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HYDROGEOLOGY OF GULF COAST AQUIFERS, HOUSTON-GALVESTON AREA, TEXAS[1]

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ABSTRACT

Aquifers in the Houston-Galveston area are composed principally of fluvial-deltaic sediments. The Alta Loma Sand is a complexly faulted, high-sand-percent unit that represents a seaward progression of fluvial, delta-plain, and delta-front facies. The Beaumont Formation, overlying the Alta Loma Sand, is a high-mud-percent unit that represents a coastal progression of delta-plain to delta-front facies. Four arbitrarily defined intervals from land surface to 2000 ft indicate superposition of dip-oriented and strike-oriented high-sand-percent trends.

Aquifer geology partly controls short-term and long-term aquifer hydrology. Dip-oriented high-sand-percent trends are optimum locations for ground-water development. Growth faults act as partial hydrologic barriers to ground-water production. Faults between Harris and Galveston Counties have partly isolated the aquifers into two subsystems. In Harris County ground water of low dissolved solids is meteoric in origin, whereas in Galveston County ground water of low dissolved solids is a mixture of meteoric and saline waters.

INTRODUCTION

Gulf Coast aquifers represent some of the most prolific sources of fresh ground water in the United States (McGuinness, 1963). In the Greater Houston, Texas, area, more than 500 million gallons per day of ground water are produced from the fresh-water section of the Plio-Pleistocene, fluvial-deltaic sediments. Severe land subsidence and fault activation, however, have resulted from this intensive production (Kreitler, 1977). Therefore, a balance between ground-water production and minimizing its adverse effects is requisite.

Previous workers (Payne, 1968, 1970, 1973, 1975; Hall, 1976; and Galloway, 1977) studying the Lower Tertiary and Cretaceous sections of Texas and Louisiana have documented the effects of aquifer geology on the occurrence of high-permeability zones and the occurrence of fresh ground water by identifying dip-oriented high-sand trends along which fresh ground water has moved further downdip. A similar approach has been applied to the study of the Greater Houston area to test whether the geologic framework exerts any control on the hydrology of the aquifers.

The principal objectives of this study are: (1) to delineate the distribution of sands and clay and structural elements in the Plio-Pleistocene aquifers beneath the Greater Houston area, (2) to identify genetic stratigraphic units, (3) to synthesize data on ground-water chemistry for the study of hydrochemical facies trends, and (4) to establish the effects of sediment distribution, growth faults, and Quaternary sea-level changes on long-term and short-term hydrology of Gulf Coast aquifers.

STRATIGRAPHIC AND HYDROLOGIC UNITS

Upper Pliocene and Pleistocene strata that crop out on the southeast Texas Coastal Plain consist principally of interbedded mud, sand, and gravel facies of fluvial-deltaic origin. Pleistocene stratigraphic units commonly recognized in the coastal plain are the Willis (originally defined by Doering, 1935), the Lissie (originally defined by Deussen, 1914), and the Beaumont Formations (originally defined by Hayes and Kennedy, 1903), from oldest to youngest respectively (Table 1). Since 1903, at least seven different stratigraphic classifications have evolved. Guevera-Sanchez (1974) identified only the Beaumont and undifferentiated Lissie-Willis in the subsurface.

A similar proliferation of hydrologic classifications have developed. Rose (1943a) classified the Upper Miocene-Pliocene-Pleistocene sediments into seven zones. Major ground-water production is from the shallower zones, zones 5 and 7. Within zone 7, Rose (1943b) identified the Alta Loma Sand, which he characterized as a massive, highly transmissive, latterally extensive sand. Wood and Gabrysch (1965) grouped Rose's zones 3, 4, 5, 6 and part of 7 into "the heavily pumped layer," recognized the Alta Loma Sand as a massive highly permeable sand, and considered the Beaumont Clay, which extends from land surface to the top of the Alta Loma Sand, as a confining layer. Jorgensen (1975) reclassified the aquifers into the Chicot and the underlying Evangeline aquifers. He defined the Alta Loma Sand as the base of the Chicot aquifer (Table 1).

PERCENT-SAND MAPS

Aquifer sand distribution was determined by the construction of six percent-sand maps using available electric logs from Harris and Galveston Counties and parts of Fort Bend, Brazoria, Chambers, and Liberty Counties. Twenty dip and strike cross sections across the study area (Fig. 1) were used to define the Alta Loma Sand and Beaumont Clay, which were found to be stratigraphic units that could be correlated through out the study area. The Alta Loma Sand is defined as the first massive and laterally extensive sand in the shallow subsurface (Fig. 2) and is equivalent to the Alta Loma Sand as defined by Rose (1943b) and Wood and Gabrysch (1965). The Beaumont Formation is defined as the unit overlying the Alta Loma Sand (Fig. 2). After the top and base of the Alta Loma were identified on cross sections, percent-sand maps of the Alta Loma (Fig. 3) and overlying

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Table 1. Geologic and hydrologic units used in this report and in recent reports.

System	Series	This Report: Arbitrary Units	This Report: Genetic Units	Guevera-Sanchez (1975) and Jorgensen (1975) Stratigraphic Units	Jorgensen (1975) Hydrologic Units	Wood and Gabrysch (1965) Hydrologic Units
Quaternary	Recent	0-500 ft	Beaumont	Quaternary Alluvium	Chicot aquifer: Upper Unit	Beaumont and Alta Loma Sand (Rose, 1943b)
	Pleistocene		500 ft*	Beaumont	350 ft*	
				Lissie	Lower Unit	
Tertiary	Pliocene	500 to 1000 ft	Alta Loma 700 ft*	Willis	600 ft*	700 ft*
				Goliad	Evangeline Aquifer	Heavily pumped layer
		1000 to 1500 ft				
		1500 to 2000 ft			3750 ft*	3500 ft*

* approximate depth to base of unit at Harris-Galveston County line.

Beaumont (Fig. 4) were constructed. In addition percent-sand maps were made of arbitrarily defined 500-foot intervals from the surface downward, 0 to 500 feet (Fig. 5), 500 to 1,000 feet (Fig. 6), 1,000 to 1,500 feet (Fig. 7) and 1,500 to 2,000 feet (Fig. 8). Faults in the Alta Loma Sand (Fig. 3) are identified by offsets observed on dip and strike cross sections.

Alta Loma Sand

The Alta Loma Sand is a complexly faulted, fluvial-deltaic genetic stratigraphic unit. The percent-sand map (Fig. 3) shows a major dip-oriented high percent-sand trend extending through eastern Harris and western Chambers Counties and southward into Galveston County. A second dip-oriented high percent sand trend occurs in western Harris and western Galveston Counties. The dip-oriented high percent sand trends in western Harris County are interpreted as being fluvial facies. Laterally they abruptly grade into a mud section interpreted as floodbasin facies (section a-a′, Fig. 9). In Brazoria County and Galveston County the high percent sand trend is dominated by deltaic distributary channel-fill sands; electric log patterns indicate massive, blocky sands which laterally grade to a mud section which is considered to be delta-plain facies (section b-b′ Fig. 9). In southern Galveston County the strike-oriented high percent sand trends are interpreted as delta-front facies (Fig. 9). These sands are thick and laterally extensive with few mud interbeds (section d-d′ and e-e′). Electric log patterns show a coarsening-upward sequence, commonly indicative of delta-front facies (Fig. 9). This resistivity change on the electric log pattern, however, may be caused by a fresh-water/salt-water transition zone.

The Alta Loma Sand is extensively growth faulted (Fig. 3 and Fig. 9). Fault movement occurred contemporaneously with deposition as evidenced by the thicker sand sections on the downthrown sides of the faults. The Alta Loma doubles in thickness from 200 ft thick in Harris County to 400 ft thick in Barzoria and Galveston Counties as it crosses several faults.

Beaumont Formation

The Beaumont deposits (Fig. 4) in Harris and Galveston counties are composed of much more mud than the underlying Alta Loma Sand (Figs. 3 and 9). The two principal sand thicks include (1) a dip-oriented high percent-sand trend that extends from western Harris County through Galveston County, and (2) a strike-oriented, high-percent sand trend that crosses southern Galveston and Brazoria counties. A much sandier section occurs in Fort Bend and Brazoria counties.

High mud sections (low percent sand) in Harris and Galveston Counties represent delta-plain facies. Dip-oriented sand trends through Fort Bend, Brazoria and Galveston Counties are deltaic distributary-channel facies. Strike-oriented sand trends are interpreted as delta-front sand facies. The surficial geology of the Beaumont Formation (Fisher and others, 1972) exhibits sand trends similar to those mapped within the subsurface Beaumont (Fig. 10). At the surface, dip-oriented distributary-sand facies extend across Harris, Galveston, Chambers, and Brazoria Counties. Strike-oriented delta-front sands occur along southern Galveston and Brazoria Counties.

Arbitrarily-Defined Intervals

The base of the Alta Loma Sand, the major fresh-water-producing sand, is at a depth of 1100 feet in southern Galveston County (Fig. 9). Extensive production of fresh water from Plio-Pleistocene sediments, however, extends to depths of 2000 feet. Genetic stratigraphic units could not be delineated below the Alta Loma because of the inability to identify laterally extensive marker beds which are required to subdivide the section. Maps of arbitrarily-defined 500-foot intervals, therefore, were made to delineate sand distribution in the upper 2000 feet of section. The arbitrarily-defined intervals have tops and bases of constant, defined elevations, whereas the elevations of Alta Loma Sand and Beaumont Formation vary because they are stratigraphic units that dip towards the

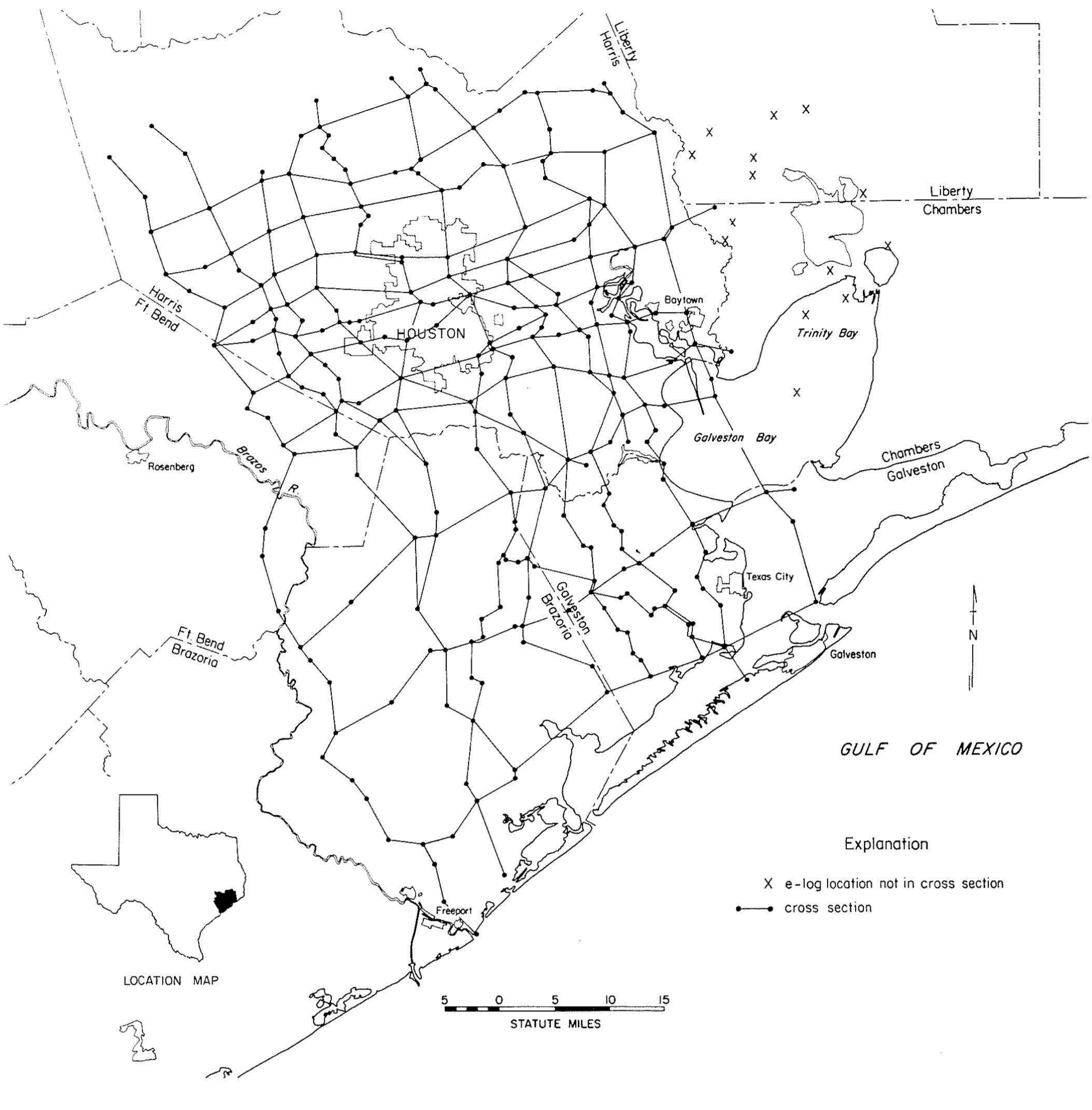

FIGURE 1. Map showing distribution of data points and cross sections used in constructing maps in figures 3-8.

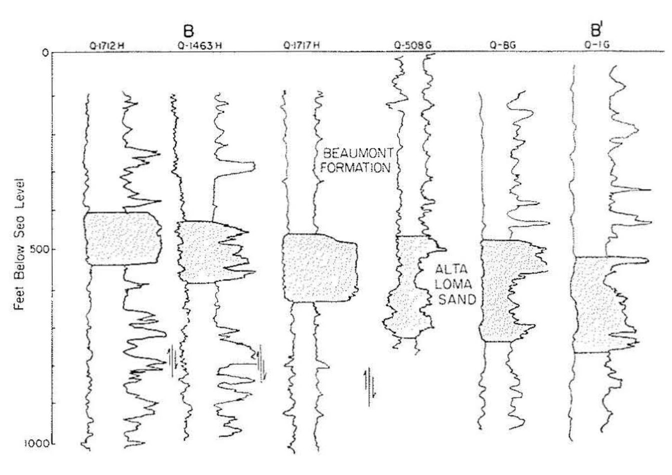

FIGURE 2. Typical electric log patterns of Alta Loma Sand and Beaumont Formation. See figure 3 for profile location.

coast. The 0 to 500 foot interval (Fig. 5) is composed of sections of both the Beaumont Formation and Alta Loma Sand and therefore resembles the percent-sand maps of the Beaumont (Fig. 4) and the Alta Loma Sand (Fig. 3). Dip-oriented sand trends occur in western Harris, through Brazoria, and Galveston counties. Strike-oriented high percent sand trends occur in southern Galveston and Brazoria Counties. Mud-rich sections occur in Harris County.

Two dip-oriented high percent sand trends dominate the 500 to 1000 foot interval (Fig. 6). One high percent sand trend occurs in eastern Harris County; the second trend crosses western Harris, Brazoria, and Galveston Counties.

Figure 7, the 1000 to 1500 foot interval, shows two dip-oriented high percent-sand trends through Harris County and ending in Galveston County. In Brazoria County this interval contains a dip-oriented, high percent-sand trend.

The 1500 to 2000 foot interval (Fig. 8) contains less sand than any of the other intervals. No major dip-oriented high percent sand trends were observed.

Superposition of High Percent-Sand Systems

The percent-sand maps of the Alta Loma Sand (Fig. 3) the Beaumont Formation (Fig. 4) and the surface sand distribution map of the Beaumont (Fig. 10) exhibit similar dip-oriented high sand trends in western Harris, northern Brazoria and western Galveston County. All three maps show strike-oriented sand trends along the present-day coast. A similar relationship can be observed on the arbitrarily defined interval maps, 0 to 500 foot interval, 500 to 1000 foot interval and 1000 to 1500 foot interval. This stacking or superposition suggests a structural instability that maintained major drainage and deltaic deposition in the same area during deposition of most of the aquifer deposits. Similar stacking of older coastal plain systems is noted by Fisher and McGowen (1967).

GROUND-WATER CHEMISTRY

Hydrochemical facies are commonly indicative of sources of recharge and direction and rates of ground-water movement. Trends in ground-water chemistry for the interval between 100 to 1000 feet in Harris and Galveston Counties were derived from Gabrysch and others (1971, 1974) in an attempt to understand better ground-water flow in these aquifers. Water chemistry data and the ionic relationships observed in the ground waters of Harris and Galveston Counties are presented here. Their geologic implications are discussed in the next section.

1. In Harris County Na^+ and Ca^{++} are inversely related (r = -0.86, n = 229) (Fig. 11). As ground water moves from northern Harris to central Harris County, Ca^{++} decreases and Na^+ increases with a Na^+/Ca^{++} mole ratio of 2.2:1 for Na^+ concentrations less than 115 mg/1.

2. Harris County ground waters show a direct correlation between Na^+ and HCO_3^- with a mole ratio of 2.8 to 1 (r = 0.80, n = 360) (Fig. 12). In Galveston County, Na^+ increases rapidly with small changes in HCO_3^-. Bicarbonate measurements were made in the laboratory (Gabrysch, personal communication, 1977) and therefore are slightly lower than actual values (Robertson and others, 1963).

3. Harris County ground waters have Na^+ concentrations that increase independently of Cl^- (Fig. 13). In Galveston County, Na^+ and Cl^- ions are directly related (r = 0.96, n = 86) with a mole ratio of 0.95 to 1.

HYDROLOGIC IMPLICATIONS OF AQUIFER GEOMETRY AND PLEISTOCENE HISTORY

The effect of the geology on aquifer hydrology should be considered for two cases: local, short-term, non-equilibrium, responses (the effects of ground-water pumpage), and the regional, long-term equilibrium responses (rates and direction of ground-water flow).

Short-term Effects

Optimum ground-water production from Gulf Coast aquifers occurs where high rates of ground-water withdrawals result in minimal potentiometric surface decline and minimal land subsidence. Optimum development, therefore, would be from the high percent-sand sections, such as the Alta Loma Sand (Fig. 3) and the 500 to 1000 foot interval (Fig. 6) in preference to development of the high mud sections, such as the Beaumont Formation and the 1500 to 2000 foot interval (Fig. 8).

Dip-oriented, sand trends in the high percent sand sections offer the best locations for future water-well fields. These sands are thick, highly permeable parts of the aquifer. Specific capacities (ground water pumped per unit water level decline in the well) of wells producing from these sands should be large. Because of the massive nature of the sands, there is little interbedded mud, and consequently these units are not as susceptible to subsidence. Superposition of thick sands will facilitate vertical recharge. The dip-orientated sand trends are parallel to the regional hydraulic gradient which also should facilitate additional recharge from the stratigraphic updip section. The cone of depression that develops from ground-water pumpage within a dip-oriented sand trend would be elliptical with the long axis parallel to the sand trend. The high percent mud sections on either side of the sand trend would act as partial hydrologic barriers, limiting the effects of piezometric decline and subsidence in the strike direction.

Growth faults also affect the short-term hydrology of the aquifer. Faults create partial or total hydrologic barriers that restrict ground water movement, piezometric decline, and subsequent land subsidence. The Ethyl fault, an antithetic fault in Pasadena, Texas, south of the Houston Ship Channel, has been traced from land surface to depths of several thousand feet. Closely spaced borings across the fault (Fig. 14) shows that eight sand units have been offset by the fault (Woodward-Lundgren and Associates, 1974). The percent offset, the ratio of displacement to bed thickness, varies from 40 percent to complete offset of the sand bed.

In comparison to ground-water flowing through a non-faulted sand, the hydraulic gradient across a faulted sand will steepen as the percent of fault offset increases. Elevation of the potentiometric surface will be lower on the ground-water producing side of the faulted sand in comparison to the nonproducing side. Resultant sediment compaction will be greater on the producing side.

Ground-water pumpage is approximately three times greater on the downthrown side of the Ethyl fault (5600

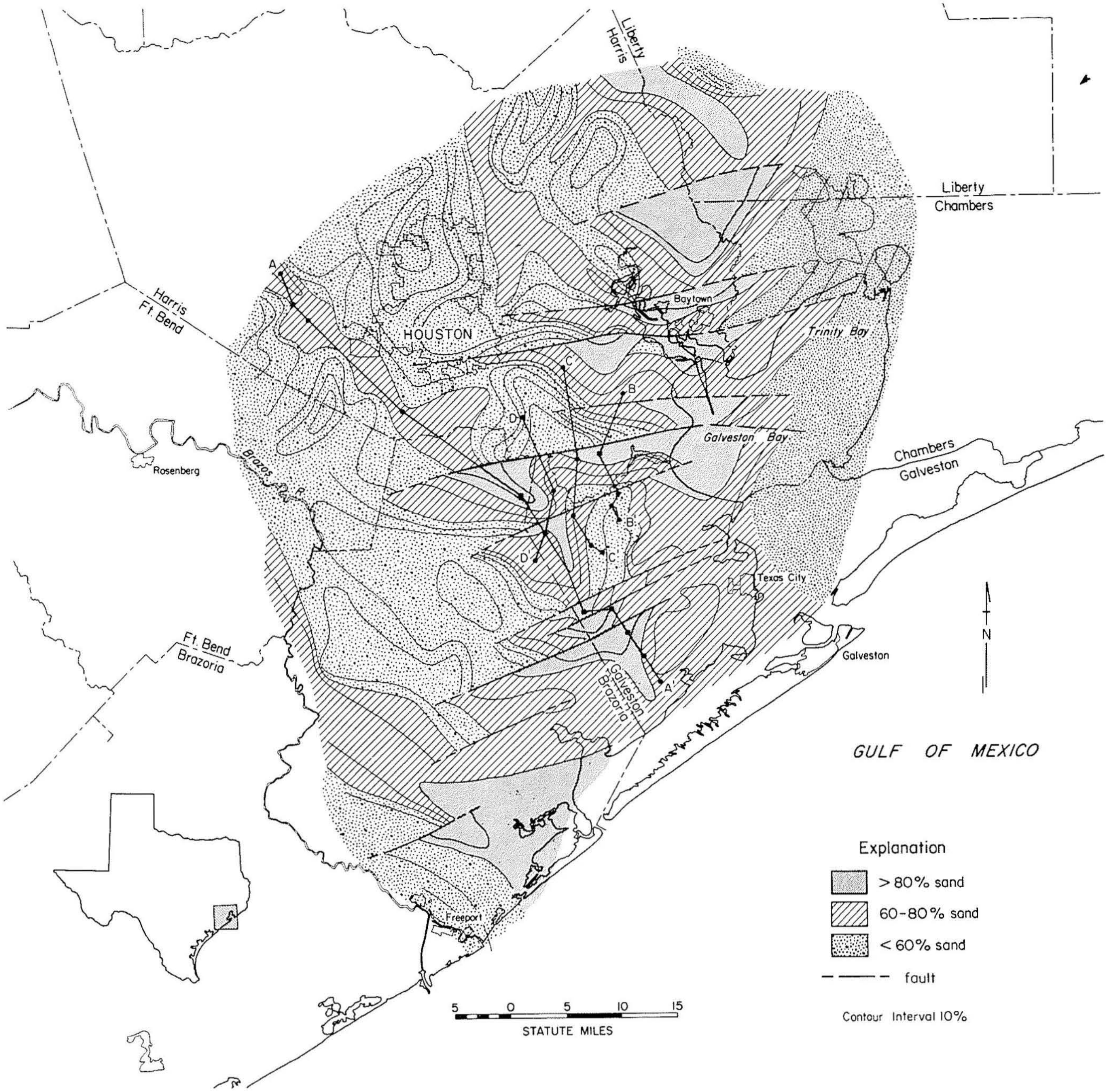

FIGURE 3. Percent-sand map of Alta Loma Sand. Cross sections A-A′, B-B′, C-C′, D-D′, E-E′ on figures 9 and 16. Map construction based on 244 data points (Fig. 1).

million gallons per year) as compared to the upthrown side (1500 million gallons per year). Ground-water production on the downthrown side is from 45 wells (Gabrysch and others, 1974) of which 80 percent produce from this faulted zone. Fifty percent of these wells produce entirely from the top 900 feet. Although no piezometric data are available to confirm a hydrologic barrier at the Ethyl fault, Kreitler (1977) observed different elevations of the potentiometric surface on either side the Long Point and Eureka Heights faults in western Houston.

Fault activation is documented by National Geodetic Survey releveling measurements (1959-1964) which show a 25 percent increase in subsidence across the Ethyl fault from 0.98 foot (upthrown side) to 1.25 feet (downthrown side). This fault movement or differential subsidence is caused by the extensive ground-water production from fault-offset sands and increased compaction on the producing side of the fault.

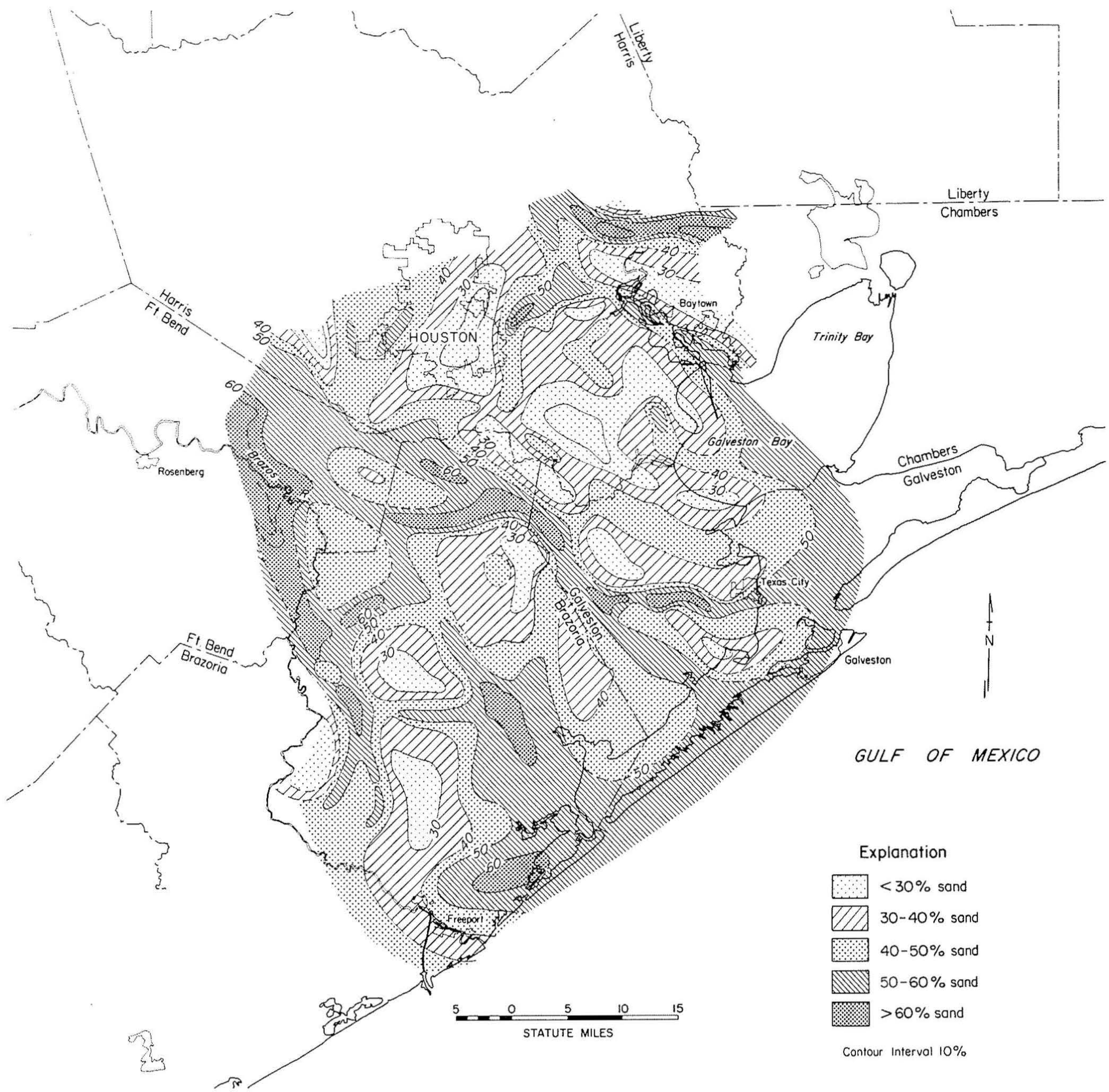

FIGURE 4. Percent-sand map of Beaumont Formation. Map construction based on 210 data points (Fig. 1).

Long-Term Effects

Rates and direction of regional ground-water flow depend on the orientation of the potentiometric surface and the lithology and geometry (boundary conditions) of the aquifer. Based on the potentiometric surface elevation of artesian wells that flowed in the late 1800's and early 1900's (Singley, 1893; Taylor, 1907; and Deussen, 1914), fresh, meteoric, ground-water movement in the Gulf Coast aquifers is toward the coast. Detailed construction of the original potentiometric surface, however, is no longer possible, because extensive ground-water production has altered the shape of this surface. Regional patterns in ground-water chemistry offer more definitive information on sources of water, recharge and discharge zones and direction of ground-water movement.

The fresh-water lens in Harris County (Fig. 15) extends to depths of 3000 feet, whereas in Galveston County the base of fresh water is only 1000 feet (Turner and Foster,

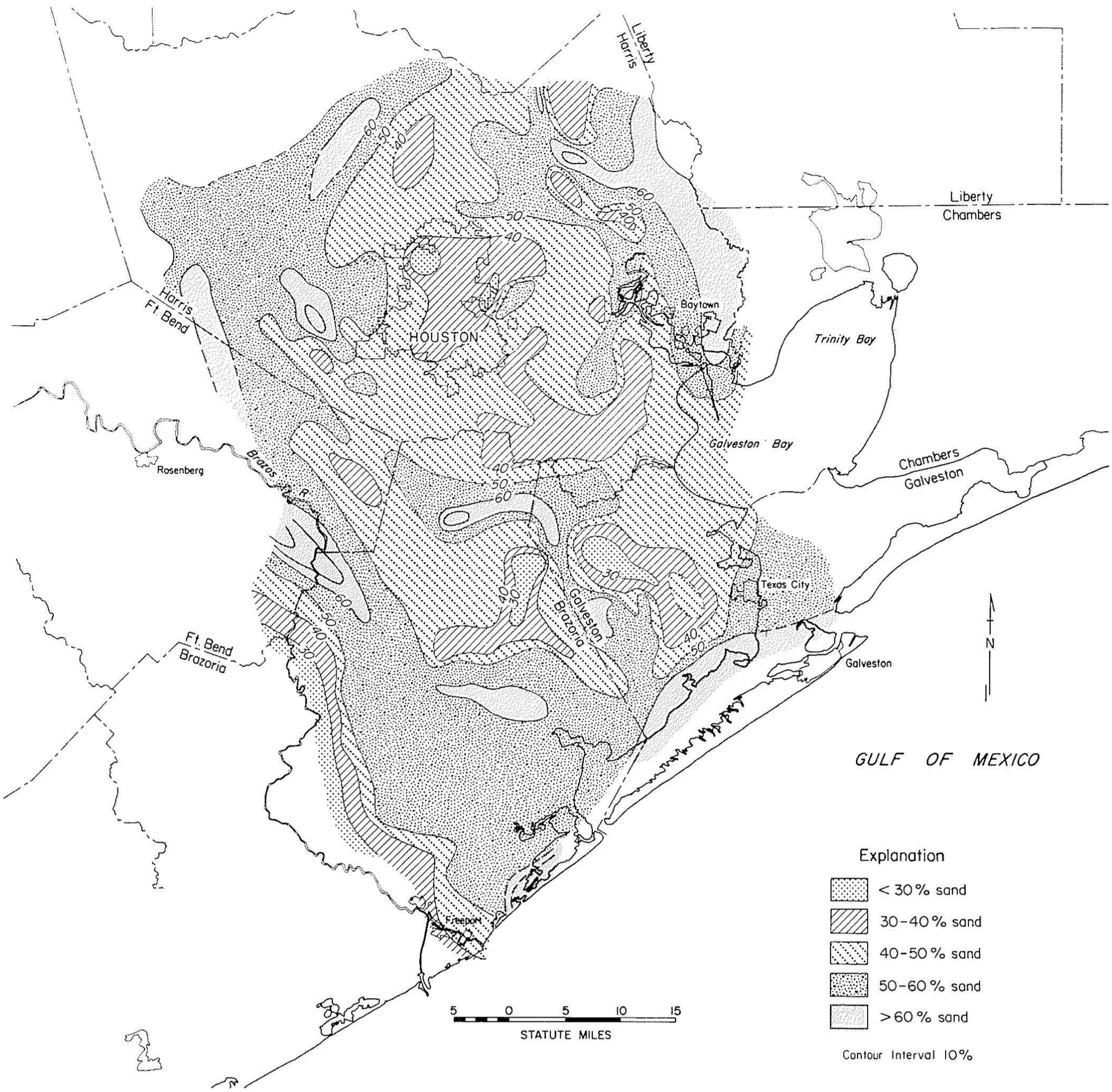

FIGURE 5. Percent-sand map of 0 to 500 feet unit. Map construction based on 228 data points (Fig. 1).

1934; Winslow and others, 1957). The fresh ground water in the two counties is composed of different hydrochemical facies. Harris County waters are Na-Ca-HCO_3-Cl or Na-HCO_3-Cl waters, whereas Galveston County waters are Na-Cl-HCO_3 waters (hydrochemical facies classification from Back, 1966).

Ground water in Harris County appears to be recharged in northern part of the county (as well as in the counties north of Harris) and discharged in southern Harris County. Calcium is the dominant cation in the northern section, whereas sodium is the dominant cation in the southern part of the county (Fig. 11). As residence time (distance of transport) of ground water increases, sodium exchanges for calcium. The longer the residence time, the greater the Na^+/Ca^{++} ratio will be (Foster, 1942, Morgan and Winner, 1962; Back, 1966; Hall, 1976). The slope of the linear regression line for Na^+ versus Ca^{++} (for Na^+-130 mg/1) is 2.2, indicating a slightly greater than 2 for 1

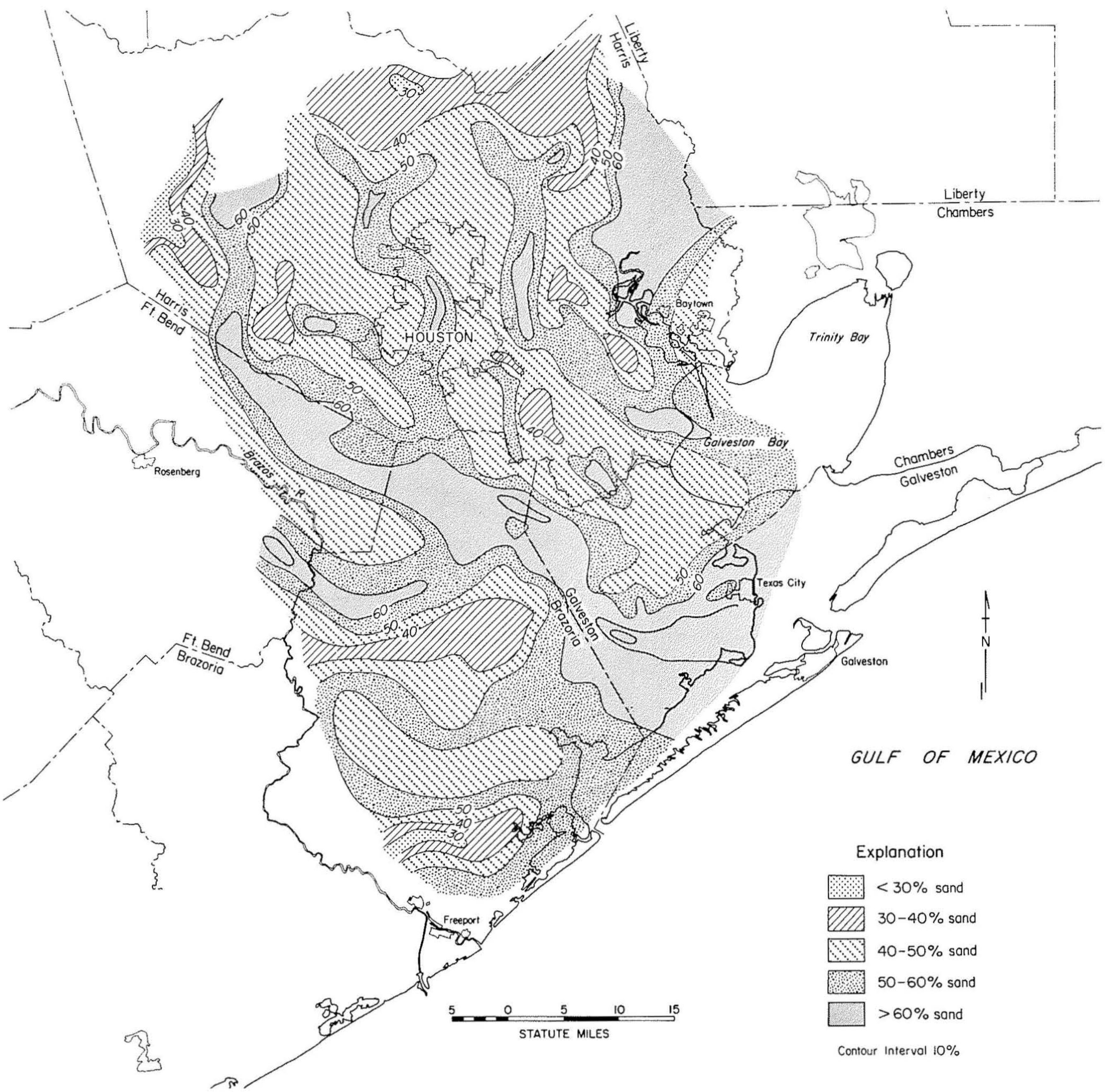

FIGURE 6. Percent-sand map of 500 to 1000 feet unit. Map construction based on 228 data points (Fig. 1).

mole exchange of Na^+ for Ca^{++}. A 2 for 1 exchange should be expected if calcium is exchanged for Na^+ on clays. The Na^+ concentrations keep rising after Ca^{++} concentrations stabilizes at 5 to 10 mg/1 (Fig. 11). Two hypotheses can explain this increase: (1), high Na^+ waters (formation water or sea water) are mixing with the Harris County water or (2) calcium carbonate continues to dissolve, and the additional Ca^{++} is exchanged for Na^+.

Bicarbonate concentrations also increases in direct proportion to sodium (Fig. 12). The slope of the linear regression line for Na^+ versus HCO_3^- indicates a 2.8 to 1 mole-ratio for all Harris County waters. Because of this direct correlation of Na^+ to HCO_3^- (Fig. 12), the sharp increase in Na^+/Ca^{++} ratios is not related to an addition of high Na waters but is related to the second hypothesis.

Foster (1950) argues that decomposition of organic material in the Gulf Coast aquifers is necessary to generate the high-sodium waters. This decomposition of or-

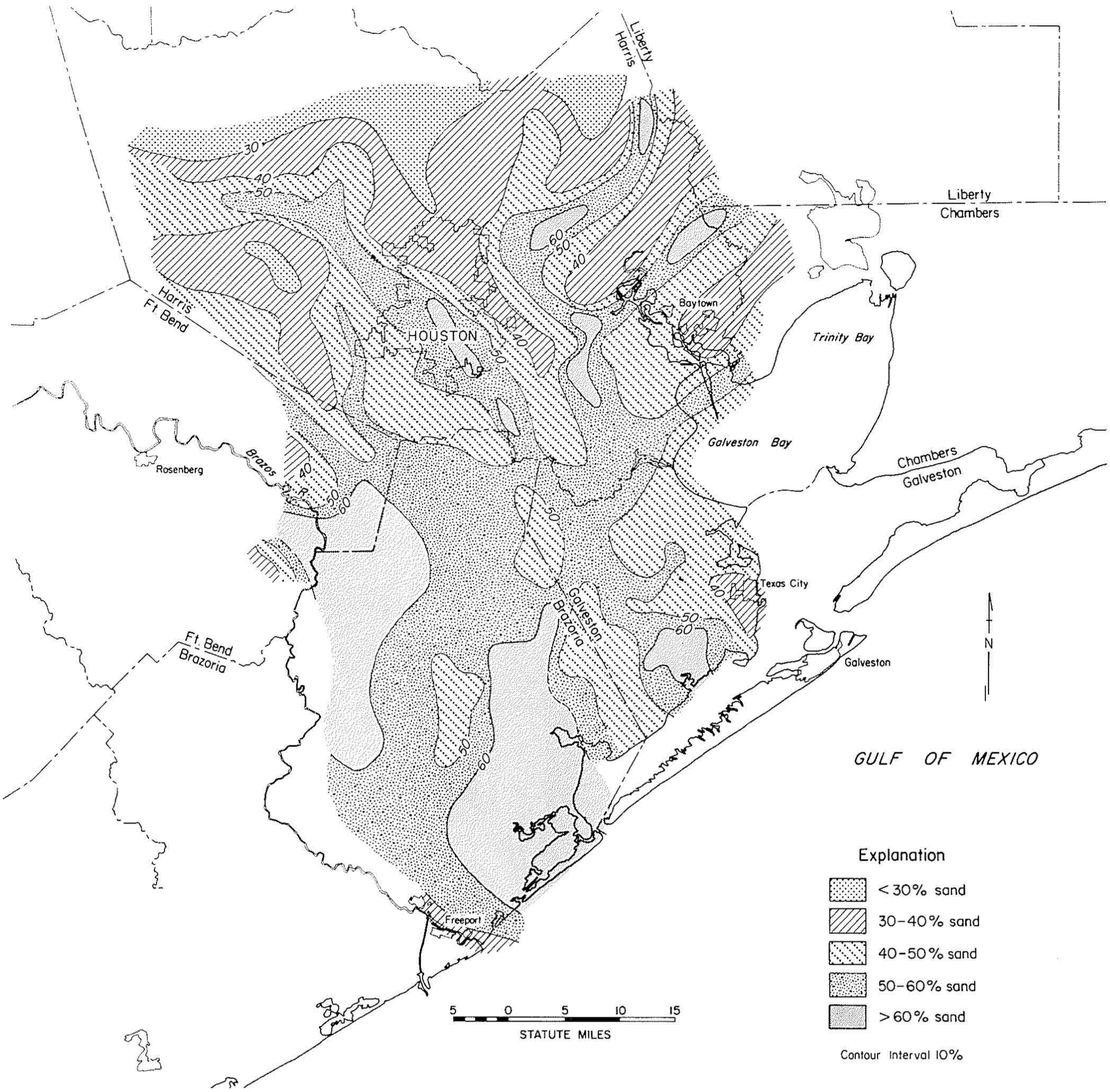

FIGURE 7. Percent-sand map of 1000 to 1500 feet unit. Map construction based on 174 data points (Fig. 1).

ganic material in the Gulf Coast aquifers provides an additional source of CO_2 which permits continuous solution of carbonate minerals and cation exchange of Ca^{++} for Na^{+}. If there is an additional CO_2 source, then equation (1) should describe the reaction.

$$CaCO_3 + CO_2 + 2(Na^{+}\text{-Clay}) + H_2O = 2Na^{+} + 2HCO_3^{-} + (Ca^{++}\text{-Clay}) \quad (1)$$

The Na^{+}/HCO_3^{-} ratio should be 1:1, not 2.8:1. If the system has no additional source of CO_2 then equation (2) should describe the reaction.

$$CaCO_3 + H^{+} + 2(Na^{+}\text{-Clay}) = 2\,Na^{+} + HCO_3 + (Ca^{++}-\text{Clay}) \quad (2)$$

The Na^{+}/HCO_3^{-} ratio for this reaction should be 2:1, which is much closer to the observed ratio of 2.8:1. The observed ratio indicates that decomposition of organic material is not supplying additional carbon dioxide. In

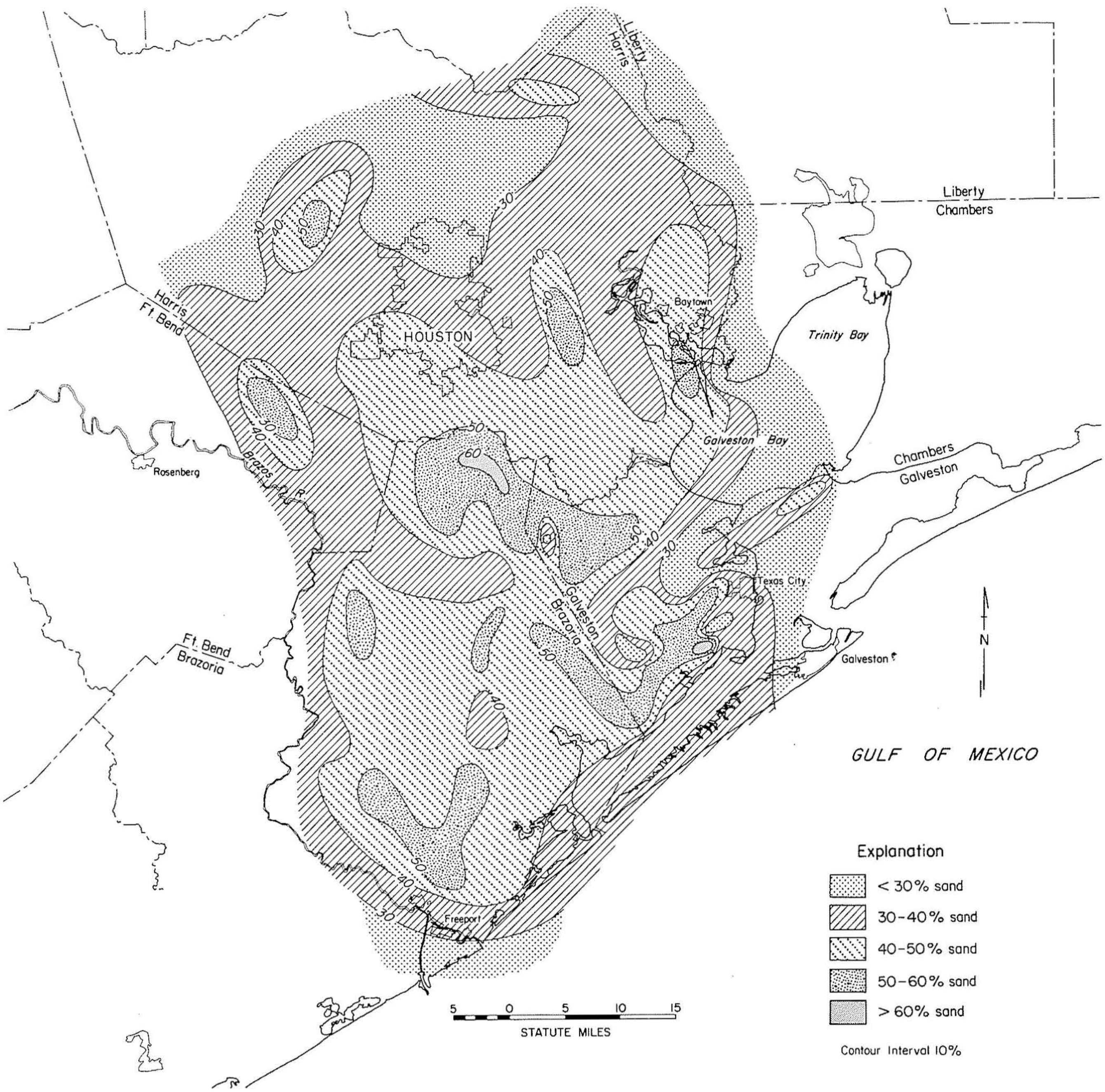

FIGURE 8. Percent-sand map of 1500 to 2000 feet unit. Map construction based on 82 data points (Fig. 1).

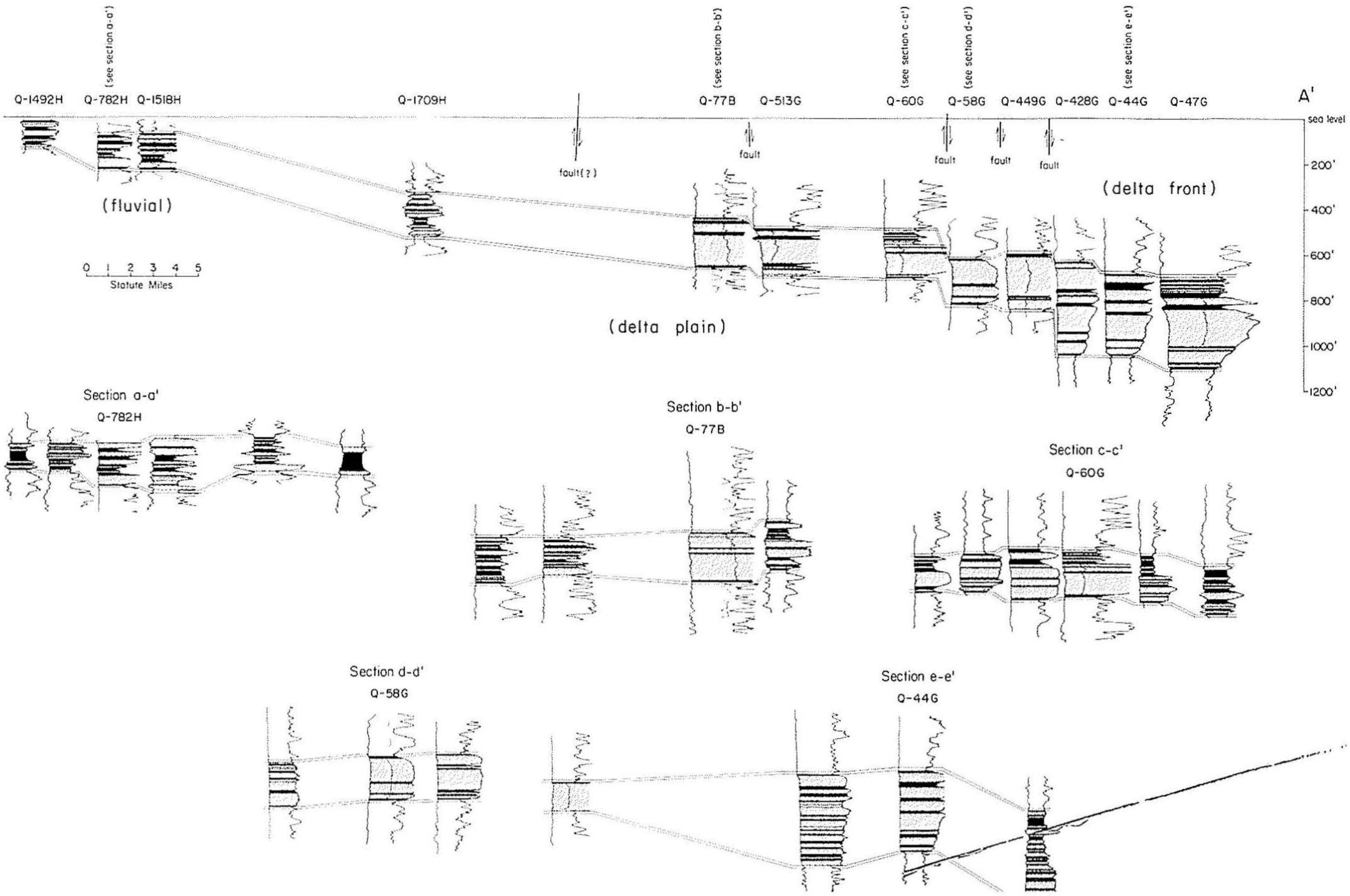

FIGURE 9. Dip and strike cross sections of Alta Loma Sand. Dip section represents transition from fluvial to deltaic to delta-front sedimentary facies. Strike section a-a' crosses fluvial sediments; strike section b-b' crosses deltaic distributary channel and delta plain sediments; and strike sections d-d' and e-e' cross channel-mouth bar and delta-front facies. Location of cross sections on figure 3.

this system, however, a source of hydrogen is needed. Pyrite oxidation is not supplying the hydrogen because the ground waters are low in sulfate.

The Na^+/HCO_3^- ratios for the Carrizo aquifer (Pearson, 1966), the Calvert Bluff aquifer, and Simsboro Sand (Henry, personal communication, 1977) are 1:1, indicating that decomposition of organic material is providing carbon dioxide. The differences in Na^+/HCO_3^- ratios between water in the Tertiary sands and in the Pleistocene aquifer in the Houston area, as well as the additional hydrogen source for the Houston area, are not understood.

In Galveston County, analysis of water chemistry indicates a mixing of meteoric water from Harris County and saline water. In comparison to Harris County waters Na and Cl^- concentrations in Galveston County increase substantially (Fig. 13), whereas Ca^{++} and HCO_3^- concentrations increase slightly (Figs. 11 and 12). Na/Cl ratios are increasing at 0.95:1 mole ratio but no correlation exists between concentrations of Na^+ and HCO_3^-.

Either sea water or formation water is mixing with meteoric water in Galveston to form the Na-Cl-HCO_3 water. Assuming communication of seawater with the aquifer through high-percent-sand trends in Galveston County (Figs. 3, 5, 6, and 7), a fresh water lens overlying intruding sea water could develop. The elevation of the potentiometric surface in Galveston County was approximately 25 to 30 ft above sea level before ground-water development (from data of Singley, 1893 and Deussen, 1914). Using equation (3) (Hubbert, 1940),

$$Z = \frac{\rho f h}{\rho s - \rho f} \quad (3)$$

the fresh-water lens would be 1000 to 1200 feet thick, which is the approximate thickness of the fresh-water lens in Galveston County (Turner and Foster, 1934).

Alternatively, Jones (1968) suggests that the Gulf coastal plain may be a discharge zone for formation water migrating updip from deeper compacting sediments. Water from the saline Miocene Fleming Formation, which underlies the fresh-water aquifer, is typically high in Na^+, Cl^-, HCO_3^- and Ca^{++} (Gabrysch and others, 1974). Elevations of the potentiometric surface of deep wells (3,000 to 7,000 ft) in Galveston County were 10 to 60 feet (1930's to 1940's) below land surface (Gabrysch and others, 1971); thus, formation waters have the hydraulic potential to migrate toward the fresh-water lens. Either source could cause the observed chemical alteration of the Galveston County fresh-water lens.

The structural framework of the aquifer, in part, controls the regional hydrology of Harris and Galveston Counties. A major fault zone between Harris and Galveston Counties separates the different water types to each county. Dip-oriented cross sections show appreciable vertical displacements and abrupt thickening of the Alta Loma sand (Fig. 16). Displacements increase to as much as 200 feet at a depth of 1000 feet.

This fault zone acts as a partial hydrologic barrier that separates two partly independent flow systems —ground-water flow in Harris County and ground-water flow in Galveston County. The abrupt change in elevation of the base of fresh water is coincident with the faulting. Below 1000 feet meteoric ground water apparently is not flowing across the boundary but is discharging into shallower aquifers in southern Harris County, and probably causing the high Na^+/Ca^{++} ratios observed in these waters. Above 1000 feet, some meteoric water is flowing across the fault from Harris County into Galveston County as evidenced by the low dissolved solids of the water in Galveston. Original elevation of the piezometric surface and sodium bicarbonate concentrations indicate no surface recharge of meteoric water in Galveston County.

The fault has greatly reduced the flow and permitted the base of the fresh-water lens in Galveston County to rise to 1000 feet. The fresh-water/saline-water interface represents an equilibrium between the energy potential of the meteoric waters and the energy potential of the saline

FIGURE 10. Distribution of high-permeability sediments (fluvial-deltaic distributary channel-fill and delta front) and low-permeability sediments (delta-plain facies) at the surface of study area. (Modified from Fisher and others, 1972).

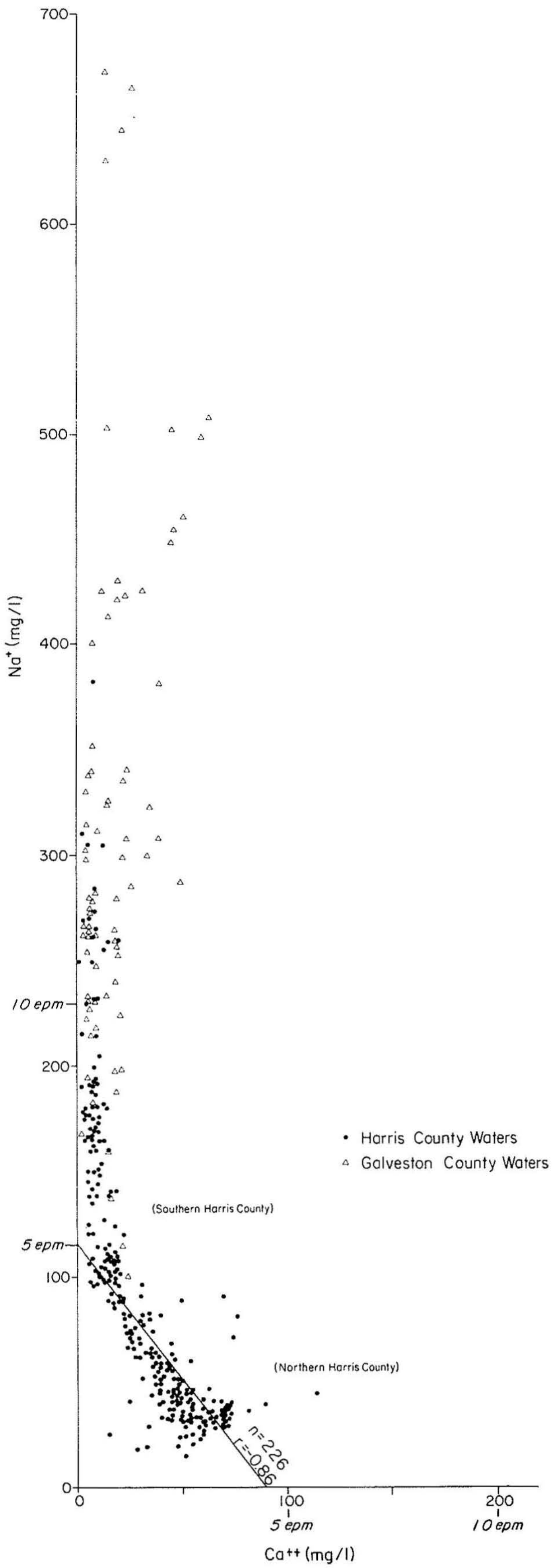

FIGURE 11. Sodium concentrations versus calcium concentrations in shallow ground waters (100 to 1000 feet) of Harris and Galveston Counties. Data from Gabrysch and others (1971 and 1974).

waters. If the hydraulic gradient of the meteoric water lens increases then the interface becomes deeper (as in Harris County); reducing the hydraulic gradient of the meteoric water will cause the interface to rise. This interface, therefore, represents a dynamic equilibrium.

Shallow Gulf Coast saline water has previously been considered to be connate water that is being flushed by fresh meteoric water (Turner and Foster, 1934; Wood and others, 1963). Because of Pleistocene changes in sea level this concept is not feasible. Sea level reached a low stand of approximately 300 feet below present sea level about 18,000 years ago (Frazier, 1974). Shoreline was as much as 120 miles gulfward from its present position (R. Morton, personal communication, 1977), and the San Jacinto-Trinity Rivers eroded deeply in the vicinity of Galveston Bay. Much of the continental shelf was subaerially exposed. The base level of the coastal hydrologic system during Pleistocene low stand was a few hundred feet below its present elevation. The hydrologic regime of the coastal aquifers must have been greatly altered. Present day discharge zones in Harris and Galveston Counties would have been recharge zones 18,000 years ago. The superposed, high percent-sand trends of Harris, Galveston, and Brazoria Counties would have been areas for optimum recharge. At that time meteoric waters would have flushed any saline water from the coastal aquifers. At low stand of sea level fresh ground water probably circulated deep beneath Galveston County.

The hydrologic regime has changed with the rise in sea level. The stacked sand systems, which were recharge zones during low stand of the sea may now be discharge zones. The hydraulic gradient of the meteoric ground water in Galveston County has been greatly reduced, and a new dynamic equilibrium has been reached between fresh water and salt water. Brackish to saline waters in the coastal aquifers are either seawater or deep formation water that has recently intruded, but are not residual waters of deposition that have yet to be flushed from the sediments.

In the Harris and Galveston Counties there is no apparent facies control of water quality as observed by Payne (1968), Hall (1976), or Galloway (1977) for Tertiary and Cretaceous units. Pleistocene sea-level changes and growth faults are the controlling parameters of the hydrochemical facies and over shadow any control from sediment distribution. Facies control of regional groundwater flow probably would become more important in a study of the entire Pleistocene coastal aquifers from Beaumont to Brownsville, Texas, an area that is similar in size with areas studied by Payne, Hall, and Galloway.

CONCLUSIONS

Coastal aquifers in the Greater Houston area are composed principally of fluvial-deltaic sediments. The Alta Loma Sand is a complexly faulted, high percent-sand unit that represents a seaward progression of fluvial, delta-plain, delta-front facies. The Alta Loma doubles in thickness because of increased sand deposition on the downthrown side of active growth faults. The Beaumont

Formation is a high percent mud unit that represents a coastal progression of delta-plain to delta-front facies.

Arbitrarily defined interval maps from the surface to depths of 2000 feet indicate that the aquifers are composed of superposed, dip-oriented, high percent-sand trends and strike-oriented high percent-sand trends.

Directions and rates of ground-water flow are controlled partly by aquifer geometry and geologic history of the Texas Gulf coast. Strike-oriented growth faults and dip-oriented high-percent sand trends may localize the effects of ground-water pumpage. Dip-oriented sands in high percent-sand units are optimum horizons for ground-water production.

Growth faults between Harris and Galveston Counties have hydrologically isolated the aquifer into two subsystems. Harris County waters are meteoric, whereas Galveston County waters are a mixture of meteoric and saline waters. Hydrochemical facies in the Harris County

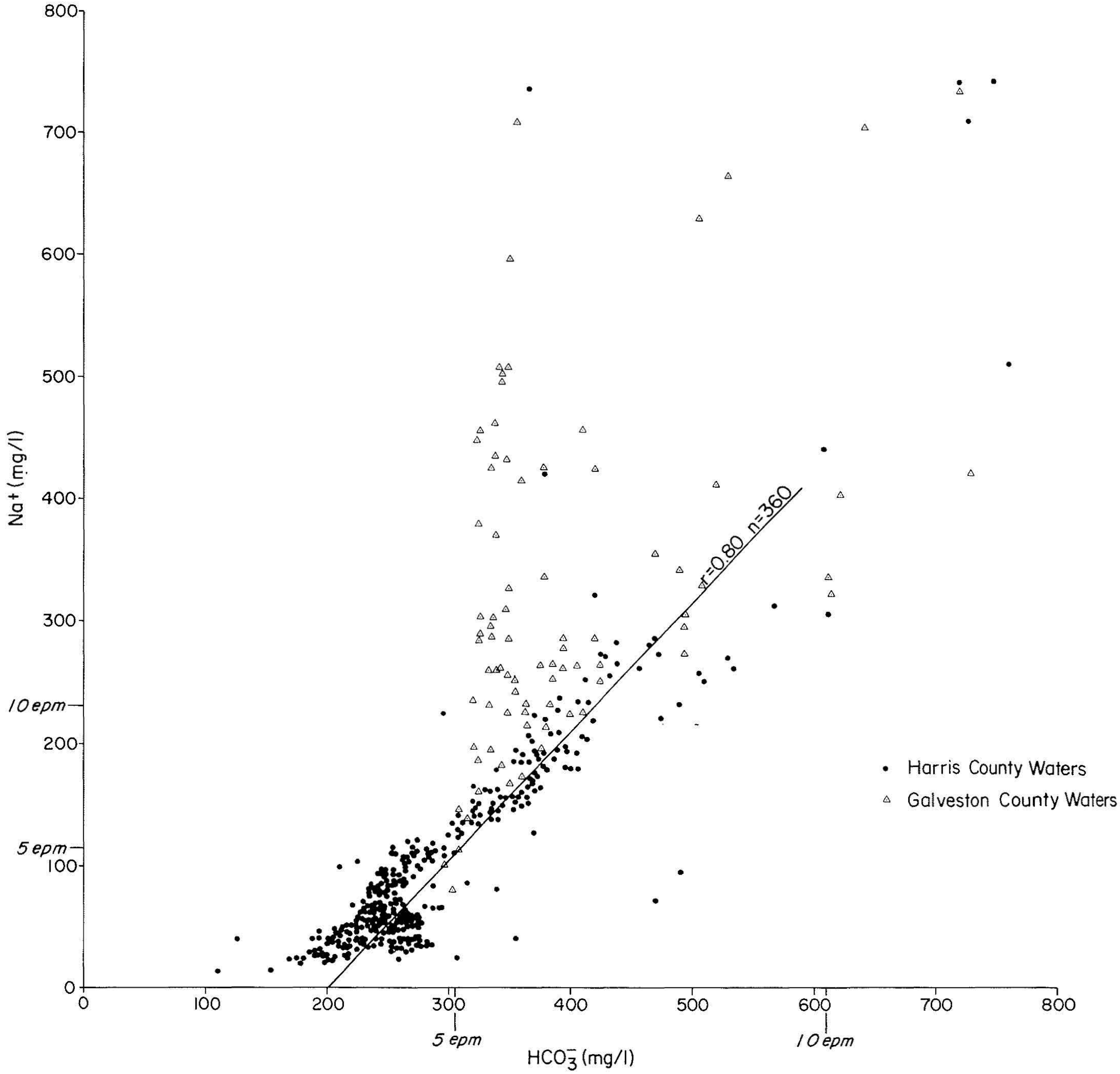

FIGURE 12. Sodium concentrations versus bicarbonate concentrations in shallow ground waters (100 to 1000 feet) of Harris and Galveston Counties. Data from Gabrysch and others (1971 and 1974).

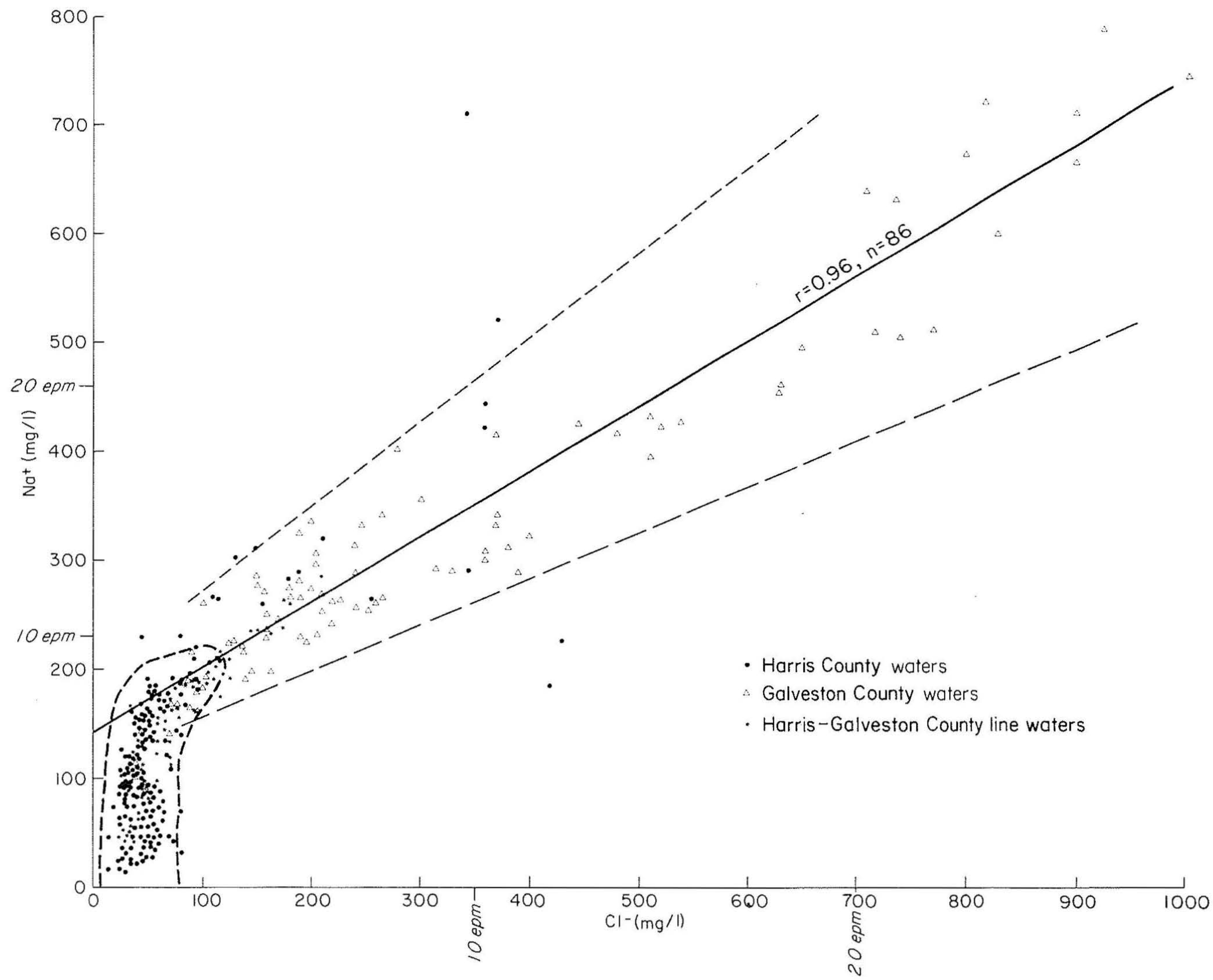

FIGURE 13. Sodium concentrations versus chloride concentrations in shallow ground waters (100 to 1000 feet) of Harris and Galveston Counties. Data from Gabrysch and others (1971 and 1974).

aquifer indicate recharge in northern Harris County and discharge in the southern part of the county. The evolution of sodium bicarbonate waters in Harris County occurs through cation clay exchange in a closed carbonate system with no additional carbon dioxide source. Hydrochemical facies in Galveston County indicate a mixing of Harris County meteoric water and a sodium chloride water from either sea water intrusion or sediment compaction.

Low sea-level stand, 18,000 years ago is inferred to have greatly altered ground-water flow in Galveston County. The present elevation of the fresh-water/salt-water interface therefore represents a recently established, dynamic equilibrium between fresh meteoric water and saline water and does not represent the flushing of waters of deposition by meteoric waters.

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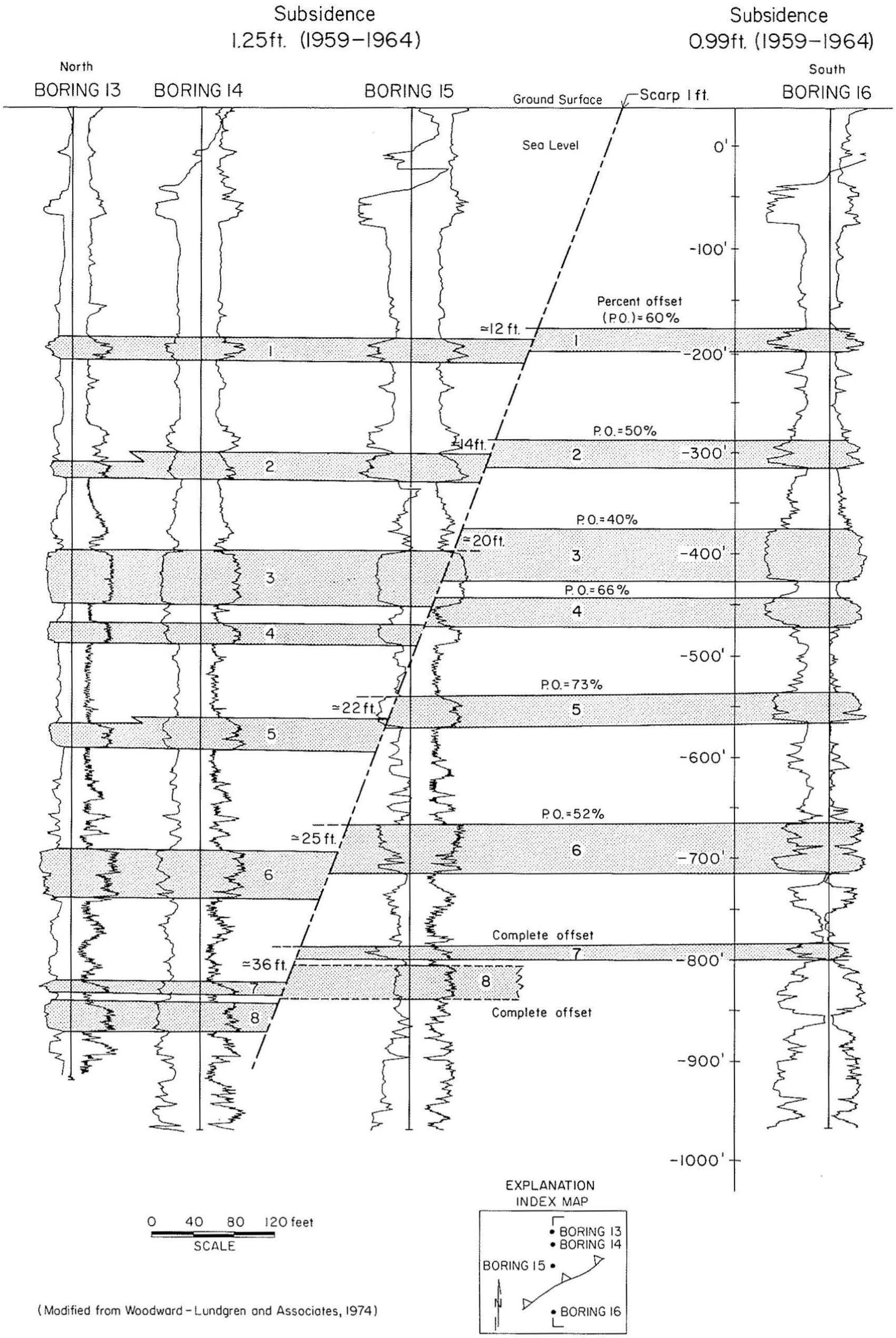

FIGURE 14. Shallow borings, subsidence, and percent offset of aquifer sands across Ethyl fault (approximately 1 mile south of Houston Ship Channel, Pasadena, Texas). Figure modified from Woodward-Lundgren and Associates (1974). Published with permission of Houston Lighting and Power Company.

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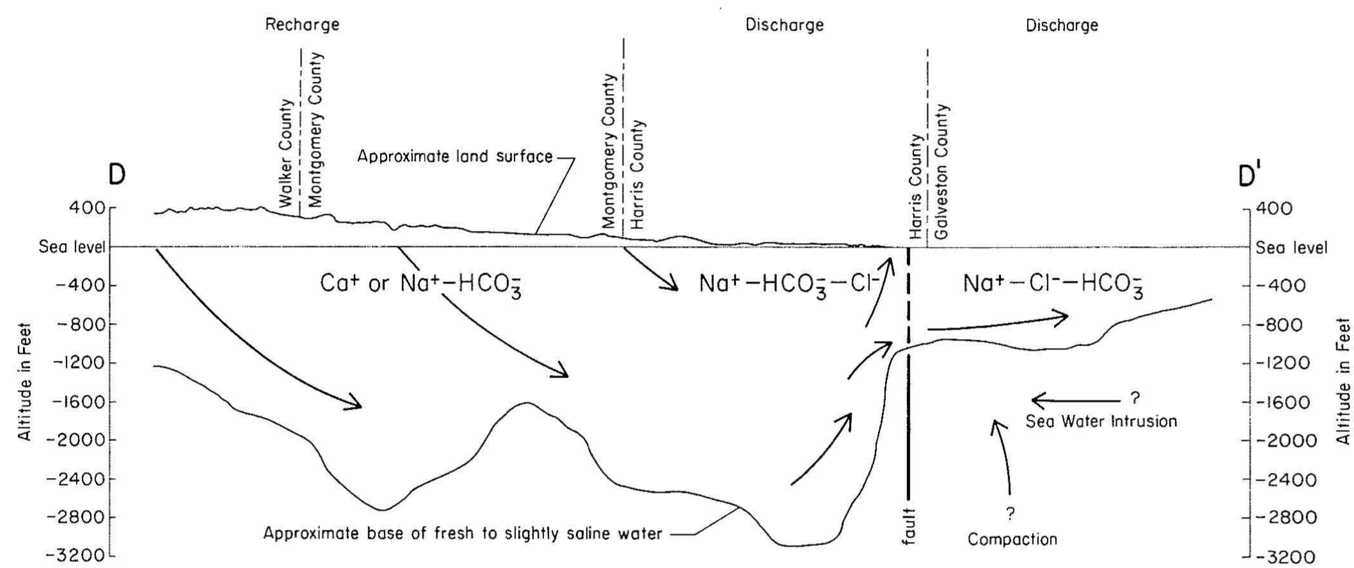

FIGURE 15. Cross section showing hydrochemical facies of aquifer and depth to base of fresh water. Cross section through eastern Liberty, Harris, and Galveston Counties. Figure modified from Wood and others (1963).

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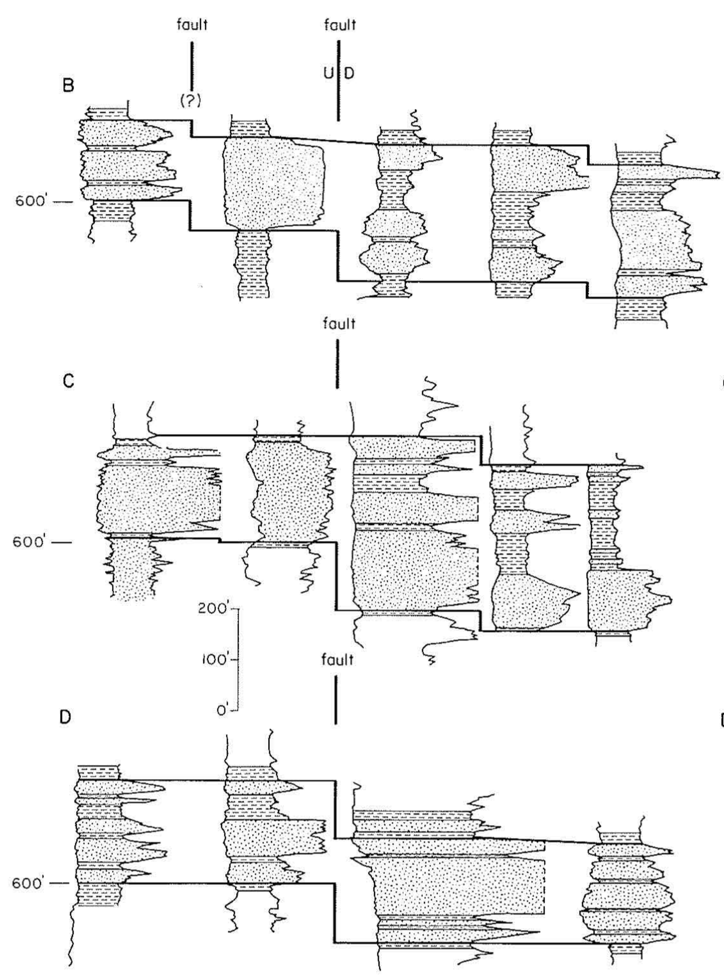

FIGURE 16. Cross sections across growth fault in Alta Loma Sand. See figure 3 for cross section locations.