larger dipole moment than that used to induce transients in the Stockholm area. Receiver geometry was also slightly different; the Faysville receiver was towed 70 m above the ground, whereas the Stockholm receiver was 50 m above the ground. Additionally, amplification probably differed between the two surveys. Raw transients from the airborne surveys will also differ from those collected on the ground for the same reasons mentioned earlier and because the

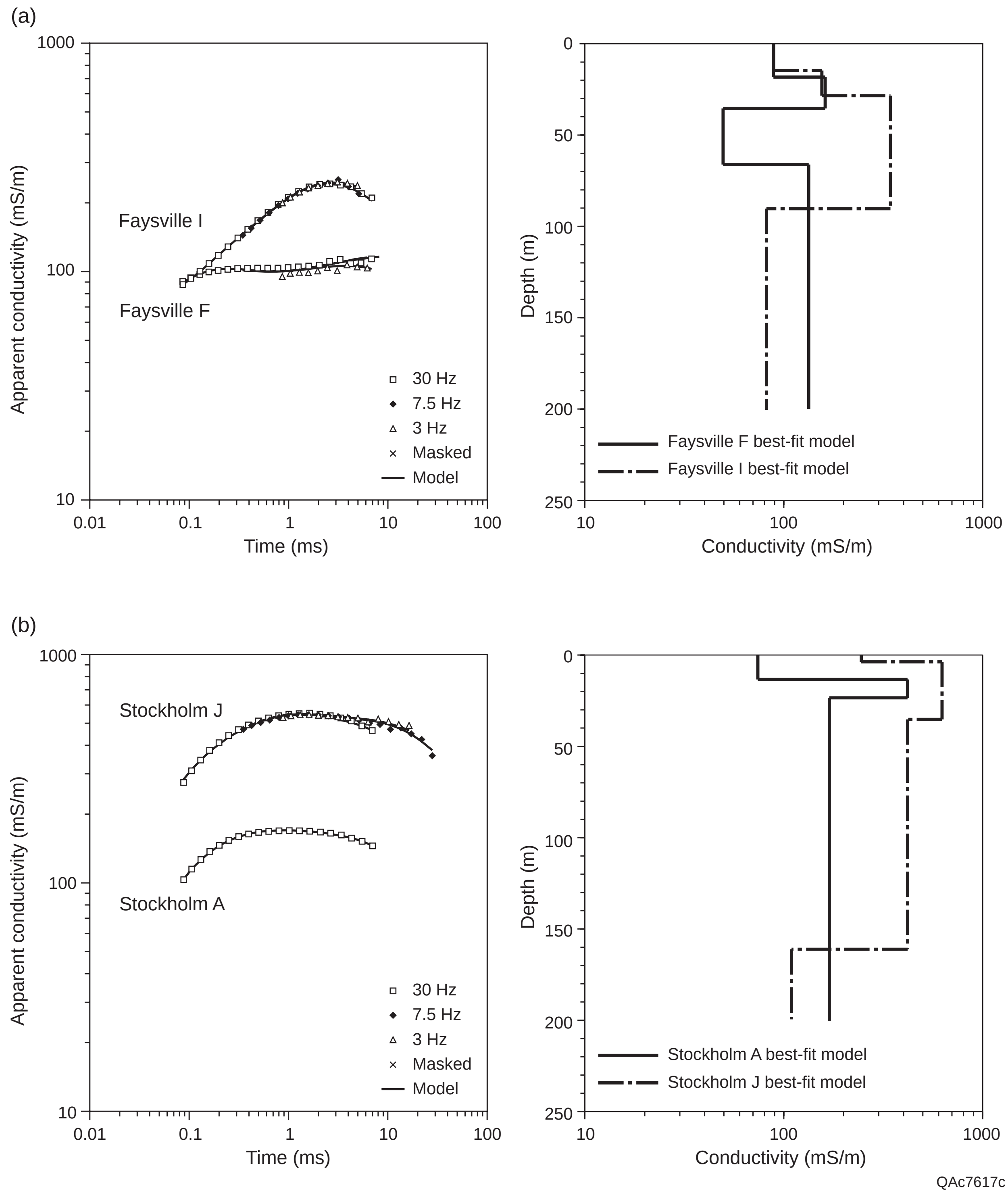

Figure 26. Comparison of (left) apparent conductivity and (right) conductivity models from relatively resistive sites (soundings F and A) and relatively conductive sites (soundings I and J) in the (a) Faysville and (b) Stockholm areas.

ground measurements were acquired with the receiver coil in the center of the transmitter loop rather than outside the transmitter loop as in the airborne surveys. Further, the ground system probably did not achieve the exploration depths that the airborne systems did because the ground-based transmitter currents, and, thus, the input signal, were much smaller. Nevertheless, the basic similarities of the airborne and ground systems in frequency and sampling times allow conductivity models calculated from transients acquired by each system to be compared throughout much of the exploration depth range.

Transient signals acquired during the Faysville and Stockholm airborne surveys (fig. 27) were measured over a time range of about 0.2 to more than 10 ms after current shutoff, similar to the time range used by the ground-based systems. Transient signals are larger for the Faysville

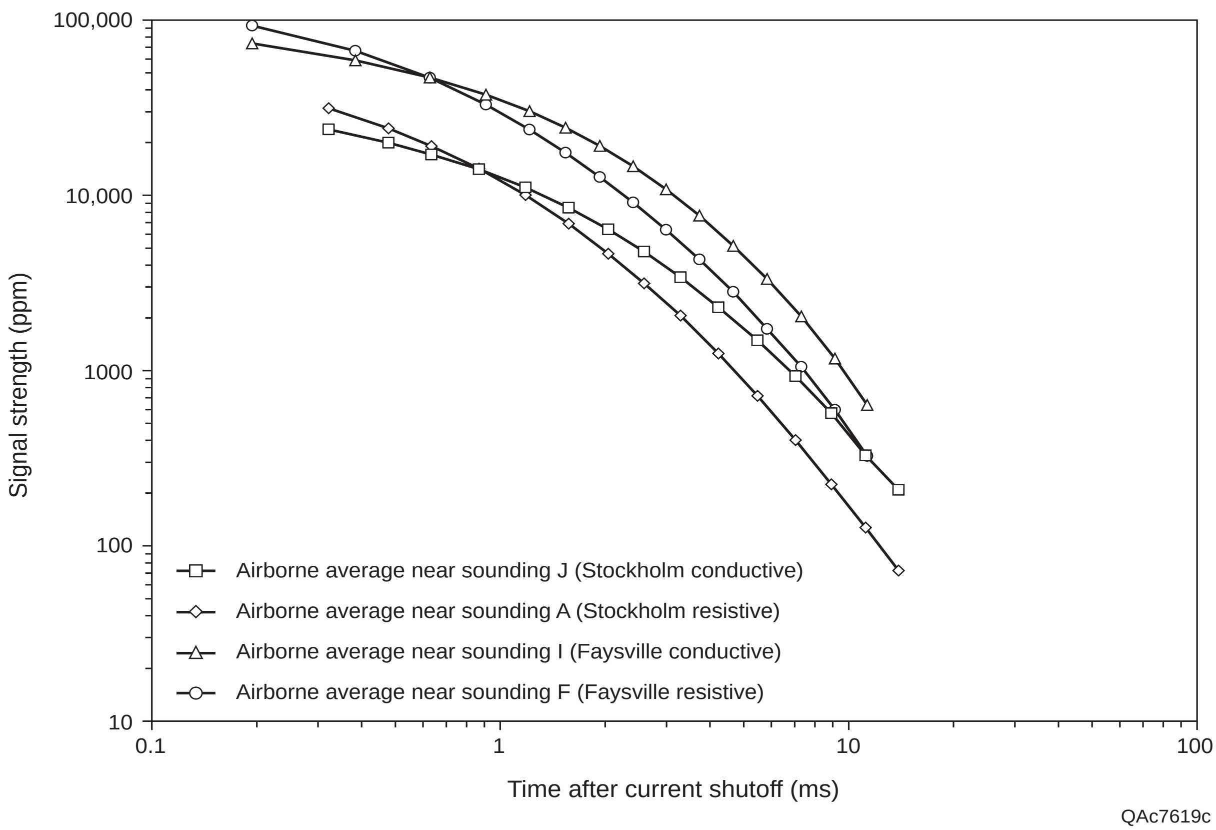

Figure 27. Average transients recorded using airborne TDEM instruments that are within 250 m of relatively resistive (sounding F) and conductive (sounding I) sites within the Faysville area and relatively resistive (sounding A) and conductive (sounding J) sites within the Stockholm area.

airborne survey than they are for the Stockholm survey, probably because of the larger input signal and possibly because of greater amplification. Transients acquired with the airborne systems decay very rapidly as did those at the same locations measured by the ground systems (figs. 23, 27) but show a linear trend on plots of logarithmic time and signal strength only at times later than 1 or 2 ms (fig. 27). The slower signal decay measured at early times by the airborne systems might be related to the acquisition geometry and the possible detection of the primary field as it passes the receiver.

As was true for the ground-based measurements, stronger transients were recorded at relatively conductive Faysville and Stockholm sites than in relatively resistive areas. The average of eight transients within 250 m of sounding J in the Stockholm area is higher at most time windows than the average of seven transients within 250 m of Stockholm sounding A (fig. 27), which falls in a more resistive part of the survey area. Similarly, the average of 55 transients within 250 m of sounding I in the Faysville area is higher at most time windows than the average of 37 transients from the more resistive area within 250 m of Faysville sounding F.

Models constructed to fit transients from Faysville airborne and ground-based systems are difficult to compare directly. Models constructed from Faysville airborne survey data consist of conductivity values at 10-m-depth intervals, whereas the models constructed from ground-survey data consist of three or four layers of varying thickness and conductivity (fig. 28). Models from the airborne survey are displayed as minimum, average, and maximum conductivities calculated for each depth for all models that fall within 250 m of a ground-based sounding. There is relatively good agreement between airborne and ground-based models at Faysville soundings F, G, L, and N and fair to poor agreement at soundings H, I, and M. In general, the conductivities modeled from the ground-based surveys are in the same range as those modeled from the airborne surveys, but are likely to differ at specific depths.

Conductivity models derived from Stockholm airborne and ground-based surveys are easier to compare because each produced similar types of models (three or four layers of varying thickness and conductivity). For the Stockholm data, all models from the airborne survey that fall

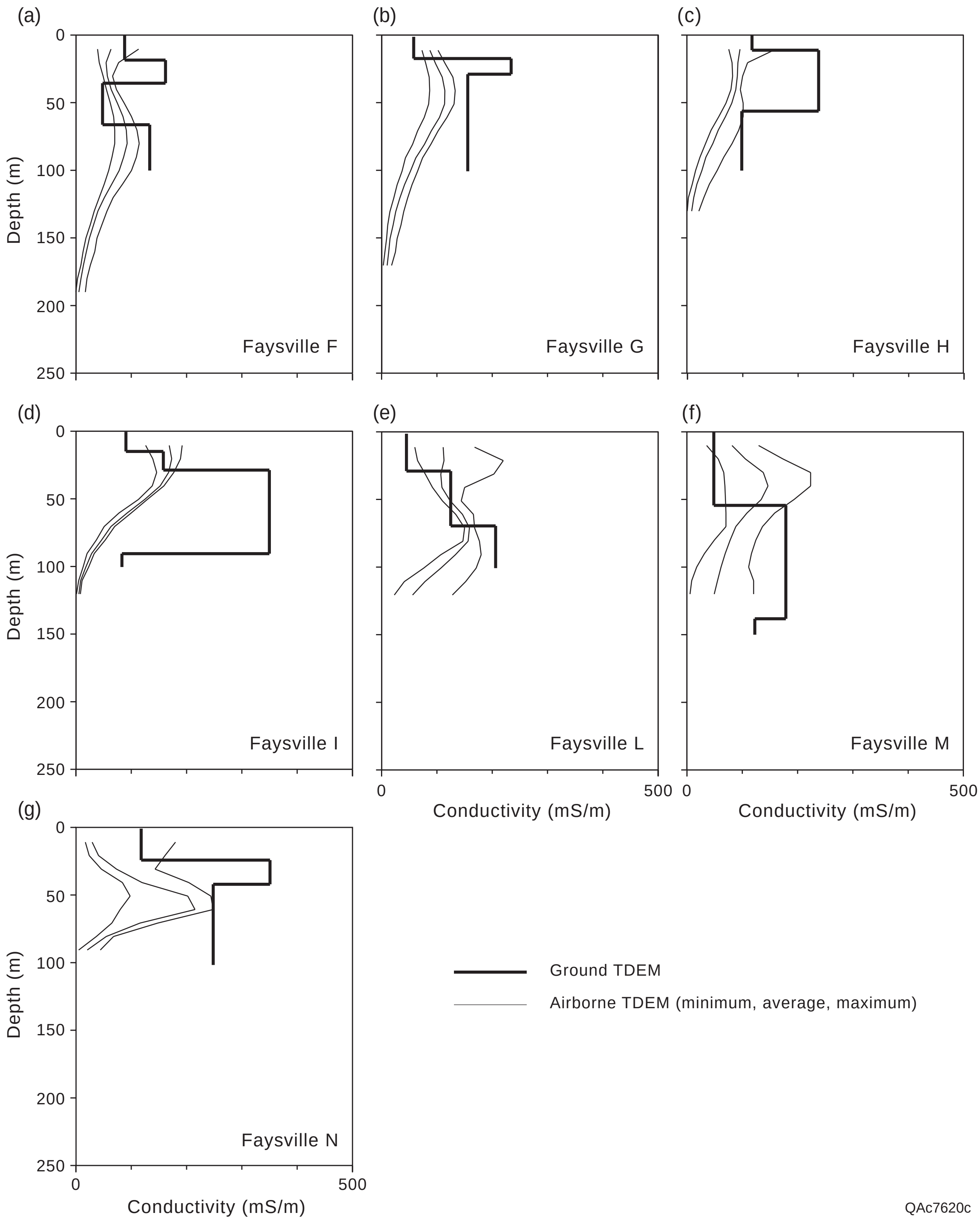

Figure 28. Comparison of conductivity models determined from ground and airborne TDEM instruments at Faysville sounding sites (a) F, (b) G, (c) H, (d) I, (e) L, (f) M, and (g) N. Minimum, average, and maximum conductivities for each depth are calculated from all airborne measurements that were acquired within 250 m of the ground TDEM sounding. Locations on figure 12.

within 250 m of a ground survey are shown (fig. 29). Similar conductivity trends are observed in models derived from airborne and ground surveys at all seven sites; models at each site indicate a thin, resistive surface layer underlain by a conductive layer, which is in turn underlain by a resistive layer. At several sites (E, J, and K), ground-based data suggest a lower conductivity at most depths than was determined from the airborne survey of the same area.

Differences in the models derived from airborne and ground-based data for each site may arise from airborne-survey noise, differing algorithms for producing conductivity models, and actual changes in ground conductivity between airborne and ground-based measuring sites. Whereas perfect agreement between conductivity models derived from both types of surveys would be desirable, lack of this level of agreement implies that relative trends observed in the airborne surveys are more reliable than absolute conductivity values derived from the data.

GROUND-WATER EXPLORATION TARGETS

Local and regional patterns evident on each of the conductivity images reflect the combined influence of hydrology (moisture content and water chemistry), geology (sediment type, porosity, and permeability), and culture (structures, agricultural practices, and power lines). For airborne EM to be useful in the search for good-quality water, we must be able to distinguish among these influences. Using aerial photographs and map data imported into the GIS data base, we can readily identify cultural artifacts in the EM data by superimposing data layers. We can also examine videotape images of the ground acquired during the overflights for evidence of cultural influence.

Hydrological and geological influences remain to be differentiated once cultural effects are identified. In the Lower Rio Grande Valley, where near-surface geologic units have been deposited in laterally extensive fluvial, deltaic, and marine sequences (Brewton and others, 1976; Brown and others, 1980; Galloway, 1982), areal patterns in the EM data give clues regarding the nature of the host geologic units if the EM signal is not overwhelmed by the influence of water-quality variations. The conductivity values themselves are an indicator of water quality.

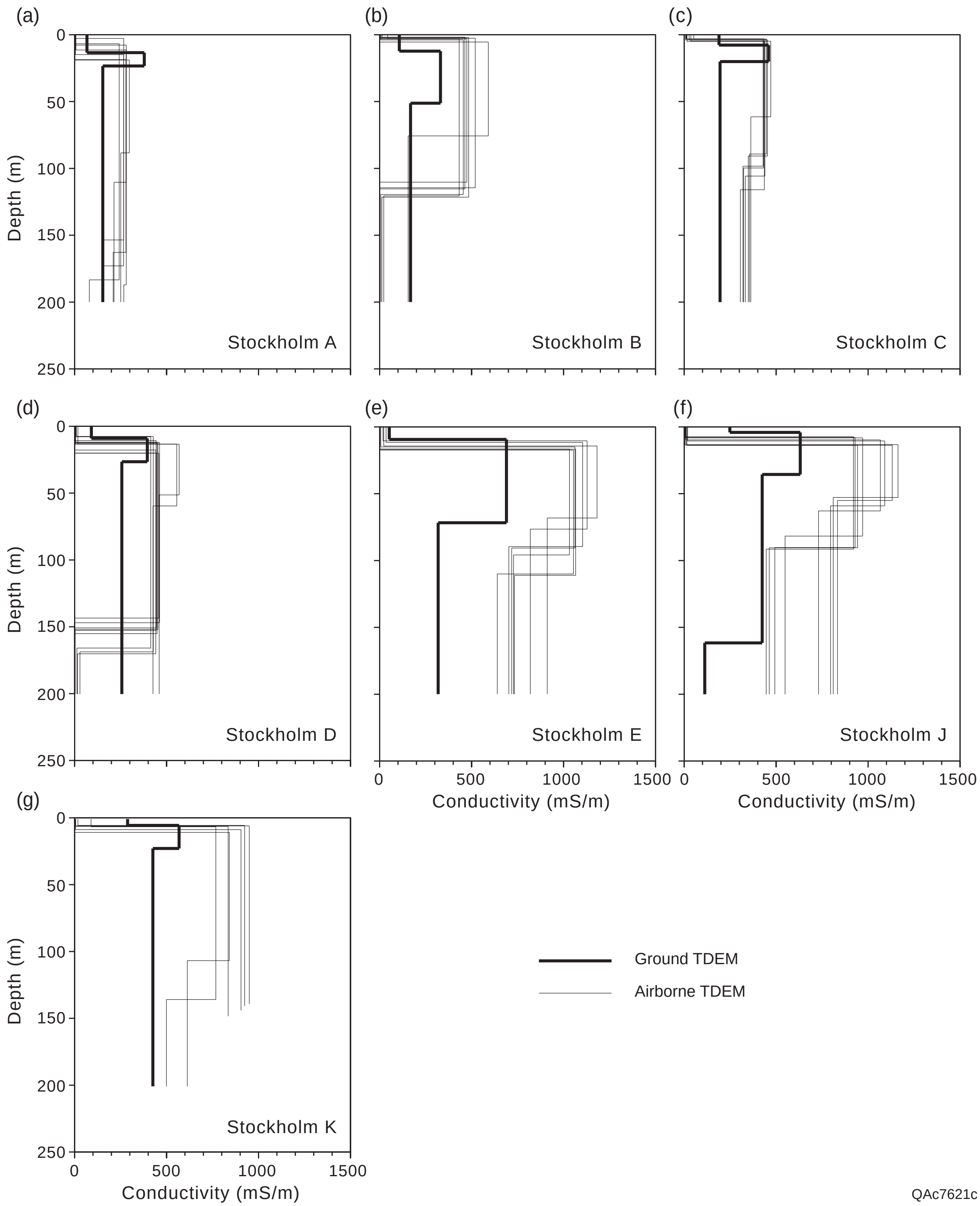

Figure 29. Comparison of conductivity models determined from ground and airborne TDEM instruments at Stockholm sounding sites (a) A, (b) B, (c) C, (d) D, (e) E, (f) J, and (g) K. All models determined from the airborne surveys are shown that were acquired within 250 m of the ground TDEM sounding. Locations on figure 10.

Geophysical Signatures

It is evident from the comparisons of sediment texture and TDS concentration with conductivity determined from data collected using airborne instruments that ground-water quality is the dominant influence on measured conductivity in the Stockholm and, to a lesser extent, the Faysville areas. From determinations of average conductivity at various depths made from airborne and ground-based geophysical data alone (figs. 16, 28, 29), we can infer that (a) ground-water quality should be generally better in the Faysville area than in the Stockholm area and (b) ground-water quality should generally improve with depth within the upper 100 to 200 m in both areas. Analyses of water from wells in these areas confirm that TDS concentrations are generally lower for Faysville wells than Stockholm wells and that Stockholm-area wells do show a trend of decreasing TDS concentrations with depth (fig. 7). Most water wells in the Faysville area are less than 50 m deep, making it difficult to determine whether water quality improves with depth in that area. Geophysical logs of deeper wells suggest that water quality deteriorates at depths greater than those investigated here.

Generalizations such as these made from the airborne geophysical data alone are themselves important conclusions, particularly in regional water-resource investigations in undeveloped areas where water depth and quality may be unknown. Beyond these general statements, we can use the shape of local geophysical anomalies at various depths, their electrical conductivities, and their conductivity relative to surrounding materials to interpret whether the anomaly is likely to represent a favorable ground-water resource for the Lower Rio Grande Valley.

We have identified four geophysical anomaly types that might be encountered in a coastal-plain setting such as the Lower Rio Grande Valley (table 7), each with unique hydrological and geological implications for water quality or quantity. Depth slices through the conductivity volume that depict sinuous features that are less conductive than their surroundings are interpreted to be the best targets for ground-water exploration. The low conductivity of these anomalies implies that the strata at that level are coarse grained and saturated with relatively fresh water. The

Table 7. Plan-view airborne geophysical signatures and interpreted geologic environment, water quality, target quality in fluvial-deltaic settings such as the Lower Rio Grande Valley.

Anomaly	Geologic environment	Water quality	Target quality
Low conductivity, sinuous	Coarse channel deposits (sand or gravel)	Fresh	Good (abundant good water)
Low conductivity, nonsinuous	Several possibilities	Fresh	Fair (good water, unknown quantity)
High conductivity, sinuous	Coarse channel deposits (sand or gravel)	Saline	Poor (abundant, poor water)
High conductivity, sinuous	Fine channel-fill deposits (silt or clay)	Fresh or saline	Poor (limited water, unknown salinity)

sinuous shape in plan view suggests deposition of the sediments in a channel or channel-complex setting. Because clay is more conductive than sand or gravel, the low conductivity of the anomaly relative to its surroundings suggests that the channel or channel complex contains less clay than surrounding sediments, assuming the pore space is filled with water of similar salinity.

Low-conductivity anomalies having a nonsinuous shape represent fair ground-water resource targets simply because the low conductivity suggests that the water salinity is low. Without a distinctive shape, it is difficult to infer a depositional environment or determine whether the anomaly includes fine- or coarse-grained strata that would influence its productivity. The most promising of the nonsinuous anomalies would be linear or arcuate features that roughly parallel the modern coastline, suggesting coarse-grained strandline or barrier-island environments.

Sinuous features having high conductivities make poor ground-water targets for two possible reasons. The high conductivities could be caused by increases in clay content associated with abandoned-channel fill, in which case the anomaly would make a poor target regardless of water quality because it would produce little water. In the case of coarse-grained fill associated with the sinuous feature, the increase in conductivity over surrounding finer grained sediments is most likely caused by the presence of highly saline water.

Target Identification

We identified potential water-resource targets within the survey areas by interpreting the airborne geophysical data using the geological and hydrological concepts described earlier. These targets generally are irregularly shaped regions of low conductivity that persist across multiple adjacent horizontal slices through the conductivity volume. They were identified by visual examination of conductivity slices, selection of significant low-conductivity zones, and adjustment of zone boundaries across multiple depth slices to maximize the target depth range. Using GIS and image-processing software, we calculated depth range, area, and conductivity range for each potential target. We used the empirical relationship between conductivity as determined from the airborne EM data and TDS as reported for existing wells (fig. 19) to predict likely water quality for each target.

Faysville Targets

There are at least nine sites within the Faysville survey area where conductivity data suggest potential water resources shallower than 200 m depth (fig. 30). These sites range in size from 0.7 to 31.6 km^2, covering a total area of about 69 km^2 out of the 260 km^2 surveyed (table 8). Each site represents an area of low conductivity that persists across several adjacent depth slices through the conductivity volume.

Favorable water-resource targets in the shallow part (10 to 60 m) of the Faysville conductivity volume are represented by sites 1, 2, 4, 6, and 7 (fig. 30). Site 1, located in the northeast part of the Faysville survey, covers the smallest area (0.7 km^2). This site is mapped on conductivity slices 10 to 50 m deep at typical conductivities between 35 and 80 mS/m (fig. 31; table 8). These conductivities project to TDS values of less than 950 mg/L (fig. 19), suggesting fresh

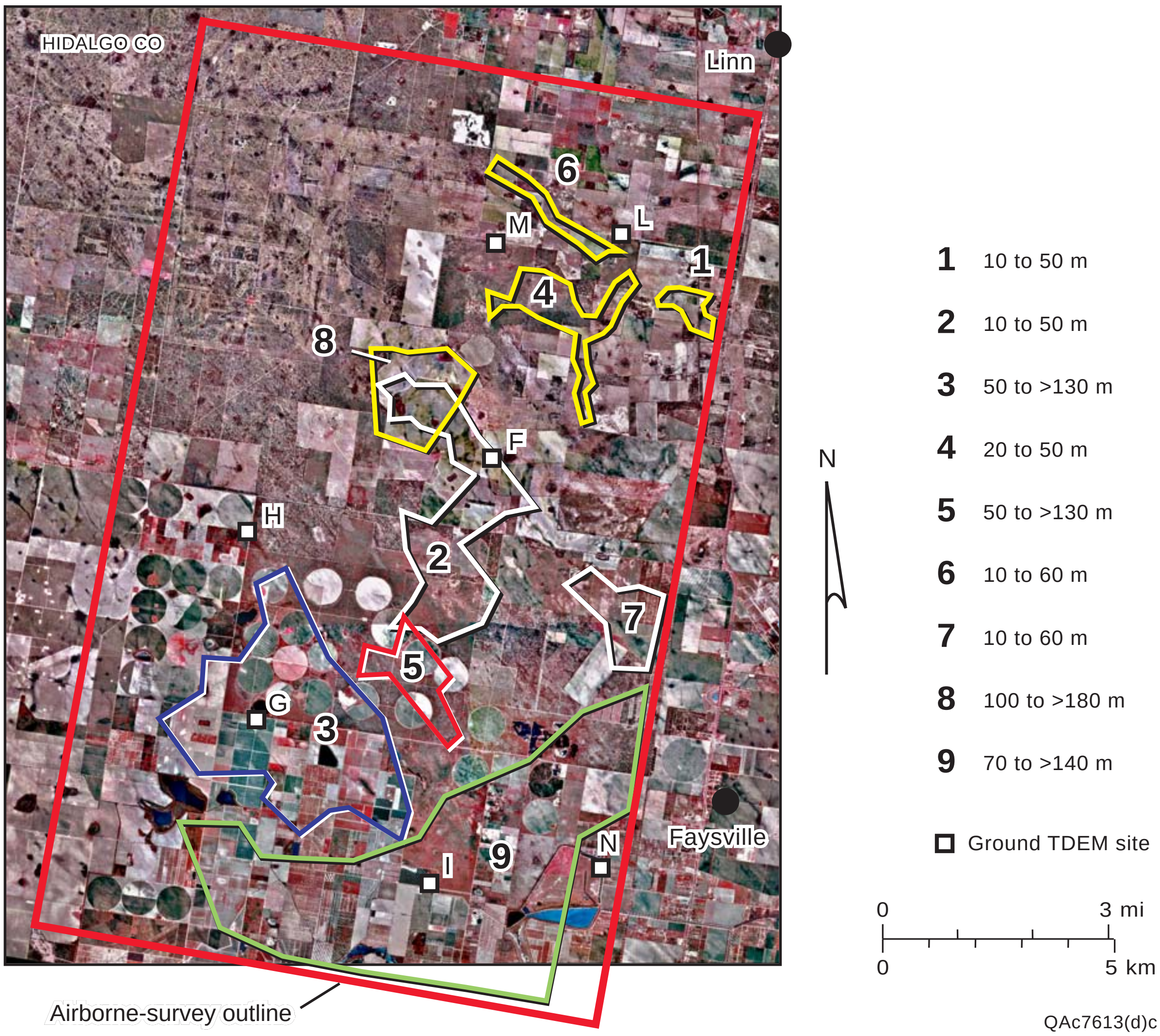

Figure 30. Favorable drilling areas and expected depth ranges to relatively low TDS water in the Faysville area chosen on the basis of conductivity measurements.

Table 8. Summary of potential ground-water targets in the Faysville and Stockholm areas (figs. 30 and 33). Water-quality and TDS estimates based on the empirical conductivity–TDS trend (fig. 19).

Faysville area

Target	Depth range (m)	Area (km^2)	Conductivity (mS/m)	Water-quality estimate	TDS estimate (mg/L)
1	10 to 50	0.7	35 to 80	Fresh	< 950
2	10 to 50	8.0	40 to 100	Fresh to sl. saline	<1,250
3	50 to >130	16.0	10 to 80	Fresh	<950
4	20 to 50	2.8	20 to 60	Fresh	<700
5	50 to >130	2.3	15 to 40	Fresh	<400
6	10 to 60	1.1	30 to 90	Fresh to sl. saline	<1,050
7	10 to 60	2.5	30 to 95	Fresh to sl. saline	<1,150
8	100 to >180	3.7	15 to 50	Fresh	<550
9	70 to >140	31.6	20 to 70	Fresh	<850

Stockholm area

Target	Depth range (m)	Area (km^2)	Conductivity (mS/m)	Water-quality estimate	TDS estimate (mg/L)
1	20 to 80	15.4	250 to 500	Sl. to mod. saline	3,200 to 6,650
2	120 to 200	22.6	20 to 200	Fresh to sl. saline	<2,600
3	100 to 200	3.2	20 to 150	Fresh to sl. saline	<1,900
4	30 to 70	4.1	350 to 550	Mod. saline	4,600 to 7,300
5	20 to 80	27.9	200 to 400	Sl. to mod. saline	2,550 to 5,300

water. Site 2 is the largest of the shallow targets, covering about 8 km^2 in the central part of the area (figs. 30, 31). It has slightly higher conductivities (40 to 100 mS/m) that translate to fresh to slightly saline water at TDS values below 1,250 mg/L (table 8). Site 4, located in the northeast part of the Faysville survey, is visible at depths of 20 to 50 m. Its low conductivities of 20 to 60 mS/m suggest fresh-water TDS values. Proximity to a major power-line intersection may influence the EM data acquired over part of this site, reducing the accuracy of the calculated conductivities and interpreted salinities.

Shallow sites 6 and 7 share identical depth ranges (10 to 60 m) and similar conductivity ranges (30 to 90 or 95 mS/m, table 8). Site 6, a narrow, sinuous feature that is about 300 m wide and 3 km long (figs. 30, 31), falls within the south part of the shallow, prolific Linn-Faysville

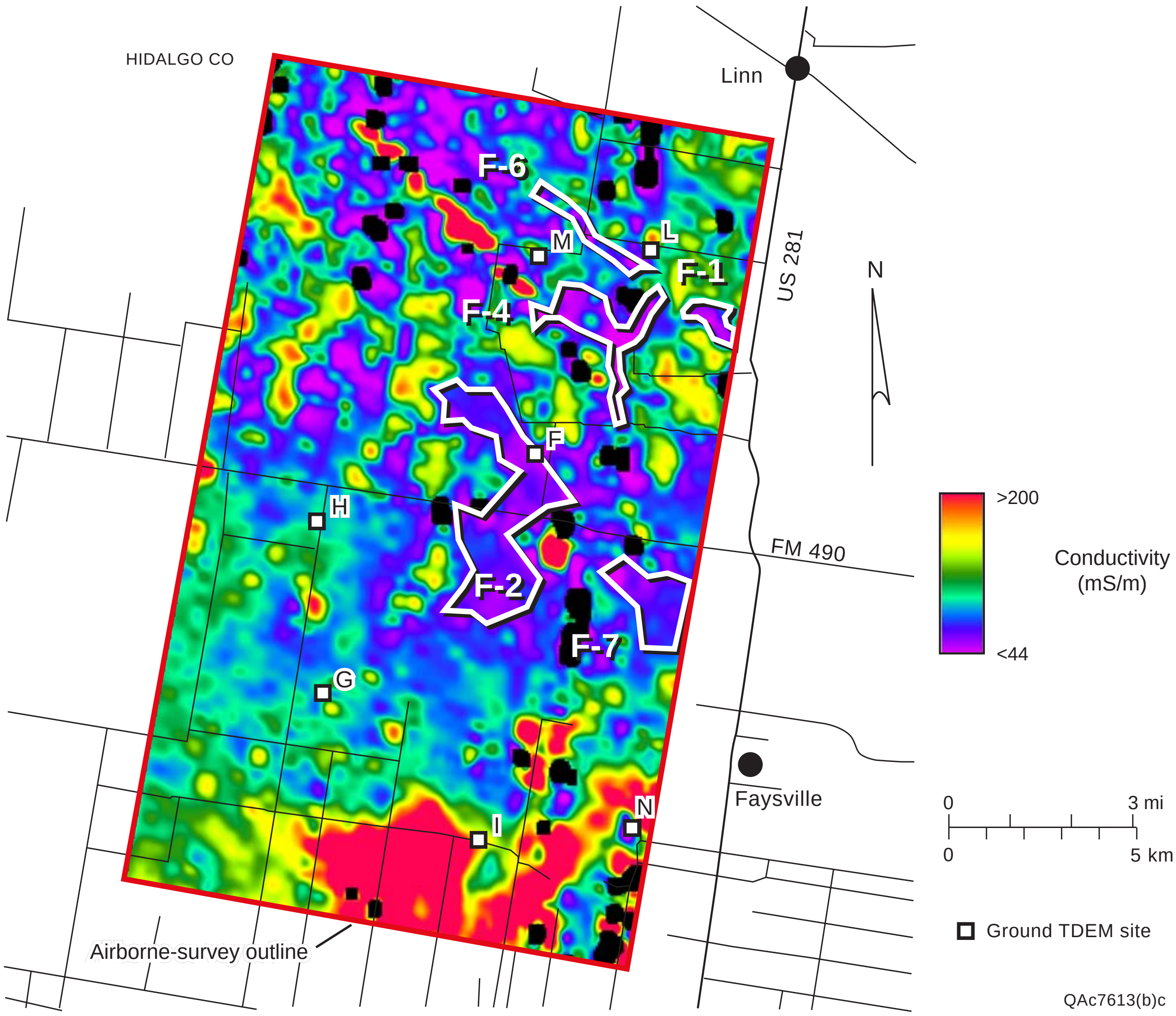

Figure 31. Apparent conductivity and drill sites 30 m below the surface in the Faysville area.

ground-water district (George, 1947; Follett and others, 1949). We interpret fresh to slightly saline water at this site and at site 7, which is located on the eastern survey boundary near Faysville. The sinuous plan-view shapes and low conductivities of each shallow site suggest relatively coarse grained channel or channel-complex deposits that are saturated by relatively fresh water.

We have identified four favorable sites that are deeper than 50 m (fig. 30; table 8). Site 3, the second largest, covers 16 km^2 in the southwest part of the survey. It consists of multiple sinuous features at depths of 50 to more than 130 m having typical conductivities less than 80 mS/m (fig. 32). We predict water within site 3 to be fresh; TDS concentration should be less than 950 mg/L at the most favorable locations within this large site. There are three major sinuous features that merge southeastward in this roughly triangular area. These features might represent merging tributary channels composed of relatively coarse deposits.

Site 5 is a small site (2.3 km^2) visible on slices between 50 and at least 130 m deep in the south-central part of the survey area (fig. 32). Calculated conductivities are 40 mS/m or less, suggesting fresh water. This site is elongate northwest-southeast, similar to the trend of site 3. Visible in the same depth range as site 3, it also appears to represent the junction of two tributary channels. Site 9, the largest site in the Faysville or Stockholm survey areas, covers more than 31 km^2 on slices between 70 and 140 m deep. It includes most of the southeast corner of the Faysville survey, representing several smaller sites within a larger area of relatively low conductivity (fig. 32). Typical conductivities range from 20 to 70 mS/m, translating to several favorable fresh-water targets likely to be hosted by coarse-grained channel deposits.

Site 8, a moderate-sized target visible at depths of 100 to more than 180 m (fig. 30), has calculated conductivities between 15 and 50 mS/m. These conductivity values suggest fresh water within this centrally located target. This site partly coincides with the north part of site 2, a shallow Faysville target, marking the only location where shallow and deep targets have both been identified. Wells drilled at appropriate locations within these sites would be expected to encounter separate zones of relatively fresh water within the upper 200 m. Field investigations of this site

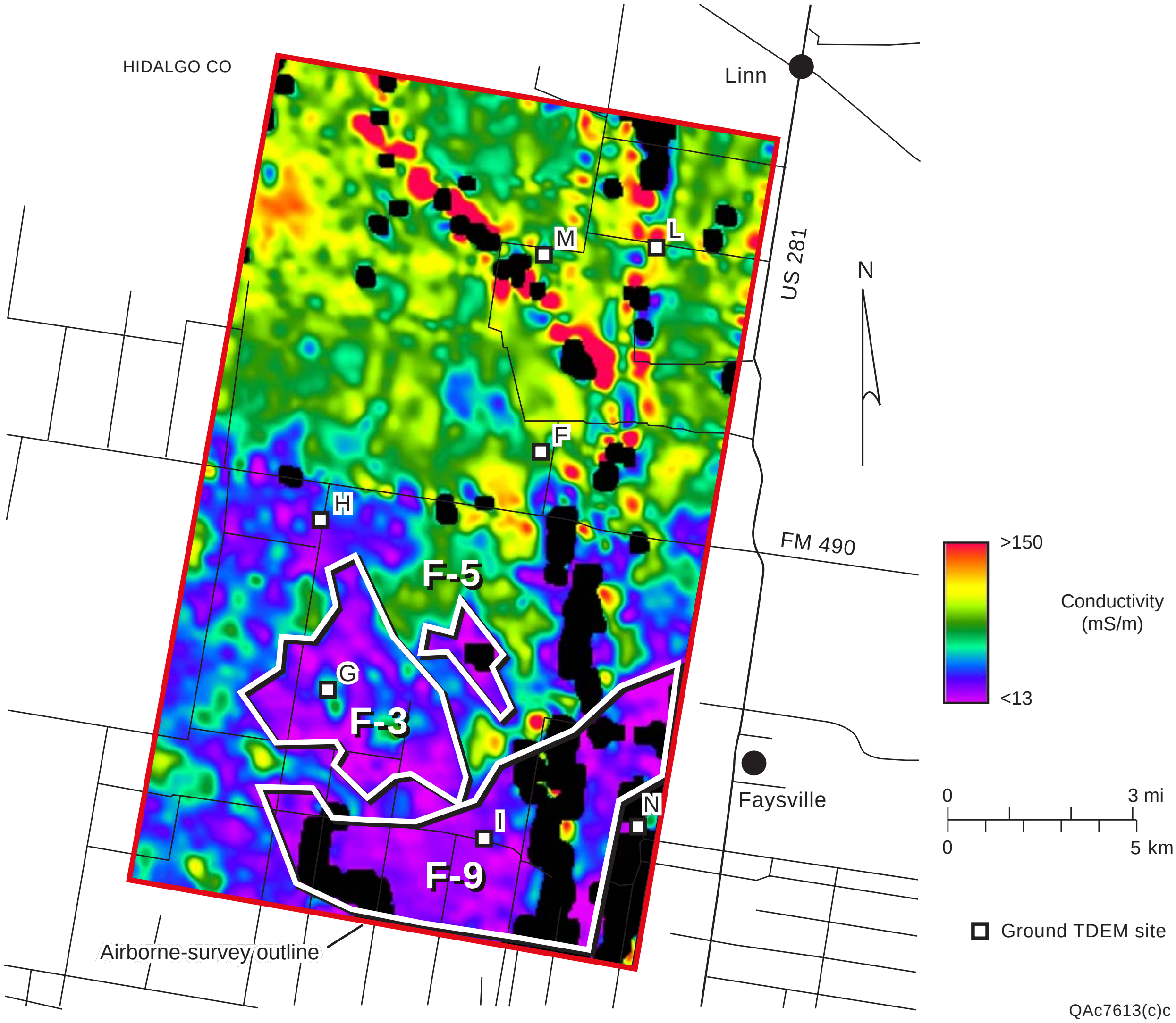

Figure 32. Apparent conductivity and drill sites 90 m below the surface in the Faysville area.

reveal the presence of a large active caliche quarry that might make the southeast part of the site appear less conductive than it actually is.

Stockholm Targets

Despite the generally finer grained deposits and higher conductivities and TDS values in the Stockholm survey area, there are at least five favorable sites where relatively fresh water might be found. All are located in the central or south part of the Stockholm survey area (fig. 33), away from the relatively high conductivities common in the northern third of the area.

Three favorable targets, sites 1, 4, and 5, were identified within the shallow part (20 to 80 m) of the conductivity volume (figs. 33, 34). Site 1, located on the western edge of the survey, covers more than 15 km^2 on depth slices between 20 and 80 m below the surface (table 8). Conductivities within this zone are much higher than target-zone conductivities in the Faysville area, ranging between 250 and 500 mS/m. These conductivities translate to higher TDS estimates that are based on the empirical conductivity–TDS trend determined using Faysville and Stockholm geophysical and water-quality data (fig. 19). On the basis of this trend, we estimate that water within this target will be slightly to moderately saline (table 8). The location of this zone of relatively low conductivity in the shallow subsurface adjacent to Delta Lake suggests that the feature might be a plume of water that has infiltrated from the lake. This potential infiltration zone extends to a depth of about 80 m and to a distance of 3 to 4 km east of the lake. Similar infiltration extending a few hundred meters from ponded water was documented in Kenedy, Kleberg, and Willacy Counties following Hurricane Beulah flooding (Baker, 1971). There are several narrow, low-conductivity, and sinuous features within site 1 that may represent relatively coarse grained channels surrounded by finer grained deposits with slightly higher conductivities.

Site 4 is a relatively small zone of low conductivity southwest of Lyford (fig. 34). It is the smallest of the shallow targets, mappable on slices between 30 and 70 m deep and covering only about 4 km^2. It has an arcuate outline that is about 1 km wide and more than 3 km long. It trends

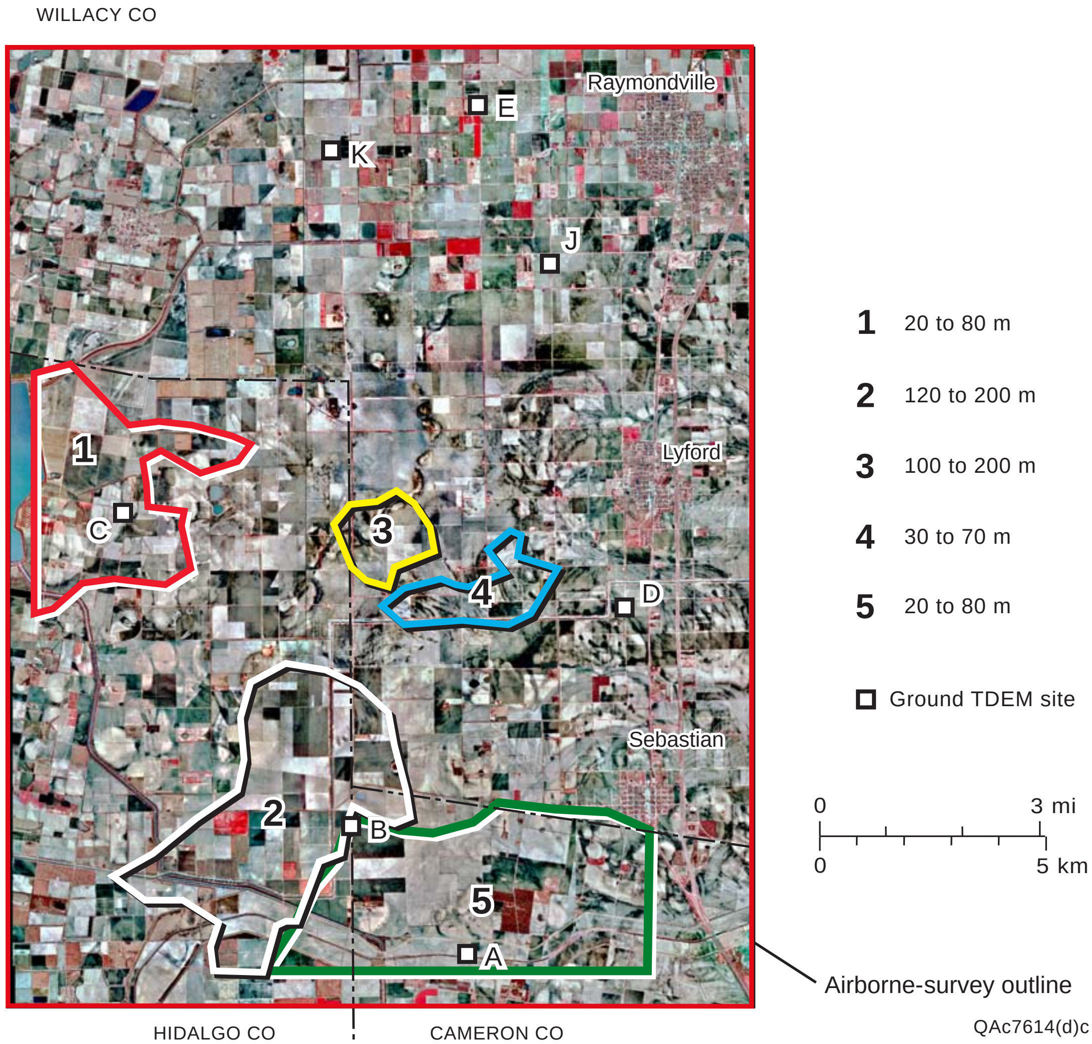

Figure 33. Favorable drilling areas and expected depth ranges to relatively low TDS water in the Stockholm area chosen on the basis of conductivity measurements.

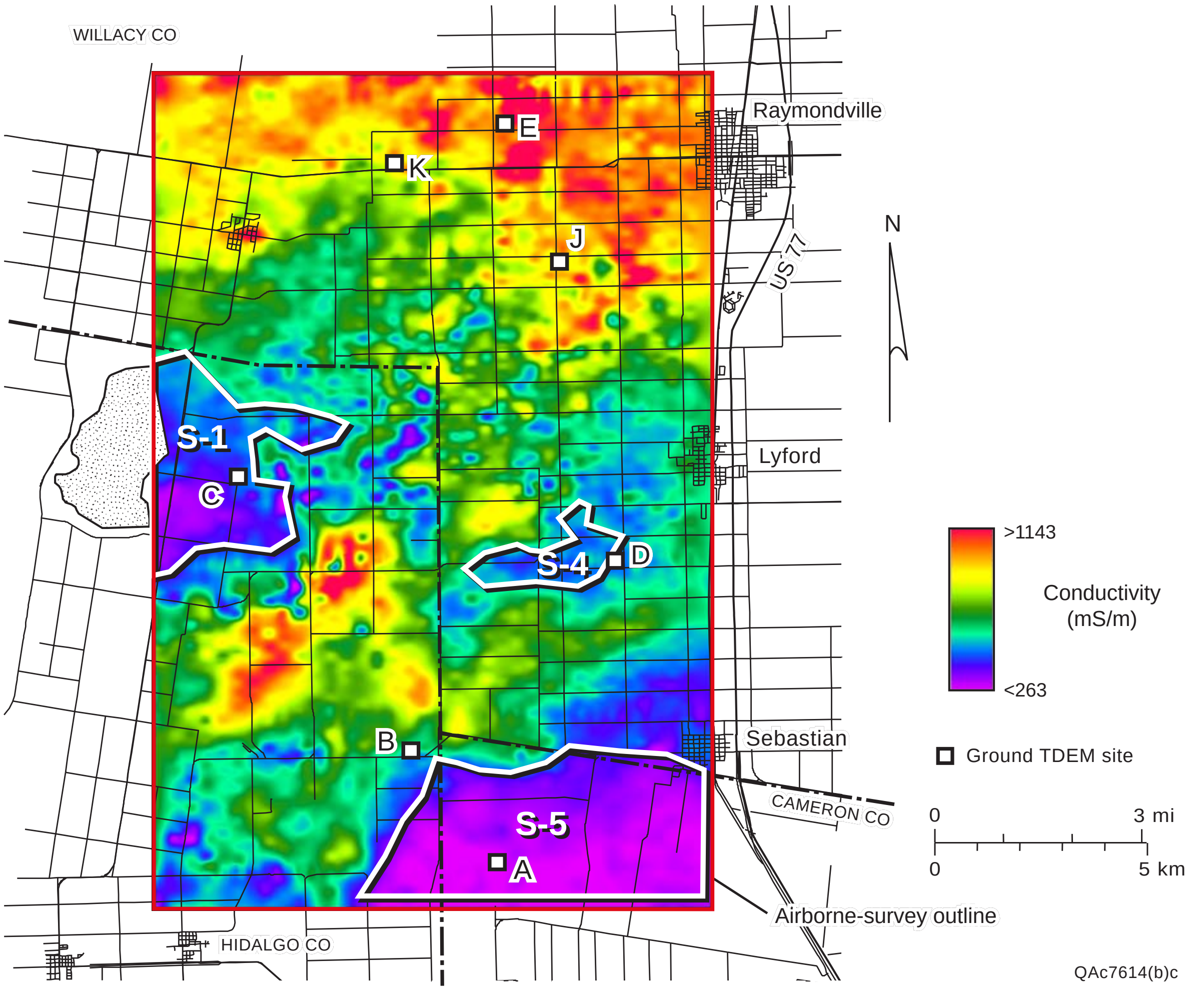

Figure 34. Apparent conductivity and drill sites 60 m below the surface in the Stockholm area.

perpendicular to the coast, suggesting a coarse-grained channel or channel-complex environment. Typical conductivities of 350 to 550 mS/m imply moderately saline water.

Site 5, located in the southeast part of the survey area, is the largest of the Stockholm targets (figs. 33, 34). It has the lowest calculated conductivities among the shallow Stockholm targets, typically ranging from 200 to 400 mS/m. This conductivity range implies that slightly to moderately saline water should be encountered 20 to 80 m below the surface. Its arcuate northwestern boundary and large lateral extent, combined with surface evidence of a major change in depositional character within the Beaumont Formation at the boundary, suggest that the boundary marks past incision into older deposits north of the boundary and more recent deposition south of the boundary. Lower conductivities within site 5 imply coarser grained sediments in the younger strata.

Due to the general trend of decreasing conductivity with depth, deep targets 2 and 3 have the lowest conductivities among all the Stockholm targets (table 8). At site 2, located in the southwest part of the survey at depths of 120 to 200 m (fig. 35), conductivities range from 20 to 200 mS/m. These values imply water quality ranging from fresh to slightly saline. Progressively deeper conductivity images depict this low-conductivity zone migrating eastward across the survey area. The eastward migration is likely to be controlled by water salinity, but subtle conductivity variations within this site reveal channel-shaped features that are either slightly more or less conductive than surrounding areas. The features with the lowest conductivities are the most likely to be coarse-grained hosts of relatively fresh water.

Site 3 is the smallest Stockholm target, encompassing slightly more than 3 km^2 on conductivity images between 100- and 200-m depth (fig. 35). Typical conductivities between 20 and 150 mS/m within this zone also suggest fresh to slightly saline water. Sinuous, low-conductivity zones are difficult to map reliably within this small site.

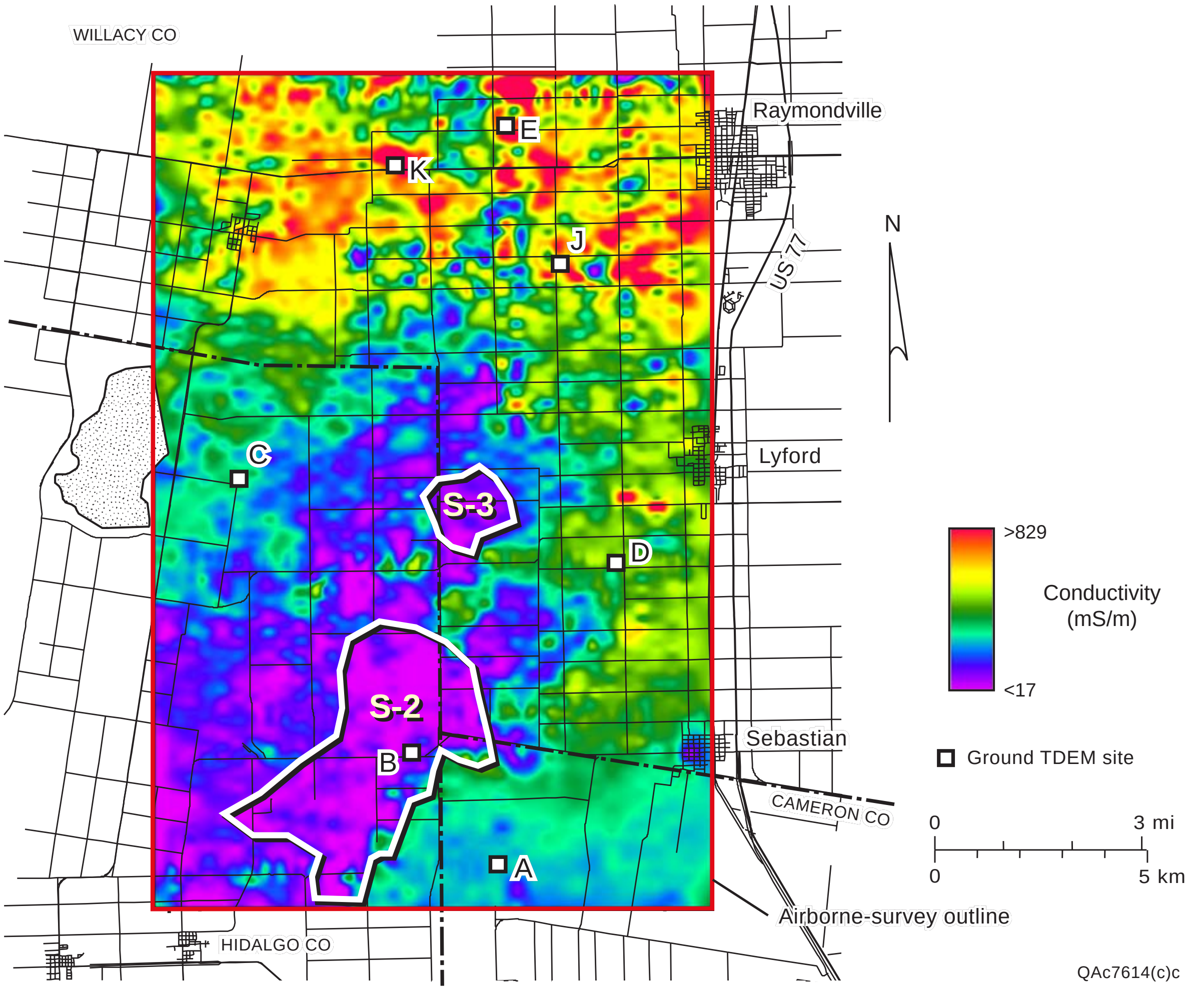

Figure 35. Apparent conductivity and drill sites 90 m below the surface in the Stockholm area.

ADVANTAGES AND DISADVANTAGES OF AIRBORNE EM

Airborne EM methods such as those employed in this study have been adapted for use in ground-water exploration from their original development as exploration tools to locate shallow, conductive ore bodies. In mineral exploration, the target is typically a discrete, highly conductive body within relatively nonconductive host rock. The targets in ground-water exploration in a coastal plain are fresh-water sands and gravels. Unlike ore bodies, these targets tend to be less conductive than surrounding materials because fresh water is less conductive than saline water and sands are less conductive than clays.

Airborne EM methods have several advantages over other methods used to locate ground-water resources. Because an aircraft is used to conduct the survey, airborne EM is a noninvasive means of rapidly surveying large areas. In this study, EM data over each 260-km^2 area were acquired in less than two days of flying. Preliminary survey results were available within a few weeks of the completion of flying, allowing rapid identification of potential ground-water resources. Airborne EM is far less expensive and yields usable results much more quickly than 2-D or 3-D seismic surveys designed for similar target depths and survey areas. Additionally, EM instruments detect a strong water-quality signal that cannot be obtained from seismic data. At best, seismic data would yield better information on host geologic units but no information on depth to water or water quality. Drilling a series of test wells over a similarly sized area, while producing information on both water quality and quantity at those locations, could never practically approach the lateral resolution obtained from airborne EM surveys. Practical limitations of time and access apply to ground-based EM surveys.

In the Faysville and Stockholm surveys, ground-water salinity is sufficiently varied and elevated for water quality to be the dominant signal measured by the airborne instruments. Despite the dominance of the water-quality signal, conductivity images at various depths suggest that textural variations influence the signal sufficiently to be detected and mapped, allowing potential targets to be identified both on the basis of water quality and quantity. In areas where there is little change in water salinity, or where TDS values are very low, the textural signal would become more significant and more evident on conductivity images. In these areas, the technique would have more applicability in the selection of highly productive targets.

Inversion of the EM data into conductivity–depth models, while lacking the vertical resolution of borehole logs, allows depths to good-quality water to be estimated. By combining target-zone thickness estimates and areal extents as mapped on adjacent conductivity slices, target volumes can be estimated. The good lateral resolution of the airborne EM data appears to support detecting and monitoring infiltration and recharge patterns, such as the infiltration plume evident adjacent to Delta Lake in the Stockholm area.

Disadvantages of airborne EM in ground-water resource investigations include practical, technical, and cost limitations. Although airborne EM is less expensive than an equivalent seismic survey, drilling program, or ground-based EM survey would be, airborne surveys are costly. They greatly benefit from, and perhaps require, preflight investigations and postflight analysis that add to the cost of the airborne survey itself. Beneficial preflight activities include acquisition of existing data on well depths and water quality, determination of approximate near-surface conductivities in the survey areas, identification of potential flight hazards and sources of EM noise, and adjustment of survey boundaries to best fit local conditions. Postflight analysis should include georeferencing of EM data, acquisition of representative ground EM measurements to verify airborne survey data, construction of conductivity volumes, removal of cultural noise, creation of conductivity images at depths of interest, comparison of conductivity data to existing data on water quality and sediment texture, and identification of favorable targets. Without these preflight and postflight activities, the EM data would lack context necessary to predict ground-water occurrence reliably.

Technical limitations include poor vertical resolution relative to borehole logs and nonuniqueness of the conductivity models. Although the models chosen represent a good statistical fit to the observed transient, similar models exist that produce equivalent fits to the observed data. In other words, an equivalent electrical response is obtained for a given layer from layers that are either a little thicker and less conductive or a little thinner and more conductive than the one used in the model. Further, models fitting data from airborne and ground-based instruments are similar but do not necessarily match. Depth and water-quality estimates made from models depend on the conductivity and depth values, which may differ from the actual values and cause erroneous water-quality estimates.

In practice, exploration depths are limited to the upper few hundred meters under typical coastal-plain conditions. Data quality and exploration depth are adversely affected by buildings, power lines, radio towers, oil and gas facilities, and other types of infrastructure, making the method poorly suited for use in heavily developed areas.

VERIFICATION AND FUTURE WORK

Ground truth for the Faysville and Stockholm airborne EM surveys consists of ground-based TDEM measurements, driller’s logs, and water analyses from wells within the footprint of the two surveys. Available data suggest that there is a relationship between conductivity as determined from the airborne data and TDS concentration in water samples from equivalent depths (fig. 19) that can be exploited to predict the location, depth, and approximate water quality of potential ground-water resources. Available data are sparse: where we have many water analyses, such as the Faysville survey area, they are from shallow wells that are concentrated in a small part of the survey area. We have fewer water analyses from the Stockholm area, where water quality is generally poorer than in the Faysville area. Comparisons of textural data and conductivity values rely on a few available driller’s logs, which are commonly unreliable representations of subsurface strata.

The next step in verifying the results of this study is to obtain water-quality data and detailed textural and geophysical logs from either new wells or unidentified existing wells within the Faysville and Stockholm target areas. These new textural and water-quality data should be compared with water-resource target predictions made from the airborne geophysical data.

Although the airborne surveys have already provided useful data on general water-quality trends, data obtained from new or appropriately located existing wells will determine how far the method can be extended in identifying specific water-resource targets and assessing their quality.

CONCLUSIONS

Results from this application of airborne TDEM methods in the Lower Rio Grande Valley, a late Cenozoic coastal-plain environment, suggest that

- airborne TDEM can be used to explore to depths of 150 to 300 m in fresh to moderately saline coastal-plain aquifers typical of the Lower Rio Grande Valley;
- ground-water quality, as measured by TDS, is the dominant signal recorded by the airborne EM instruments in the Lower Rio Grande Valley;
- at the appropriate flight-line spacing and orientation, depositional patterns and environments can be inferred from airborne EM by examining secondary effects related to changes in mineral content, porosity, and permeability that are associated with different depositional environments;
- early-time airborne TDEM data successfully distinguish geologic and soils units mapped at the surface and detect infiltration patterns near recharge areas;
- sinuous features visible on horizontal slices through the subsurface conductivity volume are good water-resource targets if the feature has low conductivity and are poor targets if the feature is highly conductive; and
- conductivity models constructed from airborne and ground TDEM measurements do not agree at every site examined, suggesting that conductivity trends within a study area are more reliable than absolute conductivity values derived from airborne measurements.

Future work to verify interpretations of the location, depth, and quality of water resources in the Faysville and Stockholm areas should include drilling of new wells within the target zones identified from the airborne geophysical survey data.

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REFERENCES

Baker, E. T., Jr., 1971, Relation of ponded floodwater from Hurricane Beulah to ground water in Kleberg, Kenedy, and Willacy Counties, Texas: Texas Water Development Board, Report 138, 30 p.

__________, 1979, Stratigraphic and hydrogeologic framework of part of the coastal plain of Texas: Texas Department of Water Resources, Report 236, 43 p.

Baker, R. C., and Dale, O. C., 1961, Ground-water resources of the Lower Rio Grande Valley area, Texas: Texas Board of Water Engineers, Bulletin 6014, v. 1, 88 p.; v. 2, 340 p.

Brewton, J. L., 1973, Areal geologic map of Pliocene/Pleistocene depositional systems of the southern Texas Coastal Zone: The University of Texas at Austin, Bureau of Economic Geology, open-file map, scale 1:125,000.

Brewton, J. L., Owen, F., Aronow, S., and Barnes, V. E., 1976, Geologic atlas of Texas, McAllen-Brownsville sheet: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Brown, L. F., Jr., Brewton, J. L., Evans, T. J., McGowen, J. H., White, W. A., Groat, C. G., and Fisher, W. L., 1980, Environmental geologic atlas of the Texas Coastal Zone, Brownsville-Harlingen area: The University of Texas at Austin, Bureau of Economic Geology, 140 p., 9 maps.

Follett, C. R., White, W. N., and Irelan, Burdge, 1949, Occurrence and development of ground water in the Linn-Faysville area, Hidalgo County, Texas: Texas Board of Water Engineers, Miscellaneous Publication M118, 51 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Frischknecht, F. C., Labson, V. F., Spies, B. R., and Anderson, W. L., 1991, Profiling using small sources, *in* Nabighian, M. N., ed., Electromagnetic methods in applied geophysics—applications, part A and part B: Tulsa, Society of Exploration Geophysicists, p. 105-270.

Galloway, W. E., 1982, Depositional architecture of Cenozoic Gulf Coastal Plain fluvial systems: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 82-5, 29 p.

Geonics Limited, 1992, Protem 47 operating manual: Mississauga, Ontario, variously paginated.

George, W. O., 1947, Ground water in the Linn district, north-central Hidalgo County, Texas: Texas Board of Water Engineers, Miscellaneous Publication M117A, 7 p.

Jacobs, J. L., 1981, Soil survey of Hidalgo County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 171 p.

Kaufman, A. A., and Keller, G. V., 1983, Frequency and transient soundings: Elsevier, Amsterdam, Methods in Geochemistry and Geophysics, No. 16, 685 p.

McCoy, T. W., 1990, Evaluation of ground-water resources in the Lower Rio Grande Valley, Texas: Texas Water Development Board, Report 316, 48 p.

McNeill, J. D., 1980, Electrical conductivity of soils and rocks: Mississauga, Ontario, Geonics Limited, Technical Note TN-5, 22 p.

Paine, J. G., Goldsmith, R. S., and Scanlon, B. R., 1998, Electrical conductivity and gamma-ray response to clay, water, and chloride content in fissured sediments, Trans-Pecos, Texas: Environmental and Engineering Geoscience, v. 4, no. 2, p. 225–239.

Parasnis, D. S., 1973, Mining geophysics: Amsterdam, Elsevier, 395 p.

Rhoades, J. D., 1981, Predicting bulk soil electrical conductivity versus saturation paste extract electrical conductivity calibrations from soil properties: Soil Science Society of America Journal, v. 45, p. 42–44.

Robinove, C. J., Langford, R. H., and Brookhart, J. W., 1958, Saline-water resources of North Dakota: U.S. Geological Survey, Water-Supply Paper 1428, 72 p.

Spies, B. R., and Frischknecht, F. C., 1991, Electromagnetic sounding: *in* Nabighian, M. N., ed., Electromagnetic methods in applied geophysics— applications, part A and part B: Tulsa, Society of Exploration Geophysicists, p. 285–386.

Texas Water Commission, 1990, The State of Texas water quality inventory, 10th ed.: Report LP 90-06, 652 p.

Texas Water Development Board, 1997, Water for Texas: a consensus-based update to the State Water Plan, volume II, technical planning appendix: Document No. GP-6-2, 348 p.

Tremblay, T.A., Wermund, E. G., Jr., and Wu, C. Y., 1996, Digital surficial deposits map of the Rio Grande Delta Plain: The University of Texas at Austin, Bureau of Economic Geology, open-file digital map.

Turner, A. L., 1982, Soil survey of Willacy County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 137 p.

West, G. F., and Macnae, J. C., 1991, Physics of the electromagnetic induction exploration method, *in* Nabighian, M. N., ed., Electromagnetic methods in applied geophysics — applications, part A and part B: Tulsa, Society of Exploration Geophysicists, p. 5–45.

Williams, Dewayne, Thompson, C. M., and Jacobs, J. L., 1977, Soil survey of Cameron County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 92 p.

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APPENDIX: DESCRIPTION OF CD-ROM CONTENTS

Project Web

The project web, located in the “web” directory of the CD-ROM, is a collection of html-compatible documents that summarize project data, concepts, and activities. It includes a project summary, maps of the Lower Rio Grande Valley, water-well data, photographs and data from the Faysville and Stockholm airborne geophysical surveys, results from the ground-based geophysical survey, a discussion of geophysical signatures and target types, electronic presentations and publications in pdf format, an annotated bibliography of selected publications, a glossary, and acknowledgments. The web can be viewed directly from the CD-ROM using a web browser or transferred from the CD-ROM for faster access. To view the web, open the file “enter_here.html” in the “web” directory with your browser.

GIS Data Set

The GIS data set, located in the “gis” directory of the CD-ROM, consists of spatial data that were used in the analysis of the Faysville and Stockholm airborne geophysical data. Included are aerial photographs, geologic maps, water wells, hydrography, major and county roads, airborne geophysical data, county boundaries, place names and locations, and favorable drilling locations. To use these files, create an ArcView project and add the shape files and raster images as needed. All files are compatible with ArcView version 3 GIS software. Files are either ArcView shapefiles or georeferenced tiff images.

Datum and Projection

All project shape files and geotiff images have been projected in meters using the Universal Transverse Mercator (UTM) projection, zone 14 north, 1983 North American Datum.

Airphotos Subdirectory

fays_airphoto.tif: 10-m resolution aerial photographic mosaic of the Faysville survey area produced from 1-m resolution Digital Orthophoto Quarter Quadrangle (DOQQ) images from the Texas Natural Resource Information System.

stock_airphoto.tif: 10-m resolution aerial photographic mosaic of the Stockholm survey area produced from 1-m resolution Digital Orthophoto Quarter Quadrangle (DOQQ) images from the Texas Natural Resource Information System.

Drill Targets Subdirectory

fays_targets: Subdirectory containing shapefile of favorable drilling targets for the Faysville survey area.

stock_targets: Subdirectory containing shapefile of favorable drilling targets for the Stockholm survey area.

Geography Subdirectory

lrgv_counties: Subdirectory containing shapefile outlining Cameron, Hidalgo, and Willacy Counties.

lrgv_hydrography: Subdirectory containing shapefile of lakes, streams, and canals within the Lower Rio Grande Valley.

lrgv_place: Subdirectory containing shapefile of Lower Rio Grande Valley place names and locations.

Geology Subdirectory

fays_geology: Subdirectory containing shapefile of surficial geologic units mapped in the Faysville area by Brewton (1973) and digitized by Tremblay and others (1996). Included are ages, depositional units, and descriptions of mapped units

stock_geology: Subdirectory containing shapefile of surficial geologic units mapped in the Stockholm area by Brown and others (1980) and digitized by Tremblay and others (1996).

Geophysics Subdirectory

fays_cdt: Subdirectory containing shapefile of conductivity-depth transform for the Faysville airborne survey. File contains locations (easting and northing in UTM meters) and 20 conductivity values (in mS/m) at 10-m-depth intervals at each site (e.g. con010_m is conductivity 10 m below the surface). Values of –99 denote no data.

fays_slices: Subdirectory containing geotiff images of the Faysville survey area depicting electrical conductivity of the subsurface on horizontal depth slices at 10-m intervals between 10- and 200-m depth. Data from the Faysville airborne survey. Conductivity ranges for each slice are as follows:

Depth (m)	**Low (mS/m)**	**High (mS/m)**
10	28	200
20	40	200
30	44	200
40	25	200
50	41	200
60	31	180
70	23	150
80	19	150
90	13	150
100	11	150
110	7	130
120	6	130
130	7	100
140	8	90
150	8	80
160	7	70
170	6	55
180	6	45
190	7	40
200	7	35

fays_tdem: Subdirectory containing shapefile of names, locations (in decimal degrees), and conductivity models of the ground-based TDEM surveys of the Faysville area. Columns include individual layer thicknesses (e.g. L1thick_m) in meters and layer conductivities (e.g. L1con_mS/m) in mS/m. Zero thickness values denote layer absence.

stock_lei: Subdirectory containing shapefile of layered-earth inversion for the Stockholm airborne survey. File contains locations (easting and northing in UTM meters) and individual layer thicknesses (e.g. L1thick_m) in meters and layer conductivities (e.g. L1con_mS/m) in mS/m. Skin depth (in meters) is also shown for each inversion. Values of –99 denote no data.

stock_slices: Subdirectory containing geotiff images of the Stockholm survey area depicting electrical conductivity of the subsurface on horizontal depth slices at 10-m intervals between 10- and 200-m depth. Data from the Stockholm airborne survey. Conductivity ranges for each slice are as follows:

Depth (m)	**Low (mS/m)**	**High (mS/m)**
10	<1	1058
20	119	1267
30	258	1294
40	264	1249
50	263	1174
60	263	1143
70	265	1090
80	193	1077
90	52	1030
100	19	939
110	17	899
120	17	829
130	18	785
140	13	729
150	20	650
160	20	600
170	20	600
180	20	550
190	15	500
200	15	450

stock_tdem: Subdirectory containing shapefile of names, locations (in decimal degrees), and conductivity models of the ground-based TDEM surveys of the Stockholm area acquired in May 2000. Columns include individual layer thicknesses (e.g. L1thick_m) in meters and layer conductivities (e.g. L1con_mS/m) in mS/m. Zero thickness values denote layer absence.

Roads Subdirectory

lrgv_countyroads: Subdirectory containing shapefile of Lower Rio Grande Valley county roads.

lrgv_majorroads: Subdirectory containing shapefile of names and locations of major roads in the Lower Rio Grande Valley.

Wells Subdirectory

fays_lithlogs: Subdirectory containing shapefile of textural information from driller's logs in the Faysville survey area. Texture is shown every 10 m between the surface and the deepest level reported. Texture key: 1=clay; 2=silty or sandy clay; 3=silt; 4=clayey or silty sand; 5=sand; 6=gravelly sand; 7=gravel.

fays_wells: Subdirectory containing shapefile of water-well data from the Faysville survey area. Data from the Texas Water Development Board water-well database and publications.

lrgv_wells: Subdirectory containing shapefile of water-well data from Cameron, Hidalgo, and Willacy Counties. Data from the Texas Water Development Board water-well database.

stock_lithlogs: Subdirectory containing shapefile of textural information from driller's logs in the Stockholm survey area. Texture is shown every 10 m between the surface and the deepest level reported. Texture key: 1=clay; 2=silty or sandy clay; 3=silt; 4=clayey or silty sand; 5=sand; 6=gravelly sand; 7=gravel.

stock_wells: Subdirectory containing shapefile of water-well data from the Stockhom survey area. Data from the Texas Water Development Board water-well database and publications.

Faysville and Stockholm Depth-Slice Animations

The "animations" directory on the CD-ROM contains movies of progressively deeper slices through the conductivity volumes of the Faysville and Stockholm areas. These animations contain 20 horizontal slices at 10-m intervals between the surface and 200-m depth. Each frame depicts conductivity variations across the area, ranging from high conductivities portrayed as "hot" colors (reds, oranges, and yellows) and low conductivities portrayed as "cool" colors (purple, blue, and green). Animations are stored in two formats–Windows movie format (.avi suffix) and Quicktime format (.mov suffix). Animations can be played using the Windows movie player on Windows platforms, using the Quicktime Movie Player on Windows, MacOS, and other platforms, or using most other video viewers.

Animation Files

fays_movie.avi, .mov: 20-frame animation in Windows video format (.avi suffix) and Quicktime format (.mov suffix) showing conductivity patterns in the Faysville survey area at 10-m depth intervals between 10 and 200 m.

stock_movie.avi, .mov: 20-frame animation in Windows video format (.avi suffix) and Quicktime format (.mov suffix) showing conductivity patterns in the Stockholm survey area at 10-m depth intervals between 10 and 200 m.