Geological Circular 83-3

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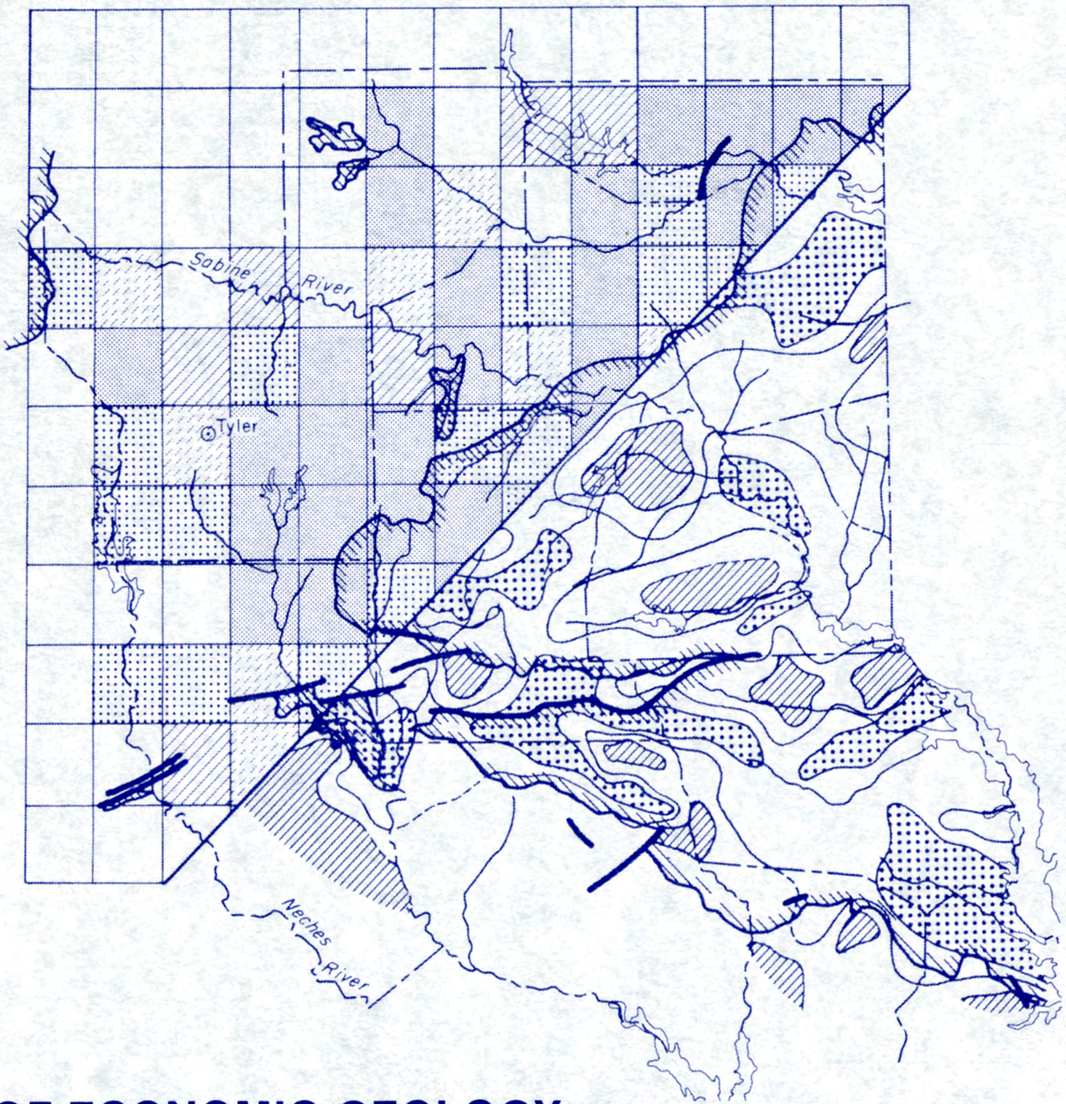

BUREAU OF ECONOMIC GEOLOGY
W. L. Fisher, Director
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ABSTRACT

Lignite deeper than 200 ft (61 m) constitutes about 60 percent of the total lignite resources in Texas. Projections indicate that meeting future demand will require mining this deep-basin lignite. However, because the principal lignite host, the Eocene Wilcox Group, is also a major fresh-water aquifer, deep-basin lignite development by surface mining or underground gasification poses unanswered questions concerning hydrogeologic feasibility and environmental impacts. A regional framework is needed to evaluate these questions and to maximize lignite recovery in a way that minimizes environmental impacts.

An integrated geologic/hydrologic analysis delineates characteristics of the Wilcox Group in the Sabine Uplift region of East Texas that are pertinent to (1) feasibility of deep mining and gasification, (2) mine-permit preparation and evaluation, (3) exploration and site selection, and (4) prediction of lignite quality. Subsurface mapping of maximum- and major-sand isoliths shows occurrence and geometry of hydrologically significant Wilcox sands that would pose the greatest obstacle to dewatering and depressurization. Three-dimensional mapping of hydraulic head data defines recharge and discharge areas and ground-water circulation patterns. Dewatering and depressurization would be more difficult in major discharge areas than in recharge areas. Vertical hydraulic gradients indicate that ground-water velocities decrease markedly with depth in the Wilcox and that potentiometric surfaces constructed from shallow head data may greatly overestimate magnitudes of the deeper hydraulic gradients. Mapped vertical hydraulic gradients can be used together with local head data to assess vertical interconnectedness of sands and feasibility of mine dewatering by gravity drainage wells. Wilcox ground water evolves along flow path from Ca^{2+}-HCO_3^- to Na^+-HCO_3^- water as a result of calcite or feldspar dissolution, or both, and cation exchange on smectitic clays. Mapping of activity indices and saturation indices derived from key reactions helps define regional ground-water circulation patterns and baseline water quality. Empirical relations between borehole resistivity logs and ground-water composition can be used to map further details of Wilcox ground-water quality. High-sodium deep-basin lignites could be attributed to high-sodium ground waters that typify the deep Wilcox sands.

Keywords: lignite, Wilcox Group, hydrogeology, ground water, East Texas, Sabine Uplift.

INTRODUCTION

Total lignite resources in Texas to depths of 2,000 ft (610 m) are estimated at 58 billion short tons, constituting more than one-fourth of the State's total energy endowment. Sixty percent of the lignite, however, is deeper than 200 ft (61 m) and thus is not generally exploitable by current surface-mining methods. Projections indicate that to meet demand in early decades of the 21st century and beyond will require mining or underground gasification of this deep-basin lignite. However, because the principal lignite host, the Eocene Wilcox Group, is also a major fresh-water aquifer, deep surface mining or underground gasification of lignite poses unanswered questions concerning hydrogeologic feasibility and environmental impacts. Deep surface mining will require extensive dewatering and depressurization programs that could deplete ground-water resources. Leaching of mine spoils may generate moderately brackish waters (< 10,000 mg/L) that could degrade ground-water quality near a mine (Dutton, 1982). The success of underground gasification will greatly depend on rates of ground-water leakage into burn cavities (McKee and others, 1981). Underground gasification will generate inorganic and organic contaminants; most of these will be contained, depending on the permeability of strata surrounding the cavity and the extent of roof collapse (Stephens and others, 1982).

Fortunately, major ground-water and lignite resources in the Wilcox Group commonly occur at different stratigraphic intervals and geographic locations, raising the possibility that deep-basin lignite could be exploited in a way that maximizes recovery while minimizing impacts on ground water. Henry and others (1979) recognized this and concluded that because the lignites generally occur in muddy interchannel sediments having relatively low permeability (Kaiser and others, 1978), potential problems of ground-water discharge into a mine or disruption or pollution of the aquifer will usually be avoided in mining of the shallow lignite (< 200 ft [61 m]). This conclusion by Henry and others (1979) is borne out by the fact that the 8 lignite mines in Texas currently mining shallow lignite have experienced few problems. As mining extends deeper, however, the risk of intersecting major Wilcox sands (Fogg and others, 1983) and in turn encountering hydrogeologic difficulties will increase. Clearly, to mine or gasify deep-basin lignite successfully while minimizing impacts, mine operators must carefully select sites and plan operations on the basis of (1) distribution and geometry of Wilcox sands and lignites and (2) ground-water hydraulics and chemistry, including locations of recharge and discharge areas, flow rates and directions, and baseline water quality.

The purpose of this ongoing study is to characterize the regional geology and hydrogeology of the lignite-bearing Wilcox Group in Texas (fig. 1) to provide a regional framework for site selection, planning, and permitting of deep-basin lignite mines and underground gasifiers. As concluded by the Committee on Ground-Water Resources in Relation to Coal Mining and others (1981, p. 190), "Presently available information and ongoing research are inadequate to provide

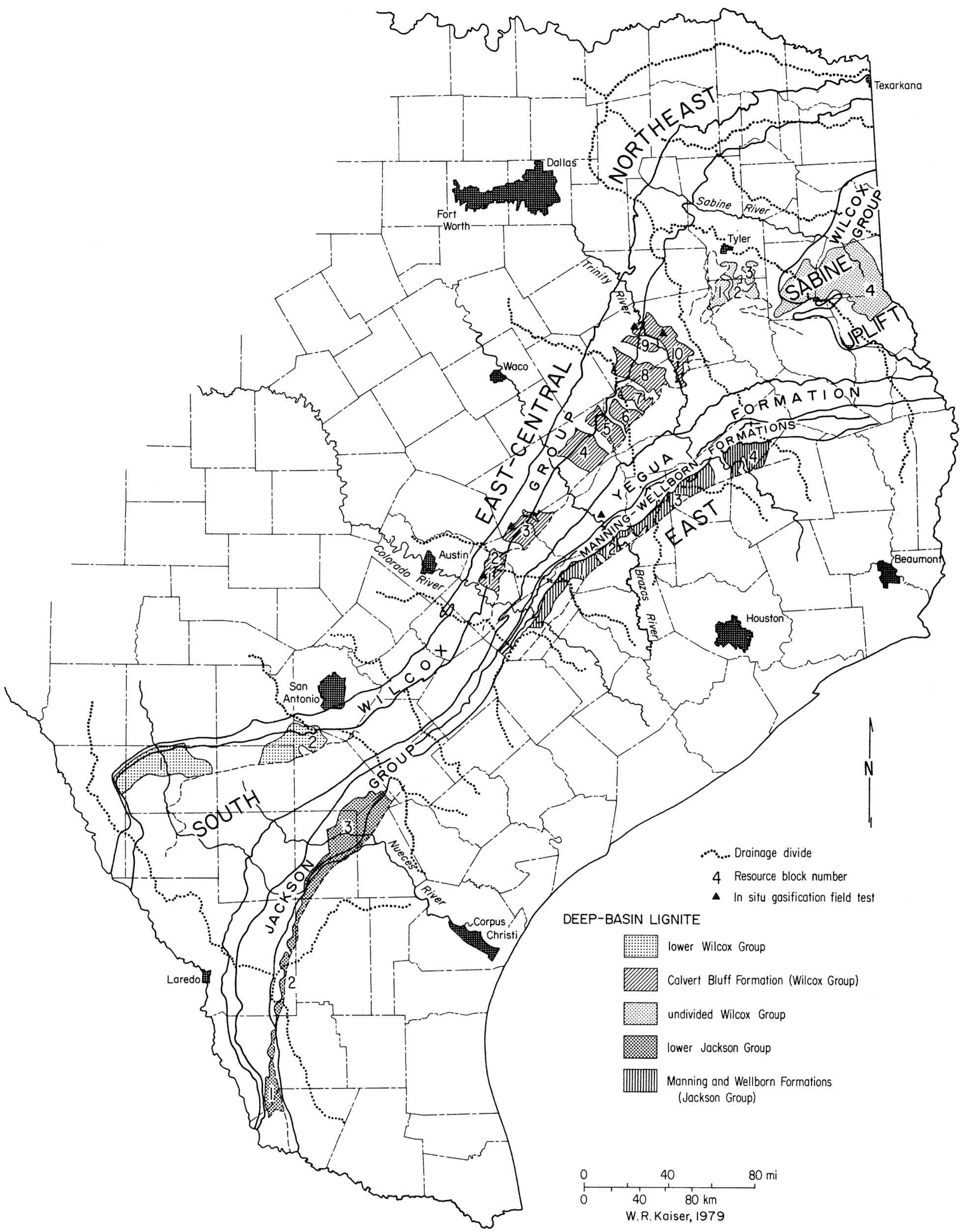

Figure 1. Distribution of deep-basin lignite in Texas (Kaiser and others, 1980). The East Texas Basin centers on the city of Tyler and includes the Sabine Uplift, the northeast lignite belt, and the northernmost end of the east-central lignite belt. The Sabine Uplift area is the focus of this paper.

a [regional] framework for analyzing the site-specific information that will be generated during hydrogeologic assessment of existing and future mine sites." The results will be helpful both to the lignite-mining industry and to State or Federal regulatory agencies responsible for reviewing and approving mine- or gasifier-permit applications. Regulatory agencies must be well informed on the lignite/ground-water system to regulate properly.

This paper describes our methods and presents selected results on the Wilcox Group in the Sabine Uplift area in northeast Texas (fig. 1). The overall project, outlined in Kaiser and others (1983), encompasses lignite resources of the entire state, including the Wilcox Group of east-central Texas, the Jackson Group and Yegua Formation of East Texas, and the Jackson and Wilcox Groups of South Texas (fig. 1). The approach is to (1) map lignite occurrence and sand-body geometry using geophysical log data and depositional systems analysis and (2) characterize ground-water circulation patterns and chemical evolution using hydraulic head data and ground-water chemistry. This integrated geologic/hydrologic approach provides a balanced description of the hydrogeologic system.

HYDROGEOLOGIC SETTING

The Wilcox Group is a thick (> 2,700 ft [823 m]) multiple aquifer system containing fluvial and deltaic channel-fill sand bodies distributed complexly in a matrix of lower permeability interchannel sands, silts, clays, and lignites. The Carrizo Sand unconformably overlies the Wilcox (fig. 2) and is a relatively homogenous, laterally extensive sand about 100 ft (30 m) thick.

The Wilcox Group and Carrizo Sand occur under both unconfined and confined (artesian) conditions. The former condition is found primarily in the large outcrop areas (fig. 1), and the latter in the central basin area (between the outcrops) where the overlying Reklaw Formation is typically a confining unit (Fogg and Kreitler, 1982). In 1974, ground water supplied about 48 percent of the water used in East Texas (B. Moltz, personal communication, 1982). Most of this ground water is pumped from the Wilcox and Carrizo aquifers.

Climate in the Sabine Uplift area is humid, and precipitation averages about 48 inches/yr (122 cm/yr). Consequently, the water table is generally shallow and sustains perennially flowing streams.

DATA BASE

The geological data base consists of about 1,100 geophysical logs (induction or long-normal resistivity and spontaneous potential) from oil and gas test wells. We used the logs to map regional distribution of lignites and sand bodies as well as water-quality variations. To help calibrate and validate lignite identification on the oil and gas logs in the Sabine Uplift

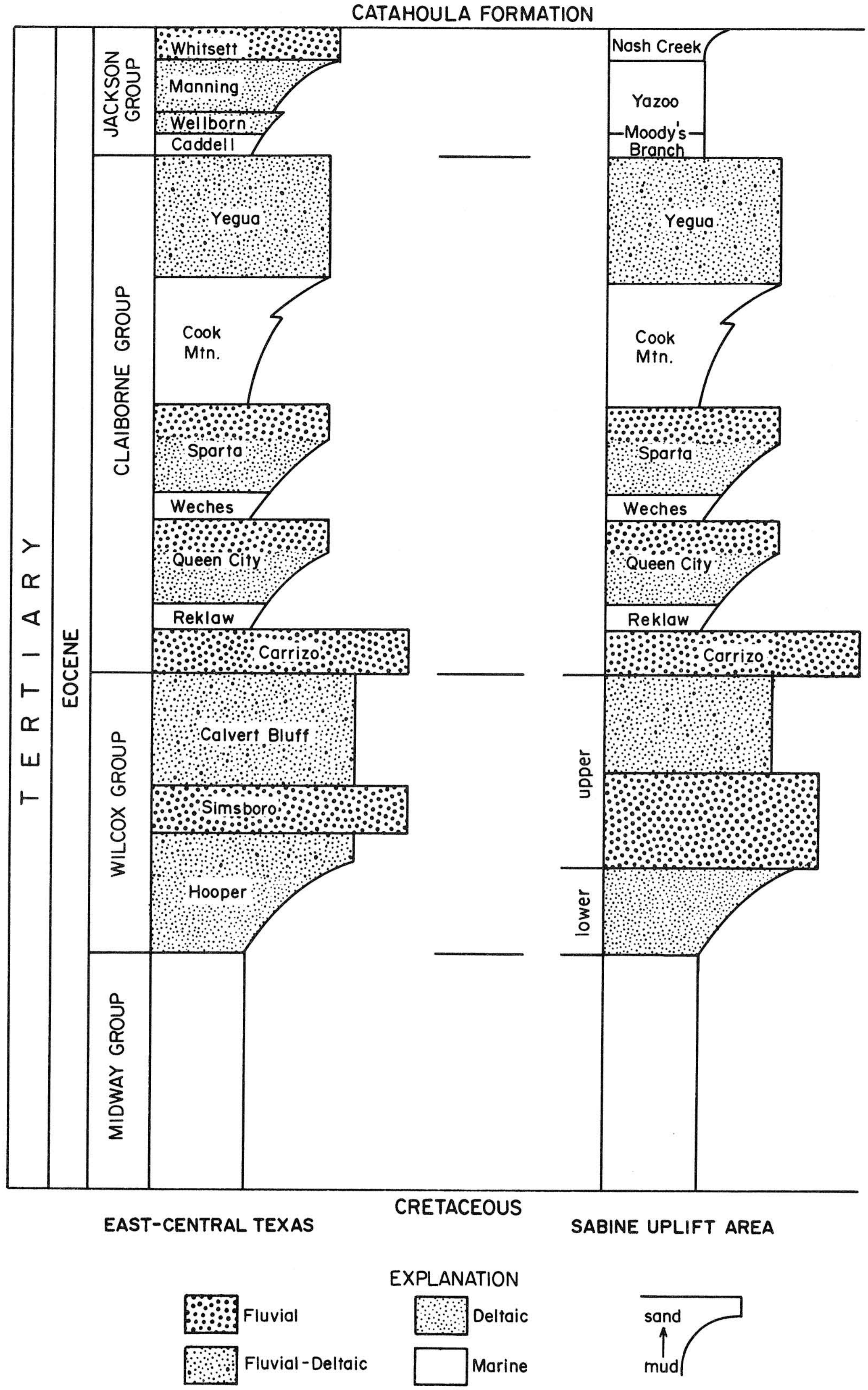

Figure 2. Eocene stratigraphy in east-central Texas and the Sabine Uplift area. The Wilcox Group is a multiple aquifer system.

area, we had 15 stratigraphic test wells drilled to depths ranging from 700 to 1,820 ft (213 to 555 m) and ran a full suite of geophysical logs (short-normal resistivity, focused resistivity, natural gamma, gamma-gamma density, neutron-neutron, spontaneous potential, and caliper) to uniquely identify lignite. A similar ongoing drilling program is being conducted in the east-central Texas lignite belt.

Hydraulic head data for the Wilcox-Carrizo (undivided) and Carrizo aquifers were obtained from computer files of the Texas Natural Resources Information System (TNRIS) and records and published reports of the Texas Department of Water Resources (TDWR) (Dillard, 1963; Broom and Myers, 1966; Anders, 1967; Broom, 1969 and 1971; Guyton and Associates, 1970 and 1972). About 600 hydraulic head measurements from the 1950's through the 1970's were used to map both horizontal and vertical ground-water flow components via potentiometric surface maps, vertical hydraulic gradient maps, and fluid-pressure versus depth analysis. As is discussed later, special precautions were taken to eliminate false hydraulic head gradients caused by water-level fluctuations and by use of data from different years. Pressure values were calculated from data on static water levels and depths to screened intervals.

The major source of water-chemistry data was TNRIS. Additional chemical data were acquired from a U.S. Department of Energy open-file report (Oak Ridge Gaseous Diffusion Plant, 1979). Chemical analyses having cation-anion balances with error greater than $\pm$ 2.6 percent were deleted from the data base. We also eliminated analyses that balanced exactly because potassium or sodium was determined by difference.

The chemically balanced analyses were processed using the computer program SOLMNEQ (Solution-Mineral Equilibrium Computations) (Kharaka and Barnes, 1973). The program calculates saturation indices and the activities of selected ions in natural waters. Activity and saturation indices were mapped for the Carrizo and Wilcox-Carrizo aquifer systems.

METHODS AND SELECTED RESULTS

Depositional Systems

To date, maps of lignite occurrence and maximum-sand distribution have been completed for the Sabine Uplift area. Only the maximum-sand map is shown (fig. 3), as it is more relevant to the hydrogeology. The lignite occurrence map and further discussion can be found in Kaiser and others (1983) and in future reports. The maximum-sand map is constructed by picking the single thickest, or maximum, sand irrespective of its stratigraphic position. The map can be prepared easily and can include areas where the stratigraphic section is incomplete (for example, at the outcrop). Experience shows that the maximum-sand map closely reflects geometries established by sand-percent and net-sand mapping. Validity of the map has been verified repeatedly by the drilling program.

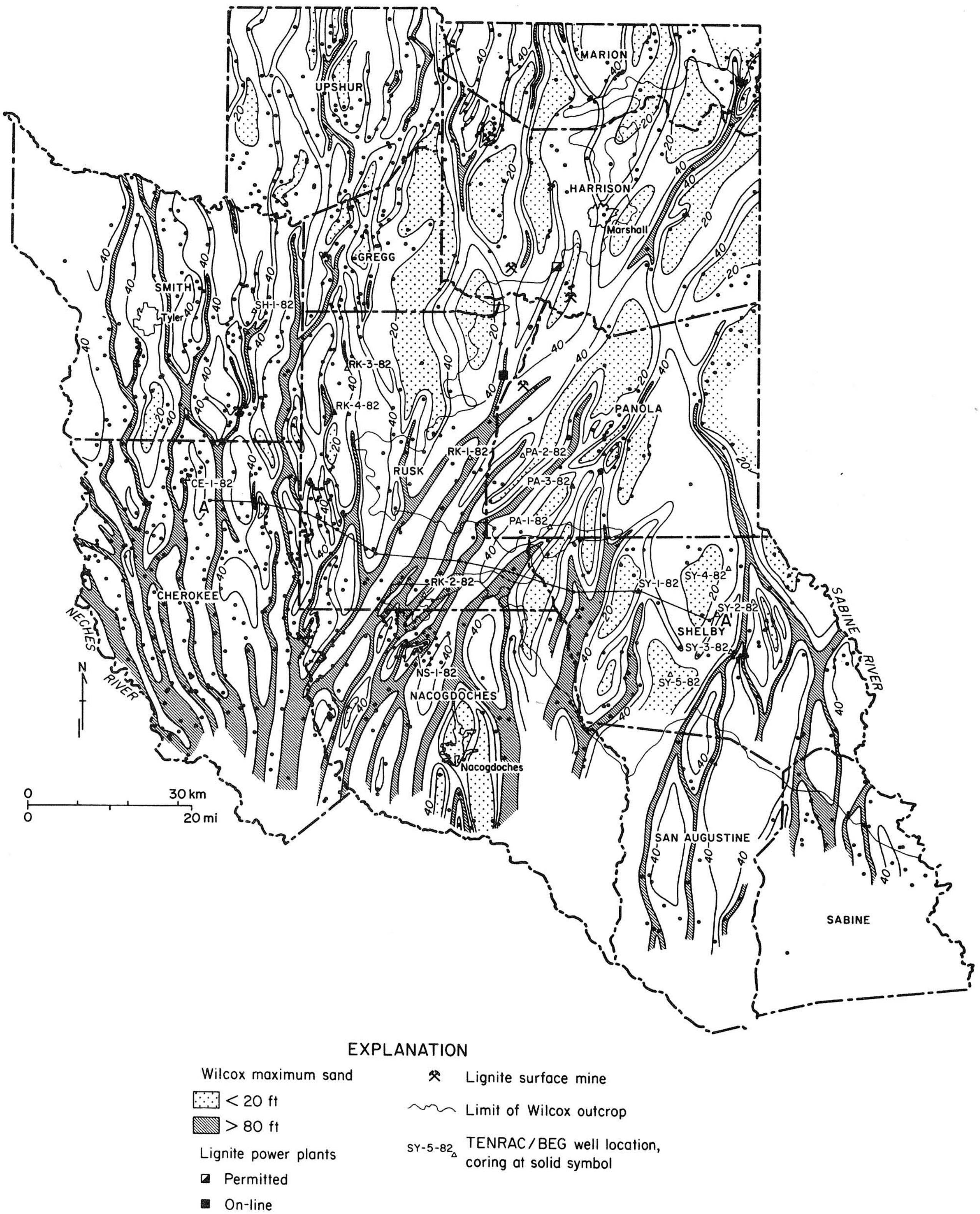

Figure 3. Maximum-sand map of the Wilcox Group. High-maximum-sand belts define areas likely to contain many well-interconnected sands.

The maximum-sand map (fig. 3) exhibits three prominent sand belts defined by maximum sands thicker than 80 ft (24.4 m) in the Sabine Uplift area. One belt occupies the western half of Cherokee County and trends slightly west of north. Another runs northeast-southwest across Panola, Rusk, and Nacogdoches Counties, merging with the former in southern Cherokee County. A third skirts the eastern edge of Panola County, extending south across eastern Shelby County into San Augustine and Sabine Counties. Sand-body continuity and interconnectedness should be greatest in these sand belts. The thickest, most laterally extensive lignite deposits tend to occur in the muddy interchannel areas separating the major sand belts. However, thick sands and lignites commonly occur near each other.

Several other regional maps are being prepared, including sand-resistivity maps showing areas of relatively rapid fresh-water influx and major-sand-thickness maps of newly identified progradational and aggradational subdivisions of the Wilcox Group. The major sands are the fluvial and deltaic channel-fill sands, identified on the basis of thickness and electric log character. Maximum- and major-sand maps are useful both for lignite exploration and for hydrogeologic interpretation (Kaiser and others, 1983). The maps effectively show distribution of the major fluvial-deltaic channel-fill sands, or the major aquifers, exclusive of the low-permeability interchannel sands (for example, splays and minor fluvial tributary sands).

Ground-Water Hydraulics

A potentiometric surface map (fig. 4) and vertical hydraulic gradient maps (figs. 6 and 7) provide a three-dimensional view of ground-water flow components in the Wilcox-Carrizo aquifer system. The three-dimensional approach is necessary because the Wilcox-Carrizo is a multiple aquifer system composed primarily of discontinuous sands distributed both vertically and horizontally.

Potentiometric Surface Map

The potentiometric surface (head) map (fig. 4) includes data identified as Wilcox, Wilcox-Carrizo undivided, or Cypress in TNRIS computer printouts and in TDWR files and published reports. Fogg and Prouty (1983) also constructed a separate head map for the Carrizo aquifer in the southern half of the Sabine Uplift area. Data identified as Cypress occur only in Marion and Harrison Counties and include (from youngest to oldest) the Queen City, Carrizo, and Wilcox aquifers; most of the Cypress data, however, are from the Wilcox and Carrizo, as evidenced by structure mapping on top of the Wilcox (Fogg and Kreitler, 1982) and by depths of the wells. The Cypress unit has not been subdivided because the upper Wilcox and lower Claiborne strata (Carrizo, Reklaw, and Queen City Formations) in Marion and Harrison Counties are difficult to define on electric logs. Hence, what has been identified as the Cypress aquifer system apparently contains no regionally continuous aquitard that would segregate the Queen City and Wilcox-Carrizo systems.

The potentiometric surface contours in figure 4 were drawn to conform closely to the data, but in some cases an anomalous data point was ignored or given less weight in the contouring process. Probable causes of anomalies include (1) variations among head measurements made at different times in areas of intense pumpage, (2) adjacent wells tapping different horizons of the Wilcox-Carrizo that have different hydraulic heads, and (3) measurement error. Seasonal water-level fluctuations are much less than the 50-ft (15.2-m) contour interval used and thus do not cause significant error in the map. The resulting potentiometric surface map is reliable for regional interpretation, but local conditions can be much more complex.

In the Wilcox-Carrizo outcrop area, the aquifer is regionally unconfined; consequently, the potentiometric surface tends to follow land surface, and ground-water circulation occurs in many subbasins, generally coinciding with the surface watersheds of major streams and tributaries. In the central basin area skirting the outcrop, Wilcox-Carrizo sands are semiconfined by muds of the Reklaw and Queen City Formations; hence, the potentiometric surface shows only a subdued correlation with topography.

The head map can be used together with other hydrogeologic maps to identify potentially important recharge and discharge areas. Major recharge areas, or potentiometric highs, occur in or adjacent to the outcrop area (figs. 4 and 5): northern Rusk County, northern Nacogdoches and southern Rusk Counties, a northwest-trending area from north-central Shelby County to northern Sabine County, and western Smith County (adjacent to the western outcrop belt). North of the Sabine River, recharge areas are not very distinct on the head map, owing apparently to flatter topography. Major discharge areas primarily correspond to the streams traversing the outcrop (figs. 4 and 5). The most obvious of these streams are (from north to south) Big Cypress Bayou, Paw Paw Bayou, Sabine River, Martin Creek, Murvaul Bayou, and Attoyac Bayou.

In the central basin area, natural recharge and discharge could occur by downward and upward leakage across aquitard strata (Fogg and Kreitler, 1982); however, the rates of leakage are, on the average, several orders of magnitude lower than ground-water flow rates in Wilcox-Carrizo sands (Fogg and others, 1983). Ground-water flow in the central basin is consequently sluggish compared to that in the outcrop.

Effects of artificial ground-water discharge, or pumpage from wells, are evident (1) in Gregg and Upshur Counties, where municipal and industrial pumpage have created a series of closed potentiometric depressions (fig. 4) and lowered heads regionally to below the streambed of the Sabine River; (2) around the city of Henderson in central Rusk County; and (3) in Nacogdoches County, where heads have been lowered below sea level. The effects of discharge

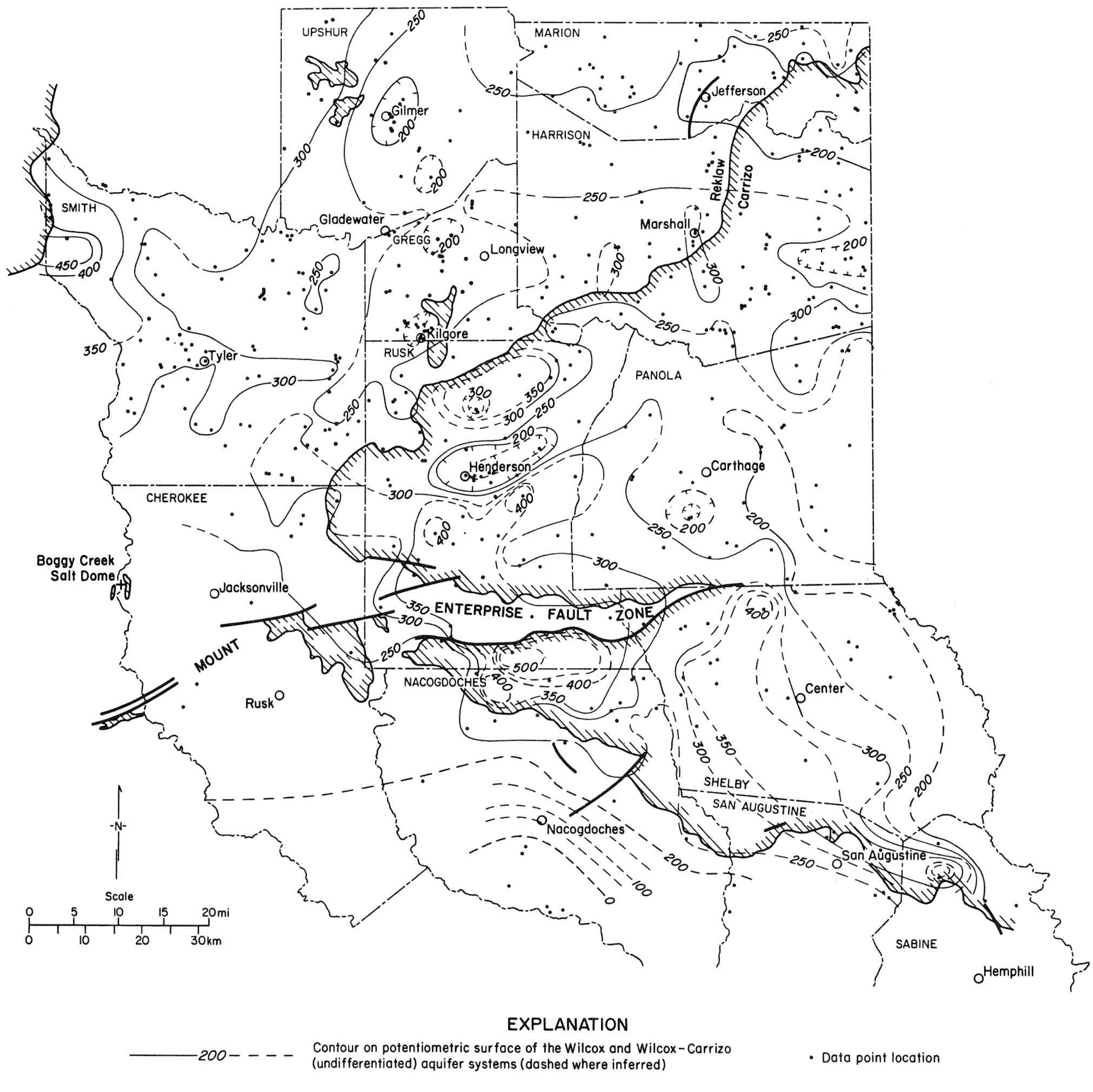

Figure 4. Potentiometric surface map, Wilcox-Carrizo aquifer system. Data are from wells tapping Wilcox and Wilcox-Carrizo (undifferentiated) strata. Measurements are from the 1960's and early 1970's. The map is considered reliable for regional interpretation but not for local hydraulic gradients.

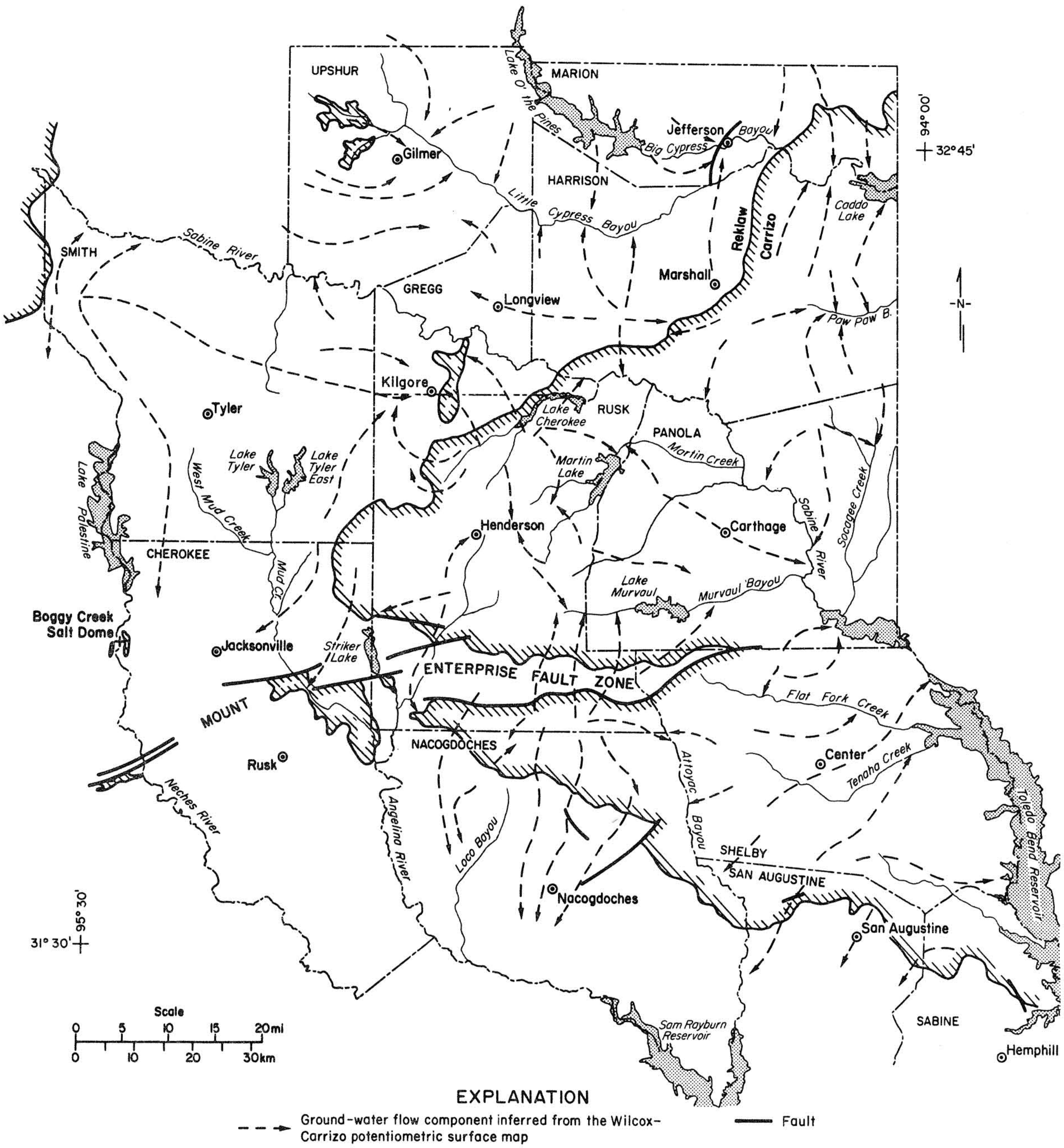

Figure 5. Ground-water flow lines inferred from the Wilcox-Carrizo potentiometric surface map. Major discharge areas are the Sabine River, Big and Little Cypress Bayous, Attoyac Bayou, and several of their tributaries. Major recharge areas are in the Wilcox-Carrizo outcrop areas in Rusk, Nacogdoches, and Shelby Counties.

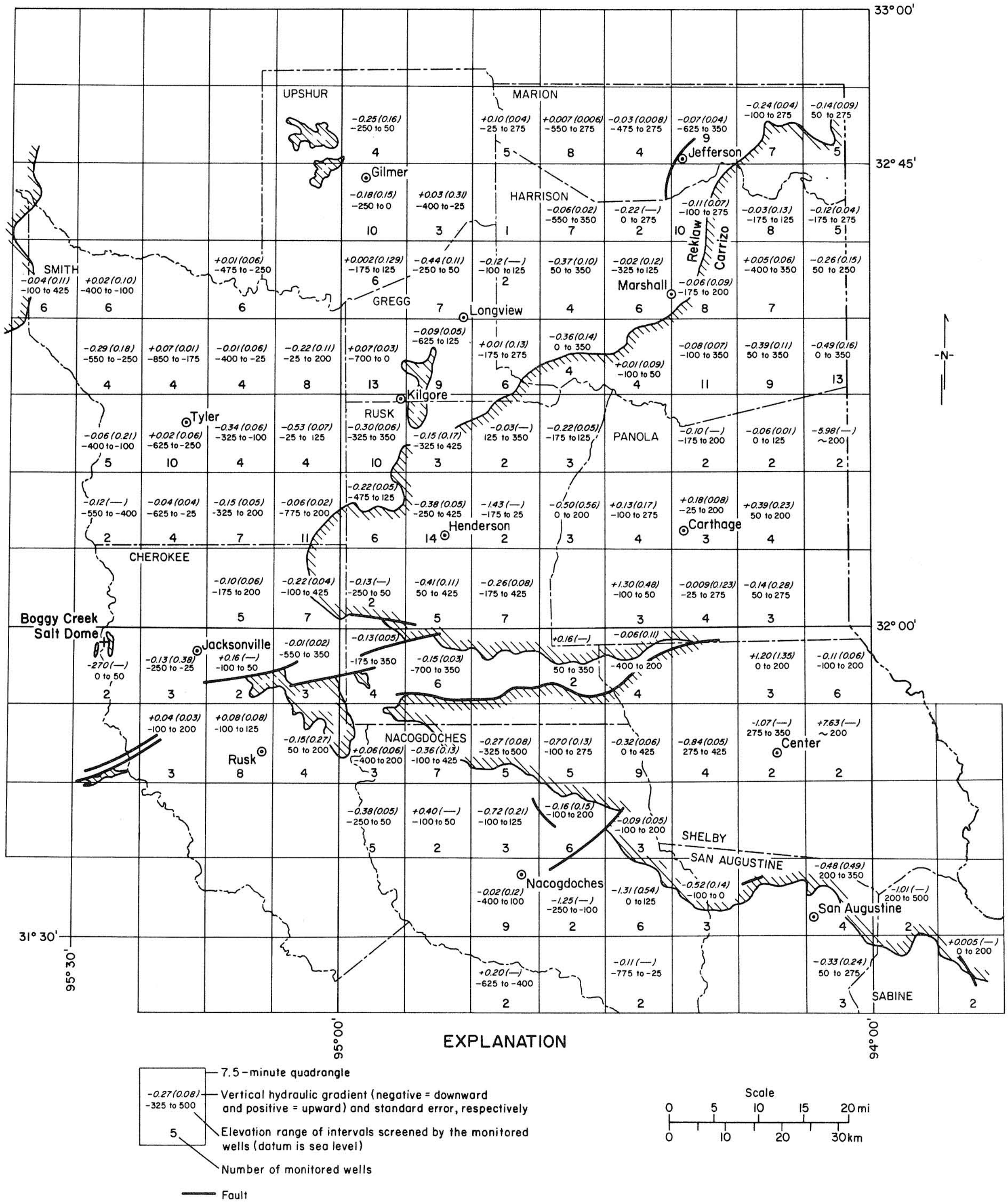

Figure 6. Map showing vertical component of the hydraulic gradient (∂h/∂z) determined by least-squares linear regression for data in each 7.5-minute quadrangle. Positive and negative values indicate potential for upward and downward movement, respectively. Presence of a measurable ∂h/∂z value indicates potential for vertical flow and poor vertical interconnection of sand bodies. The standard error values shown can be used to calculate confidence limits for the vertical hydraulic gradient.

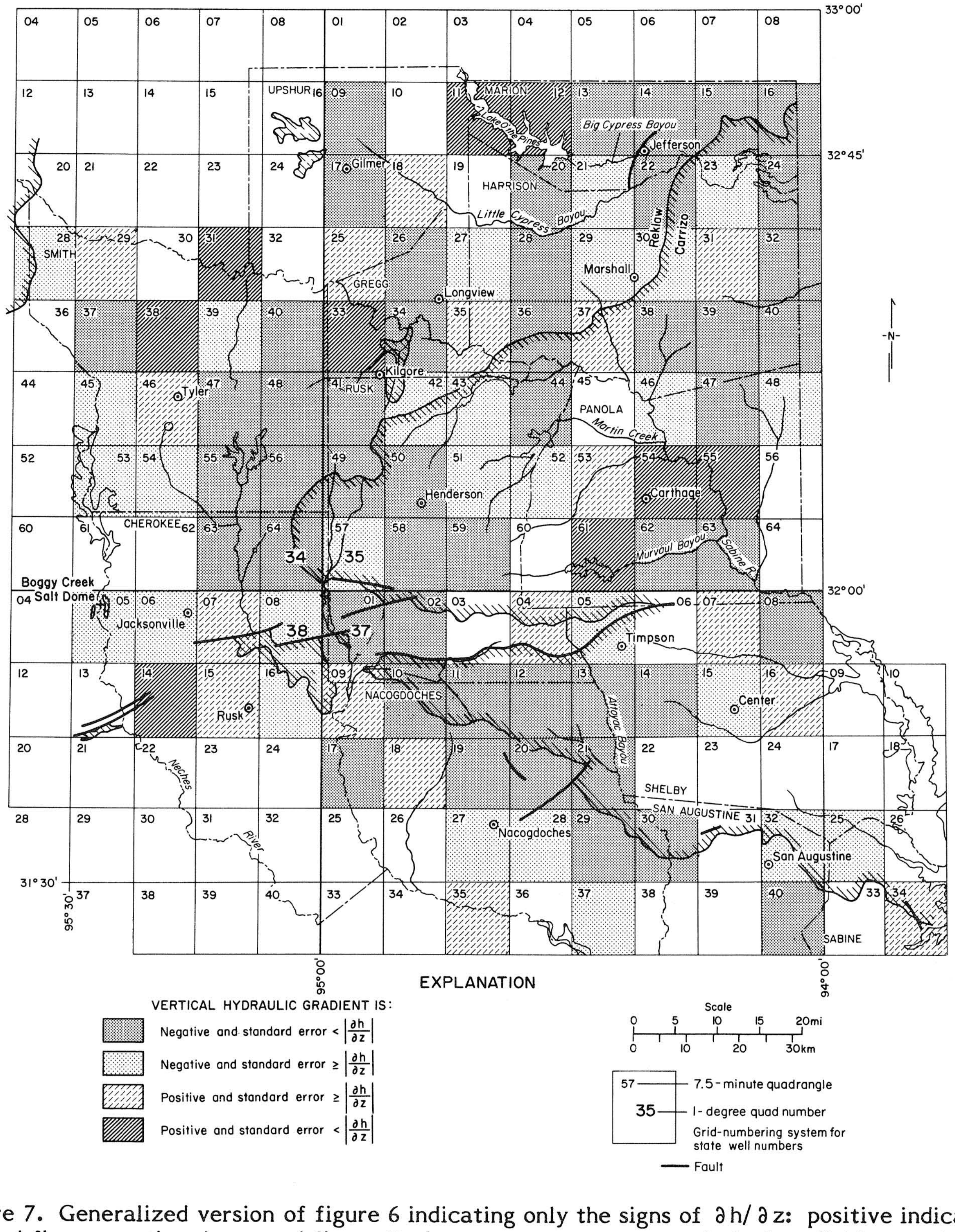

Figure 7. Generalized version of figure 6 indicating only the signs of $\partial h/\partial z$: positive indicates upward flow, negative downward flow. Darker patterns represent relatively reliable trends for which the standard error is less than the absolute value of $\partial h/\partial z$; lighter patterns indicate less reliable trends for which the standard error is greater than or equal to the absolute value of $\partial h/\partial z$.

at these locations can be used to predict regional impacts of mine dewatering and depressurization on the aquifer.

Vertical Hydraulic Gradient Mapping

Vertical hydraulic gradients were estimated in 7.5-minute quadrangles (figs. 6 and 7) from data on hydraulic head and well screen depths. Using the statistical computer package SPSS (Statistical Package for the Social Sciences) (Nie and others, 1975), least-squares regression lines were fitted to plots of hydraulic head versus elevation of the screened interval, which was represented as the bottom of the screened interval for each well. Wells having screened intervals thicker than 200 ft (61 m) were eliminated to avoid data representing hydraulic heads averaged over thick intervals. Slope of the regression line is the vertical hydraulic gradient, and sign of the slope indicates direction of potential vertical flow or leakage (negative for downward and positive for upward).

Each 7.5-minute quadrangle in figure 6 includes data on the vertical hydraulic gradient ($\partial h/\partial z$) and its standard error, elevation range of screened intervals in the quadrangle, and number of data points (that is, monitored wells). The standard error can be used to set confidence limits for $\partial h/\partial z$. For example, assuming the data are distributed normally about the regression line, there is approximately a 68-percent chance that true $\partial h/\partial z$ values are within plus or minus the standard error. More precise confidence limits could be calculated by applying a student's t distribution using the number of data points as the degrees of freedom (Hoel, 1971; Nie and others, 1975). In the generalized map of $\partial h/\partial z$ (fig. 7), only the directions of $\partial h/\partial z$ are indicated (positive indicates upward flow, negative indicates downward flow) to illustrate probable locations of recharge and discharge areas. Quadrangles in which the standard error is greater than or equal to the absolute value of $\partial h/\partial z$ are shaded with the lighter patterns. Thus, the lighter patterns indicate either lack of a consistent $\partial h/\partial z$ trend or a consistent $\partial h/\partial z$ trend that is close to zero. A value near zero means that either flow is perfectly horizontal or the sands are well interconnected vertically, causing the vertical gradient to become very small ($< 10^{-2}$) (Fogg and others, 1983).

The $\partial h/\partial z$ maps indicate that the potential for vertical flow in the Sabine Uplift area is predominantly downward. Fogg and Kreitler (1982) made similar observations using pressure versus depth data that were primarily from the Wilcox-Carrizo in the East Texas Basin, west of the present study area. The widespread occurrence of downward components contrasts sharply with the common assumption that upward flow and discharge are characteristic of a humid region having a shallow water table.

Potential for upward flow occurs in only a few areas, generally in or near bottom lands of the Sabine River basin (figs. 6 and 7). In many cases, the discharge areas no doubt are smaller than a 7.5-minute quadrangle and hence might not show up on the maps. This would explain why many of the areas appearing as discharge areas in the head map (fig. 4) do not exhibit upward-flow potential in figures 6 and 7.

Potential for vertical flow also has been studied using fluid-pressure versus depth plots (Fogg and Prouty, 1983), which show that potential for downward flow is greatest in the outcrop and decreases downdip into the semiconfined section.

Water Chemistry

The waters of Gulf Coast Tertiary aquifers typically evolve from Ca^{2+}-HCO_3^- to Na^+-HCO_3^- water. This evolution has been documented for the Wilcox-Carrizo aquifer in the East Texas Basin (Kreitler and Fogg, 1980; Fogg and Kreitler, 1982) and in the Sabine Uplift area (Kaiser and Ambrose, 1983). The dominance of Na^+ and HCO_3^- ions can be explained by the combined effects of calcite dissolution and cation exchange (Foster, 1950; Freeze and Cherry, 1979). Two generalized reactions are of special importance:

$$CaCO_3 \text{ (calcite)} + H_2CO_3 = Ca^{2+} + 2HCO_3^-$$
$$\text{Na-montmorillonite} + Ca^{2+} = 2Na^+ + \text{Ca-montmorillonite}$$

Because of these simultaneous reactions, Na^+ and HCO_3^- concentrations increase with time and distance along the flow path. Removal of Ca^{2+} by cation exchange on clay minerals (smectite represented by montmorillonite) causes the water to become or remain undersaturated with respect to calcite; thus, calcite dissolution continues. Generated in the biologically active soil zone, CO_2 combines with water to form H_2CO_3. At depth, CO_2 may be generated by coalification or by SO_4^{2-} reduction involving oxidation of organic matter or hydrocarbons (Freeze and Cherry, 1979).

Fogg and Kreitler (1982) mapped the evolving chemical trends, using concentrations, and showed that Wilcox-Carrizo waters shift from oxidizing and acidic in the recharge zone to reducing and basic deep in the aquifer. They characterized the evolution in chemistry along flow path from

pH < 7, high Ca^{2+}, low Na^+, low HCO_3^-, moderate SO_4^{2-}, high SiO_2, high Eh

to pH 8 to 9, low Ca^{2+}, high Na^+, high HCO_3^-, low SO_4^{2-}, low SiO_2, low Eh.

These trends are difficult to map as concentrations (mg/L or molarity) of single ions because of abrupt changes in concentration from well to well. We therefore decided to map log activity indices (activity ratios and products) and saturation indices (log ionic activity product divided by log K_r) derived from reactions believed to affect the evolution of Wilcox-Carrizo waters. This allowed interpretation to be linked to specific reactions. The reactions considered are:

$$Na_{.33}(Al_{1.56}Mg_{.5})Si_4O_{10}(OH)_2 \text{ Na-montmorillonite} + 0.16Ca^{2+}$$
$$= Ca_{.16}(Al_{1.56}Mg_{.5})Si_4O_{10}(OH)_2 \text{ Ca-montmorillonite} + 0.33Na^+ \quad (1)$$

$$Na_{.7}Ca_{.3}Al_{1.3}Si_{2.7}O_8 \text{ plagioclase} + 1.3H^+ + 3.45H_2O$$
$$= 0.65Al_2Si_2O_5(OH)_4 \text{ kaolinite} + 0.3Ca^{2+} + 0.7Na^+ + 1.4H_4SiO_4^0 \quad (2)$$

$$SiO_2 \text{ crystalline} + 2H_2O = H_4SiO_4^0 \quad (3)$$

$$Ca_{.16}(Al_{1.56}Mg_{.5})Si_4O_{10}(OH)_2 \text{ Ca-montmorillonite} + 10.24H_2O$$
$$= 0.16Ca^{2+} + 1.56Al(OH)_4^- + 0.5Mg^{2+} + 4H_4SiO_4^0 + 0.24H^+ \quad (4)$$

Reaction (1) is the key cation-exchange reaction, where the log activity ratio for the reaction, log $([Na^+]^{.33}/[Ca^{2+}]^{.16})$, controls the equilibrium. This log activity ratio was mapped to evaluate the evolution of Na^+-HCO_3^- water. Reaction (2) describes the leaching of feldspar in which clay, Ca^{2+}, Na^+, and SiO_2 (represented by $H_4SiO_4^0$) are generated and H^+ is consumed. This may be an important reaction in the recharge zone providing initial Ca^{2+}, Na^+, and SiO_2 (Fogg and Kreitler, 1982). The log activity product, log $([Ca^{2+}]^{.3}[Na^+]^{.7})$, involving the produced cations, was mapped. In reaction (3), the stability of crystalline silica is considered and log$[H_4SiO_4^0]$ was mapped. Reaction (4) is the hydrolysis of Ca-montmorillonite. In this case, using thermodynamic data from Galloway and Kaiser (1980), the saturation index (SI = log ionic activity product [IAP]/log K_r) was mapped. Reactions (2), (3), and (4) test possible controls on SiO_2 concentration. Regional trends in water chemistry are mappable (contourable) and vary in a predictable fashion. Apparently, by using log values, variations among water samples were smoothed. To be consistent with the solution-mineral equilibria approach, activities rather than concentrations were mapped; however, it is probable that the log of concentration would also yield mappable values.

Hydrochemical Maps

All the hydrochemical maps reflect the same regional geochemical patterns; the maps show a positive correlation with areas of recharge and distance along flow path as identified in hydraulic head mapping and outcrop geology. Two of the more instructive maps, log $([Na^+]^{.33}/[Ca^{2+}]^{.16})$ ratio and log $([Ca^{2+}]^{.3}[Na^+]^{.7})$ product, are shown in figures 8 and 10, respectively. On the map of log $([Na^+]^{.33}/[Ca^{2+}]^{.16})$ ratio (fig. 8), low activity ratios (<0.4) suggesting recharge underlie the Carrizo outcrop, such as in central Rusk County. Higher values occur basinward to the west and in apparent discharge areas, such as Martin Creek and

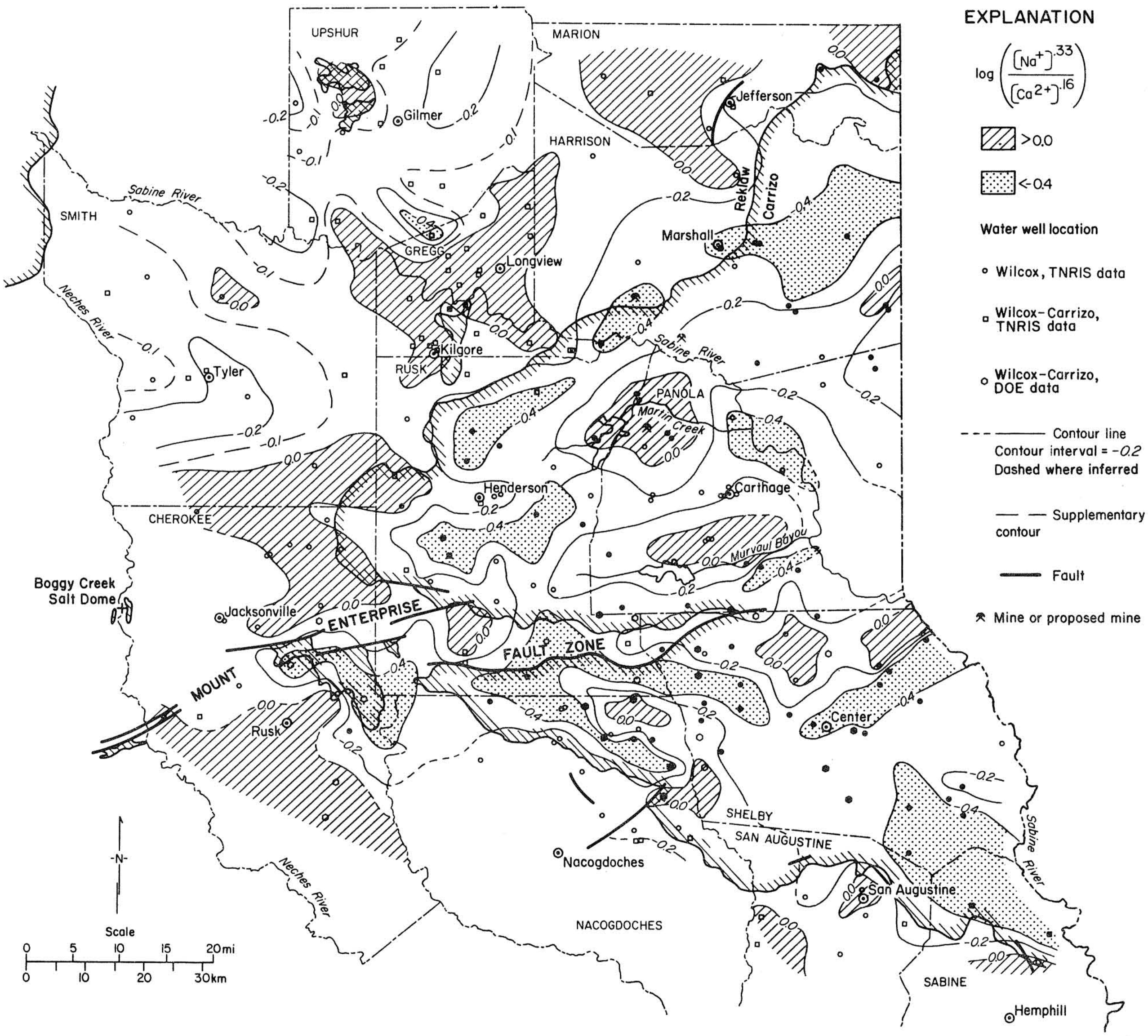

Figure 8. Map of Wilcox log ($[Na^+]^{.33}/[Ca^{2+}]^{.16}$) ratio. Log activity ratios < -0.4 indicate areas of recharge. Solid symbols designate completions at depths of < 200 ft (61 m). Most Wilcox completions are between depths of 144 and 1,000 ft (44 and 305 m).

Murvaul Bayou in Panola County. Hence, the map (fig. 8) shows a general increase along flow path in the ratio $[Na^+]/[Ca^{2+}]$, in accordance with reaction (1), which represents exchange of Ca^{2+} for Na^+ on clay minerals.

Several additional features are evident in the $[Na^+]/[Ca^{2+}]$ map. Faulting and consequent partitioning of sand bodies create complex distributions of both high and low values, as seen in east-central Cherokee County and in Nacogdoches County near the Shelby county line. Heavy pumping of the aquifer has caused large areas of drawdown in Gregg County and surrounding the town of Henderson in Rusk County. These areas are characterized by higher log ratios resulting from a combination of natural and induced discharge.

To understand the three-dimensional trends in Wilcox ground-water chemistry, one must also look at trends with depth. For example, figure 9 shows a general increase in log $([Na^+]^{.33}/[Ca^{2+}]^{.16})$ ratio with depth. The deeper waters, owing to their longer flow paths and residence times, have gained more Na^+ and lost more Ca^{2+} than have the shallower waters.

The log $([Ca^{2+}]^{.3}[Na^+]^{.7})$ product map (fig. 10) shows many of the same trends recognized on the previous map (fig. 9). Lower values (< -3.00) underlie the Carrizo outcrop in areas of recharge, for example, potentiometric highs or recharge mounds in central Rusk County (fig. 4). Recharge from the west is also indicated. Higher values reflect discharge, for example, at Martin Creek and Murvaul Bayou in Panola County.

Estimating Water Quality From Electric Logs

Because variations in electrical resistivity between strata of similar lithologies primarily result from the dissolved-solids content of the ground water, water quality can often be estimated using electrical resistivity logs (long normal or induction). We have derived empirical relations that interrelate electric log resistivity (R_o) of the formation fully saturated with water and concentrations of total dissolved solids (TDS), Na^+, HCO_3^-, and Cl^-. All but the Cl^- plot are shown in figure 11.

As Fogg and Kreitler (1982) and Kaiser and Ambrose (1983) demonstrated, Wilcox-Carrizo ground water evolves into a Na^+- HCO_3^- type. Hence it is not surprising that the plots of TDS, Na^+, and HCO_3^- versus R_o all show reasonably good correlations. The plots can be used to approximate general composition of Wilcox-Carrizo ground water where actual chemical analyses are unavailable. The method is particularly useful for delineating three-dimensional water-quality trends in the Wilcox using the many electric logs of oil and gas wells that penetrate the unit. Water-chemistry data from monitoring wells are limited in this regard because they generally represent either water from discrete sand bodies or a mixture of waters from several different sands. Nearly all the electric logs include most or all of the Wilcox Group, providing water-quality data for several different sand intervals at a given location.

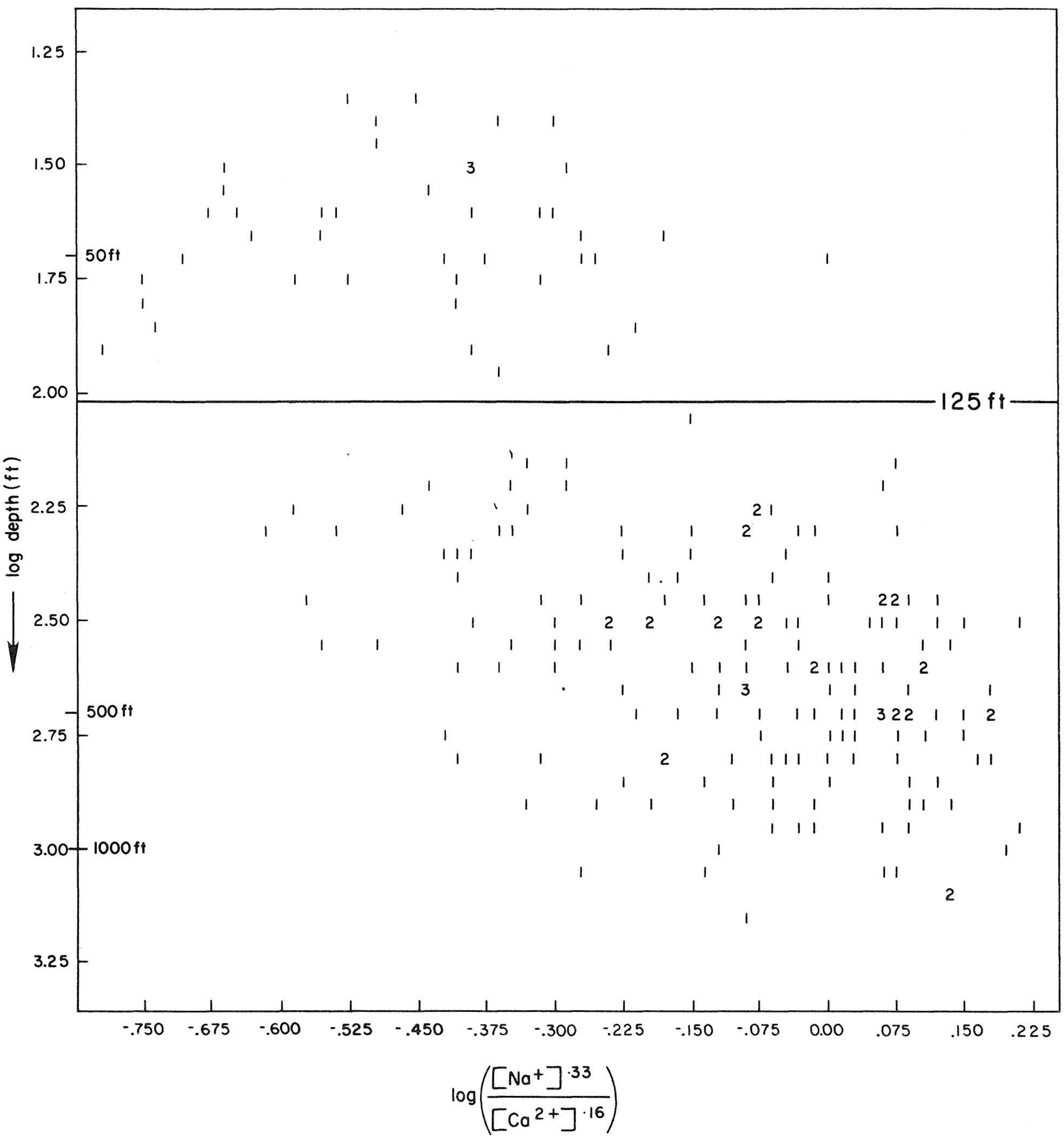

Figure 9. Plot of Wilcox log ($[Na^+]^{.33}/[Ca^{2+}]^{.16}$) ratio versus depth. The log activity ratio increases with depth, reflecting longer travel time and greater distance from outcrop.

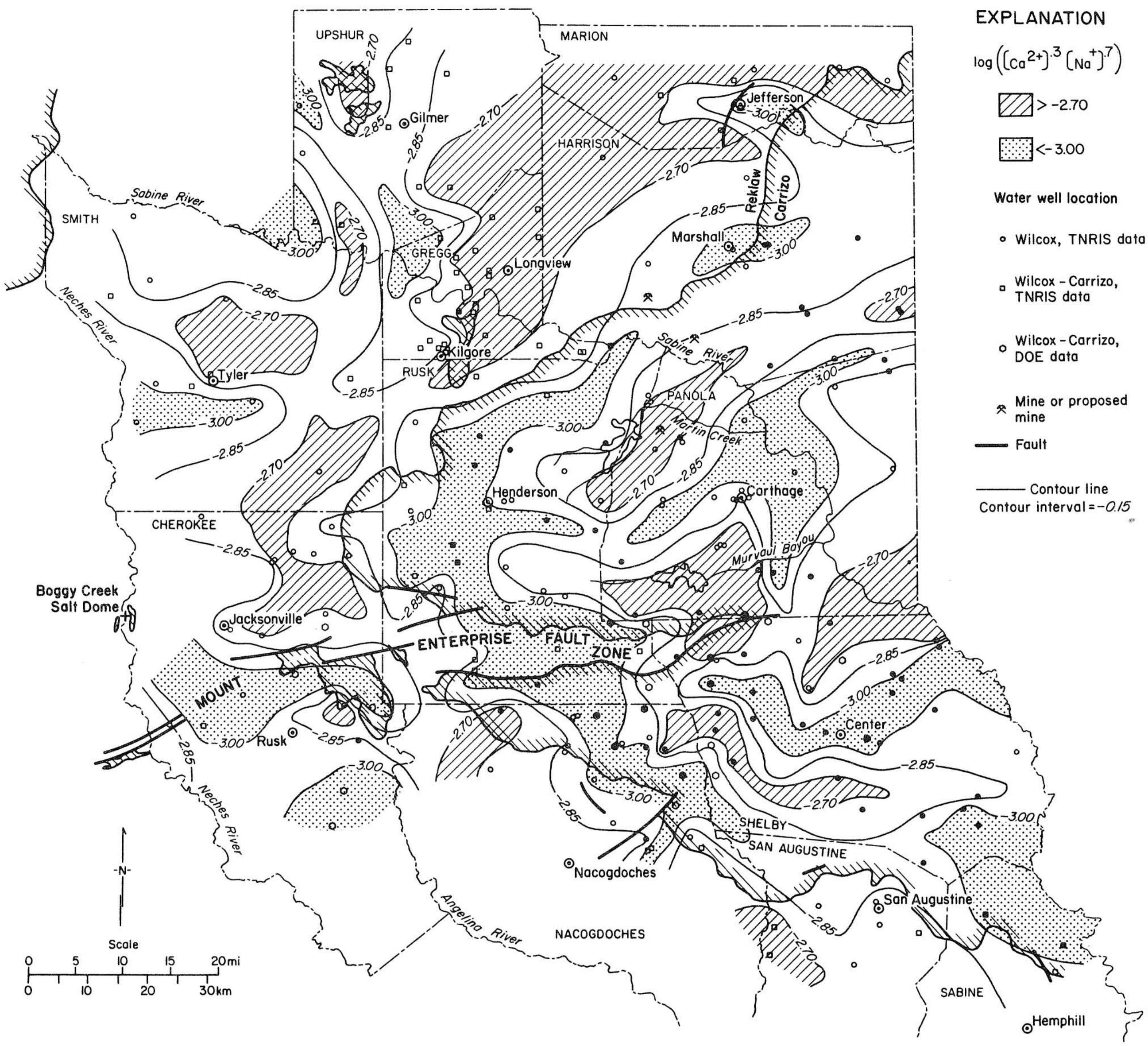

Figure 10. Map of Wilcox log ($[Ca^{2+}]^{.3}[Na^{+}]^{.7}$) product. Log activity products < -3.00 indicate areas of recharge. Solid symbols designate completions at depths of < 200 ft (61 m). Most Wilcox completions are between depths of 144 and 1,000 ft (44 and 305 m).

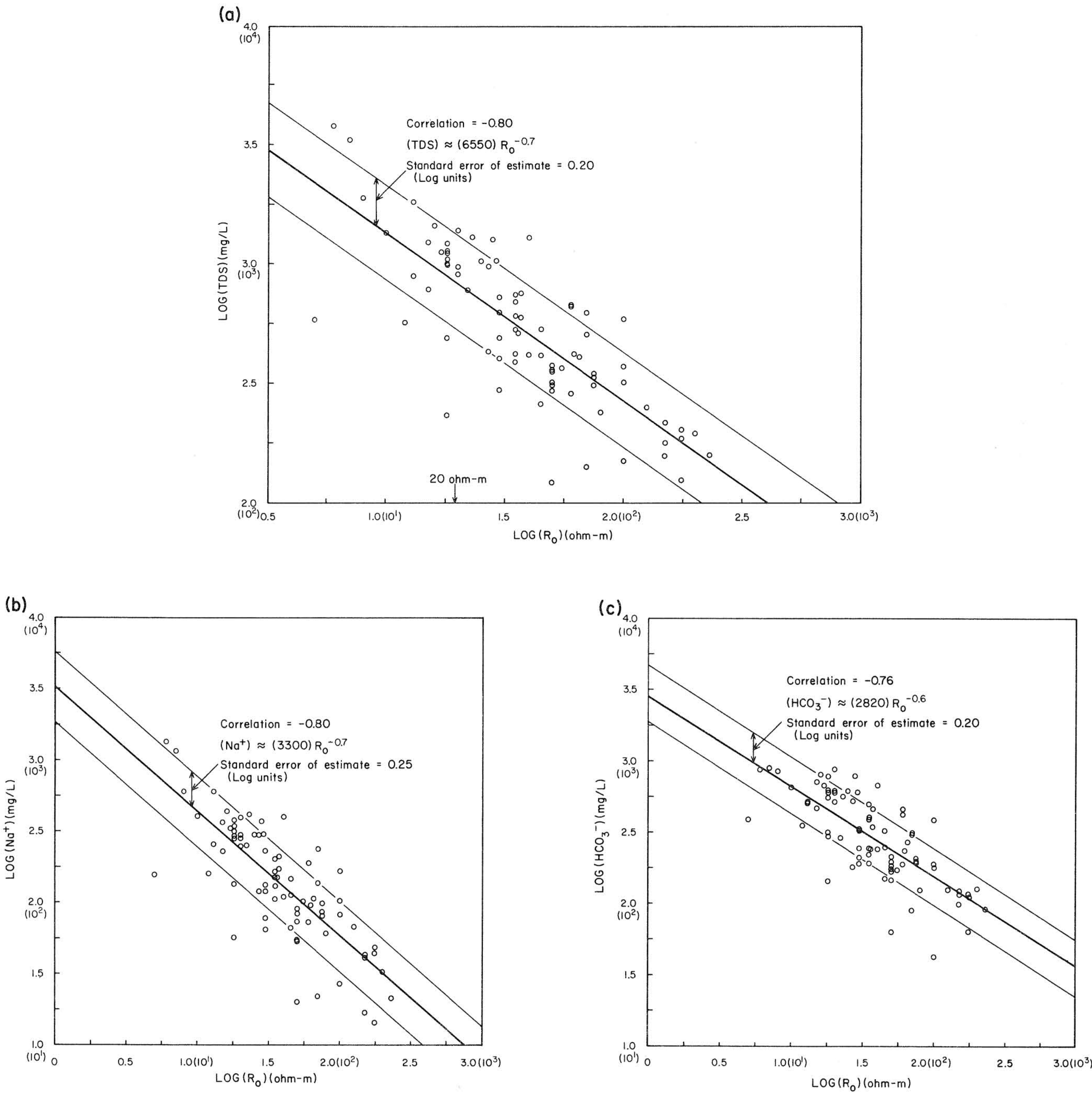

Figure 11. Graphs of (a) TDS, (b) Na^+, and (c) HCO_3^- versus electric log resistivity (R_o from 64-inch long normal or induction), Wilcox-Carrizo aquifer system, Sabine Uplift area. Data are from water wells that are screened primarily in channel-fill sands at depths of 200 to 1,200 ft (61 to 366 m).

DISCUSSION

Importance of Sand-Body Architecture to Wilcox Hydrogeology

Because the Wilcox is a multiple aquifer system, sand-body architecture (distribution, continuity, and interconnectedness of sands) is a critical control on Wilcox hydrogeology (Fogg and others, 1983). Most shallow mining is now done in interchannel areas, where average hydraulic conductivity values are low owing to a lack of permeable, well-interconnected channel-fill sands. These interchannel areas are hydrologically favorable for mining because the seriousness of dewatering and depressurization problems and of impacts on regional ground-water hydraulics and chemistry there is minimized. As mining extends deeper, however, the risk of encountering well-interconnected channel-fill sands will increase. Volumes of water that will be withdrawn for dewatering or depressurization will probably depend as much on the volumes of these sands as on the hydraulic properties of transmissivity and storativity. If a deep, well-interconnected channel sand under pressures of several hundred pounds per square inch is accidentally cut into during surface mining, catastrophes such as blowouts and high-wall failure could easily occur; moreover, the long-term environmental impacts could be increased. Similarly, the success and impacts of underground gasification will greatly depend on hydraulic conductivity and interconnectedness of sands and silts surrounding the burn zone. Planners and operators of deep mines or gasifiers will need to know the architecture of both lignites and sands in detail.

The first step in characterizing sand-body architecture is the construction of regional sand isolith maps, such as figure 3. The maximum-sand belts delineate areas most likely to contain well-interconnected channel-fill sands. Note that the Sabine Uplift area contains several extensive interchannel areas, where average hydraulic conductivities should be fairly low. Sand resistivity mapping has also proved useful for delineating preferred avenues of ground-water movement and, in turn, avenues of well-interconnected sands (Ayers and Lewis, 1983).

The effects of sand-body architecture on ground-water flow were quantitatively studied by Fogg and others (1983), who numerically modeled three-dimensional ground-water flow through Wilcox depositional systems. The area of the model centers on deep-basin lignite resource block 8 in east-central Texas (fig. 1). This area is downdip of the outcrop, where the Wilcox is regionally semiconfined. The model was constructed using data on hydrostratigraphic facies, which were characterized and mapped by interpretation of both lithofacies and hydraulic conductivity. The modeling results demonstrated that sand-body interconnectedness is of pivotal importance to ground-water flow rates and directions. Specifically, the model yielded ground-water flow rates on the order of 10^{-2} to 10^{-3} ft/day (3×10^{-3} to 3×10^{-4} m/day) in sections where channel-fill sands are numerous and interconnected, but rates of 10^{-3} to 10^{-5}

ft/day (3×10^{-4} to 3×10^{-6} m/day) in sections where channel-fill sands are either missing or too sparse to be interconnected (that is, in interchannel areas). The model also demonstrates that to maintain the observed vertical hydraulic gradients, vertical interconnectedness of Wilcox sands must be generally poor. The ratio of average vertical hydraulic conductivity to average horizontal hydraulic conductivity in the Wilcox is very low (less than approximately 10^{-3} to 10^{-4}). The low ratio is favorable to mining because it retards the vertical leakage (recharge) to sands that will drain laterally into a surface mine or to strata that will be tapped by an underground gasifier. Areas having vertically well-interconnected sands will register very small vertical hydraulic gradients. Such areas can thus be identified using local head data and the vertical gradient map (figs. 6 and 7).

Perhaps the most significant conclusion of Fogg and others (1983) is that lateral interconnectedness of channel-fill sands and hydraulic conductivity of the less permeable interchannel sands are key uncertainties in predicting Wilcox ground-water flow. We are currently researching geostatistical methods that will help resolve this interconnectedness problem. A hydrogeologic drilling and testing program is underway that will provide data on hydraulic properties of the interchannel sands.

Ground-Water Velocity With Depth

In any horizontally stratified aquifer, ground-water flow rates are expected to decrease with depth owing to increasingly greater isolation from topographically driven hydraulic gradients. The Sabine Uplift area and the greater East Texas Basin are no exceptions, as evidenced by vertical hydraulic gradient data presented in figure 6 and by Fogg and Kreitler (1982) and Fogg and others (1983). The data show rates of head decrease (recharge areas) and increase (discharge areas) with depth that would significantly decrease ground-water flow rates. For example, consider two points, one located in a recharge area and the other in a discharge area. If the water-table elevations are 400 and 200 ft (121.9 and 61.0 m), respectively, and the corresponding vertical hydraulic gradients are -0.20 and +0.20 (fig. 6), heads at a depth of 500 ft (152.4 m) would be 300 ft (91.4 m) at both locations. In other words, horizontal flow rates would be virtually zero at 500 ft (152.4 m). It is doubtful that flow rates ever become zero because the vertical hydraulic gradients probably also decrease (move closer to zero) with depth, which would result in a measurable horizontal gradient. Two important questions then arise: What is the head distribution in the deep-basin Wilcox, and is there a zone at depth where flow rates are, for practical purposes, zero? Further, does the top of this zone coincide with the base of fresh water (which generally lies in the middle or lower third of the Wilcox, depending on sand distribution)?

Current head data, which are primarily from the upper third of the Wilcox, are inadequate for answering these questions. A chief goal of our hydrogeologic testing program is to collect deeper head data, to 1,700 ft (518 m), using a downhole-pressure tester and water wells screened in selected intervals. The results should allow us to (1) predict deep Wilcox potentiometric surfaces from shallow data and (2) identify deep intervals having low ground-water flow rates that would be favorable for underground gasification.

Other Uses of the Regional Data

Mine Permitting

Permit applications for lignite mining should include data on site stratigraphy, hydraulic head and ground-water flow directions, and background water chemistry or quality. The regional maps and plots being generated by this study will elucidate site-specific data and provide predictive capabilities that will aid in design of ground-water data collection and monitoring programs. The regional characterization is a useful predictive tool because the hydraulic forces and depositional and chemical systems that govern Wilcox-Carrizo hydrogeology function on a regional scale.

The Railroad Commission of Texas must evaluate the technical validity and adequacy of mine permit applications. To be effective, evaluators need a good working knowledge of how the lignite/aquifer system works. Regional aquifer characterization provides a necessary framework for evaluating the permits and keeps State officials informed about the natural resources that they regulate.

Exploration and Site Selection

The sites most suitable for exploitation of deep-basin lignite will have both lignite resources and favorable hydrogeologic conditions. For instance, major channel-fill sand complexes (fig. 3) are less suitable because deep mining or gasification would jeopardize both resource recovery and the environmental integrity of the area.

Locations of recharge and discharge areas are also important to site selection (figs. 4 through 10). Deep surface mining in a major recharge area could disrupt the natural water balance and quality that sustain important fresh-water resources in the Wilcox and Carrizo. On the other hand, the fact that hydraulic head in recharge areas generally decreases by 5 to 50 ft per 100 ft of depth (fig. 6) indicates that dewatering or depressurization of deep sands in recharge areas would be somewhat easier than in discharge areas. Such vertical head differentials may in fact be exploitable with gravity connector wells, which could be used to drain upper aquifers into lower aquifers, thereby conserving both electricity (for pumping) and water resources.

In discharge areas, upward-moving ground water and a thin or nonexistent unsaturated zone would probably hinder efficient dewatering or depressurization of a mine. Moreover, in a discharge area, the chances are greater that contaminants leached from mine or gasifier wastes would be discharged to streams or shallow wells in significant concentrations.

The transition zone between recharge and discharge areas would perhaps be the most favorable hydrodynamic setting for a deep surface mine. As discussed previously, a favorable hydrodynamic setting for an underground gasifier may lie at depths where ground-water flow rates are very low.

The most favorable hydrochemical setting would be where water quality is already relatively poor. Preliminary mapping of the base of fresh water in the Sabine Uplift area has shown that TDS of much of the Wilcox ground water exceeds 1,000 mg/L. The resistivity versus TDS plot in figure 11 is the basis for the mapping.

Lignite Quality

Ground-water chemistry may provide clues to quality of the associated lignite. Analyses of deep-basin lignite obtained in Shelby and Panola Counties have revealed exceedingly high sodium contents (5- to 14-percent Na_2O in ash) compared with those in shallow Wilcox lignite currently being mined in Texas (<1 percent). High levels of sodium pose a serious threat of boiler fouling. Two possible sources of the high-sodium lignites are (1) high-sodium ground waters (>200 mg/L) that have evolved progressively along flow paths because of water/rock interactions and (2) brackish depositional waters that have not been completely flushed from the lignites. If the former explanation is correct, and it might be in view of the fact that the majority of sodium in low-rank coals is on cation-exchange sites, then one should expect that nearly all deep-basin lignites in the Wilcox Group would be high in sodium, irrespective of depositional environment. However, the latter explanation is consistent with the deltaic depositional environment assigned to these lignites. Our ongoing research of Wilcox depositional systems, ground-water chemistry, and lignite quality will, we hope, allow us to clearly identify the source of the Na^+.

HYDROGEOLOGIC DRILLING AND TESTING PROGRAM

A hydrogeologic drilling and testing program has been designed for the Sabine Uplift area to collect generically relevant information that will fill the key data gaps that we have identified. Seven test sites scattered throughout the region have been selected, and, depending on funding, additional sites will be chosen in the east-central lignite belt (fig. 1). Objectives of the program are as follows:

1. Collect data on vertical distribution of hydraulic head from shallow to deep Wilcox intervals. These data are needed to understand deep-basin ground-water circulation and may prove useful in picking optimal sites for underground gasification.
2. Test hydraulic conductivity of the lignites, which is virtually unknown in the Sabine Uplift area. Such data are needed to assess the feasibility of underground gasification, where seam conductivity is crucial to linking using reverse combustion (McKee and others, 1981).

3. Test hydraulic conductivity and continuity of the relatively fine grained interchannel sands, which commonly lie over or under lignites and hence affect feasibility of in situ gasification. These sands are also important because they form the connective framework between channel-fill sands.
4. Test hydraulic conductivity and continuity of channel-fill sands, which are the principal Wilcox aquifers.
5. Collect water samples from deep-basin strata to analyze for major ions and determine carbon-14 ages. In interchannel-splay and overbank sands, water-chemistry parameters such as the log ($[Na^+]/[Ca^{2+}]$) ratio and the log ($[Ca^{2+}]$ $[Na^+]$) product (figs. 8 and 10) should be high, reflecting longer residence times. These and other activity indices may be effective tools for assessing the degree of interconnection between major channel sands, where ground-water circulation is more active. Fogg and others (1983) hypothesized that ground-water ages could approach 10^6 years in interchannel areas owing to apparently low ground-water flow rates. Carbon-14 samples from the poorly understood interchannel sands will be used to test this hypothesis.

Methods will include downhole-pressure tests using a Schlumberger Repeat Formation Tester and pumping tests in production wells completed in lignites and sands. Pumping tests will last from 8 to 72 hours. It is hoped that the longer tests will detect lateral boundaries (or sand-body continuity) or vertical leakage across aquitards, or both. If hydraulic conductivity of the lignites is excessively low, slug tests might be used (Freeze and Cherry, 1979).

SUMMARY

Because the principal lignite host in Texas, the Eocene Wilcox Group, is also a major fresh-water aquifer, deep surface mining or underground gasification of lignite poses unanswered questions concerning hydrogeologic feasibility and environmental impacts. The present study provides a hydrogeologic framework for addressing these questions. Our results will be useful to (1) study of mining and gasification feasibility, (2) preparation and evaluation of mine permits, (3) exploration and site selection, and (4) prediction of lignite quality.

Regional sand isolith mapping (fig. 3) helps delineate both lignite occurrence and distribution of the hydrologically important channel-fill sands. Three-dimensional mapping of hydraulic head data (figs. 4 through 7) defines recharge and discharge areas and ground-water circulation patterns. Vertical hydraulic gradients in the Wilcox indicate that ground-water velocities decrease markedly with depth in the Wilcox and that potentiometric surfaces constructed from shallow-water data may greatly overestimate magnitudes of the deeper hydraulic gradients. The mapped vertical hydraulic gradients can be used together with local head data to assess vertical interconnectedness of sands and feasibility of mine dewatering by gravity drainage wells. Heads in the Wilcox generally decrease considerably with depth.

Mapping of hydrochemical changes (figs. 8 through 10) that are linked to water/rock interaction through solution-mineral equilibria of the aquifer provides baseline information on ground-water quality and the natural processes that affect it. Hydrochemical mapping also helps to define recharge areas and relative ages of ground waters. Further details on general chemical composition of ground water can be obtained from electrical resistivity logs and empirical relations between resistivity and concentrations of dissolved solids (fig. 11). High-sodium deep-basin lignite could be attributed to high-sodium ground waters that typify the deeper Wilcox sands.

Integrated with the interpretation of existing data is a drilling and testing program designed to collect pertinent data on distribution of hydraulic head deep within the Wilcox aquifer, on hydraulic conductivity of the lignites and associated sands, on continuity of selected sands, and on the hydrochemistry of Wilcox ground water.

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