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PRELIMINARY ENVIRONMENTAL ANALYSIS OF A

GEOPRESSURED-GEOTHERMAL TEST WELL IN

BRAZORIA COUNTY, TEXAS*

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ABSTRACT

Preliminary environmental data, including current land use, substrate lithology, soils, natural hazards, water resources, biological assemblages, meteorological data, and regulatory considerations have been collected and analyzed for approximately 150 km^2 of land near Chocolate Bayou, Brazoria County, Texas, in which a geopressured-geothermal test well is to be drilled in the fall of 1977. The study was designed to establish an environmental data base and to determine, within spatial constraints set by subsurface reservoir conditions, environmentally suitable sites for the proposed well. Preliminary analyses of data revealed the need for focusing on the following areas: potential for subsidence and fault activation, susceptibility of test well and support facilities to fresh- and salt-water flooding, possible effects of produced saline waters on biological assemblages and ground-

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water resources, distribution of expansive soils, and effect of drilling and associated support activities on known archeological-cultural resources.

Based on predicted values of bulk compressibilities, declines in reservoir pressure, well drainage radius, and depth and thickness of reservoir sandstones, preliminary estimates of surface subsidence resulting from reservoir sand compaction range from 9 cm/yr (0.3 ft/yr) during the first two years of fluid production, to 6 cm/yr (0.2 ft/yr) during a 5-year period. These rates do not include possible subsidence resulting from compaction of shales associated with reservoir sands. Differential subsidence may occur across known growth faults which, when projected to the surface, strike near the proposed well sites. Although current land use maps show an agriculturally-dominated region, facilities that could be adversely affected from significant amounts of subsidence and/or fault activation include: two petrochemical plants; a small unincorporated community along Chocolate Bayou; several gas, crude, and product pipelines; and paved highways.

Flood distribution maps, which project "100-year" flood levels between 1 and 3 meters above ground surface (approximately 3-5 m or 10-16 ft in elevation) in the main prospect area, indicate the need to institute flood-protection measures at the well site. In addition to the possibility of fresh-water flooding, salt-water flooding accompanying passage of a hurricane must be considered, as indicated by flood levels associated with Hurricane Carla.

Probable locations of fluid production and disposal facilities should have little direct impact on important biological assemblages and habitats; however, accidental discharge of geothermal brines that may contain significant amounts of boron could affect small areas of fresh-water marshes near the well sites and larger areas of fresh- to brackish- and salt-water marshes with their associated estuary habitats along Chocolate Bayou and Chocolate Bay gulfward of the well sites. These biologically productive areas provide nurseries for commercial shrimp, blue crabs, and game fish.

Although fresh-water aquifers underlie the geothermal prospect area, contamination from properly managed temporary emergency surface storage of saline waters is unlikely because of low permeabilities of clay substrates at or near the surface. High shrink-swell potentials which characterize the clays, however, should be considered in the construction of pipelines, roads, and other facilities.

A preliminary investigation of archeological-cultural resources in the prime (based on reservoir conditions) prospect area has revealed that production activities may affect known cultural resources which are potentially eligible for inclusion within the National Register of Historical Places. A more detailed investigation of the archeological-cultural resources has been proposed.

INTRODUCTION

Information presented in this report was collected and analyzed as part of a preliminary environmental analysis of potential geopressured-geothermal energy resource areas in Brazoria and Kenedy Counties, Texas (fig. 1). Although specific geopressured-geothermal prospect areas and environmental problems associated with location of a specific test well are considered, the report is not, nor was it intended to be, an environmental impact assessment. Approximately 150 km^2 (60 mi^2) were analyzed within each of the Brazoria and Kenedy County geopressured-geothermal prospect zones, with the objectives of: (1) conducting an environmental comparative analysis of candidate sites for geopressured-geothermal test wells, and (2) providing an environmental data base for future well development with the possibility of full scale energy production.

Part of the study of the prospective areas involved producing a series of large scale maps (1:24,000) or, where appropriate, tables in order to depict and describe selected environmental characteristics concerning current land use, environmental geology, natural hazards, soils, biologic assemblages, water resources, meteorologic conditions, and regulatory agencies. In addition, a methodology (only briefly described here) was developed employing transparent-translucent overlay maps and matrices for the purpose of identifying and classifying possible detrimental interactions between geopressured-geothermal de-

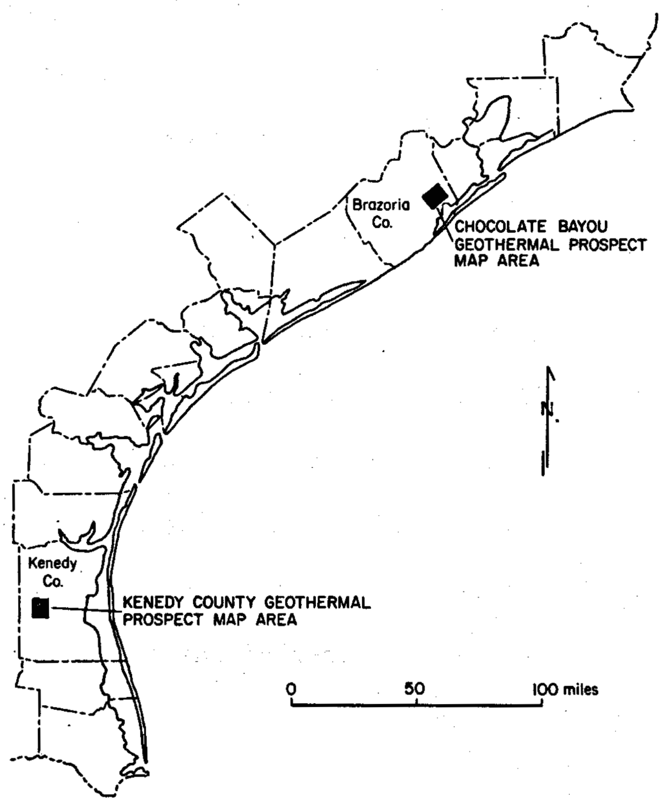

Figure 1. Location of geopressured-geothermal prospect areas, Brazoria and Kenedy Counties, Texas.

velopment activities and selected environmental characteristics. Possible detrimental interactions were evaluated by considering both the potential effect of a test well and associated activities on the environment and the potential effect of the environment on the test well and associated activities. Stated another way, activities were evaluated in terms of (1) their probable effects on environmental quality and natural processes, and (2) their capability for effective utilization of the environment with minimal loss or damage from natural processes or events.

Because the first geopressured-geothermal test well (Austin Bayou Prospect*) is to be drilled in Brazoria County around the first of the year 1978, the Brazoria County prospect area received emphasis and is the only one discussed here. Evaluation of the Brazoria County area and the prospect well in terms of expected reservoir characteristics and potential as a geopressured-geothermal energy resource are reported by Bebout and others (in press).

GENERAL SETTING--BRAZORIA COUNTY PROSPECT AREA

The area for which environmental data was collected and analyzed in Brazoria County encompasses about 150 km^2 (60 mi^2). The center of

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* The geopressured-geothermal test well is referred to as the Austin Bayou Prospect by Bebout and others (in press), but because of its final proposed location adjacent to Chocolate Bayou, it is sometimes referred to in this report as the Chocolate Bayou Prospect.

the area, which is near the proposed site of the test well, is located approximately 56 km (35 mi) southwest of Houston and 22 km (14 mi) inland from the Gulf shoreline of Galveston Island (fig. 2). Liverpool, with a population of 340 in 1974 (Dallas Morning News, 1976) is the only incorporated community within the mapped area. Two cities with populations of 10,000 or greater that are near but off the mapped area are Alvin, with a 1974 population of 12,500 located about 16 km (10 mi) north of Liverpool, and Angleton, with a 1974 population of 10,000 and located 19 km (12 mi) southwest of Liverpool (fig. 2).

The area within which the first test well is to be located--as determined through analyses of geopressured-geothermal reservoir characteristics including temperature of geothermal waters, net sand thickness, and permeability (Bebout and others, in press)--lies near the center of the 150 km^2 area and covers roughly 5 km^2 (2 mi^2). The actual test well and proposed surface support facilities, including separators, cooling tower, tanks, and disposal wells, will encompass only about .02 km^2 (5.5 acres) (Draper and others, 1977). Although in the following sections, environmental data maps and tables are presented for the entire area of analysis (150 km^2), emphasis is placed on the smaller prime prospect area (5 km^2; 1250 acres) in discussing and evaluating possible locations for the test well in terms of environmental characteristics.

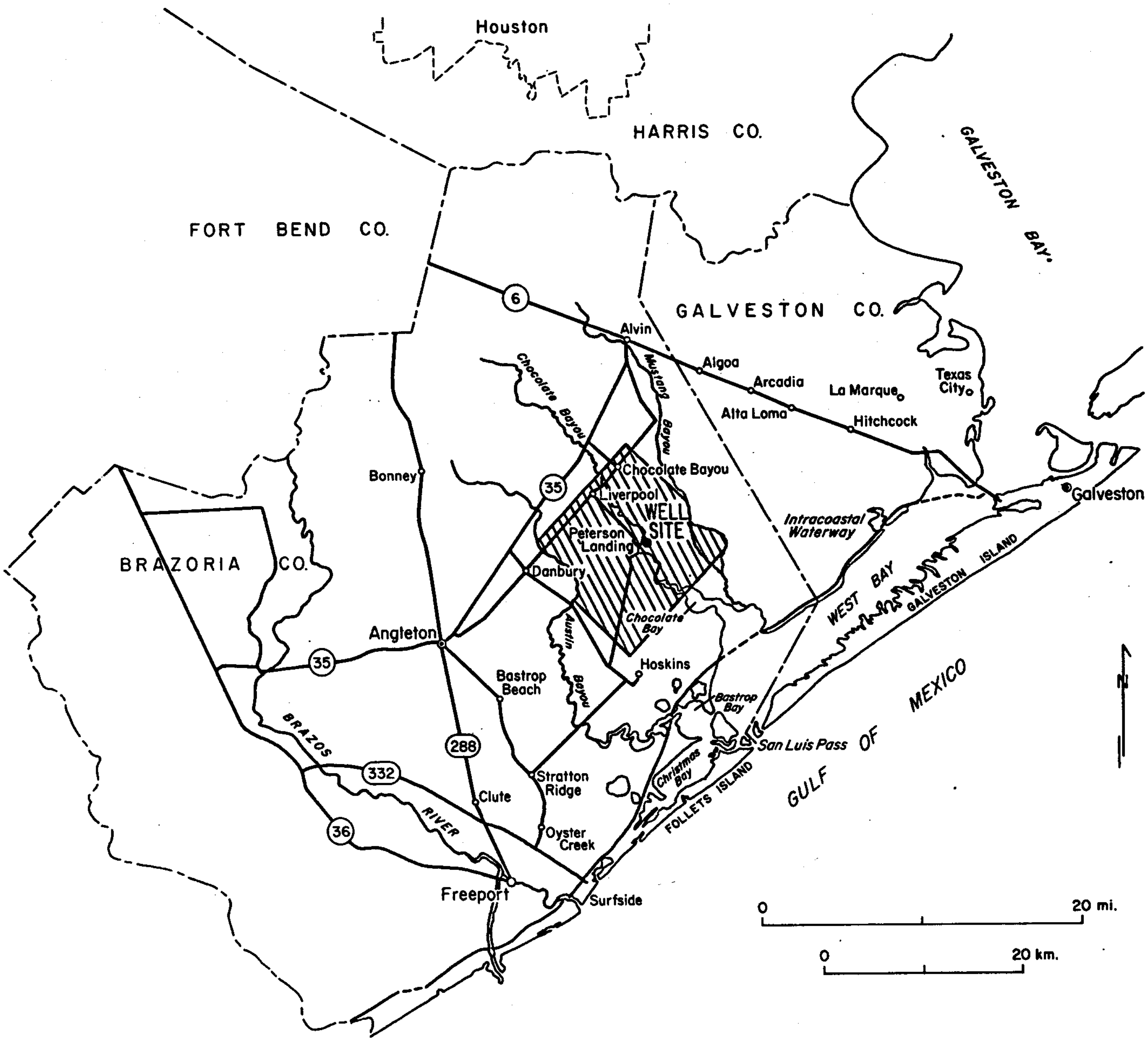

Figure 2. Location of Brazoria County geopressured-geothermal prospect area. Various environmental characteristics were mapped in the area shown by line pattern.

ENVIRONMENTAL CHARACTERISTICS

Environmental characteristics that are described and analyzed for the geopressured-geothermal prospect area were identified on the basis of: (1) their relevance and applicability to development of geopressured-geothermal energy resources, (2) their relevance and applicability to the specific geopressured-geothermal prospect area in Brazoria County, and (3) the availability of existing environmental data describing the prospect area.

In the following sections, various environmental characteristics are discussed, followed by an analysis and evaluation of environments in the prime prospect area in terms of selecting environmentally suitable locations for the test well.

CURRENT LAND USE

Current land use patterns were mapped using 1975 color IR aerial photographs, scale 1:120,000, supplemented locally with large scale (1:20,000), 1975 color IR aerial photographs. Mapping was updated where possible through field reconnaissance during the summer of 1977.

Current land use patterns in the Brazoria County prospect area are dominated by agricultural lands which include cropland and range-pasture/grasslands (fig. 3). Dominant crops in the area include rice, grain sorghum, and soy beans. The distribution of cropland and grass-

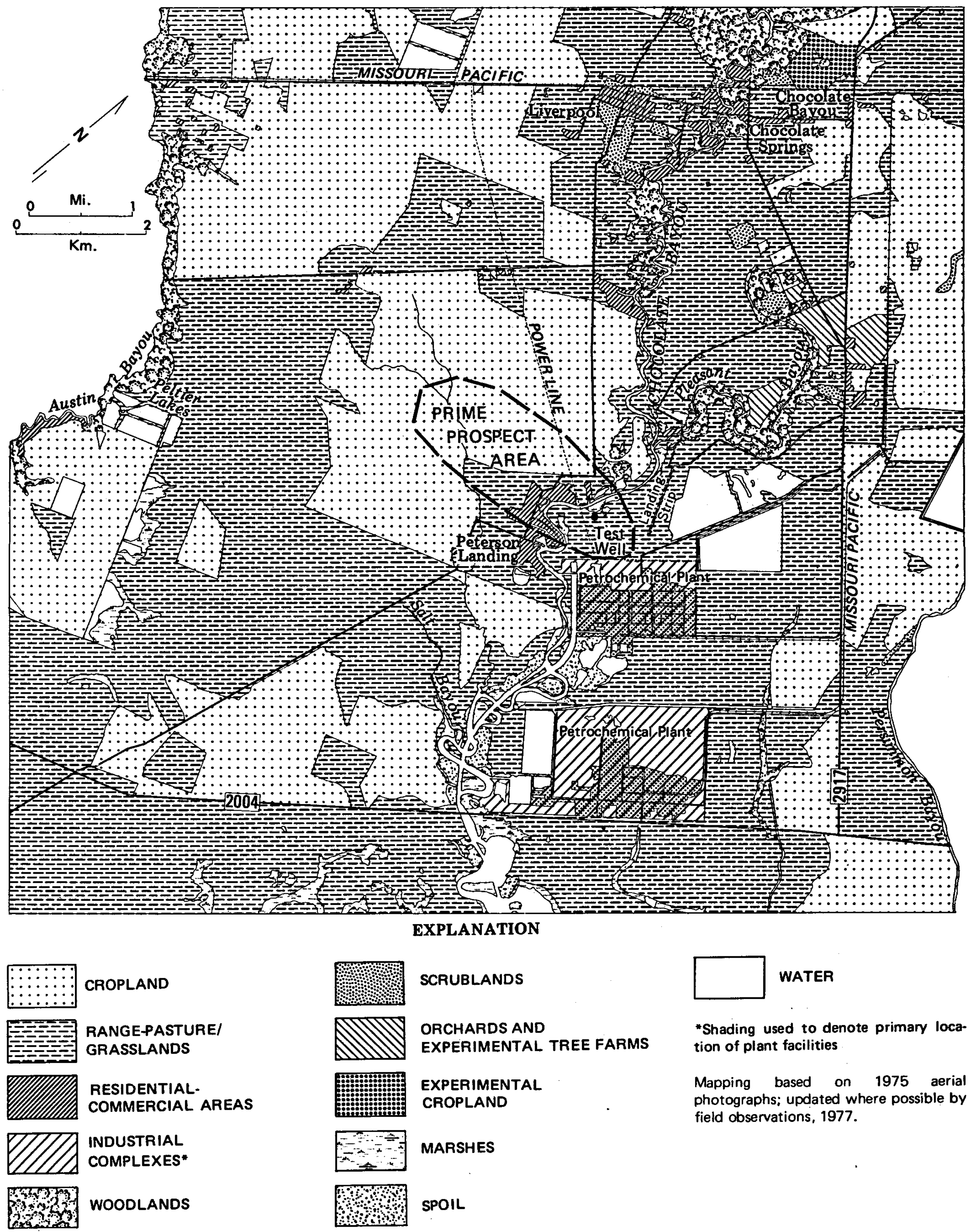

Figure 3. Current land use in the Brazoria County prospect area.

land varies from year to year as areas may be placed in or out of crop production. The map unit, range-pasture/grasslands, includes (in addition to those areas that appear to be permanently utilized and maintained as grassland, improved pasturelands, etc.) areas of cropland that were out of production and supporting other than cropland-type vegetation during the mapping period.

Current residential-commercial developments shown on the land use map include the incorporated community of Liverpool, located in the northern part of the map area; an unincorporated community on the west bank of Chocolate Bayou in the vicinity of Peterson Landing; and several permanent and second home developments along or near Chocolate, Pleasant, and Austin Bayous.

Industrial development is dominated by two petrochemical plants, Monsanto Chemical Intermediates Company and Amoco Chemical Corporation, located on the east bank of Chocolate Bayou, gulfward of the residential-commercial developments. The Monsanto Company (northern-most plant in fig. 3) manufactures intermediate hydrocarbon products and organic chemicals, and the Amoco plant, principally polyolefins. The petrochemical plants are serviced by a dredged canal that dissects natural meanders formed along the lower reaches of Chocolate Bayou; the canal, approximately 3.7 m (12 ft) deep and capable of handling barge traffic, connects with the Intracoastal Waterway in West Bay about 14 km (9 mi) gulfward of the Monsanto plant.

Several farm to market roads are present in the area, some of which connect to State Highway 35 which is located just off the map (fig. 3) about 3 km (2 mi) northwest of Liverpool. Spurs off the Missouri-Pacific Railroad (located along the northwest edge of the map area) connect with facilities at the two petrochemical plants. A major power transmission line passes through the heart of the map area providing power to the petrochemical plants. Many gas, crude, and product pipelines also cross the area (fig. 4).

Other land use categories depicted on the current land use map include woodlands, located primarily along Chocolate, Austin, and Pleasant Bayous; experimental cropland where research is conducted on experimental plantings such as rice, orchards, and experimental tree farms and nurseries, most of which are no longer maintained and are presently overgrown with understory; scrubland which includes a mixture of scrubs and local patches of grassland; dredge spoil which outlines the dredged canal along the lower reaches of Chocolate Bayou; marshes, which are generally brackish- to fresh-water types northwest of Farm to Market Road 2004 (more detailed and complete information on marshes is presented in the section on biological assemblages); and known archeological-cultural resources* located along the east bank of Chocolate Bayou across from Peterson Landing.

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* Archeological-cultural resources are not shown on maps published in this report.

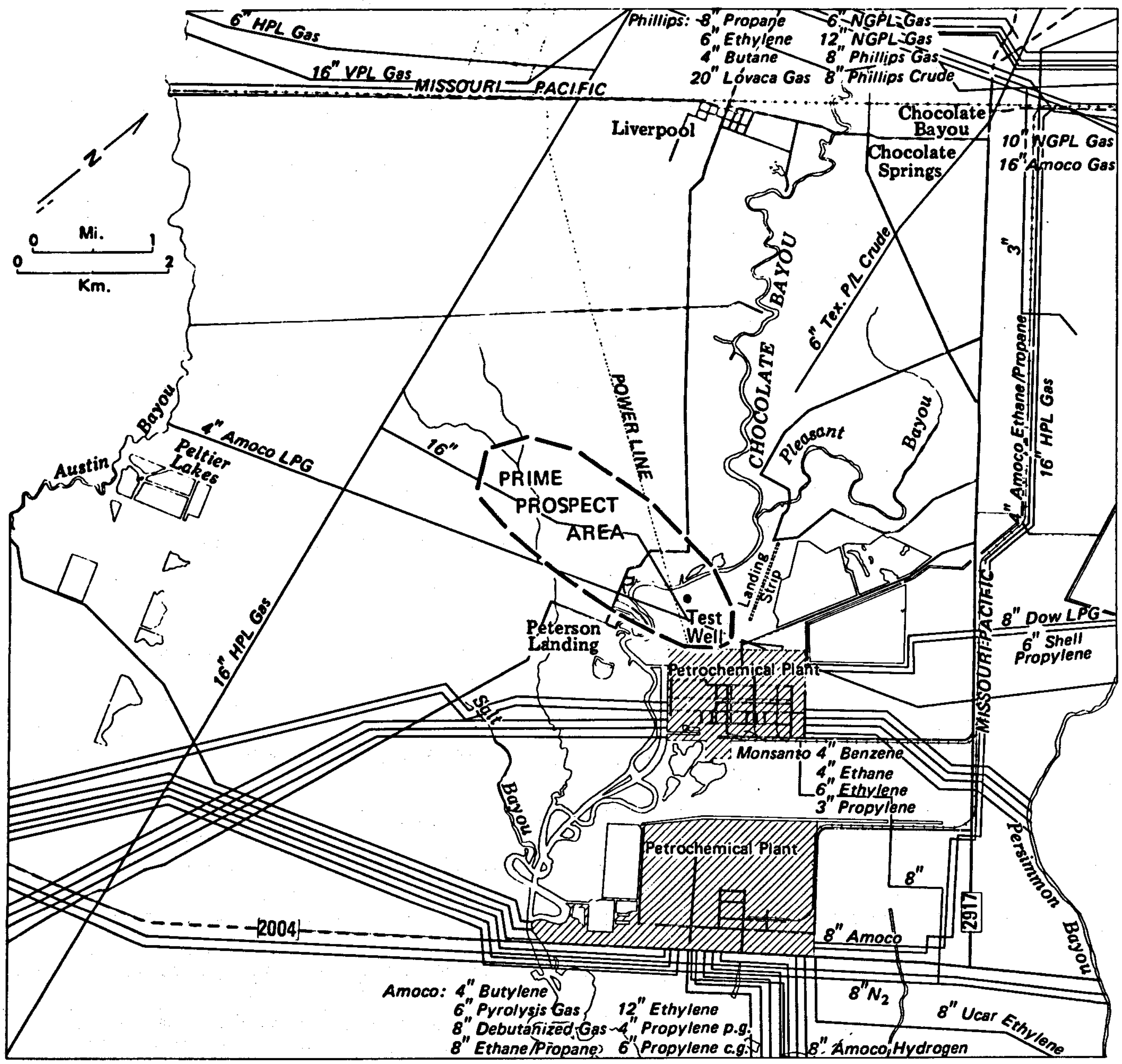


Figure 4. Approximate location of product, crude, and gas pipelines in the Brazoria County prospect area. (From Dewitt and Company Inc., Houston, Texas)

Selection of Test Well Site on the Basis of Current Land Use

Current land use in the prime prospect area (fig. 3) is dominated, areally, by range-pasture/grasslands and cropland, but also occurring in the area are: (1) the unincorporated community development along the west side of Chocolate Bayou near Peterson Landing, (2) small areas covered by marshes and trees (treated in the section on biological assemblages), and (3) known archeological-cultural resources. The Monsanto Company petrochemical plant is located near but southeast of the prime prospect area.

In terms of current land use, the most suitable areas for development of the test well and support facilities are those areas presently utilized as range-pasture/grasslands and, as a second choice, cropland. The least suitable areas, of course, are those occupied by community development, archeological-cultural resources, and marshes.

Range-pasture/grassland areas (the first choice for development) exist on both sides of Chocolate Bayou. Although areas mapped as range-pasture/grasslands may be alternately in and out of crop production, recent field checks and interpretation of aerial photographs indicate that areas mapped as range-pasture/grasslands on the east side of Chocolate Bayou (in the prime prospect area) have been more permanently maintained as grasslands than on the west side where cultivation is more commonly practiced. Permanent removal of 5 to 6 acres (approximate area of one test well and support facilities) of cropland is, realistically, inconsequential. So, for a test well, there should be little advantage in choosing grassland over cropland areas. Should the area eventually be developed for full scale energy production with development of additional wells and construction of a power plant, however, larger amounts of cropland would be permanently removed from production. In addition, areas of cropland surrounding geopressured surface facilities could be affected inadvertently by accidental discharges of geopressured-geothermal fluids which may be brines containing high concentrations of boron.

The fact that industrial facilities have already been established on the east side of Chocolate Bayou adds support to the choice of locating the test well on the east side in an area mapped as range-pasture/grasslands, near the existing petrochemical plant facilities and away from community development. This location would also be favorable for the eventual construction of a power plant because of the established industrial facilities.

A factor which has not yet entered the discussion, however, is the direction of expansion of the geopressured-geothermal resource should the test well indicate favorable reservoir conditions for energy development. Expansion is likely to occur in the area west of Chocolate Bayou (personal communication, Robert Loucks, 1977). Drilling additional wells in the western part of the prime prospect area, farther and farther away from a power plant constructed on the east side of Chocolate Bayou, may lead to inefficiencies in fluid transmission in the form of heat loss between the production well and power plant.

The possibility of eventual expansion west of the bayou warrants additional analysis.

Because the prime prospect area extends about 3.2 km (2 mi) west of the bayou, location of the test well on the west side would allow placement of the well at a greater distance from community development than on the east side. In addition, there would be more area (open space) for energy development in the prime prospect area, but there remains the problem of the permanent loss of some amount of cropland. Surface facilities for a 25 megawatt power plant should require about 10 acres (Riemann and others, 1976). Removal of that amount of cropland (assuming there are no additional losses from accidental fluid discharges) is probably insignificant because it represents less than .01 percent of the cropland acreage harvested in Brazoria County in 1976 (table 1). Should additional industries locate in the area to take advantage of the geothermal fluids, however, additional cropland would be lost. Nevertheless, there is sufficient area (open space) for development of the 25 megawatt plant and additional industrial facilities on the west side of Chocolate Bayou as well as on the east side.

The area selected as a possible site for the test well, prior to the analysis of existing environmental characteristics, is shown in figure 3. Although this particular site is located mostly on grasslands, it also covers part of an area that may contain significant archeological-cultural resources--Indian shell middens known as the

TABLE 1. HARVESTED ACRES FOR BRAZORIA COUNTY, 1976

(from Texas Crop and Livestock Reporting Service, 1976 Texas County Statistics)

CROP		HARVESTED ACRES
Upland Cotton		3,250
Rye		800
Sorghums		
(Grain)		37,200
(Hay)		1,400
Corn (Grain)		8,900
Soybeans		7,400
Rice		57,700
Other Hay-Excluding Sorghums		7,000
	TOTAL	123,650

Three-Oaks Site. Archeologists believe the Three-Oaks Site may have been the principal Indian camp related to a burial site and fishing camp which were excavated from an area known as Shell Point along the east side of Chocolate Bay southeast of the prime prospect area (Hole and Wilkinson, 1973). European contact and Indian artifacts have been found at the Three-Oak Site (Hole and Wilkinson, 1973). The site has been assigned an identification number by the Texas Historical Commission and is potentially eligible for inclusion within the National Register of Historical Places. A more detailed archeological investigation of this area is recommended in order to identify and mark areas that should be excavated or left undisturbed because of their cultural value.

In conclusion, in terms of current land use, there are advantages when considering future potential and development of geopressured-geothermal resources for locating the test well on either side of Chocolate Bayou in areas away from existing community development and known archeological-cultural resources. The fact that there are areas currently utilized as range-pasture/grasslands near existing industrial developments with ready access to power transmission lines and rail and water transportation routes supports the prospect of locating the test well on the east side of Chocolate Bayou at the eastern extremes of the prime prospect area and near the petrochemical plant.

POTENTIAL FOR SUBSIDENCE AND FAULT ACTIVATION IN THE BRAZORIA COUNTY PROSPECT AREA

Subsidence and in some cases fault activation have been attributed to the production of oil and gas, ground-water, and geothermal fluids, although they can also be attributed to natural, on-going processes associated with sediment deposition, compaction, and contemporaneous growth faults. In the Houston area, land surface subsidence resulting from both oil and gas and shallow ground-water production has been well documented (Pratt and Johnson, 1926; Snider, 1927; Winslow and Doyel, 1954; Gabrysch and Bonnet, 1975; Kreitler, 1977b; and Gustavson and Kreitler, 1976). In addition, activation of faults from fluid withdrawals and fluid pressure declines has been documented (Gustavson and Kreitler, 1976; Kreitler, 1977a, 1977b). "The Houston area has more than 240 km of active faults, making it the most active area for faulting in the Coastal Zone," (Gustavson and Kreitler, 1976, p. 23). Gustavson and Kreitler (1976) and Kreitler (1976) also note that subsurface faults projected to the surface are commonly coincident with active surface faults indicating a relationship between the two. Surface expression of many faults, however, is commonly very subtle to non-existent.

Several subsurface faults have been detected in the Brazoria County prospect area (fig. 5) (Bebout and others, in press). The faults are similar to others along the Texas Gulf Coast in being mostly down-to-basin growth faults that strike subparallel to the coast and flatten and converge at depth (Bruce, 1973). Fault patterns in the prospect area have been complicated to some extent by the occurrence of salt domes (Danbury Dome and Hoskins Mound).

Because the fault planes are curvilinear with the angle of dip increasing toward the earth's surface, subsurface faults were projected upward at angles of both 45° and 60° in an effort to locate a zone within which any surface expression of the faults would likely occur (fig. 5). The range in angles of projection are in agreement with angles of faults reported by Quarles (1953) and Bruce (1973) as well as with calculted angles for faults which cross two subsurface horizons in the prospect area. Kreitler (1976; 1977b) extrapolated faults at 45° and found good coincidence between extrapolated faults and sur-

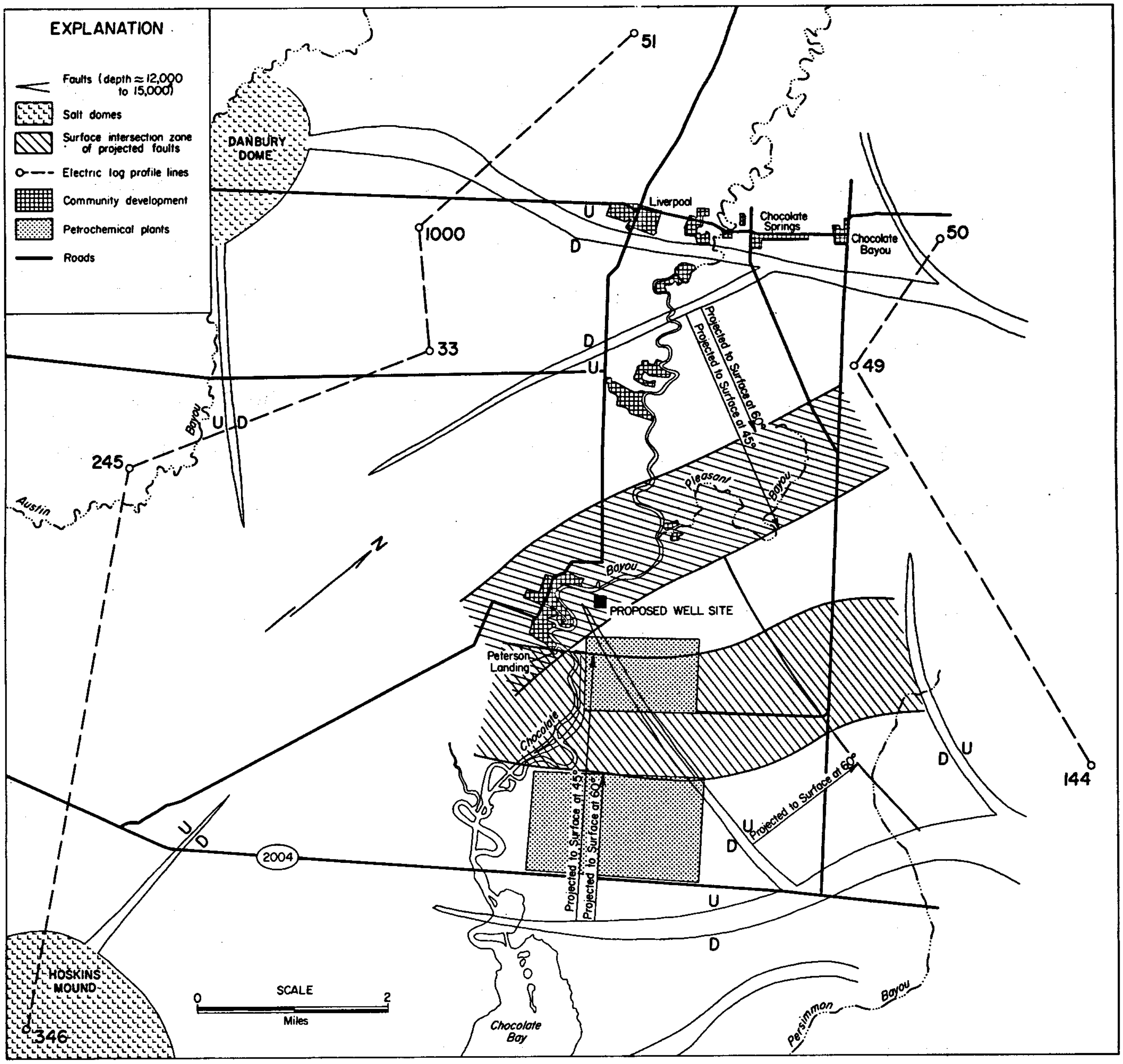


Figure 5. Location of subsurface growth faults and zone of expected surface intersection when faults are projected upward at 45 and 60 degrees. (Location of subsurface faults from Bebout and others, in press)

face faults and lineations.

Although active surface faults have not been located in the Brazoria County prospect area, there is some evidence of surface and near-surface fault activity. Construction of profiles from electric logs of relatively shallow Pleistocene sedimentary units along two lines shown in figure 5 reveals sediment thickening toward the coast that cannot be explained by depositional slope alone; the variation in sedimentary sequences indicates the presence of growth faults between wells at points 245 and 346 along the southern-most profile and between points 49 and 144 along the northern-most profile (C. W. Kreitler, personal communication, 1977). The location of a growth fault(s) between points 49 and 144 coincides with surface projections of the eastern subsurface fault as shown in figure 5.

Surface expressions of faults have also been related to rectilinear drainage patterns in Houston and surrounding areas (Kreitler, 1977a). The approximate north-south trend of Chocolate Bayou within the western-most fault projection zone follows the general trend of the projected fault (fig. 5). Furthermore, the northeast-southwest trend of Chocolate Bayou in the area of the 60° projection line of the eastern-most fault is in agreement with the fault trend. Moreover, the fault projection (at 60°) coincides in part with an aerial photographic lineations mapped by Fisher and others (1972). It is possible that these patterns of channel development in Chocolate Bayou are fault related. An abandoned Pleistocene channel located southwest of Chocolate Bayou also shows patterns that are possibly fault related.

As noted previously, fault activation in some areas may be related to fluid production. In fact, there is evidence that fault planes control fluid migration and subsequently, the area over which pore fluid pressure reduction and subsidence occur (fig. 6); thus, the faults, which are planes of weakness that may be activated with fluid pressure declines and reservoir compaction, become boundaries across which there may be differential compaction effectively compartmentalizing subsidence (Kreitler, 1977a, 1977b).

Surface facilities that could be adversely affected by significant amounts of subsidence and faulting are depicted in the map of current land use (fig. 3) and include two petrochemical plants, numerous product, gas, and crude pipelines (fig. 4), residential-commercial developments, and paved roads.

Two important questions need to be addressed: (1) how much subsidence is likely to occur from geopressured-geothermal fluid production, and (2) will varying the location of the test well within the prime prospect area significantly reduce the chances of damage to surface structures if significant subsidence and fault activation do occur?

Difficulty of Accurate Prediction

Accurately predicting the potential and the amount and rate of subsidence that may accompany production of geopressured-geothermal

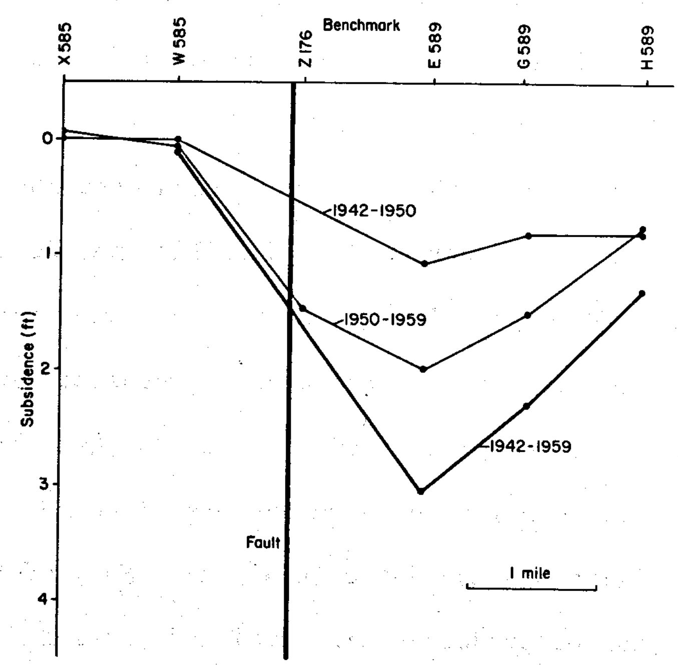


Figure 6. Land subsidence over Chocolate Bayou oil and gas field. Note coincidence of differential subsidence with lineation and surface trace of extrapolated fault. (From Gustavson and Kreitler, 1976)

fluids in the Brazoria County Chocolate Bayou prospect area is a complex problem. The problem is demonstrated in the case of the Wilmington oil field in California where subsidence prediction models were unsuccessful until the field had undergone 65 to 75 percent of its probable ultimate subsidence; the field subsided approximately 9 m (28 ft) in 27 years before subsidence was arrested by water injection programs (Allen and Mayuga, 1969).

A comparison of those factors which contribute to subsidence versus those that contribute to stability may help simplify the problem (table 2). Through this analogy process, one might conclude that the chances for subsidence in the Brazoria prospect area are high, on the basis that over 60 percent of the factors that characterize the prospect area are similar to those factors which may contribute to the susceptibility of subsidence (table 2). Many of these factors, such as thickness of production interval and pressure declines, are major ones, but two factors that can have substantial influence and perhaps overriding control over other factors regarding potential for significant subsidence in the area of Chocolate Bayou are: (1) the amount of cementation in reservoir sands and in overburden sands, and (2) the depth from which production will occur which determines the overburden thickness.

The importance of these two positive factors--cementation and overburden--has been noted by Allen and Mayuga (1969) who state that in addition to a decline in reservoir fluid pressures, the following

TABLE 2. FACTORS TENDING TO INFLUENCE GEOTHERMAL SUBSIDENCE (FROM ATHERTON AND OTHERS, 1976) COMPARED TO FACTORS THAT CHARACTERIZE THE BRAZORIA COUNTY PROSPECT AREA

FACTOR TYPE (* major; ϕ minor)	FACTORS WHICH MAY CONTRIBUTE TO SUBSIDENCE SUSCEPTIBILITY	FACTORS WHICH MAY CONTRIBUTE TO SURFACE STABILITY	FACTORS CHARACTERIZING PROSPECT AREA
1. RESERVOIR FLUID			
* Phase	All-liquid	Vapor-liquid mixture (vapor dominated, to a lesser extent)	● Liquid dominated
Pressure	Geopressured (overpressured)	Low (below hydrostatic)	● Geopressured
Density	High	Low	● High
ϕ Dissolved Solids			High
ϕ Temperature			>300°F
2. PRODUCTION FLUID			
* Volumes	Large	Small	● Large
* Fluid levels[1]	Large drops, long time, extensive areas	No drops	?
* Pore pressures[1]	Large drops, long time, extensive areas	No drops	● Large drops, long time, extensive areas
Formation flashing	None	Extensive, continual flashing	?
3. GEOHYDROLOGY			
Natural recharge[1]	Low rates	High rates	?
4. RESERVOIR MATERIALS			
* Type	Sediments	Igneous or metamorphic	● Sediments
Predominant grain size	Coarse	–	Fine
Grain shape	Angular	Rounded	● Angular
Porosity - Primary	25-40%	Very low	Low
- Secondary	High	Low	● Secondary, 5-25%
* Consolidation/cementation	Unconsolidated, lacking cementation (loose or friable)	Consolidated, cemented	Cemented
* Preconsolidation[2]	None	Much	?
Hydrothermal alteration	Present	Absent	● Present
Admixed clay content (*sorting*)[3]			?
Admixed mineral content	High mica, montmorillonitic clays	None	● Mixed-layer illite and montmorillonite in shales
Age	Miocene and younger	Older than Miocene (22 million years)	Oligocene
* Thickness (in communication)	Great vertical section	Small vertical section	● Great vertical section
* Deformation properties[4]	Highly deformable	Slightly deformable	?
5. ASSOCIATED MATERIALS			
Type	Clays, siltstones, shales	Volcanic flows and shallow instructions	● Sandstones, shales, interbedded sandstones and shales of moderate thickness; intercommunication between sands impaired by shales
Occurrence	Many thin strata of large total vertical thickness, interbedded with reservoir materials but not impairing communication between them (less susceptible if distributed in few thick strata)		
6. RESERVOIR GEOMETRY			
Width/thickness ratio[5]	Large	Small	● Large (for several wells)
7. OVERBURDEN			
* Thickness	Small (< 3000 ft)	Great	Great, > 14000 ft
* Competence	Incompetence, unconsolidated sediments	Competent, consolidated	Possibly competent
* Deformation properties[6]	Highly deformable	Slightly deformable	?
Density	High	Low	Low
8. SITE GEOLOGY, STRUCTURE			
Folding	Gentle, broad, synclinal	Sharp, anticlinal (arched)	● Gentle broad synclinal
Flank dips	Less than 25°	Greater than 25°	● Less than 25°
Faulting	Normal, graben blocks	Reverse or thrust	● Normal, graben blocks
Fracturing	Much, recent	Little, old, sealed	?
Regional stresses	Tensional	Compressional	● Tensional
Stratigraphy			

[1] Depend(s) upon formation properties, which may be studied by preliminary well tests.
[2] Preconsolidated materials have previously experienced loads greater than their present load.
[3] If high pressures did not always accompany the presence of admixed clays in geopressured zones, they will be preconsolidated.
[4] Elastic constants, compaction coefficient, yield stress, etc.
[5] Of the producing zone.
[6] Can the overburden materials possible respond more slowly than the reservoir materials below.
● Characteristics similar to those listed in column 2.

conditions are necessary for subsidence (of the Wilmington type):

1. "The reservoir rocks must be compactable (uncemented) and unable to effectively resist deformation upon a transfer of load from the fluid phase to the grain to grain contacts."
2. "The overburden must lack internal self support and be of such a nature as to easily (deform) downward and supply a constant load to the underlying formation."

Cementation of Reservoir Sands

The degree of cementation has a significant influence over reservoir compaction and ultimately subsidence. According to Allen and Chilingarian (1975), cementation is by far the single most important factor controlling (limiting) mechanical sand compaction. Without significant compaction in the sands in the prospect area, subsidence would be dependent on compaction of mudstone (shale) associated with the producing sand reservoirs. This may be an important consideration because below depths of about 300 m, as pore fluid pressure is reduced, sands may compact more than shales (Allen and Chilingarian, 1975). In the Wilmington field, cumulative compaction was 67.6 percent in the sands and 32.4 percent in the shales (siltstones) (Allen and Mayuga, 1969). The sands, however, were not cemented.

In the prime prospect area, the net thickness of sandstone within the proposed production interval (the total interval which is about 730 m (2400 ft) thick includes interbedded shales) is expected to be approximately 255 m (840 ft); these sandstones apparently have undergone a rather complex history of cementation, leaching, and recementation at moderate to intermediate and geopressural depths as noted below (Bebout and others, in press).

The prime prospect area lies between two areas that can be characterized by differences in depositional and compactional histories that were operative during and after the time (Oligocene) the prospective reservoir sands (Frio Formation) were deposited (Bebout and others, in press). One area to the west and southwest, south of Danbury Dome, has a history of rapid sedimentation and accompanying subsidence which resulted in little early cementation and relatively complete compaction by burial of sediment. The other area to the northeast (Chocolate Bayou oil and gas field) has less rapid sedimentation and subsidence, instituting a longer period of early cementation which inhibited complete sediment compaction. Later periods of leaching and cementation ended in higher porosities and permeabilities in the reservoir rocks to the northeast where sediment accumulation was less rapid and compaction less complete than to the west where sands became well compacted and cemented yielding much tighter reservoir rocks with lower porosities and permeabilities. Characteristics of the prospective geopressured-geothermal reservoir sandstones, expectably, lie somewhere in between characteristics of sandstones in these two opposing areas.

Some of the changes in reservoir properties regarding secondaryleached porosity have occurred after the sands were under geopressured condition. This (geopressured condition) may be a particularly important factor because secondary pore spaces produced under geopressured conditions could be maintained by the abnormal pore fluid pressures which counteract effective stress (grain to grain stress caused by the overburden) thereby preventing closure or deformation of the pore spaces. Furthermore, late stage cementation that has occurred includes (in addition to Fe-rich carbonates) precipitation of the clay mineral--kaolinite, which may fail as effective stress is increased. Thus, even if reservoir sands are moderately-well cemented, it is possible that alterations under hydrothermal and geopressured conditions, coupled with locally incomplete grain to grain cementation, may leave "room" for compactional deformation in sandstones when fluid pore pressures are reduced. Until cores have been taken and detailed compressibility tests conducted, the question about cementation and compactional deformation cannot be adequately answered.

Overburden

Thickness. The depths, -4,115 to -5,030 m (-13,500 to -16,500 ft) (Bebout and others, in press), from which geopressured-geothermal fluids will be produced in the prime prospect area, far exceed the production depths of most areas that have subsided in response to fluid withdrawal (tables 3 and 4). The importance of overburden thickness in resisting subsidence is noted by Atherton and others, 1976:

TABLE 3. MAXIMUM SUBSIDENCE AND PRODUCTION DEPTHS FOR PETROLEUM, GROUND WATER, AND GEOTHERMAL SUBSIDENCE AREAS

(Modified from Atherton and others, 1976)

Ground Water Subsidence Areas

	Maximum Subsidence	Production Depth
San Joaquin Valley California	9.15 m	90-900 m
Santa Clara Valley California	4 m (1969)	50-300 m
Houston-Galveston Texas	1-2 m (1969)	50-600+ m
Denver Colorado	.4 m (1962)	?-760 m
Ely-Picacho Arizona	2.3 m (1969)	100-300+ m
Las Vegas Nevada	1 m (1969)	60-300? m
Savannah Georgia	.2 m (1969)	
Baton Rouge Louisiana	.3 m (1969)	40-900(?)
Osaka Japan	3-4 m (1969)	10-200? m
Mexico City Mexico	8 m (1969)	chiefly 10-50m
Taipei Basin Taiwan	1 m (1969)	30-200?
London England	.7 ft ?	90-? (1969)

Petroleum Subsidence Areas

	Maximum Subsidence	Production Depth
Wilmington California	8.8 m (1928-1970)	600-2,300 m (most 600-1,100 m)
Long Beach California	.75 m (1925-1967)	median 1,690 m
Inglewood California	1.73 m (1911-1963)	median 900 m
Huntington Beach California	1.22 m (1933-1965)	median 930 m
Goose Creek Texas	1 m (1918-1925)	200-1,400 m
Lake Maracaibo Venezuela	.3-3.3 m (1926-1954)	
Po Delta Italy	~2 m	? (one well ~700 m)
Nigata Japan	.8 m (1900-1960)	?-1,000 m

Geothermal Subsidence Areas

	Maximum Subsidence	Production Depth
Wairakei New Zealand	4.7 m (1956-1974)	150-1,360 m
Broadlands New Zealand	.175 m (1969-1975)	430-1,200 m
Kawerau New Zealand	.028 m (1970-1971)	460-915 m

Proposed Production Depth of Geopressured-geothermal Test Well: -4,300 to -5,030 m

TABLE 4. LAND SUBSIDENCE AND SURFACE FAULTING ASSOCIATED WITH OIL AND GAS FIELDS, HARRIS COUNTY, TEXAS*

(From Kreitler, 1977b)

Field No.	Field Name	Producing Horizon (m)	Total Production (10^6bbl)	Subsidence (m)	Faulting (m)
1	South Houston	1,460	39.3 (1974)	0.3 (1942-1958)	0.45 (1972)
2	Clinton	915-2,134	2.7 (1974)		0.7 (1972)
3	MyKawa	1,483-2,645	4.1 (1974)	0.5 (1942-1973)	0.5 (1942-1973)
4	Blue Ridge	1,420-2,381	21.0 (1974)	0.2 (1942-1973)	0.15 (1966-1972)
5	Webster	1,481-2,564	41.3 (1974)		0.45 (1942-1975)
6	Goose Creek	1,490-1,310	60.3 (1926)	1.0 (1917-1926)	0.43 (1917-1926)

* Harris County is adjacent to and northeast of Brazoria County.

"Two factors contribute to the significance of overburden thickness in determining the amount of reservoir compaction which is expressed at the surface as subsidence. In terms of engineering mechanics, the structural resistance to bending of a slab or disc representing the overburden is proportional to the cube of its thickness (Timoshenko and Woinowsky-Krieger, 1959). Thus, a very small increase in overburden thickness substantially reduces its tendency to deform. Second, expansion may occur within the overburden to compensate for the contraction of the reservoir materials (Allen, 1968). The thicker the overburden, the less compaction is likely to be transmitted to the ground surface."

The purpose of tables 3 and 4 is not to imply that production depth is the controlling factor over subsidence susceptibility, but to point out that fluid production in the prospect area will be from reservoirs more than twice the depth of those reservoirs associated with subsidence listed in the tables.

The additional overburden, more than 2000 m, should be influential in limiting the amount and rate of subsidence but apparently will not necessarily prevent it. Gustavson and Kreitler (1976) note that over the Chocolate Bayou oil and gas field (north of the prospect area), where production is from -2438 to -3962 m, the surface has undergone more than 0.3 m of subsidence. The subsidence appears to be associated primarily with gas production from geopressured sediments (fig. 7). This is the same geopressured-geothermal fairway from which the test well will produce at a down dip location. One difference between these two areas is that reservoir porosities are expected to be lower in the prospect area than in the Chocolate Bayou oil and gas field (Bebout and others, in press). The lower porosities, although detrimental in terms of fluid production, are beneficial in terms of mitigating compaction and subsidence.

Cementation in the Overburden. In addition to the positive factor of having a thick overburden, the amount of cementation in overburden sands at moderate to intermediate depths may help prevent deformation and subsequent translation of reservoir compaction into surface subsidence. Bebout and others (in press) note that precipitation of calcite and quartz has reduced porosity to less than 5 percent in sands at shallow to intermediate depths. This high degree of cementation should provide relatively rigid sedimentary layers above the production zone.

The factor that will counteract and perhaps override the resistance to deformation by well-cemented overburden sedimentary layers is the presence of growth faults which are planes of weakness in the prime prospect area (fig. 5).

Possibility of Subsidence Based on Expected Reservoir Characteristics

According to Geertsma (1973, p. 735), "a sizable degree of com-

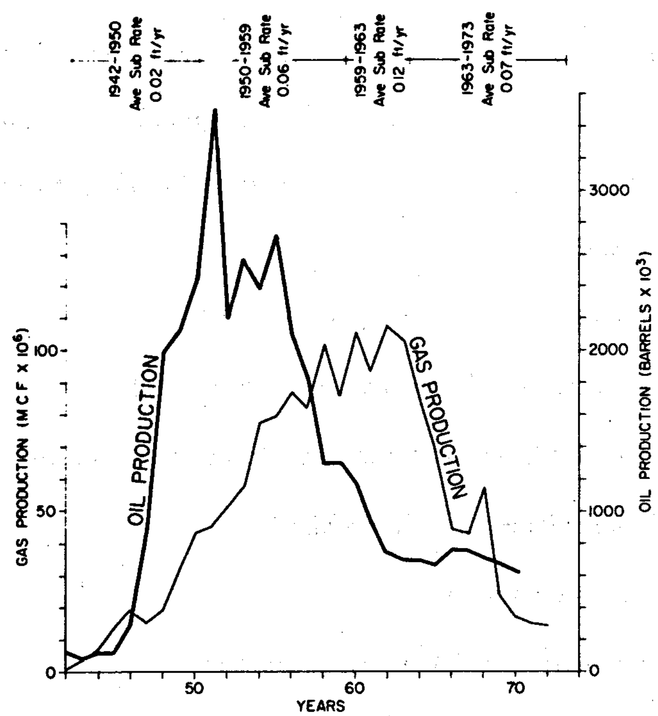


Figure 7. Comparison of rates of subsidence to oil and natural gas production from Chocolate Bayou oil field between the years 1942 and 1973. Production rates of oil and gas from the Railroad Commission of Texas. (From Gustavson and Kreitler, 1976)

paction can be expected even in hard rock for the particular conditions of large pore-pressure reductions and a sufficiently large producing interval." The amount of reservoir compaction that is translated to the surface as subsidence, however, must also be related to the production depth and the radius of the production zone. To estimate the order of magnitude of subsidence resulting from reservoir sand compaction that may accompany geopressured-geothermal fluid production from a single test well, the following equations from Geertsma (1973) were used:

$$u_z\,(r, o) = -2\,c_m\,(1-\nu)\,\Delta_p\,H\,A\,(\rho, \eta) \tag{1}$$

where u_z = vertical displacement; z = vertical coordinate

r = radius from the vertical axis through the nucleus

c_m = uniaxial compaction coefficient

ν = Poisson's ratio

Δ_p = pore (reservoir) pressure reduction

H = height of production interval

A = $R \int_0^\infty J_1\,(\alpha R)\,J_0\,(\alpha r) e^{-D\alpha}\,d\alpha$ for ranges of values ρ and η

ρ = r/R

η = D/R

R = reservoir radius

D = depth of burial

$$c_m = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)}(1-\beta)c_b \quad (2)$$

and

where c_m = uniaxial compaction coefficient

ν = Poisson's ratio

c_r = rock matrix compressibility

c_b = rock bulk compressibility

β = c_r/c_b

Values used to solve equation 2 are as follows: Poisson's ratio, 0.25 (Geertsma, 1973); rock matrix compressibility (quartz) $0.18\text{X}10^{-6}$ psi^{-1} (Gardner and others, 1974); and rock bulk compressibility, $1.2\text{X}10^{-5}$ psi^{-1} (estimated value for sandstone in geopressured zone, Gregory, 1977). Substituting these values into equation 2 yields a uniaxial compaction coefficient of $6.58\text{X}10^{-6}$ psi^{-1}.

To solve equation 1, the following estimated values (from Gregory, 1977) which characterize the prime prospect area are used in conjunction with the uniaxial compaction coefficient (c_m) as shown above, and a value for A as determined from Geertsma's (1973) tables (approximately 0.17 when r/R = 0 and D/R = 1.5):

Δ_p = 428 psi (after 2 year production period)

Δ_p = 708 psi (after 5 year production period)

H = 840 ft (net sand thickness within proposed perforated interval)

R = 10,500 ft

D = 15,300 ft (mean depth of perforated interval between -14,100 and -16,500 ft)

The following amounts of surface subsidence from sand compaction at the site of the test well are indicated by solving equation 1: 18.3 cm (7.2 in) after two years of fluid production and 30.7 cm (12.1 in) after a five year period of production. The rate of subsidence for the 5-year period is about 6 cm/yr (0.2 ft/yr); the rate of subsidence attributed to gas production from the geopressured zone in the Chocolate Bayou oil and gas field north of the test well site is 3.7 cm/yr (0.12 ft/yr) for a comparable period (1959-1963) (Gustavson and Kreitler, 1976).

It should be emphasized that many assumptions were made both with respect to the above equation and the values used in solving it. Some of the assumptions inherent in the equation were noted by Geertsma (1973) and include: (1) a disc-shaped reservoir, (2) uniform pressure reduction throughout the reservoir, and (3) homogeneous deformation with respect to the reservoir and its surroundings. Nevertheless, in theory, the equation provides a method for estimating the potential magnitude of subsidence related to reservoir sand compaction by using parameters relevant to geopressured fluid production, such as potentially large declines in pore pressure, relatively thick production intervals, a large drainage radius, and deep production zones.

Although not considered in the above calculations, potential subsidence accompanying compaction of shales interbedded with reservoir sandstones could be more significant than that associated with reservoir sands. In a theoretical treatment of geothermal fluid production from geopressured zones in Kenedy County, Texas, Gustavson and Kreitler (1976) estimated subsidence resulting from potential mudstone compaction to range from 0.3 m to 6.3 m for pressure declines of 100 to 500 psi; the net thickness of mudstone used in estimating the maximum value of subsidence (6.3 m) was 146 m. The net thickness of shale (mudstone) within the proposed perforated interval of the test well may be as much as 400 m (Gregory, 1977). With such a large sequence of shale, subsidence accompanying shale compaction could be critical.

Although there are many uncertainties, perhaps the single most important indicator that some subsidence will occur as pore pressures are reduced in the Chocolate Bayou geopressured reservoir is that subsidence has already occurred with fluid (gas) production from the same geopressured fairway updip to the northeast in the Chocolate Bayou oil and gas field (Gustavson and Kreitler, 1975).

Location of the Test Well in Terms of Potential Subsidence and Fault Activation

As previously mentioned, surface facilities in the Brazoria County prospect area that could be adversely affected by subsidence (which can increase the extent of flooding by fresh and salt water) and by fault activation (which can have a direct effect on various structures) include two petrochemical plants, numerous pipelines, a community development along Chocolate Bayou, paved roads and railroad tracks (see discussion of current land use). But the question that remains is: if subsidence and fault activation do accompany geopressured fluid production, can varying the location of the test well within the prime prospect area reduce the potential impact to the surface facilities?

In most cases, subsidence bowls produced by subsurface fluid withdrawal are centered around areas of maximum production; the Wairakei geothermal field in New Zealand is a notable exception (Atherton and others, 1976). The size of the bowl is affected by many variables.

Using equation 1 (presented on a preceding page), it is possible to theoretically determine variations in the amount of subsidence for given distances from the test well by varying r (the radius from the vertical axis through the nucleus). Table 5 shows how the amount of subsidence may vary depending on the horizontal distance from the test well. If the test well is located along the western extremes of the prime prospect area, distances between the well and the nearest petrochemical plant and the well and the western edge of community development along Chocolate Bayou would be approximately 4.3 km (2.7 mi) and 2.6 km (1.6 mi) respectively. If the test well is located on the east side of the Bayou, distances from the petrochemical plant would range between 1.3 km (0.8 mi) and 0.8 km (0.5 mi), and from the community development 0.8 km (0.5 mi) to 0.3 km (0.2 mi). According to table 5, there are definite differences in expected subsidence with respect to the relevant distances. The theoretical treatment is

TABLE 5. ESTIMATED SUBSIDENCE ACCOMPANYING RESERVOIR SAND COMPACTION AT SELECTED DISTANCES FROM THE TEST WELL AFTER FIVE-YEAR PRODUCTION PERIOD

Determined from equation 1 (see text) by varying r
(radius from vertical axis through nucleus)

Distance from Test Well (radius from vertical axis through nucleus)		Estimated Subsidence	
Miles	Kilometers	Inches	Centimeters
0.	0.	12.1	30.7
0.4	0.64	12.0	30.4
0.8	1.29	11.6	29.5
1.2	1.93	10.6	26.8
1.6	2.57	9.7	24.7
2.0	3.22	8.5	21.5
2.4	3.86	7.4	18.8
2.8	4.5I	6.3	15.9
3.2	5.15	5.2	13.2
3.6	5.79	4.2	10.7

complicated, however, by the possibility that subsidence may be compartmentalized by faults which affect fluid migration and pressure declines, and by the possibility of higher amounts of subsidence than shown in the table.

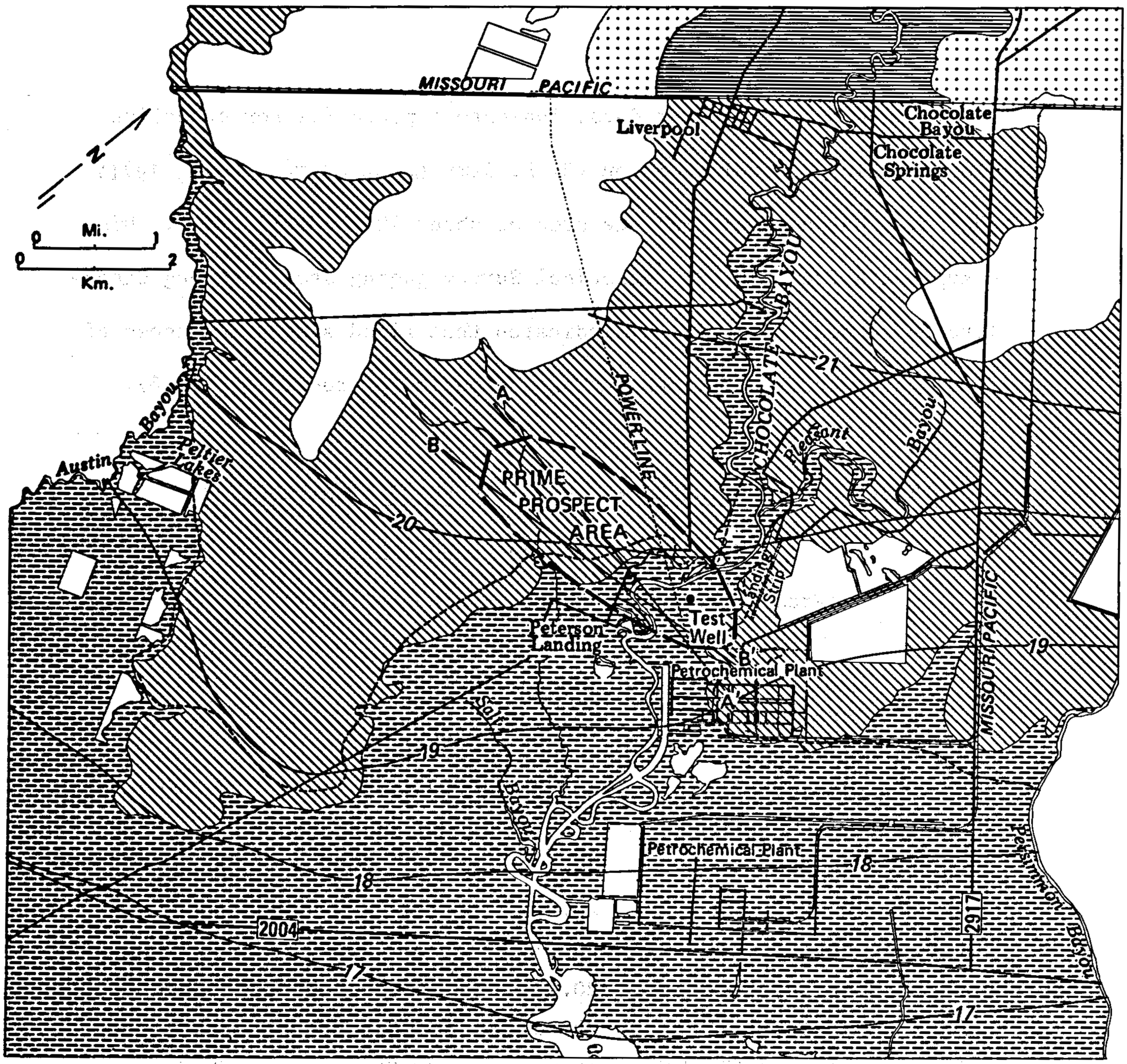
Although it is impossible to know how much the potential impact of subsidence and fault activation can be mitigated by location of the test well at the western extremes of the prime prospect area, the western area would still have to be first choice when considering the potential subsidence and fault activation that may accompany geopressured-geothermal fluid production from a single test well. Wherever the well is located, however, the possibility of subsidence coupled with the presence of growth faults, when viewed in the context of current land use, emphasize the need to institute detailed monitoring programs (including precise leveling and seismic monitoring surveys) before and during the time of production of geopressured-geothermal fluids.

FLOOD POTENTIAL--BRAZORIA COUNTY PROSPECT AREA

Relatively large portions of the Brazoria County prospect area are susceptible to inundation by flood waters along bayous that drain the area and by salt-water flooding associated with hurricane storm surge (fig. 8). The extent and levels of inundation accompanying periods of flooding and possible effects on the location of the geopressured test well and support facilities, were determined from reports and/or maps on: (1) flooding along Chocolate Bayou north of the Missouri Pacific Railroad (U. S. Army Corps of Engineers, 1971), (2) flood hazard boundary maps for Brazoria County (Federal Insurance Administration), and (3) flooding associated with Hurricane Carla (U. S. Army Corps of Engineers, 1962; Fisher and others, 1972).

Potential for Fresh-water Flooding along Chocolate Bayou

Precipitation records, runoff, historical and current flood



EXPLANATION

Standard Project Flood*

Intermediate Regional Flood* (equivalent to "100-year" flood)

Approximate area of storm-surge tidal flooding by Hurricane *Carla*

Area of "100-year" flood, includes area flooded by Hurricane *Carla*

—20— Base flood elevation line with elevation in feet

Line delineating areas of 100-year coastal flooding with velocity (wave action); velocity hazard applies to areas gulfward (southeast) of line.

*Shown only above Missouri-Pacific Railroad at top of map.

Figure 8. Areas susceptible to flooding in the Brazoria County prospect area. (From U. S. Army Corps of Engineers, 1962, 1971; Federal Insurance Administration flood hazard boundary maps; and Fisher and others, 1972)

levels, and other relevant data, indicate a potential for extensive flooding along Chocolate Bayou (U. S. Army Corps of Engineers, 1971). The bayou has a total drainage area of about 407 km^2 (159 mi^2). Discharge data from a U. S. Geological Survey gaging station along Chocolate Bayou near Alvin Texas, indicates that flood stages in excess of 20 ft have occurred 7 times during the period of record (table 6).

TABLE 6. THE HIGHEST FLOODS IN ORDER OF MAGNITUDE FOR CHOCOLATE BAYOU NEAR ALVIN, TEXAS

(From U. S. Army Corps of Engineers, 1971)

Order No.	Date of Crest	Gage Heights		Estimated Peak Discharge
		Stage feet	Elevation feet, msl	cfs
1	July 14, 1939	22.90 (1)	33.21	11,500 (2)
2	October 8, 1949	21.80	32.11	7,400
3	March 18, 1957	20.60	30.91	4,280
4	June 24, 1968	20.52	30.83	4,160
5	October 16, 1957	20.47	30.78	4,100
6	June 19, 1961	20.37	30.68	3,970
7	July 12, 1961	20.00	30.31	3,510
8	September 13, 1961	19.94	30.25	3,460
9	August 27, 1959	19.85	30.16	3,370
10	November 14, 1961	19.48	29.79	3,050

(1) Estimated from flood mark.

(2) Estimated by Corps of Engineers.

General flood characteristics of Chocolate Bayou are shown in table 7. Although these characteristics were determined for an area

TABLE 7. GENERAL FLOOD CHARACTERISTICS OF CHOCOLATE BAYOU

(From U. S. Army Corps of Engineers, 1971)

Flood Seasons	Spring and summer (intense local thunderstorms of short duration--past flooding has occured mostly during these times)
	Winter-general storms extending over periods of several days
	June-Oct.--Tropical disturbances that may produce torrential rainfall
Flood Velocities During Major Storms	
Channel	2.9 ft/sec (2 mi/hr) in unobstructed reaches
Floodplain	1 ft/sec generally, although varies widely
Duration	Commonly several days due to flat terrain and small conveyance capabilities
Rate of Stage Change from Bankfull to Extreme Flood Peak	About 2 days following intense rainfall

upstream from the main prospect area, they provide an approximate assessment of conditions that may be expected at the prime prospect area during periods of fresh-water flooding.

Land that would be inundated by Intermediate Regional Floods and Standard Project Floods (U. S. Army Corps of Engineers, 1971) are shown along the upper margin of the flood hazard map (fig. 8). Intermediate Regional Floods are those that have a recurrence interval of about once in every 100 years. It is possible, though, for a "100-year" flood to occur during any year and even during successive years. The flood that occurred along Chocolate Bayou in 1939, (table 6) was about one-half foot lower than the computed Intermediate Regional Flood (U. S. Army Corps of Engineers, 1971).

The Standard Project Flood as defined by the U. S. Army Corps of Engineers represents the "flood that can be expected from the most severe combination of meteorological and hydrological conditions considered reasonably characteristic of the geographical area in which the drainage basin is located, excluding extremely rare conditions." Assumptions with respect to storm rainfall used to estimate the extent of the Standard Project Flood at the Chocolate Bayou gaging station are: 7.88 inches of rainfall in three hours, 11.76 inches in six hours, 20.86 inches in 24 hours, and a total of 25.68 inches in 96 hours (U. S. Army Corps of Engineers, 1971). Flood levels expected during the Standard Project Flood are approximately 2 ft above levels of the 1939 flood (table 6).

The areal extent of the Intermediate Regional Flood and the Standard Project Flood upstream from the Missouri Pacific Railroad (fig. 8) (railroad marks lower limit of area studied by Corps of Engineers) indicates the probability of significant fresh-water flooding downstream in the prime prospect area during such floods. Estimated levels of flooding in the prospect area, however, cannot be adequately treated without also considering floods associated with hurricanes.

Potential for Storm-Surge Tidal Flooding during Hurricanes

The Brazoria County prospect area lies within an area along the coastal zone that is susceptible to storm-surge tidal flooding during passage of tropical storms and hurricanes. Destructive hurricanes can be expected to make landfall along the Texas Coast on the average of about once every three years (Bodine, 1969). Hurricane frequency studies by Simpson and Lawrence (1971), indicate that for an 80 km (50 mi) segment of the Gulf shoreline that centers approximately on Chocolate Bay, the probability (percentage) that a tropical storm, hurricane or great hurricane will occur in any one year is as follows:

All tropical cyclones (Winds 40 mph or higher)	18%
All hurricanes (Winds 74 mph or higher)	14%
Great hurricanes (Winds greater than 125 mph)	4%

The earliest and latest dates of tropical cyclones making landfall within the 80 km (50 mi) segment of shoreline that centers on Chocolate Bay, are June 17 and October 17 (Simpson and Lawrence, 1971).

Although hurricane winds can be extremely damaging, even more destructive with respect to man and his activities along the coastal zone, are storm-surge tides that accompany passage of a hurricane. Hurricane Carla which made landfall near Port O'Connor (approximately 160 km (100 mi) southwest of the Brazoria County prospect area) in 1961, flooded about 1.7 million acres of coastal land, including entire communities, and caused damage in excess of $408 million (U. S. Army Corps of Engineers, 1962). The level of storm surge flooding associated with Carla reached a high of about 6.7 m (22 ft) above mean sea level at Port Lavaca, on Lavaca Bay, southwest of Brazoria County. In Chocolate Bay maximum surge elevations associated with Carla were about 5 m (17 ft) (Reid and Bodine, 1968). The high still-water elevation determined for one point near Peterson Landing was 4.5 m (14.7 ft) (U. S. Army Corps of Engineers, 1962). The approximate areal extent of land inundated by Carla in the Brazoria County prospect area is shown in figure 8. Flooding would have been much more extensive had Carla made land fall at a point nearer Chocolate Bay.

Because torrential rainfall can accompany hurricane passage and aftermath storms, (rainfall associated with Hurricane Beulah was in excess of 76 cm (30 in) for a 4 to 5 day period; Brown and others, 1974), the most extensive flooding along coastal areas may result from a combination of fresh-water flooding along streams and bayous and salt-water flooding by storm surge. To determine flood levels and the extent of inundation expected with a recurrence interval of about 100 years (based on statistical probability), Federal Insurance Administration flood hazard boundary maps of Brazoria County were used. The areal extent and levels of flooding expected during such events (100-year floods) for the Brazoria County prospect area are depicted in figure 8.

<u>Selection of Test Well Site on the Basis of Flood Potential</u>

Land surface elevations (as indicated by U. S. Geological Survey topographic maps) in the prime prospect area range from a high of about 5.5 m (18 ft) above mean sea level along the western margin of the area to less than 1.5 m (5 ft) along Chocolate Bayou. Maximum elevations on the east side of the Bayou in the prime prospect area, are slightly in excess of 4.5 m (15 ft).

A comparison of land surface elevations with flood level elevations expected during 100-year floods suggests that the minimum depth of flooding would be about 0.6 m (2 ft) on the west side of Chocolate Bayou in the prime prospect area, as compared to a minimum of about 1 m (3.3 ft) on the eastern side (fig. 9). Furthermore, almost all of the prime prospect area on the east side of Chocolate Bayou was inundated by Hurricane Carla, whereas over 60 percent of the land in the prime prospect area on the west side of the bayou was not affected. The area flooded by Carla correlates closely with areas designated zone "V" on Federal Insurance Administration flood hazard boundary maps. The "V" designation identifies areas affected by a "100-year coastal flood with velocity (wave action)." Flood insurance rates in areas designated zone "V" are substantially higher than in areas desig-

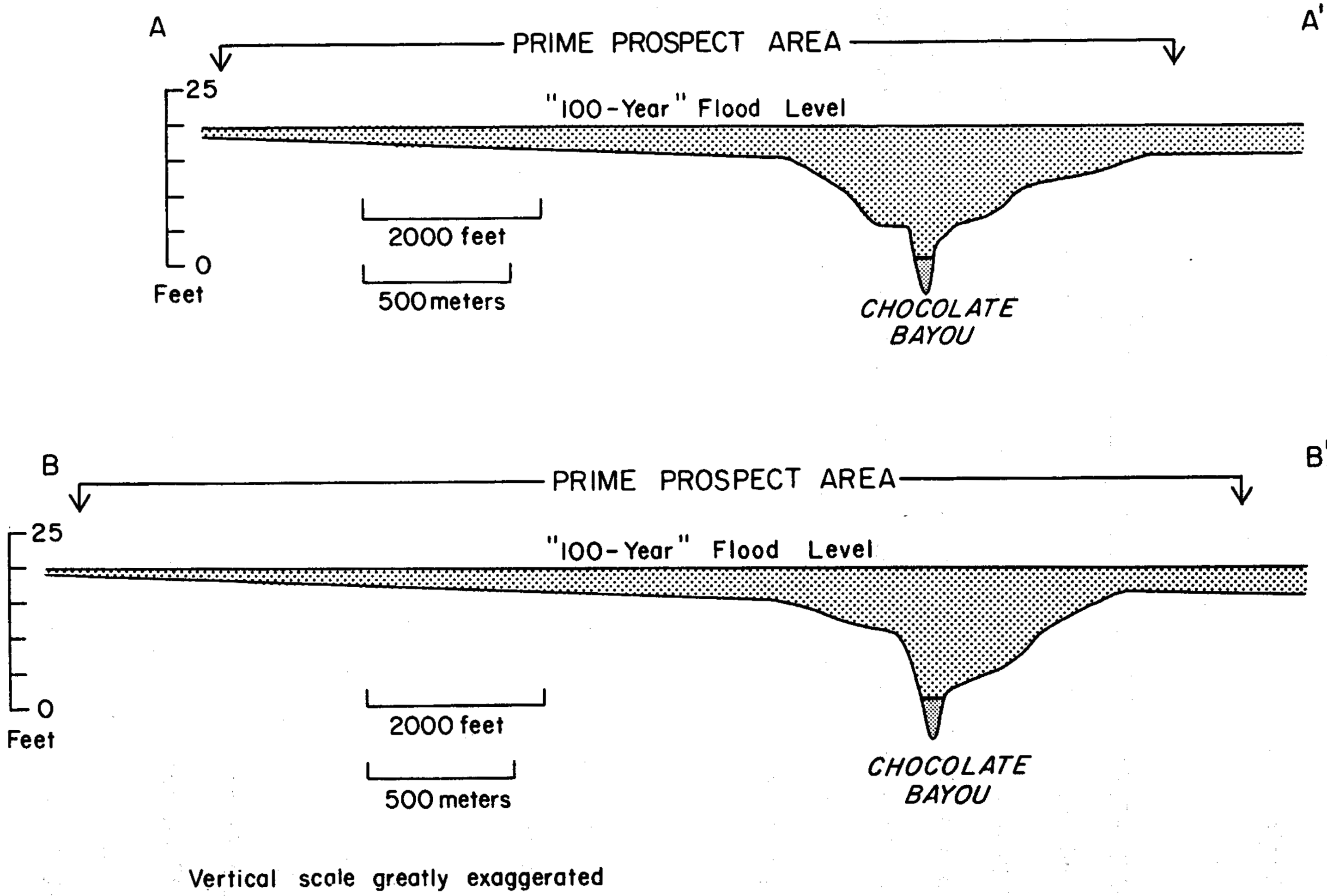


Figure 9. Cross sections indicating 100-year flood levels along lines A-A' and B-B' (fig. 8) in the prime prospect area.

nated zone "A" which also lie within 100-year flood zones but are not affected by the "velocity" hazard.

The most suitable site for the test well in terms of flood potential, or more precisely, in terms of avoiding flood-prone areas, is along the western margin of the prime prospect area where high land surface elevations would afford some degree of natural flood protection for the test well and surface support facilities. Location of the test well and support facilities on the east side of Chocolate Bayou will require implementation of flood protection measures including the placement of surface facilities on land with naturally high elevations and the construction of dikes. Surface elevations at the site of the proposed test well as shown in figure 8, range from about 3 to 5 m (10-16 ft). Levels of inundation during the 100-year flood at this site would range approximately between 1 and 3 meters.

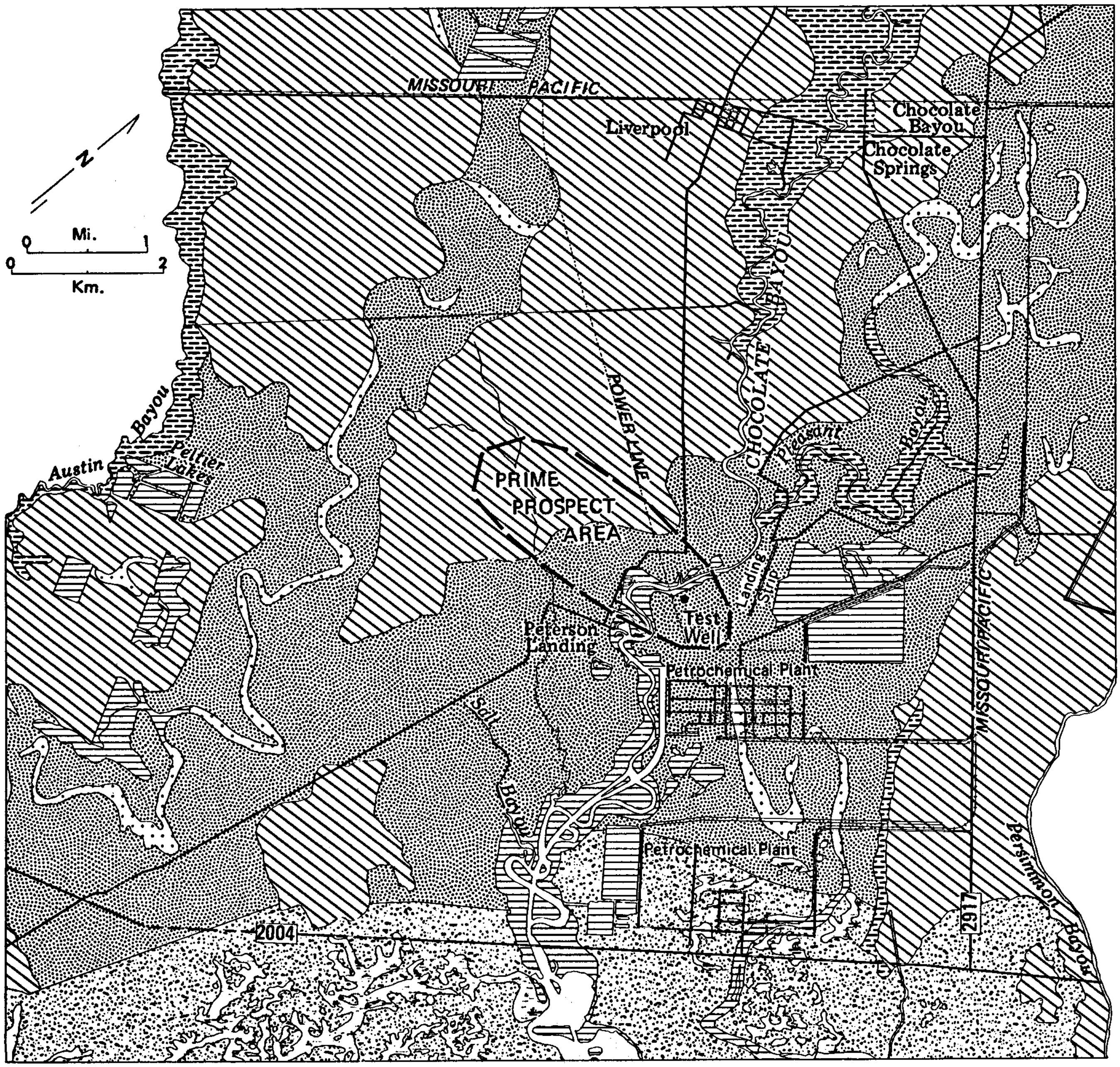
SUBSTRATE LITHOLOGY AND SOILS

Knowledge of shallow substrate lithology and soils helps to differentiate areas on the basis of factors such as permeability, potential for ground-water recharge, expansive clays, corrosivity, and drainage characteristics, which in turn aid in evaluating possible problems associated with construction and geopressured fluid handling and disposal activities.

The Brazoria County prospect area lies within a Pleistocene fluvial-deltiac system composed of: (1) distributary and fluvial sands and silts, including levee and crevasse splay deposits, (2) interdistributary mud including bay and flood-basin facies, (3) marine deltaic sand that is reworked and locally veneered by thin marsh and lacustrine mud, and (4) mud-filled abandoned channels and tidal creeks (fig. 10) (Fisher and others, 1972). Modern-Holocene features, present in the map area include: (1) tree-covered areas of alluvium, sand, silt, and mud along active headward eroding streams, (2) mud filled and locally marsh covered abandoned channels and courses, and (3) marshes primarily along bayous and around natural ponds.

Areas underlain by substrates composed of sand and silt such as those associated with distributary and fluvial channel sands and silts and marine deltaic sands, are considered potential ground-water recharge areas because of moderate to high permeabilities that characterize the sands. Areas underlain by interdistributary and flood-basin muds are much less permeable because of the high clay content. The clay content can create problems for man-made structures because of high shrink-swell potentials.

To provide a more detailed look at expected surface conditions with respect to permeability, shrink-swell potential, corrosivity and other factors, a soils map of the prime prospect area was constructed from unpublished soils maps prepared by the United States Department of Agriculture Soil Conservation Service, (fig. 11). Characteristics of various soil series that occur in and near the prime prospect area are summarized in table 8.



EXPLANATION

Distributary and fluvial sands and silts, including levee and cravasse splay deposits

Interdistributary mud, including bay and floodbasin facies

Marine deltaic sand, delta front and reworked delta facies; may be veneered by thin marsh or lacustrine mud

Abandoned channel and course, mud filled

Tidal creek, fresh to brackish-water marsh-covered, mud-filled

Small active headward-eroding streams, tree-covered, alluvium, sand, silt, mud, alluvium absent locally

Undifferentiated reservoirs, ponds, spoil, fresh to brackish marsh, mud and local sand substrate

Figure 10. Environmental geologic map of the Brazoria County prospect area. Map units depicted are Pleistocene to Recent. (From Fisher and others, 1972)

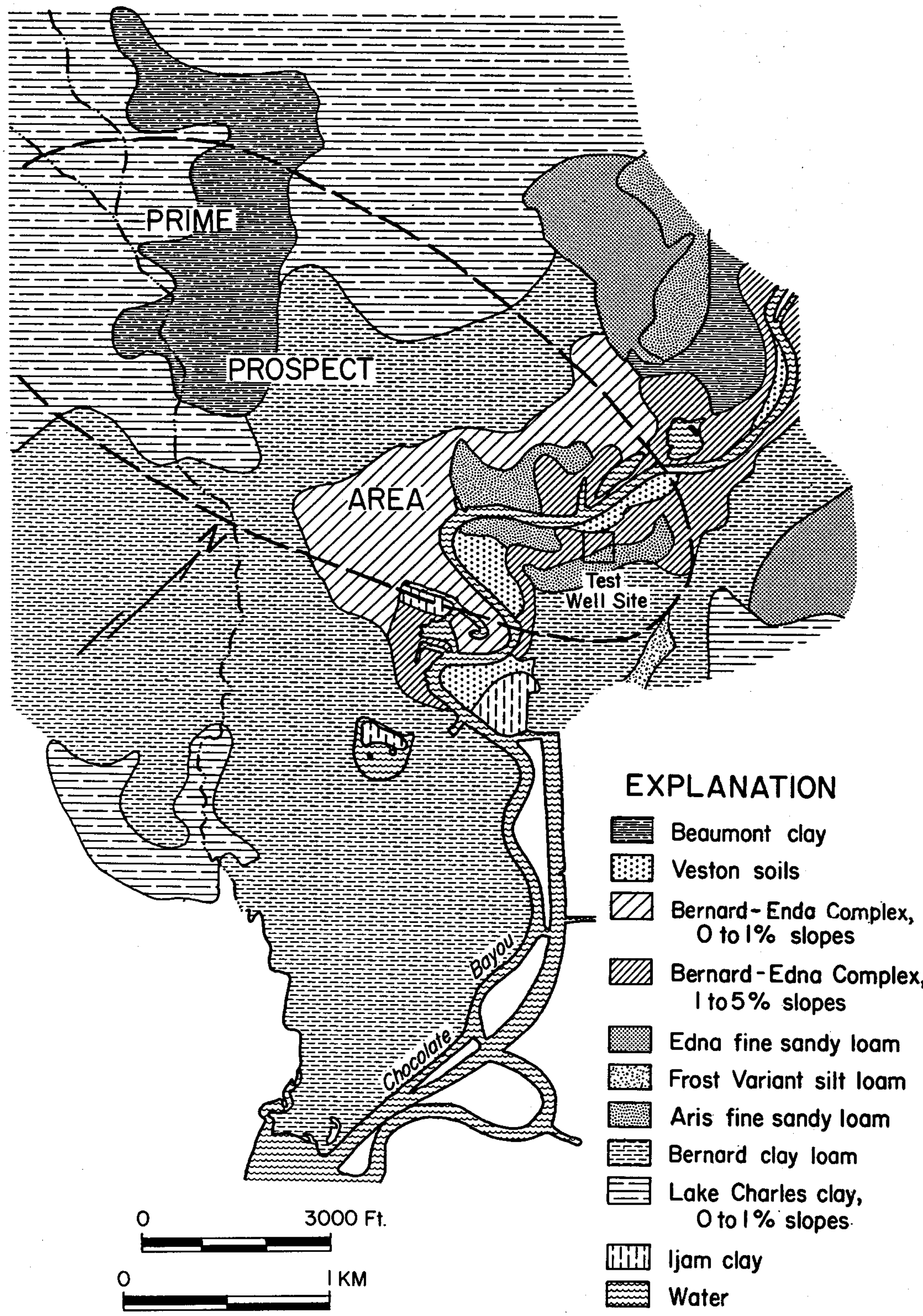


Figure 11. Distribution of soils in the vicinity of the Brazoria County prospect area. (From U. S. Department of Agriculture, Soil Conservation Service, unpublished maps)

TABLE 8. GENERAL CHARACTERISTICS OF SOILS

IN THE VICINITY OF THE BRAZORIA COUNTY PROSPECT AREA

(Compiled from descriptions of soil series established by U. S. Department of Agriculture Soil Conservation Service)

SERIES	DEPTHS (inches)	LITHOLOGY	SLOPES	PERMEABILITY (inches/hour)	SOIL REACTION (pH)	SALINITY (MMHOS/cm)	SHRINK-SWELL POTENTIAL	CORROSIVITY		HIGH WATER TABLE		
								STEEL	CONCRETE	DEPTH (ft)	KIND	MONTH
Aris	0-21	fine sandy loam	mainly less	0.6-2.0	5.6-7.3		low	high	moderate	0-2	perched	Nov-Mar
fine sandy loam	21-28	sandy clay loam	than 1% but	0.2-0.6	5.1-6.5		moderate	high	moderate			
	28-60	clay	up to 3 %	<0.06	5.1-6.5		high	high	moderate			
	60-70	clay loam		<0.06	5.1-7.3		high	high	moderate			
Beaumont	0-20	clay	0 to 1 %	0.06-0.2	4.5-6.0		high	high	moderate	0-2	apparent	Nov-Mar
clay	20-40	clay		<0.06	4.5-5.5		high	high	moderate			
	40-60	clay		<0.06	5.1-7.8		high	high	moderate			
Benard	0-6	clay loam	mainly less	0.06-0.2	6.1-7.3		moderate	high	low	0-3	apparent	Dec-Feb
clay loam	6-60	clay	than 1% but	<0.06	6.1-7.8		high	high	low			
	60-78	clay loam	up to 3%	<0.06	6.6-8.4		high	high	low			
	78-90	sandy clay loam		---	---							
Edna	0-9	loam	0 to 5%	0.6-2.0	5.6-7.3		low	high	low	0-1.5	perched	Dec-Mar
sandy loam	9-38	clay		<0.06	5.6-7.3		high	high	low			
	38-50	clay loam		<0.06	6.6-8.4		high	high	low			
	50-65	sandy clay loam		<0.06	6.6-8.4		high	high	low			
Frost	0-11	silt loam	0 to 1%	0.2-0.6	4.5-6.5		low	high	moderate	0-1.5	apparent	Dec-Apr
silt loam	11-68	silt loam, silty clay loam		0.06-0.2	4.5-8.4		moderate	high	low			
Ijam	0-8	clay	mainly less	0.10-0.12	6.6-9.0	4-16	high	high	high	0-3.0	apparent	Sep-May
clay	8-62	clay	than 1% but up to 10%	0.10-0.12	6.6-9.0	4-16	high	high	high			
Lake Charles	0-20	clay	mainly less	0.06-0.2	6.1-7.8		high	high	low	0-2.0	apparent	Dec-Feb
clay	20-70	clay	than 1% but	<0.06	6.6-8.4		high	high	low			
	70-80	clay	up to 8%	<0.06	6.6-8.4		high	high	low			
Veston loam	0-12	loam, sandy clay loam, fine sandy loam	0 to 1%	0.6-2.0	6.6-8.4	>4	low	high	high	0-2.0	apparent	Jan-Dec
	12-24	loam, fine sandy loam, clay loam		0.6-2.0	7.9-9.0	>8	low	high	high			
	24-60	silty clay loam, loam, silty loam, fine sandy loam		0.06-0.2	7.9-9.0	>8	moderate	high	high			

Selection of Test Well Site on the Basis of Substrate Lithology and Soils

Interdistributary and flood-basin muds underlie the western half of the prime prospect area; the eastern half, which includes a portion of Chocolate Bayou, is dominated by fluvial and distributary sands and silts, and locally marshes with muddy substrates (fig. 10). In terms of lithology as indicated by these map units, the more permeable substrates which are potential ground-water recharge areas, lie along both sides of Chocolate Bayou. Discharged (whether by accident or design) hypersaline geopressured-geothermal waters would more likely enter shallow ground-water aquifers in these areas of higher permeability than in areas underlain by impermeable to low permeability mud. Thus, containment of inadvertently discharged fluids could best be realized within the western half of the prime prospect area where interdistributary and flood-basin muds occur. Evaluation of permeabilities associated with various soils mapped in the area, however, indicates relatively low permeabilities for most of the soils at depths of approximately 70 to 150 cm (28 to 60 inches). These low-permeability soil zones will offer some protection to ground water because they will inhibit infiltration of potentially harmful fluids. Evaluation of possible test well sites with regard to permeability and potential ground-water recharge is also treated in an analysis of ground-water resources in a later section.

Clay-rich soils such as the Lake Charles clay, Bernard clay loam and Beaumont clay which characterize much of the prime prospect area (fig. 11), have high shrink-swell potentials. Expansive clay soils such as these can cause damage to surface and near surface facilities such as paved roads, buildings, power lines, and buried pipelines (Gustavson, 1975). By locating surface support facilities on fine sandy loams of the Aris series (fig. 11), some degree of protection against expansive soils should be realized. At depths below 71 cm (28 in), however, clay content increases in the Aris series, resulting in higher shrink-swell potentials than at the surface (table 8). Corresponding with the increase in clay content is a decrease in permeability and internal drainage which can produce a shallow perched water table and, subsequently problems for construction activities. Because of the extent of expansive soils in the prime prospect area (fig. 11, table 8), the use of engineering techniques may be more appropriate in mitigating damage from soils with high shrink-swell potentials, than trying to locate surface support facilities on naturally stable soils. Current engineering techniques employed to reduce damage to surface structures include using lime in subbase material for surface stabilization, and reinforcing concrete slabs with steel bars or post-tension cables (Gustavson, 1975).

All soils in the prime prospect area have high corrosivity with regard to steel (table 8). Soils of the Ijam and Veston series have high corrosivity with respect to concrete. These two soils can easily be avoided because of their limited areal extent along Chocolate Bayou within the prime prospect area (fig. 11)

The test well and surface support facilities, if located at the proposed site as shown in figure 10, will be in an area depicted as Pleistocene fluvial and distributary channel sands and silts on the environmental geology map. Soils that occur at this site are the Aris fine sandy loam and a complex of the Bernard clay loam and Edna fine sandy loam (fig. 11). Shrink-swell potentials characterizing the soils are low to moderate near the surface but increase to high below depths of about 0.6 m (2 ft) in the Aris and 15 to 23 cm (0.5-0.75 ft) in the Bernard-Edna complex (table 8). Corrosivity of the soils with respect to concrete is moderate to low. Slopes of up to 5 percent in the Bernard-Edna complex will need to be a consideration in designing and constructing surface facilities which include perimeter dikes.

WATER RESOURCES

The necessity of producing and disposing of large quantities of hot saline waters in geopressured-geothermal energy development emphasizes the need for mapping and describing ground- and surface-water resources in order to analyze and evaluate how they may be affected should geothermal fluids come into contact with them. Chemical analyses by Kharaka and others (1977) of water from wells in the Chocolate Bayou oil and gas field in Brazoria County indicate high salinities and high concentrations of potentially harmful chemicals such as boron in formation waters from the geopressured zone (table 9). Although essential

TABLE 9. CHEMICAL-COMPOSITION (MG/L) OF FORMATION WATERS FROM WELLS IN THE CHOCOLATE BAYOU OIL AND GAS FIELD, BRAZORIA COUNTY

(From Kharaka and others, 1977)

Well Number	Kitchen #1	Cozby #2	Gardner #1
Perforation Interval (m)	2,648-51	3,324-64	3,588-92
Measured Temperature °C (°F)	100(212)	114(237)	129(264)
Pressure, OBHP (PSI)	4,000	6,770	7,589
Total Dissolved Solids	42,000	3,100	68,500
Na	16,500	1,075	24,000
K	130	8.5	300
Rb	0.35	<0.2	0.80
NH_3	9.8	8.8	26
Mg	60	3.0	235
Ca	290	100	2,000
Sr	22	5.8	380
Fe	0.15	11.0	8.0
Mn	0.52	----	2.7
Cl	23,200	1,740	40,500
HCO_3	1,660	90	520
SO_4	39	12	0.6
SiO_2	1.6	0.85	0.32
B	42	1.8	30
pH	7.0	5.2	6.3

NOTE: Formation waters analyzed in Cozby #2 and Gardner #1 are from the geopressured zone. Low salinities of water from Cozby #2 are the result of condensed vapor which is thought to have diluted formation water by a factor of 20 (Kharaka and others, 1977).

to plant growth, boron can be toxic at concentrations slightly above the optimum value; concentrations of only 1 mg/1 and 3 mg/1 are permissible for irrigating most boron-sensitive and boron-tolerant crops, respectively (Scofield, 1936; Sandeen and Wesselman, 1973). Current plans with respect to the geopressured-geothermal test well call for fluid production rates of up to 40,000 barrels a day. The water will be disposed of by injecting it, via disposal wells, into salt-water bearing formations that do not contain oil, gas, or geothermal resources. This method of disposal is considered environmentally the most acceptable because the produced saline waters will be less likely to affect surface and near-surface water resources. The possibility of inadvertent spills and discharges of geothermal fluids points out the need for mapping and describing ground-water and surface-water characteristics in the Brazoria County prospect area.

Ground-Water Resources

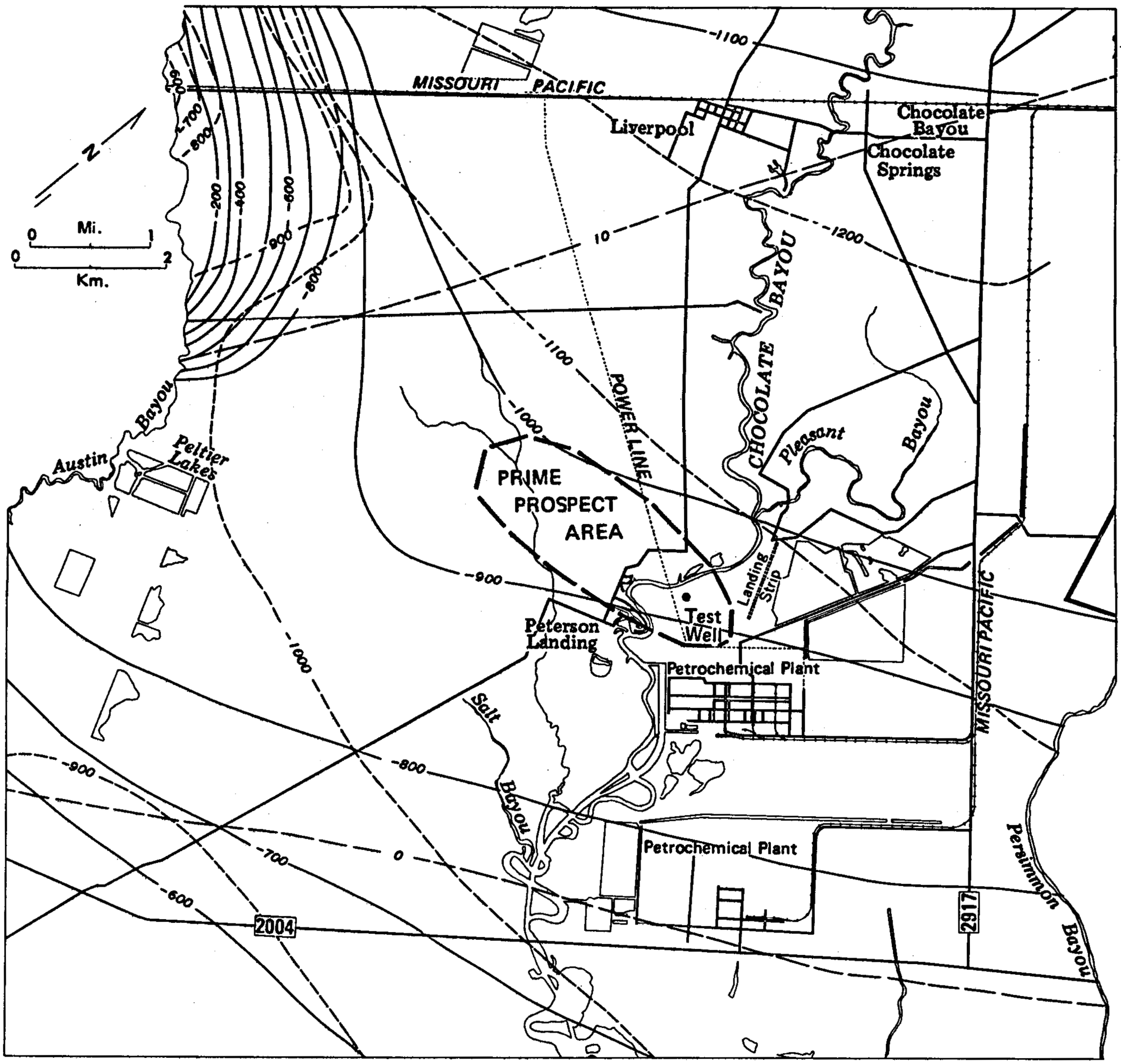
The following discussion of ground-water resources in the Brazoria County prospect area is based primarily on a report by Sandeen and Wesselman (1973).

Fresh and slightly saline ground water in the Brazoria County prospect area are produced from two major aquifers: the Chicot and Evangeline. The Chicot which is the shallower of the two aquifers has been subdivided into an upper and lower unit. The upper unit in the Brazoria County prospect area consists of interconnected shallow sands and stream alluvium and ranges in depth from near the surface to about 30 to 90 m (100 to 300 ft) below mean sea level. The upper unit is either a water table or an artesian aquifer. Water levels of wells screened in this unit are shown in figure 12.

The lower unit of the Chicot aquifer, which is generally separated from the upper unit by clay, is an artesian or leaky artesian aquifer. In the Brazoria County prospect area, the base of the lower unit of the Chicot dips toward the southeast and ranges in depth between approximately 275 m (850 ft) and 320 m (1050 ft) below mean sea level.

An unconformity separates the base of the Chicot from the underlying Evangeline aquifer. Distinction between these two aquifers is based on differences in stratigraphic position, lithology, permeability and water level. The Evangeline aquifer consists of alternating sands and clays that range in thickness from approximately 610 m (2,000 ft) to 1,065 m (3,500 ft) at the northern edge and southern edge of Brazoria County, respectively. The maximum thickness of the zone containing fresh to slightly saline water in the Evangeline aquifer, however, is about 335 m (1,100 ft).

The quality of the water in the Chicot and Evangeline aquifers varies with location, partly as a result of salt domes that are present in the area. The distribution of the fresh water (less than 1,000 mg/l of total dissolved solids) and slightly saline water (1,000 to 3,000 mg/l of total dissolved solids) in the Brazoria County prospect area is shown in figures 12 and 13, in terms of the following approxi-



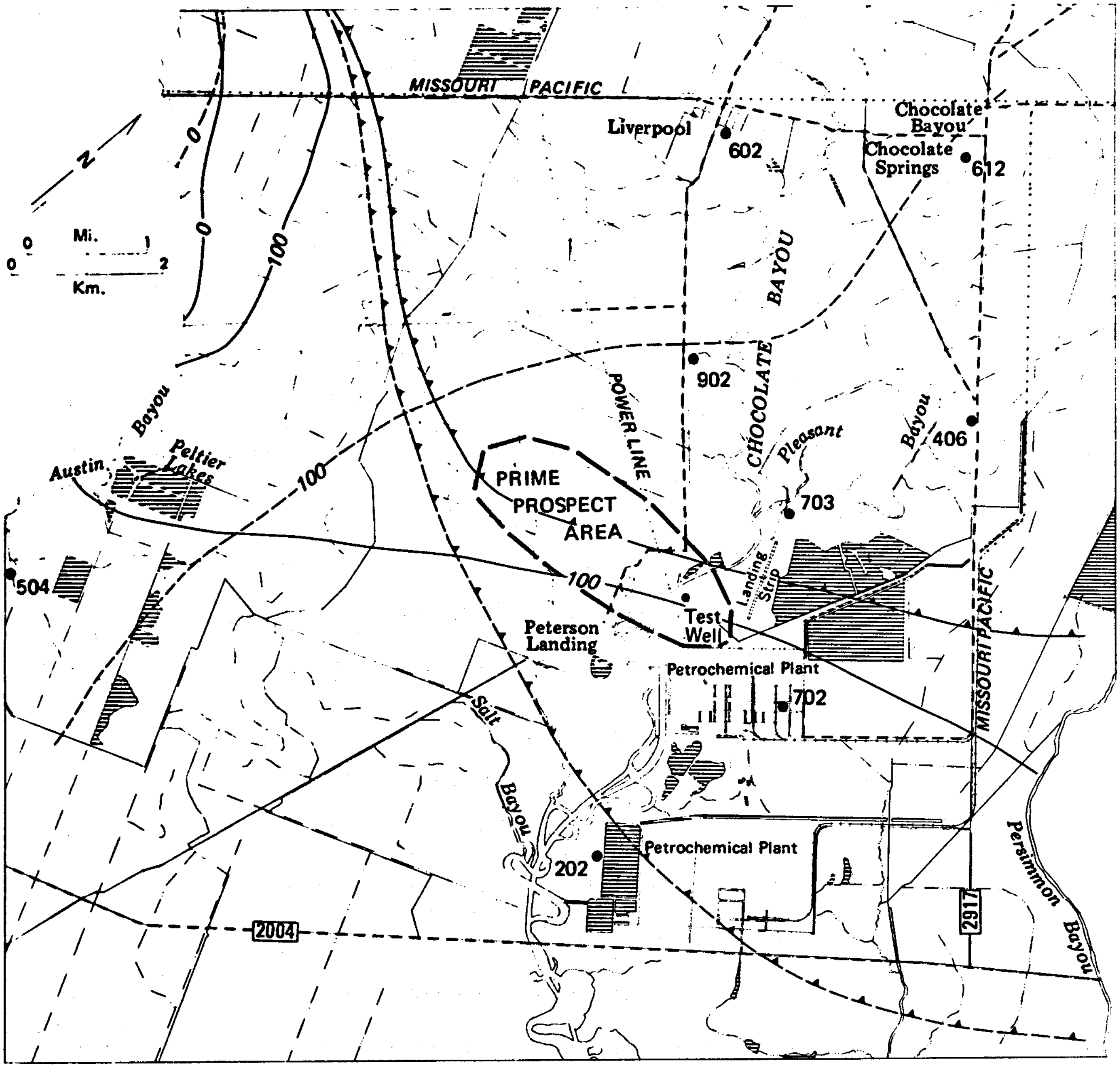
EXPLANATION

— — 0 — — Approximate elevations (ft) of water levels in wells screened in upper unit of Chicot Aquifer (1967)

—— -800 —— Approximate elevation (ft) of base of fresh water

- - - -800 - - - Approximate elevation (ft) of base of slight saline water

Figure 12. Ground-water features in the Brazoria County prospect area. (From Sandeen and Wesselman, 1973)



EXPLANATION

GROUND WATER

Evangeline Aquifer

Approximate downdip limit of fresh water

Approximate downdip limit of slightly saline water

Evangeline and Lower Unit of Chicot Aquifers

—100— Approximate thickness (ft) of sand containing fresh water

---100--- Approximate thickness (ft) of sand containing slightly saline water

● Approximate location of water wells for which water quality data are reported

SURFACE WATER

Reservoirs and ponds

Natural and man-made waterways

permanent

intermittent

Figure 13. Ground-water and surface-water features in the Brazoria County prospect area. (Ground water data from Sandeen and Wesselman, 1973, and Neftel and others, 1976; surface-water features modified from U. S. Geological Survey topographic maps)

mate characteristics: (1) elevation of water levels in wells screened in the shallowest aquifer--the upper unit of the Chicot, (2) elevation of the base of fresh water and slightly saline water, (3) downdip limit of fresh and slightly saline water in the deepest aquifer--the Evangeline, and (4) thickness of sands containing fresh and slightly saline water in the Evangeline and lower unit of the Chicot. The presence of a salt dome (Danbury Dome) in the western corner of the map area is reflected by changes in the distribution of fresh and slightly saline water in the area of the dome (figs. 12 and 13).

Results of chemical analyses of water from wells located within the Brazoria County prospect area (fig. 13) are shown in table 10. As indicated by dissolved solids and specific conductance (total dissolved solids in mg/l can be roughly estimated using 50 to 60 percent of the specific conductance in micromhos per centimeter at 25° C), all but two of the wells listed in the table contained fresh water (less than 1,000 mg/l total dissolved solids) at the time of sampling and analysis; water from wells 702 and 703 contained approximately 2,000 mg/l total dissolved solids and can be classified as slightly saline. As noted in table 9, concentrations of boron (which are often high in water from the geopressured zone) were not analyzed in the water wells listed, however, of 21 analyses of water in other wells located in Brazoria County, boron exceeded a concentration of 1 mg/l in only one, where the concentration was 1.9 mg/l (Sandeen and Wesselman, 1973).

In 1967, ground-water pumpage in Brazoria County was about 43

TABLE 10. CHEMICAL ANALYSES OF WATER FROM WELLS IN THE BRAZORIA COUNTY PROSPECT AREA

(Compiled from Sandeen and Wesselman, 1973, and Naftel and others, 1976)

WELL	202	406	504	602	612	702	703	902
WATER BEARING UNIT	C	CU	CU	CU	CL	CL	CU	C
DEPTH OR PRODUCING INTERVAL (FT)	750-838	65	140	145	220	924	30	400
DATE OF COLLECTION	3-6-69	5-17-39	5-18-39	5-25-67	8-28-46	5-25-67	5-17-39	5-24-67
TEMPERATURE (°C)	—	—	—	—	—	—	—	—
SILICA (SiO_2)	14	—	—	—	—	—	—	—
IRON (Fe)	0.30	—	—	—	—	—	—	0.01
CALCIUM (Ca)	10	—	—	—	—	—	—	—
MAGNESIUM (Mg)	3.0	—	—	—	—	—	—	—
SODIUM (Na)	210	87	184	—	—	—	394	—
BICARBONATE (HCO_3)	415	494	412	428	578	406	508	624
CARBONATE (CO_3)	0	—	—	0	—	0	—	0
SULFATE (SO_4)	.0	10	8	14	40	1.6	122	17
CHLORIDE (Cl)	260	100	320	175	130	890	945	142
FLUORIDE (F)	1.1	—	—	—	—	—	—	—
NITRATE (NO_3)	.02	1.5	—	—	—	—	—	—
BORON (B)	—	—	—	—	—	—	—	—
DISSOLVED SOLIDS	693	588	867	—	—	—	2,106	—
HARDNESS AS $CaCO_3$	38	368	398	308	141	150	1,020	160
RESIDUAL SODIUM CARBONATE (RSC)	6.03	—	—	0.85	—	3.65	—	7.03
SODIUM ABSORPTION RATIO (SAR)	15	—	—	—	—	—	—	—
SPECIFIC CONDUCTANCE (MICROHOS AT 25°C)	1,440	—	—	1,190	—	3,330	—	1,370
pH	8.0	—	—	7.6	—	7.9	—	7.7

C = Chicot aquifer
CL = Chicot aquifer, lower unit
CU = Chicot aquifer, upper unit

million gallons per day, of which approximately 52 percent was used for irrigation, 30 percent for industrial purposes, and 18 percent for public and domestic supplies. Almost all drinking water came from ground water in 1967. Most of the heavy use of ground water, as indicated by cones of depression in 1967, was in the southern part of Brazoria County near Brazosport and Freeport which are southwest of the prospect area. The magnitude of land-surface subsidence that has accompanied ground-water withdrawal in the Freeport area is more than 0.5 m (1.5 ft). A small cone of depression in the upper unit of Chicot was present in the Danbury area near the western corner of the Brazoria County prospect area in 1967, indicating ground-water usage in that area. Heavy ground-water pumpage from the artesian aquifers in Harris and Galveston Counties to the northeast and east of Brazoria County have resulted in movement of ground water from Brazoria County toward cones of depression in those two counties. Estimates indicate that about 5 million gallons of fresh water a day in the Chicot aquifer are moving across the northeastern part of Brazoria County into Harris and Galveston Counties. Maps prepared by Gabrysch and Bonnet (1975) depicting land-surface subsidence associated with ground-water withdrawal for several counties in the Houston-Galveston area, show about 0.15 to 0.3 m (0.5 to 1.0 ft) of subsidence may have occurred in the Brazoria County prospect area between 1943 and 1973.

Surface-Water Resources

Surface water has been the major source of fresh water in Brazoria County as indicated by usage in 1967 when consumption of surface water was 417 million gallons per day as compared to 43 million gallons per day of ground water (Sandeen and Wesselman, 1973). Numerous surface-water features are present in the Brazoria County geopressured-geothermal prospect area including several bayous, a complex network of irrigation ditches and canals, and man-made reservoirs (fig. 13). The primary source of fresh water is apparently the Brazos River which crosses Brazoria County southwest of the prospect area. Water is transported from the Brazos via two major canals, one of which supplies water to areas west of Chocolate Bayou (South Texas Water Company Canal), and the other (Briscoe Canal) supplies areas east of the bayou.

To determine the quality of surface water in the area of geopressured-geothermal fluid production, water quality information on Chocolate Bayou was collected because of the location of the bayou with respect to the prime prospect area. Locations along and gulfward of Chocolate Bayou for which there are existing water quality data are shown in figure 14. Of these locations, only one (location #3) is within the Brazoria County prospect area, but by considering water quality information upstream and downstream, probable ranges of values for some water quality parameters can be estimated for the prime prospect area. The prime prospect area lies between sampling stations 2 and 3 (fig. 14, table 11). The two petrochemical plants southeast of

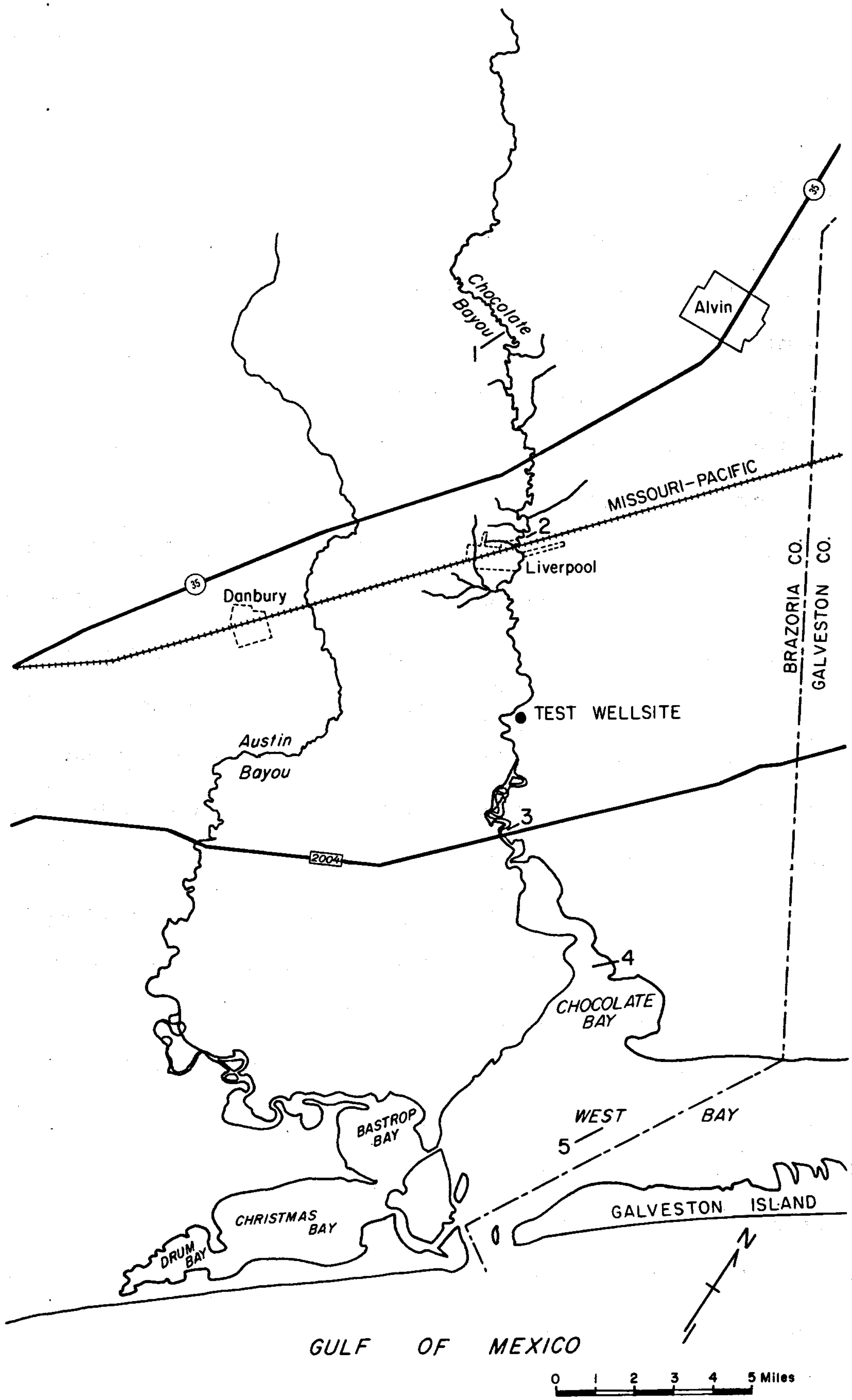


Figure 14. Location of water quality sampling stations along Chocolate Bayou, Chocolate Bay and West Bay, reported in table 11.

TABLE 11. COMPARISON OF CHEMICAL ANALYSES OF WATER FROM THE GEOPRESSURED ZONE WITH WATER FROM CHOCOLATE BAYOU, CHOCOLATE BAY AND WEST BAY

Values are in milligrams per liter unless otherwise noted	Gardiner #1 Chocolate Bayou oil and gas field (geopressured zone)	SAMPLING STATIONS★ Chocolate Bayou Ranges of values for analyses in 1975-1976				Chocolate Bay 1976-1977	West Bay 1971
		1	2	3		4	5
				Surface	Depth 9-12 ft		
TDS	68,500	272-666	300-1,000*	1,400-15,500*	10,500-17,500*	13,000-20,500*	25,500-36,600**
NA	24,000	38-160				7,200	
K	300	2.4-6.8					
NH_3	26	0.01-0.14	0.01-0.48	0.01-1.0		0.03-0.08	
Mg	235	10-30					
Ca	2,000	43-84					
Mn	2.7	0-0.01					
Cl	40,500	49-260	30-266	725-9,300			
HCO_3	520	138-341					
SO_4	0.6	23-89	22-53	117-1,250			
SiO_2	87	3.9-32					
B	30	0.11-0.4					
pH (units)	6.3	6.4-8.0	7.0-8.1	7.70-8.30	7.60-8.60	8.0-8.4	7.2-8.2
Temp (°C)	129	15-29	15.6-28.3	18.5-30.0	19.0-29.5	9.5-15.5	16-30.6
Conductivity (micromhos)		502-1,400	600-2,000	2,800-31,000	21,000-35,000	26,000-41,000	

★ See figure 14 for location of sampling stations

* Calculated as 50% of conductivity

** Salinity in parts per million

Data sources: Gardiner #1, Kharaka and others, 1977; sampling station 1, U. S. Geological Survey, 1976; sampling stations 2 and 3, Texas Water Quality Board (now part of Texas Department of Water Resources) unpublished water sampling data inventory; sampling station 4, U. S. Geological Survey unpublished data; sampling station 5, Martinez, 1971.

the prime prospect area and north of station 3 (fig. 14) have permits from the Texas Water Quality Board (Texas Department of Water Resources) to discharge up to a maximum of 19.5 million gallons per day of industrial process water, storm water, and domestic sewage into Chocolate Bayou. These discharges may have an effect on water samples from station 3.

Selection of Test Well Site on the Basis of Water Resources

In the prime prospect area, usable ground water (fresh and slightly saline water) occurs from near the surface as indicated by water levels in wells completed in the upper unit of the Chicot aquifer, to depths of about 328 m (1075 ft) as indicated by the base of slightly saline water (fig. 12). The base of fresh water occurs between 275 m (900 ft) to 305 m (1000 ft).

Because of plans to dispose of waste water by injection into saline aquifers at depths between 610 m (2000 ft) and 2135 m (7000 ft) (Bebout and others, in press), the quality of ground-water resources should not be adversely affected. The shallowest depth of injection will be approximately 275 m (900 ft) below the base of sands containing slightly saline water in the prime prospect area (fig. 12). Injection wells are presently used by the Monsanto Chemical Company just southeast of the prime prospect area. At one well, fluids are injected at depths between 610 m (2000 ft) and 1950 m (6400 ft), at rates approximating 20,000 barrels per day and at injection pressures of near 750 psi (open file report, Texas Department of Water Resources). Bebout and others (in press) estimate that there are between 455 m (1500 ft) and 550 m (1800 ft) of sandstone suitable for injection of geothermal waters between the depths of 610 m (2000 ft) and 2135 m (7000 ft) in the prime prospect area.

Surface casing in the geopressured-geothermal test well will be set to a depth of 335 m (1100 ft) (Draper and others, 1977) which is below the base of the sands containing slightly saline water. Four to six 10,000 barrel holding tanks will initially be used for temporary surface storage and cooling of produced geothermal fluids, although a cooling tower may eventually be required (Draper and others, 1977).

In light of the proposed methods of producing, storing and cooling geothermal fluids, it is unlikely that they will come into contact with surface- or ground-water resources regardless of the location of the test well and support facilities within the prime prospect area. In the event of accidental surface discharges, however, the specific location of the test well within the prime prospect area could have a bearing on the degree to which water resources are affected. For example, location of the test well in areas of permeable sand (which may serve as ground-water recharge areas) would allow discharged geothermal fluids to percolate downward into shallow ground-water aquifers (upper unit of the Chicot). As indicated in the discussion of substrate lithology and figure 10, permeable recharge areas may coincide with relict distributary and fluvial channel sands that occur in the east half of the prime prospect area and along both sides of Chocolate Bayou. Low permeability soils (fig. 11, table 8) covering much of this area, however, should help retard movement of fluids into ground-water aquifers. Locating the test well in the western extremes of the prospect area would place it in an area mapped as Pleistocene interdistributary and flood-basin muds on the environmental geology map (fig. 10) and in an area mapped as Lake Charles Clay on the soils map (fig. 11). These are areas of low permeability and would offer some protection to underlying ground-water aquifers. A possible problem with location of the test well on the west side, however, is that if inadvertently discharged fluids did reach deeper ground-water aquifers, water quality in public wells to the east at Peterson Landing could be adversely affected. As noted previously, ground-water movement in the deeper aquifers is toward the east and northeast because of heavy pumpage in adjacent Harris and Galveston Counties.

The major surface-water feature in the prime prospect area that might be affected by inadvertently discharged geothermal waters is Chocolate Bayou. Surface-water salinity reported by Moffett (1975) for water samples taken between the mouth of Pleasant Bayou, which discharges into Chocolate Bayou just upstream from Peterson Landing, and a point near Farm to Market Road 2004 ranged (approximately) between 1,500 to 18,000 parts per million in 1969-1971; salinities for bottom waters were substantially higher. These salinity ranges agree with those expected for the prime prospect area as shown by table 11. These data suggest that the salinity of Chocolate Bayou in the prime prospect area is generally unsuitable for many human uses, but the fact that important biological assemblages (discussed in the following section) are adapted to the existing salinity conditions indicates the need to protect Chocolate Bayou from geothermal fluids. This could best be accomplished by locating the test well at sufficient distances from the bayou to allow containment of accidentally discharged fluids.

BIOLOGICAL ASSEMBLAGES

Flora

The prospect area displays typical characteristics of the Gulf Prairies and Marsh Vegetation Area as described by Gould (1962). These are broad expanses of nearly level grasslands traversed by wooded meandering rivers and bayous flowing into the Gulf. The climax vegetation of the Gulf Prairie is the "tall-grass" prairie which forms a dense cover of tall range species common to the eastern prairie regions of the United States (Thorp, 1952). However, in the study area, much of this assemblage has been replaced by rice and grain cultivation and grazing. In the southeastern part of the prospect area below Farm to Market Road 2004 a transition occurs from the typical grassland assemblage to one dominated by sedges and rushes. Fresh water ponds dot the prospect area--a region of poor drainage. Natural drainage is modified by irrigation and drainage ditches, which support water tolerant shrubs and trees.

The Chocolate Bayou prospect area is divided into five vegetation assemblages based on species composition and physiognomy. Vegetation map units were interpreted from 1:120,000 winter (February) 1975 color IR photographs, supported by field reconnaissance, and from published information. Table 12 lists the common plant species found in each of these assemblages. A description of each vegetation assemblage as shown in figure 15 follows:

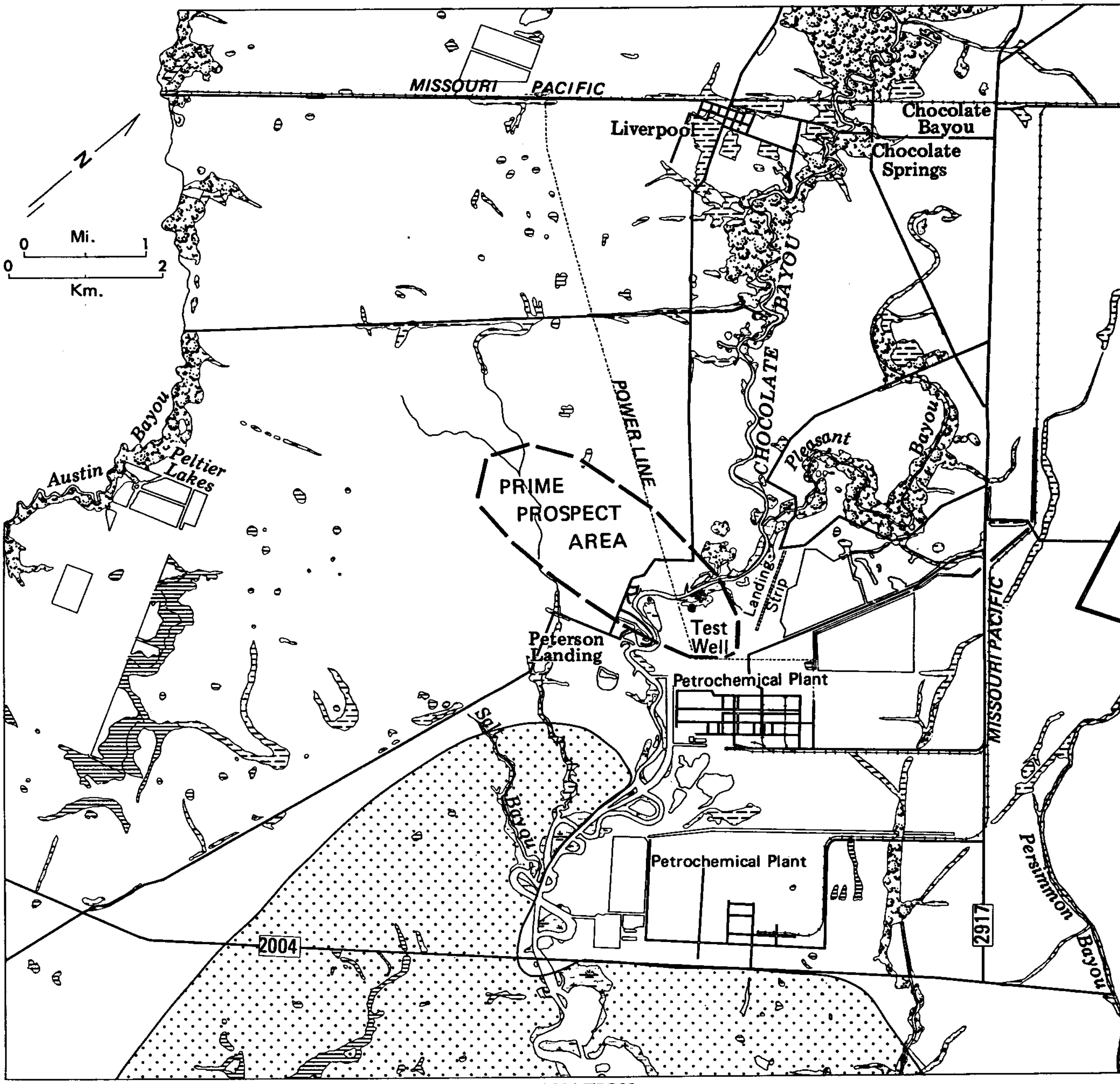
(1) Fluvial Woodlands: The Fluvial Woodlands assemblage comprises the timbered areas along the floodplains of the Austin, Chocolate, and Pleasant Bayous and a portion of New Bayou. The assemblage is characterized by several species of Oak, Green Ash, American and Cedar Elm, Hackberry, and Pecan. Understory shrubs are dense to sparse depending on the tree canopy and predominantly consist of Yaupon, Pepper-vine, and to a lesser extent, Indigo-Bush Amorpha. Grape vines are abundant while Greenbriar, Trumpet-Creeper and Japanese Honeysuckle are common. Spanish Moss drapes some tree branches along the bayous' edge.

For each of the bayous, some special characteristics are also notable. For instance, Austin Bayou is characterized by more river bottom species including Dwarf Palmetto, Water Elm, and Water Hickory. Chocolate and Pleasant Bayous display inner zones where Oak is more predominant, and the higher and drier outter zone is dominated by tall (approximately 20 m) Loblolly Pine.

TABLE 12. PLANT SPECIES FOUND IN THE CHOCOLATE BAYOU PROSPECT AREA GROUPED BY VEGETATION ASSEMBLAGE

(Plant species identification was aided by Correll and Johnston, 1970, Hitchcock, 1950, and Vines, 1960. Nomenclature after Correll and Johnston, 1970)

1. Fluvial Woodlands			
Swamp Red Oak	*Quercus falcata* var. pagodifolia	Pecan	*Carya illinoinensis*
Water Oak	*Quercus nigra*	Water Hickory	*Carya aquatica*
Post Oak	*Quercus stellata*	Mulberry	*Morus rubra*
Virginia Live Oak	*Quercus virginiana*	Chinese Tallow Tree	*Sapium sebiferum*
Overcup Oak	*Quercus lyrata*	Yaupon	*Ilex vomitoria*
Willow Oak	*Quercus phellos*	Possum-haw	*Ilex decidua*
Green Ash	*Fraxinus pensylvanica*	Dewberry	*Rubus* sp.
Eastern Red Cedar	*Juniperus virginiana*	Bastard Indigo	*Amorpha fruticosa*
American Elm	*Ulmus americana*	Wax Myrtle	*Myrica cerifera*
Cedar Elm	*Ulmus crassifolia*	Grape	*Vitis* sp.
Loblolly Pine	*Pinus taeda*	Trumpet-creeper	*Campsis radicans*
Black Willow	*Salix nigra*	Japanese Honeysuckle	*Lonicera japonica*
Hackberry	*Celtis laevigata*	Greenbriar	*Smilax* sp.
Water Elm	*Planera aquatica*	Rattan-vine	*Berchemia scandens*
Dwarf Palmetto	*Sabal minor*	Pepper-vine	*Ampelopsis arborea*
	Poison Ivy	*Rhus toxicodendron*	
2. Frequently Flooded Fluvial Areas			
Eastern Baccharis	*Baccharis halimifolia*	Chinese Tallow Tree	*Sapium sebiferum*
Black Willow	*Salix nigra*	Japanese Honeysuckle	*Lonicera japonica*
Hackberry	*Celtis laevigata*	Grape	*Vitis* sp.
3. Fresh Water Pond			
Bulrush	*Scirpus* sp.	Coon-tail	*Ceratophyllum* sp.
Cattail	*Typha latifolia*	Water Milfoil	*Myriophyllum* sp.
Water Smartweed	*Persicaria punctata*	Musk Grass	(Algae)
Pondweed	*Potamogeton* sp.	Bladderwort	*Utricularia* sp.
	Duckweed	*Lemna* sp.	
4. Marsh			
Smooth Cordgrass	*Spartina alterniflora*	Heliotrope	*Heliotropium curassavicum*
Sea Ox-eye Daisy	*Borrichia frutescens*	Sea Blite	*Suaeda* sp.
Salt Meadow Cordgrass	*Spartina patens*	Swertia	*Swertia* sp.
Glasswort	*Salicornia* sp.	Bulrush	*Scirpus* sp.
Salt Cedar	*Tamarisk* sp.	Cattail	*Typha latifolia*
	Rush	*Juncus* sp.	
5. Tallgrass Prairie			
Indian Grass	*Sorghastrum avenaceum*	Crinkle-awn	*Trachypogon secundus*
Little Bluestem	*Schizachyrium scoparium*	Dropseed	*Sporobolus* sp.
Big Bluestem	*Andropogon Gerardi*	Panic Grass	*Panicum* sp.
Switch Grass	*Panicum virgatum*	Dallis Grass	*Paspalum dilatatum*
Florida Paspalum	*Paspalum floridanum*	Bermuda Grass	*Cynodon dactylon*
	Carpet Grass	*Axonopus compressus*	
Eastern Baccharis	*Baccharis halimifolia*	Tickle-tongue	*Zanthoxylum Clava-Herculis*
	Macartney Rose	*Rosa bracteata*	



EXPLANATION

Fluvial Woodlands: Water tolerant hardwoods, several species of Oak, Green Ash, American and Cedar Elm, Hackberry and Pecan, mammals, fowl and snakes.

Frequently Flooded Fluvial Areas: Black Willow and Eastern Baccharis, water tolerant plants, fresh water reeds and rushes, mammals and fowl.

Fresh Water Pond: Several species of fresh water submerged and emerged plants, algae, fowl.

Marsh: Fresh-, brackish- and salt-water marshes, includes salt tolerant to fresh water plánt species, mammals, snakes and fowl.

Tall Grass Prairie: Tall grass species and sedges, Eastern Baccharis and Tickle-tongue, much of the area cultivated or grazed, fowl and mammals.

Known Range of the Red Wolf (*Canis rufus*)

Figure 15. Vegetation assemblages identified in the Chocolate Bayou prospect area; range of the Red Wolf. (Surface water features can be identified by referring to figure 13)

(2) Frequently Flooded Fluvial Areas: This assemblage is characteristic of small streams and irrigation and drainage ways and, therefore, to some extent is a product of man's alteration of the environment. Characteristic species are Black Willow and Eastern Baccharis. Hackberry, Chinese Tallow and Japanese Honeysuckle are also common. Cattail and fresh water reeds and rushes are also present.

(3) Fresh Water Pond: Numerous ponds dot the study area, especially near rice fields where water is abundant and drainage is controlled. They are characterized by variable water levels and impermeable substrate. Notable species of this assemblage are Cattails, Bulrushes, Water Smartweed, Coontail, Water Milfoil, and Bladder Wort (Wilson, personal communication). This assemblage also provides cover and food for water fowl. At least three species present that provide food for water fowl are Pondweed, Duckweed, and Musk Grass.

(4) Marsh: This assemblage occupies lowlands along the banks of Chocolate Bayou where storm tidal inundation intermixed with fresh water floods and runoff causes variable salinities. The flora ranges from salt tolerant species near the bay to fresh marsh species along the bayou in the vicinity of the prime prospect area. A. W. Moffett (1975) collected marsh plants along Chocolate Bay in 1969 and found Smooth Cordgrass (*Spartina alterniflora*) as the dominant emersed plant. Additional species have been collected near the intersection of Chocolate Bayou and Farm to Market Road 2004. These are Sea Ox-eye Daisy, Salt Meadow Cordgrass, Glasswort, Salt Cedar, Heliotrope, Sea Blite,

and Swertia. In the prime prospect area on the north bank of Chocolate Bayou, Bulrush and Cattail were noted. These species conform to an orderly plant succession from salt- to fresh-water marsh described by Fisher and others (1972) and also are those predicted by salinity data in this report for Chocolate Bayou.

(5) Tall Grass Prairie: The Tall Grass Prairie assemblage occupies the broad level plains in the prospect map area. In its climax state, this assemblage is characterized by a dense cover of tall grass range species and sedges (Thorpe, 1952). Much of the region, however, has been converted to rice and grain cultivation and cattle grazing. Areas under cultivation essentially have native species removed while grazed areas display some form of modified assemblage due to grazing pressures. In addition, the native range was characterized by several woody shrubs, of which some of the remnants now occupy fallow ground along roadsides and in open fields. Notable species are Eastern Baccharis, Tickle-tongue, and Macartney Rose. The Tall Grass Prairie assemblage has been compiled from grass species identified by the Brazoria County Soil Survey (in press) for soil associations in the area. It is characterized by species of Big and Little Bluestem, Indian Grass, Switchgrass, Florida Paspalum, Crinkleawn, and Dropseed, as well as Bermuda Grass and Carpet Grass, which are not true tall-grass species. It should be noted that the Bluestems and Indian Grass are good forage species which are susceptible to decline under heavy grazing (Gould, 1962). The introduced species, Bermuda and Carpet Grass, on the other hand,

are also good forage species, but more readily withstand the pressures of trampling and grazing. In heavily grazed pastures, these latter species will become more dominant.

Endangered Plant Species

A table has been prepared from Rare Plant Study Center and Texas Parks and Wildlife Department data (Blevens and Novak, 1975) (table 13) listing the plant species that are most directly threatened with extinction in Brazoria County and its environs. Information on frequency and distribution is also given. Further field study is needed to determine whether any of these species occur in the prime prospect area and what measures must be taken to protect them.

Discussion of Vegetation Assemblages with Reference to the Test Well Site

To determine the best sites for the test well, not only must the attributes of a single assemblage be examined, but also the role of the assemblage as part of the entire biological community. Natural factors which influence the existence of a particular community are as important as the existance of the community itself. For instance, in evaluating each assemblage, the role of water availability and drainage and salinity stand out as prime natural factors in determining their composition and distribution (Blevins and Novak, 1975). Other factors such as existing man-made changes and the impacting activities

TABLE 13. RARE AND ENDANGERED PLANT SPECIES THAT HAVE BEEN IDENTIFIED IN BRAZORIA COUNTY AND ITS ENVIRONS

(From Blevins and Novak, 1975)

GENERA/SPECIES	COMMON NAME	RARENESS	DISTRIBUTION
Bothriochloa exaristata (Grass Family)	Awnless Bluestem	5-H(B)	Information needed
Carex gigantea (Sedge Family)	Giant Sedge	6-E(B)	Harris County; also in Polk County, East Texas
Chloris texensis (Grass Family)	Texas Windmill Grass	6-E	Information needed; also in Rio Grande Plains
Hymenoxys texana (Sunflower Family)	Texas Bitterweed	7-I	Houston area—not collected since 1900
Ilex Cassine (Holly Family)	Dahoon Holly	6-I(B)	Brazoria County only
Ilex myrtifolia (Holly Family)	Myrtle Holly	7-I(B)	Brazoria County?—no precise information
Leitneria floridana (Corkwood Family)	Corkwood	5-I?(B)	Brazoria County—near Angleton and Lake Jackson
Lithospermum tuberosum (Borage Family)	Bulb Gromwell	7-I(B)	Brazoria County—1914; also in Polk County—1914
Machaeranthera aurea (Sunflower Family)	Houston Machaeranthera	6/7-I	Near Houston, Harris County
Oenothera sessilis (Evening Primrose Family)	Coastal Evening Primrose	7-I(B)	Last collected c. 1858
Ophioglossum vulgatum (Adder's-tongue Family)	Common Adder's-tongue	5-E(A)	Coastal Prairie; also in East Texas
Rhododon ciliatus (Mint Family)	Prairie Bobwort	5-E	Coastal Prairie; also in East Texas
Sabal minor, trunked form (Palm Family)	Louisiana Palm	5-E(B)	Coastal Prairie
Scirpus cubensis (Sedge Family)	Cuban Bulrush	6/7-I(B)	Brazoria County—known only from Eagle Nest Lake, collected once in 1958
Scleria Baldwinii (Sedge Family)	Baldwin Stone-rush	6/7-I(B)	Harris County
Scleria minor (Sedge Family)	Minor Nut-rush	6-E(B)	Matagorda County; also in Newton County, E. Texas
Wolffiella gladiata (Duckweed Family)	Sword Bog-mat	6-I(B)	Brazoria National Wildlife Refuge only

Rareness and distribution are indicated by the following scale:

Rareness

- 5 Scarce, endangered in Texas
- 6 Very rare, acutely endangered in Texas
- 7 Presumed extinct, with no records since 1930 from Texas

Distribution

- *A Distributed widely on the continent or in the world
- *B Distributed broadly but regionally in North America and extending into Texas
- E Distributed in two of the broad vegetational areas of Texas
- H Distribution limited to 1 to 3 counties in one broad vegetational area of Texas
- I Known only from one or a few populations

* If A or B are not given, then it is implied that the species is endemic to Texas.

of constructing and operating the test well must be considered.

The boundary between prairie and forest is indirectly related to water through the effect of soil moisture which prevents prairie fires from burning into lowland forests (Harcombe and others, 1974). Urban and agricultural activities also play a major role in reducing the areal extent of forestland. A major consideration for not locating the test well site in the Fluvial Woodlands is the amount of time it takes for native forest to become reestablished--on the order of 10's of years. This assemblage also has an important part in controlling runoff and provides food and cover for a variety of mammals including squirrels, coyotes, and water fowl. In addition, the forest in the prospect area has an important aesthetic value in adding variation and relief to relatively flat monotonous topography. This is especially important, too, to home owners in the area.

The fresh to brackish marsh environment found in the prime prospect area is a vital component in maintaining the nutrient balance of the bay-marsh ecosystem. Runoff from heavy rains and related stream flooding are probably the most effective agents for transporting nutrients from these marshes to the estuary (Blevins and Novak, 1975). It is also one of the most fragile environments. Marshes are extremely susceptible to changes in water availability (i. e.) drainage from uplands and inundation due to subsidence. Salinity rates which are variable along the prime prospect area also determine marsh species composition. Since it occupies the land-water margin, these areas are easily eroded when cleared, which induces a permanent loss of the plant assemblage. Ultimately, changes in this plant assemblage will affect the finned and shell fish fishing industries downstream, as well as destroy food sources and habitats for a variety of wildlife.

Frequently Flooded Fluvial Areas reflect nature's response to man's alteration of the environment. Species characteristic of this assemblage are those that return quickly to a disturbed area. An important feature of this assemblage is its role in influencing drainage rates and erosion by stabilizing stream banks and man-made levees. They are also a source of nutrients for the bay-marsh region and provide cover for mammals and habitat for fowl.

The Tall Grass Prairie occupies the highest ground in the prime prospect area. When cleared, grass assemblages rather quickly become reestablished, provided that soil characteristics are not changed. In these areas the most important effect of the construction of the test well site will be on surface water quality and the flow of nutrients into the marshes and bay.

Some of the effects of land alteration on the hydrologic regime associated with the construction of the test well site can be anticipated: clearing, compacting, and paving will decrease surface permeability, construction of platforms or levees to protect the site will locally alter drainage patterns, and potential subsidence from geopressured-geothermal water extraction may result in changing water levels. Fresh water runoff from the prairies directly affects salinity and turbidity of marsh and bay waters. Increases in turbidity may upset nutrient balance and impair photosynthetic processes of lower trophic levels (Rowe and Williams, 1974). Over much of the area, natural drainage patterns are already modified by agriculture and irrigation practices.

Fauna

The following is a description of the more important faunal species living in or utilizing the prime prospect area.

Waterfowl. The prime prospect area is located in the southern terminus of the Central Flyway (Blevins and Novak, 1975). Because of the abundance and quality of habitat, hundreds and thousands of ducks and geese winter in the region. Species of waterfowl are diverse and consequently utilize every available kind of aquatic habitat, in addition to the rice and grain fields. To some extent they virtually utilize every environment in the prime prospect area, but aquatic habitats are the most important. The Texas Parks and Wildlife Department has designated Chocolate Bay and Chocolate Bayou and its perimeter as excellent bird watching areas.

Squirrels. Two native species of squirrels, the Eastern Fox Squirrel (Sciurus niger) and the Eastern Gray Squirrel (Sciurus carolinensis), are present in the region (Blevins and Novak, 1975). Squirrels are primarily woodland species and are affected by modification or destruction of the forest. The habitat of the Fox Squirrel consists of open mixed hardwood forest with patches of clearing, but the Gray Squirrel requires a continuous forest of mature hardwood with dense understory. Consequently strip-clearing can improve fox-squirrel habitat only, and complete clearing destroys habitat for both squirrel species. Both require mast-producing hardwoods for food and prefer hollow trees for dens. The Texas Parks and Wildlife Department has designated the Fluvial Woodlands along Chocolate, Austin, and Pleasant Bayous in the prospect area as a good fox squirrel habitat.

Southern Bald Eagle. The Southern Bald Eagle (*Haliaeetus leucocephalus*), a designated endangered species, has also been reported to nest in Brazoria County. The Southern Bald Eagle requires tall trees near rivers or lakes for perching and nesting, requirements which are fulfilled by the Fluvial Woodlands.

Aquatic fauna. The Chocolate Bayou estuarine system is a major nursery habitat and game fish habitat on the Gulf Coast. Moffett, (1975)* determined seasonal abundances of macro-biota in the Chocolate Bayou estuary and reports that major nursery areas for commercial shrimps (*Penaeus axtecus*, *P. setiferus*), Blue Crabs (*Callinectes sapidus*), estuarine game fishes, and other marine forms are present. Bay Anchovy (*Anchoa mitchilli*), Atlantic Croaker (*Micropogon undulatus*), and Gulf Menhaden (*Brevoortia patronus*) were the dominant fish species collected. Principal game fish are Red Drum (*Sciaenops ocellata*),

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* See Moffett, 1975, . . . for additional aquatic species data.

Spotted Sea Trout (*Synoscion nebulosus*), and Southern Flounder (*Paralichthys lethostigma*). The Eastern Oyster (*Crassostrea virginica*) is also plentiful in Chocolate Bay but cannot be harvested from the waters which contain high coliform bacteria counts (Moffett, 1975). Fresh-water Catfish (*Ictaluridae*) and Sunfish (*Centrarchidae*) are caught in the upper bayous.

Peripheral salt marshes and bayous offer protection and nutrients to estuarine and non-estuarine fauna during juvenile development and for breeding. Brackish water, fresh water, and salt water marshes benefit the nursery system by removal of undesirable or excessive nutrients that contribute to pollution and adverse phytoplankton blooms (Blevins and Novak, 1975).

Important undesirable effects from the test well site may be increased turbidity due to runoff from construction and clearing, and chemical and thermal pollution from accidental spill of geothermal fluids, drilling fluids, fuel, or sewage. Turbidity levels can have effects on photosensitive flora and fauna by restricting available light. Table 11 provides data on salinity ranges in the bayou versus salinity concentrations of geothermal brines. It is obvious from these data that while many estuarine organisms can survive changes in salinity, the concentrations present in geothermal fluids will radically deviate from the normal chemical and salinity range. In addition, trace elements such as boron may exist in harmful quantities. A consequence of thermal pollution can be illustrated by the following data:

In a report by the Texas Water Quality Board on fish kills in major channels, ports, and water ways of Texas (Espey, Huston & Assoc., Inc., 1976), three out of five fish kills in Chocolate Bayou resulted as a consequence of oxygen depletion. Moffett (1975) has shown that mean bottom water dissolved oxygen and temperature values for Chocolate Bayou and Chocolate Bay are inversely related. As water temperatures are increased, dissolved oxygen levels decrease. Although temperature has not been proven to be responsible for oxygen depletion in these specific cases, thermal discharges coupled with other variables could possibly produce this effect.

Alligator. Brazoria County has one of the largest alligator populations of the state (Blevins and Novak, 1975). The American Alligator (*Alligator mississippiensis*) is classified as endangered mainly for protection from overhunting. Their numbers are presently increasing. Alligator habitats are primarily in the coastal marsh areas with inland habitats primarily along stream corridors. A good to excellent habitat occurs along Austin Bayou in Brazoria County. The upper reaches of Chocolate Bayou, upstream from the prime prospect area, are also considered prime alligator territory.

Red Wolf. The endangered status of the Red Wolf (*Canis rufus*) is due to a combination of factors including habitat reduction, hybridization, parasites, a high natural mortality rate, and shooting by man (Blevins and Novak, 1975). The Red Wolf is an open country animal, travelling in a "circuit-type" pattern over a range of 25-30 square miles. Present habitats or range areas are in the lower Coastal Prairie and marsh areas. In Brazoria County, it has dwindled to 91,000 acres and continues to be reduced by urban and industrial development. The known range of the Red Wolf has been delineated by the Texas Parks and Wildlife Department and is shown in figure 15 in a modified version so as not to include the area occupied by the petrochemical plant. Encroachment upon Red Wolf territory needs to be considered not only in reference to the location of the test well site, but also to future development associated with utilization of the energy resource.

Selection of Test Well Site on the Basis of Biological Assemblages

The preceding data show that the region in which the prime prospect area is located is characterized by a rich and diversified biological community. Several basic ecosystem relationships are apparent. Floral species present are dependent on the highly variable hydrologic and salinity regime. Aquatic and terrestrial wildlife depend on the diversity of vegetation assemblages to satisfy different habitat and feeding requirements. Modification of any one of these interdependent components can have an affect on the total community.

In terms of conservation of biologic resources, the preferred locations for the test site in the prime prospect area will be on higher elevations occupied by the Tall Grass Prairie assemblage either east or west of Chocolate Bayou. The characteristics of the assemblage that support this choice are: (1) the Tall Grass Prairie assemblage generally shows a high resiliency, (2) it occupies the largest land area, (3) it is the least specialized type of habitat for wildlife, and (4) in its modified state it probably supports the least diversified fauna. It is preferred that the test site be located on the east side near the petrochemical plant where land modifications by industrial activity already exist. The Tall Grass Prairie is an important link in the hydrologic regime of the area. Modifications or interruptions of natural drainage patterns should be avoided. The greatest direct hazard would be leakage or spillage of geothermal brines. Because of the salinity and temperature of geothermal fluids, severe impacts to flora and the bay-marsh ecosystem may result if accidental releases occur.

METEOROLOGICAL CHARACTERISTICS

Climatological Data

Normal annual temperature at Angleton, Texas, approximately 19 km (12 mi) southwest of the prime prospect area, is 69.1°F (20.6°C). The highest temperature occurs most frequently during July and August and ranges around 97°F (36.1°C) and the lowest usually occurs in January and ranges around 20°F (-6.7°C) (fig. 16). Normal annual precipitation is 52.17 in (132.5 cm), although variations have occurred during the past 16 years from a low of about 34 in (86 cm) in 1963 to a high

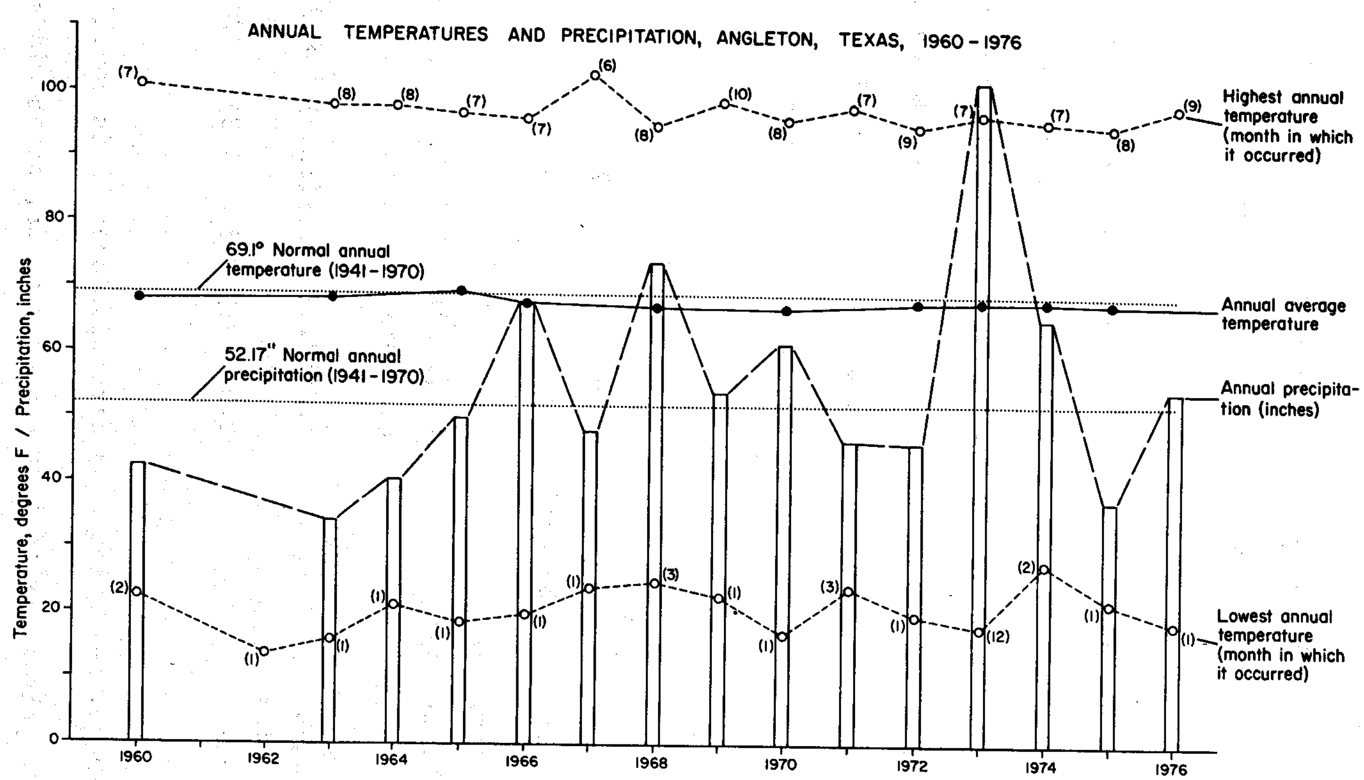

Figure 16. Temperature and precipitation for Angleton, Texas. (Compiled from records of the U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service)

of near 100 in (254 cm) in 1973 (fig. 16). As indicated by comparing normal monthly precipitation and monthly precipitation during 1976, there can be a large variation between monthly precipitation levels during any one year and "normal" monthly precipitation levels based on several years (fig. 17).

Two major wind systems predominate along the Texas Coastal Zone: (1) southeasterly winds from March through November, and (2) strong (although of short duration) northerly winds from December through February (Fisher and others, 1972). Wind direction and speed recorded at Clute, Texas, in conjunction with the Texas Air Control Board's continuous air quality monitoring station, is shown below for the years noted.

	1974	1975	1976
Resultant wind direction overall	121°	155°	142°
Wind speed, mi (km) per hr			
High one-hr average	21.4(34.2)	25.2(40.3)	28.8(46.0)
Low one-hr average	0.4 (0.6)	0.4 (0.6)	0.3 (0.5)
Arithmetic mean of one-hr averages	8.0(12.8)	7.9(12.6)	8.2(13.1)
Resultant wind speed overall	2.0 (3.2)	3.0 (4.8)	2.0 (3.2)

As indicated above, resultant wind direction overall is southeasterly. Although not as persistent as southeasterly winds, north winds accompanying a severe polar front may blow at an average wind speed of

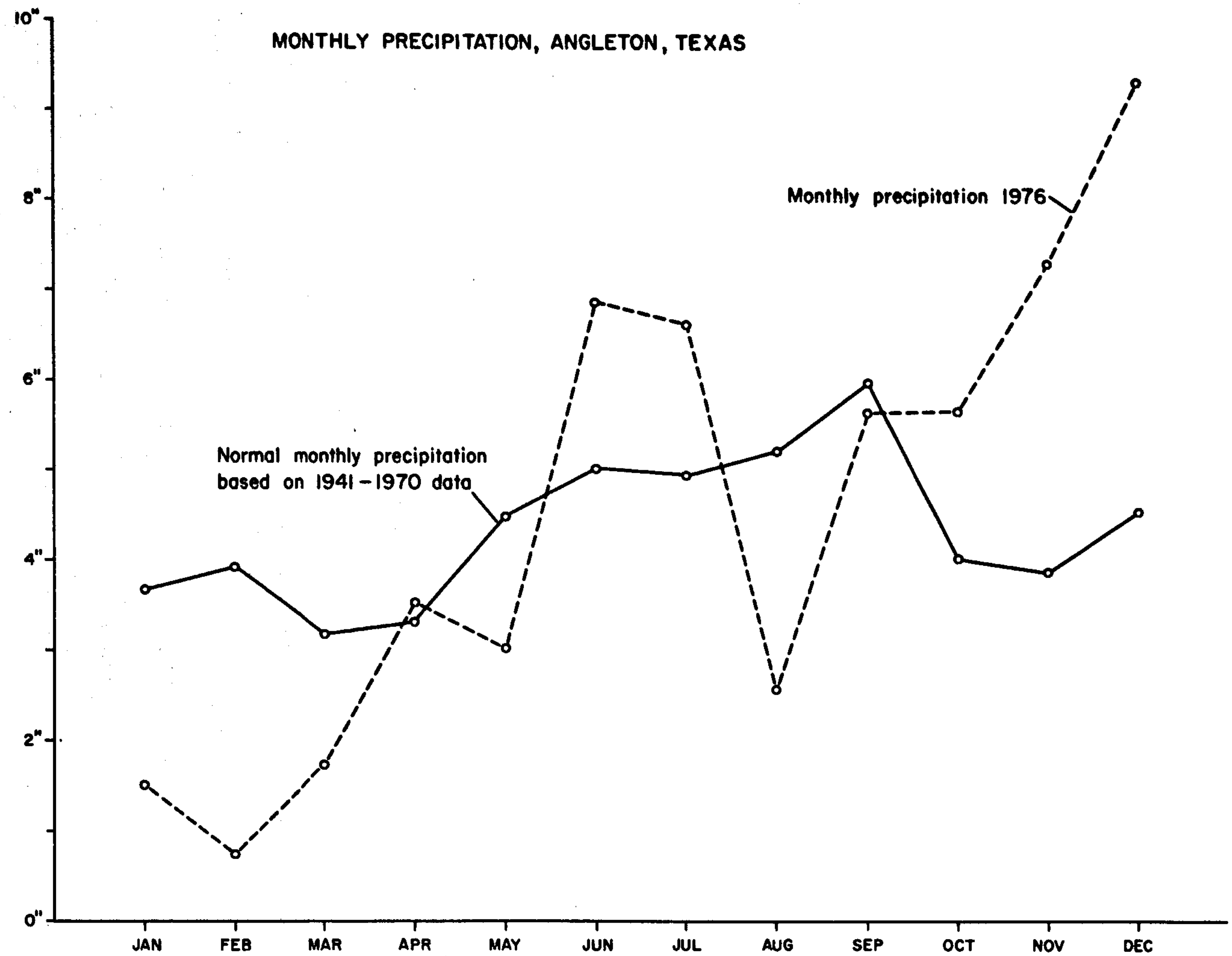

Figure 17. A comparison between monthly precipitation levels during 1976 with normal monthly precipitation levels based on the period 1941-1970, Angleton, Texas. (Compiled from records of the U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service)

64 kilometers (40 mi) per hour during a 24-hour period (Fisher and others, 1972). Precipitation often accompanies these sudden 24- to 36-hour storms.

Ambient Air Quality

Air quality information was assembled from reports by the Texas Air Control Board for continuous and non-continuous air quality monitoring stations located in Brazoria, Galveston, and Harris Counties. Air quality data from continuous air monitoring stations in region 7 (which includes Brazoria County) indicate that ozone and nonmethane hydrocarbons are commonly at levels that exceed the maximum allowable as defined by national ambient air standards (table 14). Total suspended particulates (TSP) recorded by noncontinuous air monitoring stations have occasionally exceeded national standards during the last five years at Clute and Alvin although standards were not exceeded in 1976 (fig. 18). Selected gaseous concentrations measured in Clute and Alvin are shown in figure 19 for comparison purposes. Sulfur dioxide and nitrogen dioxide apparently have not exceeded national standards at either location during the years for which data is presented; national standards have not been set for ammonia. The graphs showing total oxidants (fig. 19) are useful for making relative comparisons between Clute and Alvin, but because of the air sampling method used for determining these values, a direct comparison with national standards cannot be made (Texas Air Control Board, 1975).

TABLE 14. COMPARISON SUMMARY OF CONTINUOUS AIR MONITORING STATION DATA WITH AMBIENT STANDARDS

(Data compiled from Texas Air Control Board Continuous Air Monitoring Network Data Summaries, 1974-1977)

Year	Station Location (Region 7)	Ozone - High One Hour Average	Ozone - Second Highest Hour	Ozone - Percent of Time > 0.08 ppm	Carbon Monoxide 2nd Highest Hour	Carbon Monoxide 2nd Highest 8 Hours	Nonmethane Hydro-carbons 6-9 AM High	Sulfur Dioxide 2nd Highest 24 Hours	Sulfur Dioxide Annual Mean	Sulfur Dioxide 2nd Highest 3 Hours	Nitrogen Dioxide Annual Mean	Methane - High One Hour Average	Methane - Percent of Time > 5.0 ppm
	Maximum allowable by ambient air standards (parts per million)		0.080	0.0 %	35	9	0.24	0.14	0.03	0.50	0.05	no standards	%
1974	Houston, East	0.219	0.205	3.0	33.9	15.9	7.2	0.02	0.00	0.14	0.02	11.2	1.5
	Harris County (Aldine)	0.204	0.165	3.4	3.4	2.4	2.2	0.00	0.00	0.00	0.02	7.3	0.4
	Texas City	0.277	0.234	4.2	6.0	4.2	2.3	0.02	0.00	0.00	----	10.5	2.8
	Clute	0.116	0.110	1.3	8.9	3.4	3.8	0.00	0.00	0.01	0.00	4.7	0.0
1975	Houston, East	0.288	0.223	3.7	9.0	4.7	3.9	0.02	0.00	0.13	0.03★	8.0	1.8
	Harris County (Aldine)	0.321	0.300	4.2	6.7	4.4	2.1	0.00	0.00★	0.08	0.02★	5.6	0.1
	Texas City	0.222	0.193	4.6	3.4	1.9	5.4	0.01	0.00★	0.12	0.01★	9.0	1.0
	Clute	0.160	0.155	2.8	7.4	3.0	3.1	0.01	0.00★	0.01	0.01	4.4	0.0
1976	Houston, East	0.297	0.267	4.2	8.6	6.7	3.4	0.01	0.00	0.07	0.02	8.3	2.0
	Harris County (Aldine)	0.272	0.255	7.7	7.9	6.2	3.9	0.00	0.00	0.00	0.02	5.1	0.0
	Texas City	0.225	0.203	5.1	5.5	2.6	3.8	0.01	0.00	0.21	0.01	6.6	0.4
	Clute	0.186	0.186	4.0	5.2	2.3	4.5	0.00	0.00	0.03	0.01	4.0	0.0
1977 (1st quarter)	Houston, East	0.121	0.106	0.7	12.5	6.4	2.8	0.01	0.00*	0.06	0.03*	8.6	3.3
	Harris County (Aldine)	0.098	0.106	0.4	3.1	2.2	3.3	0.00	0.00*	0.00	0.02*	6.2	0.6
	Texas City	0.085	0.073	0.1	0.9	0.3	0.7	0.00	0.00*	0.02	0.02*	1.7	0.0
	Clute	0.105	0.104	1.8	5.2	2.7	3.6	0.00	0.00*	0.01	0.01*	3.6	0.0

★Set of data does not meet E. P. A. criteria for calculating an annual mean

*Quarterly mean

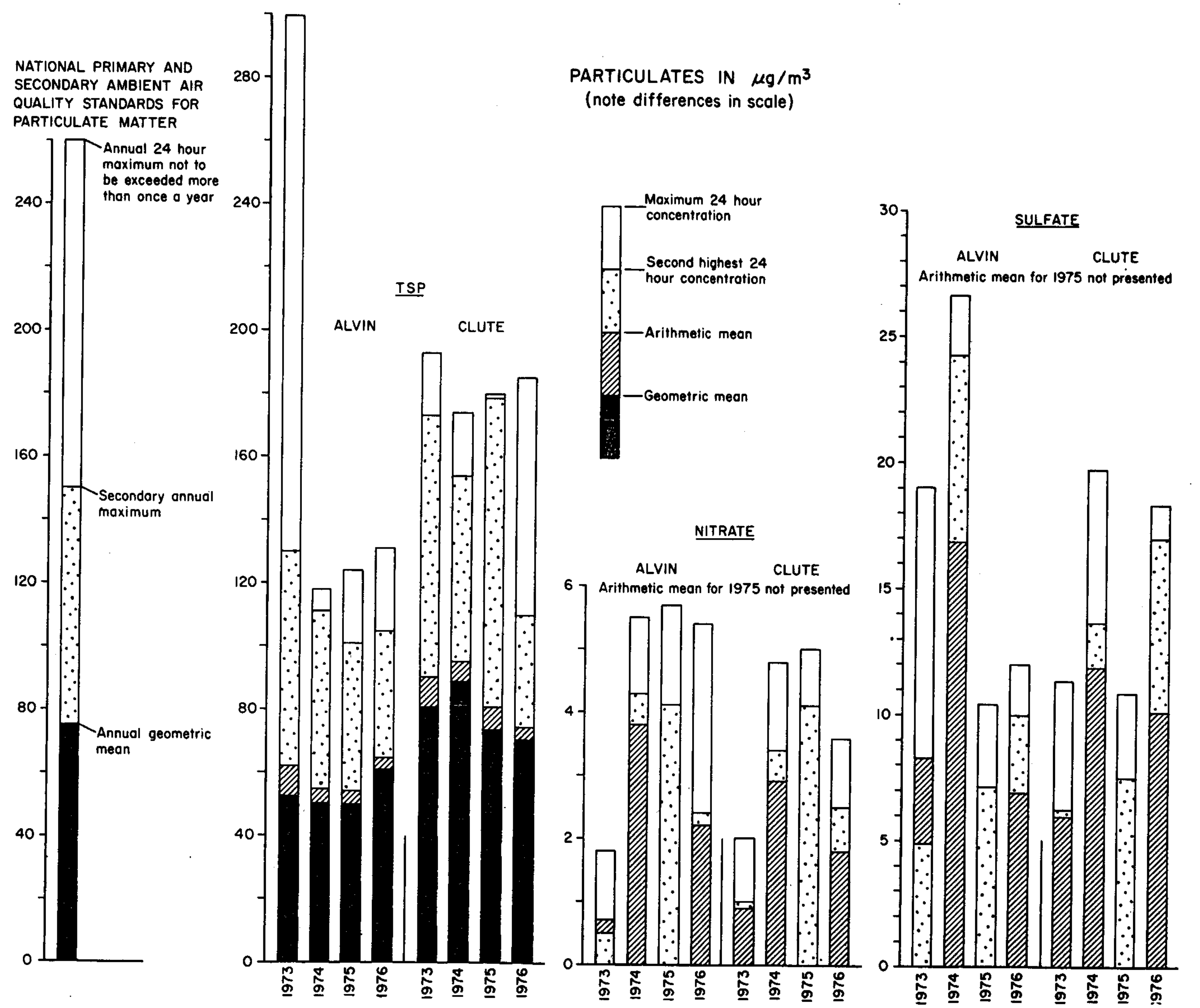

Figure 18. Concentration of particulates including total suspended particulates (TSP), nitrate, and sulfate at Alvin and Clute, Texas. (From Texas Air Control Board annual data summaries, 1973-1976)

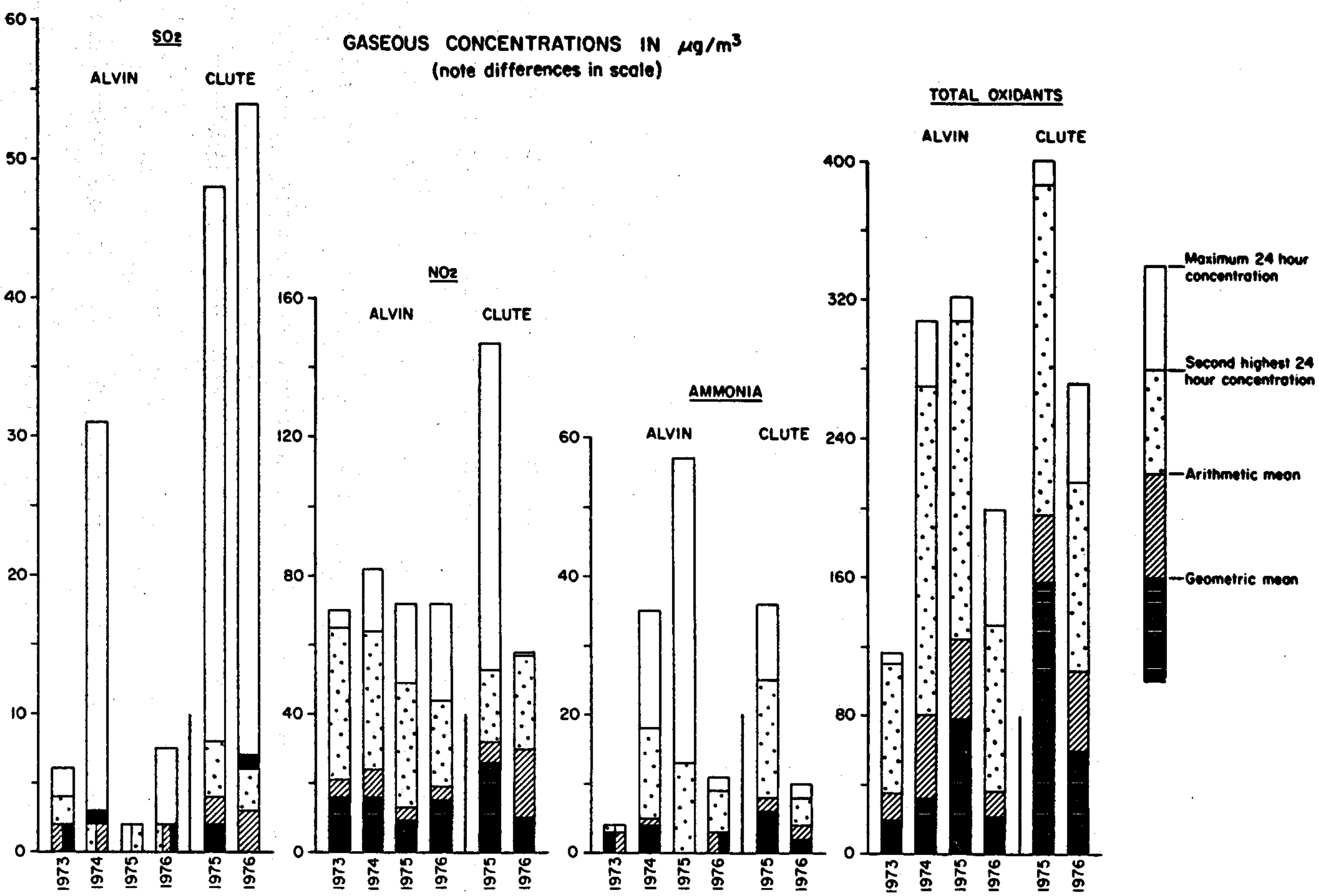

Figure 19. Concentration of sulfur dioxide, nitrogen dioxide, ammonia and total oxidants at Alvin and Clute, Texas. (From Texas Air Control Board annual data summaries, 1973-1976)

Selection of Test Well Site on the Basis of Meteorological Characteristics

Perhaps the most important climatological factor with regard to selecting suitable well sites within the prime prospect area is the resultant southeasterly wind direction. Location of the test well at certain points on the east side of Chocolate Bayou will place it in an upwind position with respect to residential-commercial development near Peterson Landing. Although air pollutants associated with geopressured-geothermal fluid production have not yet been adequately identified, volatile carbon compounds, ammonia and hydrogen sulfide are potential pollutants. Texas ambient air quality standards (set by the Texas Air Control Board), which are supplementary to national standards, specify that the net ground level concentration of hydrogen sulfide cannot exceed 0.08 parts per million for a 30-minute average in areas used for residential, business or commercial purposes. The net downwind concentration of hydrogen sulfide in other areas (vacant land, rangeland, industrial property, etc.) cannot exceed 0.12 ppm for a 30-minute average. The net downwind concentration is equivalent to the downwind concentration minus the upwind concentration.

The Texas Air Control Board has established rules with regard to storing and handling volatile carbon compounds in Brazoria and other counties. Compliance with set rules should leave few air quality problems that could be alleviated by varying the location of the test well within the prime prospect area. In terms of meteorological characteristics, then, suitable sites for geopressured-geothermal wells are present on both the east and west side of Chocolate Bayou within the prime prospect area. The persistent southeasterly winds should be considered, however, in placing the well on the east side of Chocolate Bayou across from residential-commercial development at Peterson Landing.

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