# AN ENVIRONMENTAL OVERVIEW OF GEOPRESSURED-GEOTHERMAL DEVELOPMENT: TEXAS GULF COAST

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## GEOTHERMAL GEOPRESSURED ENERGY DEVELOPMENT, TEXAS COASTAL ZONE

Environmental studies dealing with the development of geopressured-geothermal resources in the Texas Coastal Zone indicate that the major impacts on the ecosystem are likely to result from surface disposal or accidental release of geothermal fluids, from surface subsidence induced by fluid withdrawal, and from habitat loss resulting from the construction of the power plant and well field.

In view of this, the following site specific and general environmental studies are recommended. Some of these studies are already underway in Texas.

### Site Specific Studies

Recommended site specific data acquisition for the assessment of potential environmental impacts on ecosystem quality is already underway in several areas of interest in Texas. Baseline environmental analyses and mapping have been completed for the 50 $mi^2$ areas that contain the Brazoria County and Kenedy County geopressured-geothermal fairways. Habitats of rare or endangered species have been mapped where possible. Additional analyses and maps describe current land use, subsidence and faults, flood potential, lithology and soils, water resources, and meteorological characteristics. As testing of these areas continues and as additional development occurs, analyses of impacts to ecosystem quality will be updated. During 1979, two additional test sites in DeWitt and Colorado Counties are contemplated for prospect areas in the Wilcox Formation geopressured-geothermal fairways. Environmental analyses will also be completed for these areas. Until additional test sites are identified, no new site specific studies are contemplated and no additional funds are needed.

## General Studies

The major unresolved problems to be addressed prior to large scale development of geopressured-geothermal resources include:

I. Ecosystem Studies

1. Brine effects on wildlife, including shell- and finfish. Determine the long-term potential for degradation of fish and wildlife populations if geopressured-geothermal fluids are released into the Gulf of Mexico. Although onshore disposal of geothermal fluids by injection is contemplated, the high cost of injection makes disposal into the Gulf of Mexico attractive, especially for near-shore or off-shore developments. Surface disposal or accidental release of geopressured-geothermal fluids is likely to degrade surface water and is likely to result in displacement, mortality, or reduced population vitality of certain species, e.g., due to the uptake of heavy metals.

2. Effects of subsidence. Ascertain the long term effects of subsidence especially in sensitive transitional coastal environments, that directly affect the fin- and shell fish industry and tourism. These are major spawning areas for fin- and shell fish, and include salt marshes which produce much of the biomass along the Gulf Coast. Critical concerns are determining the effects of increased water depth of these environments and determining how organisms respond to the changes.

3. Trace elements to aquatics, fish, and wildlife. Determine the significance of trace elements including but not limited to Cu, Fe, Mn, Be,

B, Cd, Pb, Zn, and As in aquatic food nets, fish, and wildlife in terms of origin, methods of transport, concentration factors, transfer rates, and the eventual storage site at each trophic level.

Cost Estimate for General Tasks--1979

| Task | Equipment (1000 dollars) | | Operating Funds (1000 dollars) | |
|---|---|---|---|---|
| 1. Effects of brine release on ecosystem | 15 | 5 | 110 | 120 |
| 2. Effects of subsidence | 10 | 3 | 60 | 66 |
| 3. Effect of trace elements on ecosystem | 15 | 5 | 110 | 120 |
| | 40 | 13 | 280 | 306 |

## II. Geothermal Fluid Disposal

The critical problems of geothermal fluid disposal are (1) if large volumes of fluid are disposed into surface saline waters, what will be the impact on the ecosystems, (2) if large volumes of fluid are disposed into the subsurface, are the reservoirs hydrologically suitable to accept large volumes of fluid, (3) will these fluids leak into fresh ground-water systems, and (4) is there a potential for induced seismicity?

The research needs for area (1), effect of disposal on surface waters, are detailed in the Ecosystem section where this problem is addressed from the point of view of ecosystem studies. Studies in three areas need to be conducted to determine the impact of deep well injection on the environment: (1) reservoir suitability; (2) potential leakage, and (3) potential induced seismicity.

(1) Analyses of geometry, volume, orientation, porosity, permeability, and chemical interactions of the disposal reservoirs are needed to determine reservoir suitability.

(2) Leakage of saline fluids into fresh ground-water aquifers may result from large volume disposal of geothermal fluids. A study is needed to determine if large-scale injection could cause salt water intrusions.

(3) High resolution, low amplitude seismic monitoring is needed at the injection well for the test site or at a high volume injection well presently in operation to determine if full scale injection operations may induce seismicity. A microseismic monitoring study is currently underway at the geopressured-geothermal test well in Brazoria County.

Cost Estimates for General Tasks-Water Quality-1979

| Task | Operating Funds (1000 dollars) |
|---|---|
| 1. Reservoir Suitability | 50 |
| 2. Leakage | 50 |
| 3. Induced Seismicity | 125 |
| | 225 |

III. Subsidence

Programs to evaluate potential environmental impacts due to subsidence and faulting resulting from geopressured-geothermal energy production are categorized into the following groups: (1) Subsidence monitoring, (2) seismicity monitoring, (3) mechanisms of subsidence and faulting, (4) impacts of subsidence on biologic systems, (5) impacts of subsidence on economic and social systems, and (6) methods of indirect measurement of crustal elevation change and reservoir compaction.

1. Subsidence monitoring. Benchmark monitoring to determine background subsidence, not related to production of geothermal fluid, and benchmark monitoring over producing geopressured-geothermal reservoirs are necessary to determine natural and induced rates of subsidence. Ongoing programs are presently identifying the regional component of subsidence. A high density network of benchmarks at the Pleasant Bayou prospect has been installed and leveled. After fluid production at the test well has been operational for approximately one year, the benchmarks over the field should be relevelled. If other fairways are considered for testing or full scale production, benchmark networks need to be established.

2. Seismicity monitoring. Microseismic activity is being monitored at the Brazoria County test well site. Additional information is needed to understand whether there is presently any natural seismic activity in the Gulf Coast. Selected deep oil and gas field and large fluid injection programs should also be monitored to determine if microseismicity is associated with these operations. Microseismicity needs to be monitored at any test well operation.

3. Mechanisms for subsidence and faulting. The potential of land subsidence from geopressured-geothermal fluid production is unknown at this time. There is presently no large-scale water production from the geopressured zones. Subsidence measurements over geopressured-gas fields are complicated by oil and formation-water production from the hydropressured zone (e.g., Chocolate Bayou field). There is no definitive case of known subsidence from the fluid production from the

geopressured zone. Three approaches can be taken to evaluate the problem: (1) construct a high yield well in the geopressured zone, produce it to see if subsidence results, (2) conduct compressibility studies of sediments from geopressured zone, and (3) draw analogies to subsiding areas resulting from fluid production.

All three of these approaches have been or are being used in evaluating subsidence potential in the Texas Gulf Coast. (1) A well is being drilled at the Pleasant Bayou site and land surface is being monitored for elevation changes. (2) The Center for Earth Sciences and Engineering is conducting compressibility tests on core from the Pleasant Bayou site and predicting subsidence, and (3) studies of analogous subsidence from ground water, and oil and gas production have been made (e.g., Gustavson and Kreitler, 1976). These ongoing studies hopefully will resolve the major questions; therefore no recommendations are made in this area.

4. Impact of subsidence on surface ecosystems. The geothermal-geopressured fairways in the Frio Formation underlie bays, estuaries, bayous, and lowlands of the Texas Gulf Coast. Much of the subareal land has an elevation below 15 ft (5 m). Broad, regional land subsidence from geothermal-geopressured water production could significantly alter the ecosystems in these low-land areas.

The following program is recommended. Determine the geographic area of low-land ecosystems and provide an estimate of areas that would undergo changes as a result of varying amounts of subsidence. If the amount of wet-lands to be impacted is relatively small, the regional impact is small. If the area is large, the regional impact may be significant. See Ecosystem studies for additional recommendations for the impact of subsidence on ecosystems.

5. Economic impacts from subsidence. The economic impact that subsidence has had on the Texas Coastal Zone is not known. A few studies have addressed specific problems or areas. A comprehensive study is needed that addresses all facets of subsidence which may have economic impact.

6. Indirect measurements of reservoir compaction. Reservoir compaction is the prime unknown which will determine if subsidence will be a critical problem. Compaction can be estimated by repeated gravity surveys. In areas of fluid withdrawals, changes in gravity measurements may result from either fluid withdrawal and compaction or land subsidence. Gravity studies to measure reservoir compaction should be initiated.

Cost Estimates for General Tasks

| | | |
|---|---|---|
| 1. | Subsidence Monitoring (detailed network over one field with survey before and after production) | $ 75,000 |
| 2. | Seismic Monitoring (detailed microseismic monitoring one field for one year) | 125,000 |
| 3. | Gravity Measurements (detailed network over one field with survey before and after production) | 50,000 |
| 4. | Subsidence Impact on Ecosystems | 75,000 |
| 5. | Economic Impacts | 100,000 |

IV. Air Quality Monitoring

Until the potential impacts of geopressured-geothermal development on ambient air quality are thoroughly understood, each geopressured-geothermal site should be monitored for air quality. The pollutants of potential concern are methane, non-methane, hydrocarbons, and ammonia, because these substances are known to occur in geopressured formation fluids. The oxidation of $H_2S$ produces $SO_2$, a pollutant of increasing concern on the Texas Gulf Coast. As other potential pollutants are recognized from analyses of geopressured-geothermal or from substances such as corrosion inhibitors and biocides introduced into cooling tower waters, additional parameters may be added to the list. Meteorological data should be collected concurrently with air quality data.

All air quality monitoring should conform to Environmental Protection Agency Quality Assurance procedures and should meet or exceed all Federal performance and dimensional specifications including those in Federal Register, Vol. 36, No. 84, dated April 30, 1979.

Estimated Cost: Site Specific Air Quality Monitoring

Methane

Non-methane hydrocarbons

Sulfur dioxide

Hydrogen sulfide

Ammonia

Meteorological data

$125,000/yr.

## Socioeconomic and Demographic Research

Our recommendations for socioeconomic and demographic research follow the recommendations and conclusions of Letlow and others, 1976, and Lopreato and Blissett, 1977.

Letlow and others, 1976, have concluded that initial exploration and testing phases of geothermal development are likely to produce few positive or negative impacts on Gulf Coast communities. Lopreato and Blissett, 1977, confirm the need for attitudinal surveys at potential sites and for additional communication to area residents. For these reasons and because large-scale industrial utilization of geothermal energy is not likely to occur until geothermal energy becomes a <u>proven</u> economic resource at some future time, only two social research tasks are recommeded at this time.

(1) Attitudinal Survey at Site.

"Before the test-bed site is finally determined, a random sample survey of citizens in the potential site area should be conducted that would identify attitudes toward the expectations of the resource development," (Lopreato and Blissett, 1977).

(2) Citizen Conference.

"During the period when an environmental report is being conducted for the test site, a Citizens' Conference on Geothermal Development should be held in the area. All geothermal research groups might be involved as informants, with the sociocultural and institutional groups working most closely on conference organization with the citizens. The conference would provide a mechanism for disseminating information to the public body likely to be most affected by early resource development and would offer an opportunity for imput from the populace," (Lopreato and Blissett, 1977).

## Budget

| | Operating Fund |
|---|---|
| I. Attitudinal Survey | |
| Single survey | $ 30,000 |
| Surveys at Kenedy, DeWitt, and Colorado County Sites | 90,000 |
| II. Citizen Conferences | |
| Conferences at Kenedy, DeWitt, and Colorado County Sites | |
| Costs are not predictable but could be limited to $500 per site | |

# INTRODUCTION

## Study Region Description

Areas of known geopressured sediments in Texas lie along the Gulf Coast or a few miles inland (fig. 1). Bebout and others (1975, a and b; 1976; 1978) have defined several geothermal fairways -- areas where geothermal resources are most likely to occur -- along the Texas Gulf Coast (fig. 2). The sediments that are most likely to contain geopressured-geothermal resources are within the Tertiary Frio, Vicksburg, and Wilcox Formations and probably occur largely within deltaic facies of these formations (fig. 3). Together these maps define the geographic extent of the Texas Coastal Plain area to be affected by development of geopressured-geothermal resources.

### Geology

The outer Gulf Coastal Plain is composed of Quaternary sediments (fig. 4). These sediments are comprised of systems of fluvial sands and muds; strandplain sands and marshes from the Sabine River westward to Galveston Bay; barrier island sands and delta plain sediments along the Texas Coast and an aeolian sand sheet in South Texas (Brown and others, 1976, in press; Fisher and others, 1972, 1973; McGowen and others, 1976, 1976 a). Bay and estuarine sands and muds occur landward of the barrier islands, and shoreface sands and shelf muds dominate the coastal portion of the Gulf of Mexico. Throughout the Tertiary and Quaternary the same basic patterns of clastic sedimentation occurred along the Gulf Coast such that sedimentary units at depth have modern analogues, either currently forming or exposed at the surface of the Gulf Coastal Plain.

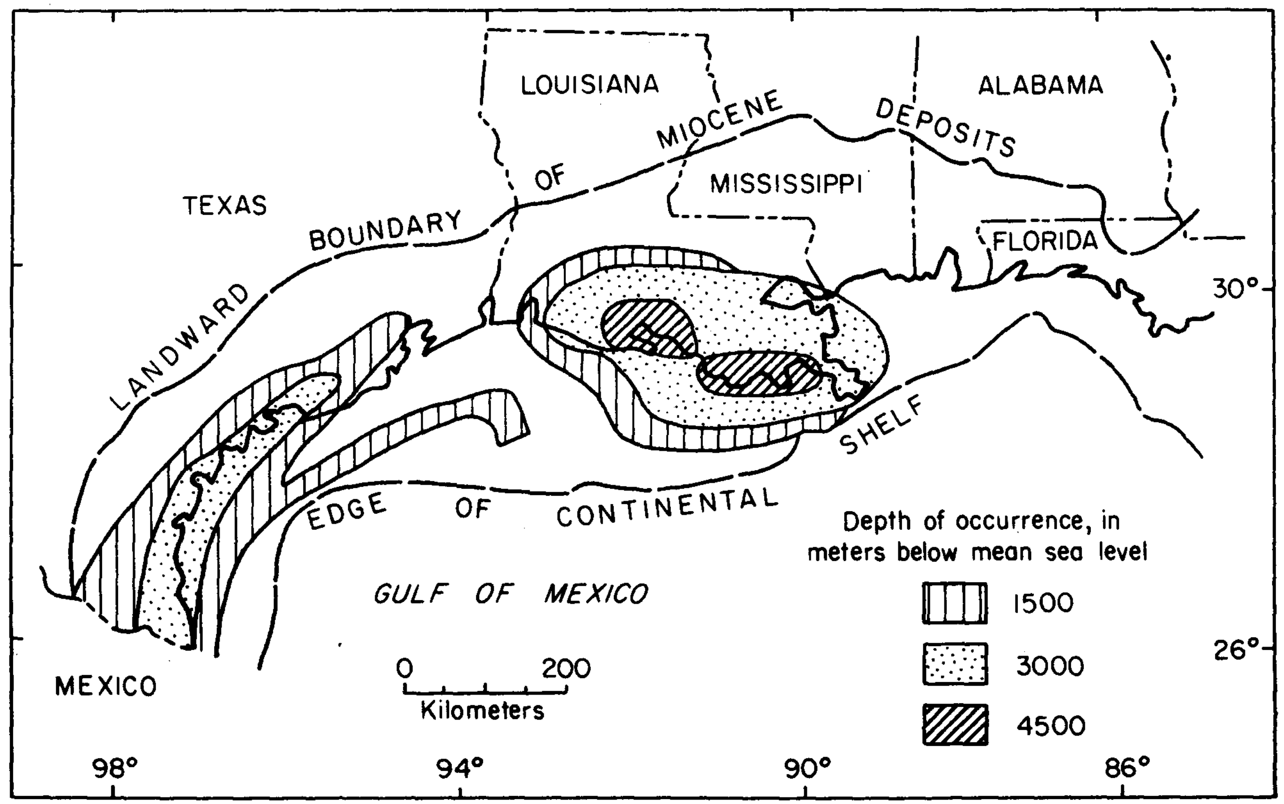


Figure 1. Occurrence of geopressured sediments in the Gulf Coast Basin.

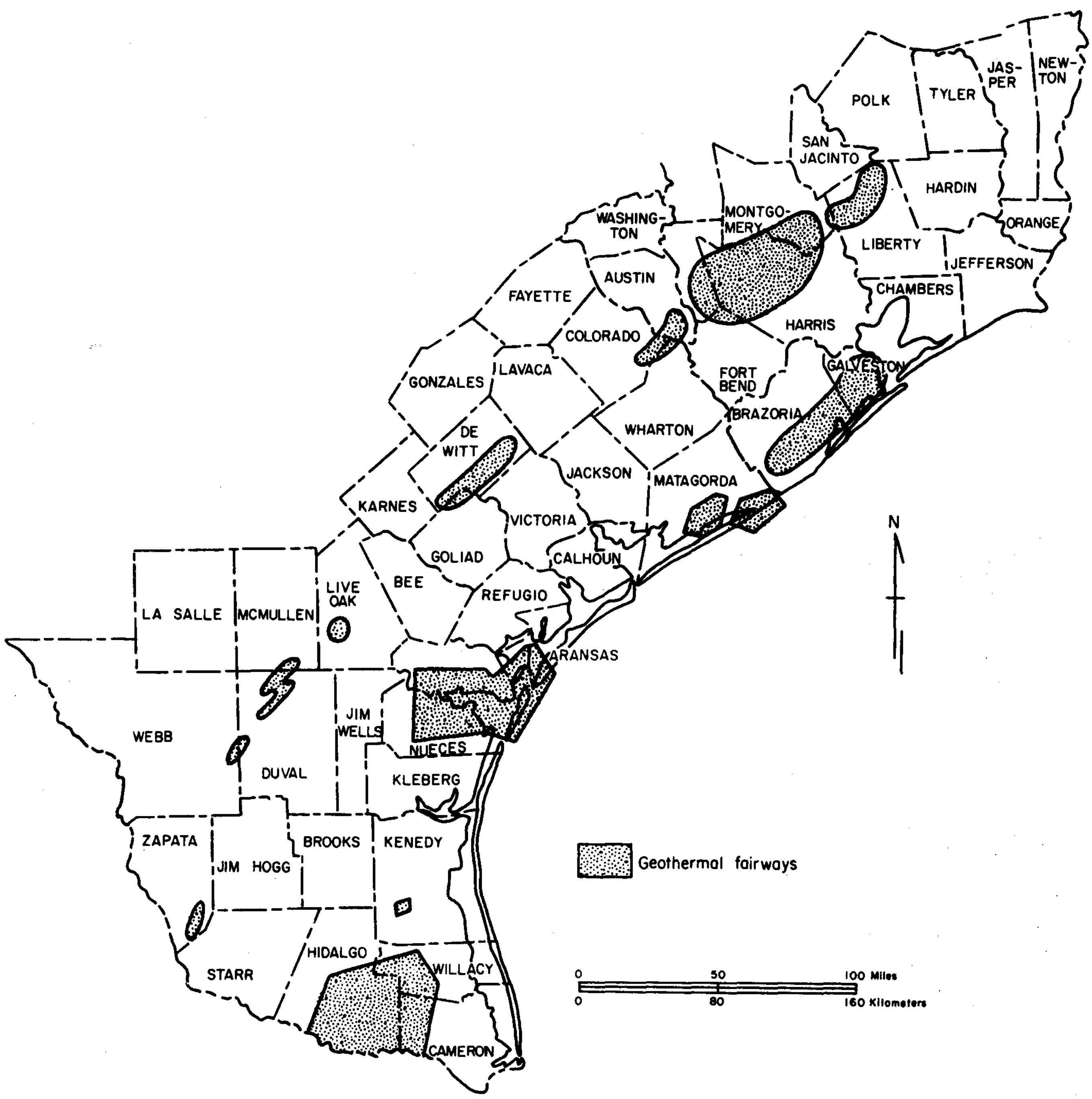


Figure 2. Geopressured-geothermal fairways.

| SYSTEM | SERIES | GROUP/FORMATION |
|---|---|---|
| Quaternary | Recent<br>Pleistocene | Undifferentiated<br>Houston |
| Tertiary | Pliocene | Goliad |
| | Miocene | Fleming |
| | | Anahuac |
| | —?——?— | |
| | Oligocene | Frio |
| | | Vicksburg |
| | Eocene | Jackson |
| | | Claiborne |
| | | Wilcox |
| | | Midway |

Figure 3. Stratigraphic section, Texas Gulf Coast.

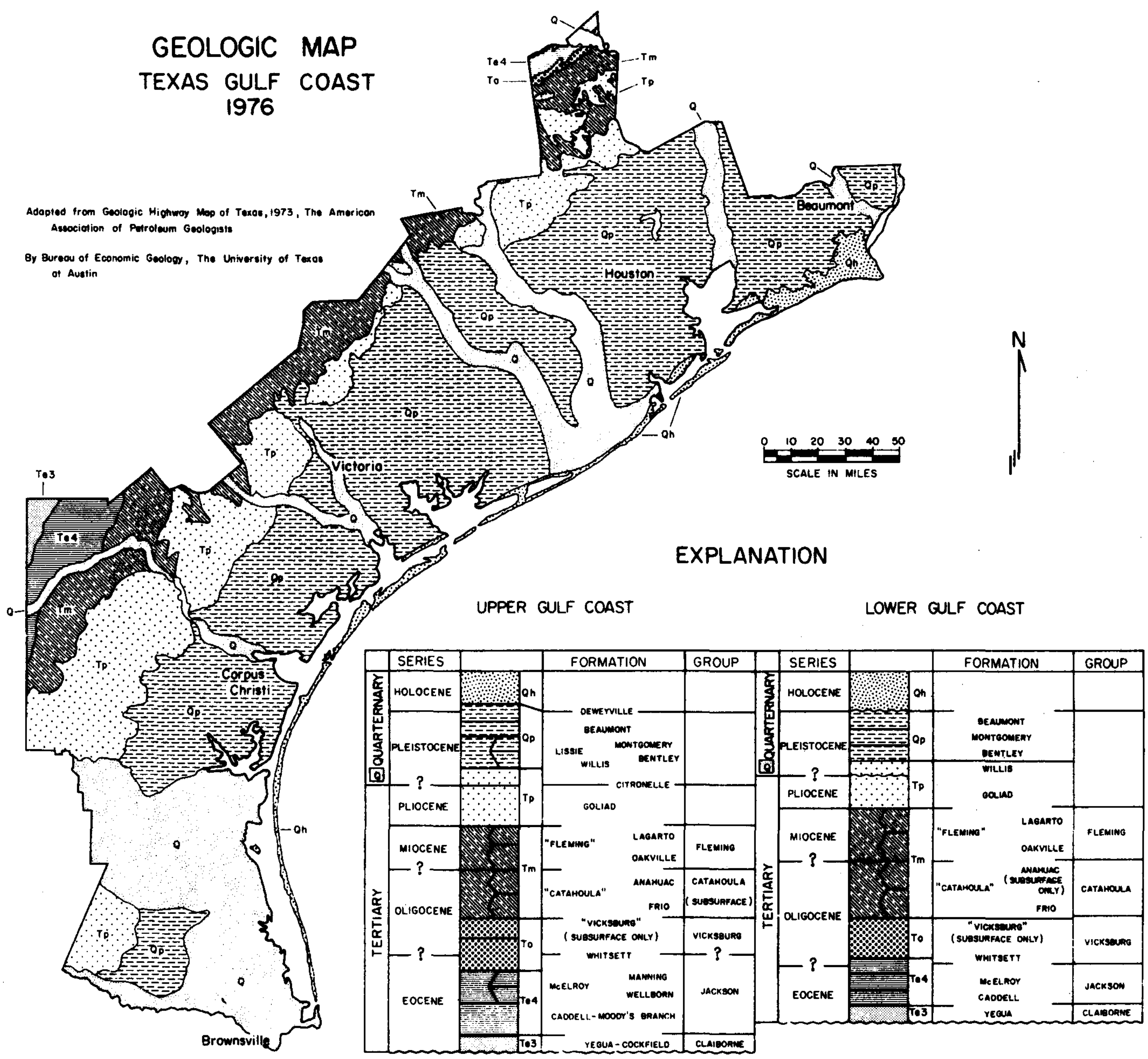


Figure 4. Geologic map, Texas Gulf Coast.

The major structural features of the Gulf Coast are salt domes and systems of growth faults. Salt domes and associated salt ridges result from the upward movement of relatively low-density diapirs of Jurassic Louann Salt through denser overlaying clastic sediments. Growth faults may be related to several processes including differential compaction between adjacent masses of mixed sand and shale, and basinward slippage of coastal sediments along bedding planes.

Growth fault systems along the Gulf Coast are a major factor in providing structural closure for hydrocarbon reservoirs. They may also serve as hydrologic barriers to the updip migration of formation fluids, providing a seal for some potential geopressured-geothermal reservoirs. Conversely, they may provide migration routes for formation fluids.

Recent fault activity has been clearly demonstrated along the Gulf Coast of Texas (Kreitler, 1976, 1977 a and b) and most of the active surface faults appear to be extensions of growth faults recognized in the subsurface. However, gradual slippage along these fault planes has resulted in few, if any detectable earthquake shocks. The coastal areas of Texas and Louisiana are considered as low seismic risk areas.

The surface morphology of the Coastal Plain of Texas is dominantly a flat, featureless plain, composed of relic Pleistocene deltaic plains broken by wide river valleys and estuaries and rarely by low mounds. The mounds are the land surface expression of salt domes. South of Baffin Bay about 30 miles south of Corpus Christi, an extensive sand sheet occurs with numerous active and inactive eolian features--dunes, sand sheets, and deflation basins. The Coastal Plain is separated from the Gulf of Mexico by an extensive system of barrier island bays and lagoons extending from Galveston Bay to the Rio Grande.

## Soils

A wide variety of soils is presently along the Coastal Plain but several generalizations can be made (fig. 5). Much of the area is only poorly to moderately drained. Clayey soils are only slightly permeable and are expansive and corrosive and have a low bearing capacity. Loamy and sandy soils are underlain by poorly permeable, clayey B horizons with notable exceptions being modern and ancient beach-and barrier-island sands. Marsh lands are underlain by organic rich soils, peats, and mucks. Both shrink-swell and corrosion potentials are high for these soils. Bearing capacity is very low.

## Vegetation

Marked diversity in climate and vegetation occurs along the Texas coastal area (fig. 6). Rainfall decreases from over 150 cm (66 in) per year in East Texas to less than 66 cm (26 in) per year in South Texas. Mean annual temperature increased from 20°C (69°F) in East Texas to 23°C (74°F) in South Texas. Corresponding largely to the change in available moisture the major vegetation associations change from coastal marsh in East Texas to prairie grasses with hard wood mottes in Central Texas to chaparral in South Texas. Salt marsh is locally present all along the Texas coast.

It is important to recognize that a hierarchy of systems--geologic, soil, vegetative, and zoologic--are present on the Gulf Coast. Soils are largely dependent on the character of the geologic substrate, topography, and climate; natural vegetation is dependent on soil type and climate; and the animal life that occupies the region is in many cases dependent on vegetation. Tidal range controls the landward extent of salt marsh vegetation, while for many other species the range in available moisture controls to a large extent their geographic range.

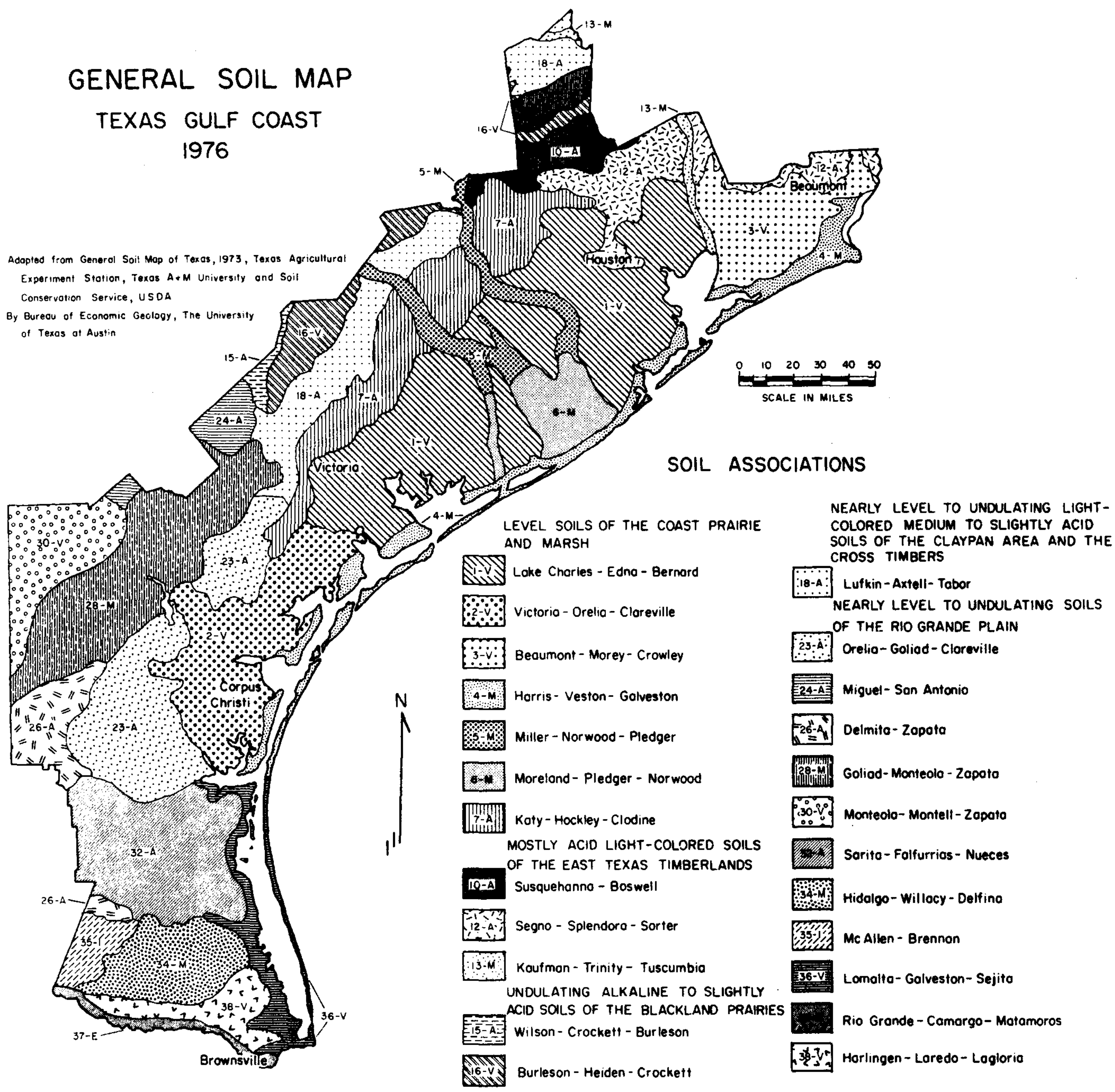


Figure 5. General soil map, Texas Gulf Coast.

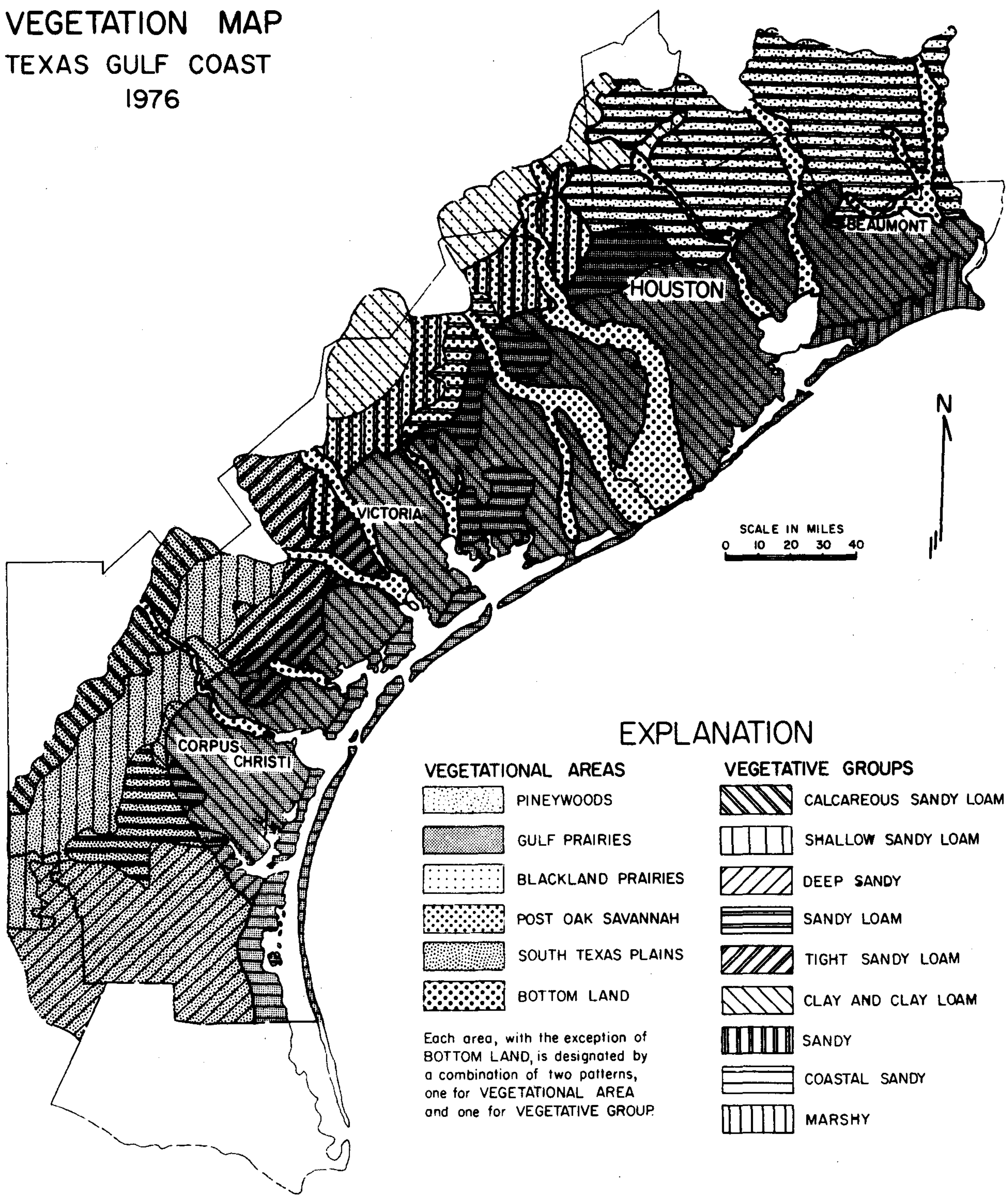


Figure 6. Vegetation map, Texas Gulf Coast.

## Land Use

Current land use on the Texas Gulf Coast is largely as cropland and rangeland (McGowen and others, 1976, 1976a; Fisher and others, 1973, 1972; Brown and others, 1976, in press) (fig. 7). Near the Louisiana-Texas border forested lands and wetlands increase in importance. Major urban areas are Brownsville, Harlingen, Corpus Christi, Victoria, Houston, Galveston, and Beaumont.

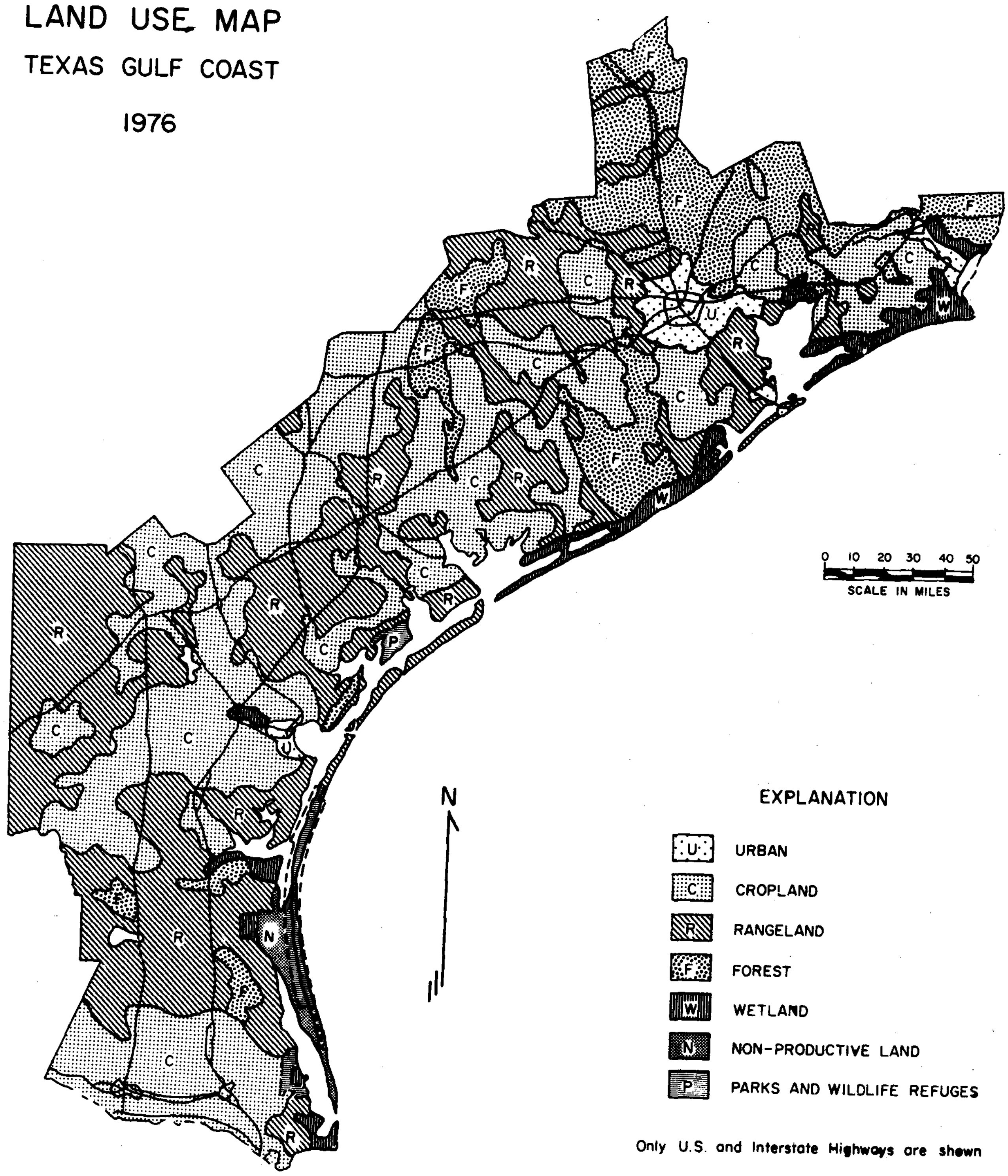


Figure 7. Land use map, Texas Gulf Coast.

## RECOGNITION OF GEOPRESSURED-GEOTHERMAL RESOURCES IN THE TEXAS GULF COAST

Jones (1969), Wallace (1970), Dorfman and Kehle (1974), and Papadopulos and others (1975), among many others, described the potential geothermal resources of the area. Early assessments of geopressured-geothermal resources were universally optimistic. Papadopulos and others (1975) estimated that recoverable thermal and mechanical energy from geopressured-geothermal fluids of the Gulf Coast would range from 2880 to 19,580 mw centuries (14,4000 to 108,650 mw (20 years)). Dorfman and Kehle (1974) suggested that Tertiary sediments along the Gulf Coast would contain a reserve of at least 20,000 mw centuries of electrical power. Furthermore, this was in addition to any methane or other hydrocarbons dissolved in the geothermal fluids. In defense of these early estimates it should be understood that detailed regional maps of sand distribution, sand thickness, temperatures, and rock permeabilities within the geopressured zone were not generally available.

Recent work by Bebout and others (1975, 1976, 1977, 1978) has shown that geothermal reservoirs of sufficient size, temperature, and permeability--91 m (300 ft) thick, 129 $km^2$ (50 $mi^2$) in area, 150°C (300°F), 20 md--to support one 25 mw (20 year) generating facility are not common. To date only five areas on the Texas coast have been identified with adequate size, temperatures, and porosity to be considered as a strong candidate for testing by drilling a well. Eleven other areas have been identified as possible sites.

# CURRENTLY RECOGNIZED GEOPRESSURED-GEOTHERMAL PROSPECT AREAS AND FAIRWAYS

The five prospect areas are the Armstrong, Nueces, Brazoria, DeWitt, and possibly the Colorado Counties prospects (fig. 2). According to Bebout and Loucks (1976) the sand bodies for the prospect areas range in cumulative thickness from 61 to 183 m (200 to 600 ft) and each extends over an area of 125 $km^2$ (50 $mi^2$), with the exception of the Brazoria prospect area. Fluid temperatures in the three prospective reservoirs range from 121°C (250°F) to at least 165°C (330°F). Permeability data are sparse, but suggest that permeabilities of 18 to 20 md are to be found at depths of 3350-3660 m (11,000-12,000 ft). At this depth fluid temperatures are about 121°C (250°F) and while temperature increases with depth, permeability decreases in the hotter, deeper reservoirs. The large reservoirs of hundreds of square miles, extent with large permeabilities predicted by previous workers do not exist in the Frio, Wilcox, and Vicksburg Formations; rather only 15 fairways and 5 possible prospect areas have been recognized (tables 1 and 2).

Testing of the Brazoria County prospect area began in July 1978, with the spudding in of Pleasant Bayou #1, the first geopressured-geothermal test well. Because of technical difficulties this well was plugged in January 1978 and Pleasant Bayou #2 was initiated in February 1979.

Table 1. Fairway characteristics

| Fairway | Extent of sand bodies | Temperature range | Limiting factors permeability/reservoir continuity |
|---|---|---|---|
| Hidalgo, Willacy, and Cameron Counties | Deltaic sands 100-600 ft thick below 9,000 ft | -- | Very low permeability |
| Nueces County | Deltaic sands high sand/shale percentage below 9,000 ft | -- | Very low permeability, low temperature |
| Armstrong Ranch, Kenedy County | -- | -- | -- |
| Aransas, Nueces, and San Patricio Counties | 500 ft thick 200 sq miles 10,000-16,000 ft deep | 300-320°F | Very low permeability, numerous faults result in questionable reservoir continuity |
| South-central Matagorda County | 200 ft thick 100 sq miles 15,700 ft deep | 300°F | Very low permeability |
| Northeast Matagorda County | 150 ft thick 13,700 ft deep | 300°F | Very low permeability |
| Brazoria County | 1,200 ft of sand below 12,600 ft | 278-314°F | Low to moderate permeability 18-20 millidarcys locally |

From Bebout and others (1975a, b).

Table 2. Wilcox geothermal fairways.

| Name | Areal Extent (mi²) | Sandstone Thickness | | Depth to | |
|---|---|---|---|---|---|
| | | Total (ft) | Individual Beds (ft) | 300°F | Top of Geopressure (ft) |
| Zapata | 48 | 340 | 20-150 | 10,200 | |
| Webb | 48 | 400 | 10-20 | 10,800 | 8,700 |
| Duval | 140 | 400 | 10-50 | 11,000 | 9,000-10,000 |
| Live Oak | 75 | 240 | 10-40 | 11,300 | 9,400 |
| De Witt | 280 | 700 | 10-50 | 10,500-19,900 | 10,100-10,700 |
| Colorado | 200 | 850 | 10-20 | 12,300 | 11,400 |
| Harris | 1,375 | 3,600 | 10-60 | 11,000-13,500 | 11,100-13,300 |
| Liberty | 200 | 460 | 10-60 | 12,500-13,800 | 12,300 |

## POTENTIAL ENVIRONMENTAL CONCERNS

Geopressured-geothermal resources of the Texas and Louisiana Gulf Coast are currently being evaluated as thermal-hydraulic energy sources for generation of electric power. Concurrent studies are underway to determine the environmental effects of development of these resources (Gustavson and Kreitler, 1976; Gustavson and others, 1978; and White and others, 1978). The most significant environmental concerns are subsidence or faulting resulting from the withdrawal of enormous volumes of formation waters and the disposal of highly saline brines.

### Geothermal Fluid Production and Surface Subsidence

The utilization of geopressured-geothermal resources requires the withdrawal of enormous volumes of geothermal fluids from the subsurface. It is probable that fluid withdrawal from aquifer sandstones in the geopressured system will allow fluids from adjacent mudstones to flow into the sandstone aquifers as a pressure gradient is established. This induced dewatering of geopressured mudstones will probably allow a certain amount of compaction of mudstones to take place, in conjunction with sandstone compaction. Transmittal of the compaction to the surface may result in subsidence (see Gustavson and Kreitler, 1976; and White and others, 1978, for a discussion of compaction and subsidence models). The impact of subsidence in undeveloped upland areas will probably be minor. Subsidence in or near coastal lowlands, floodplains, wetlands, or developed areas could result in a significant environmental impact in that slight changes in land elevation can result in extensive lateral shifts in wetlands vegetation zones, increased flood potential, and extensive property damage.

## Faulting

Active faulting on the Gulf Coast has been recognized in several areas and, in part at least, fault planes may control or geographically limit subsidence. This is not to say that the Gulf Coastal Plain of Texas and Louisiana is a seismically active area. Recent fault movement in the Gulf Coast has been documented, but the movement has apparently been too local and too slow to generate seismic shocks. Damage to structures such as pipelines, roads, buildings, and airfields is the major result of fault movement.

## Geothermal Fluids

Analyses of fluids from the geopressured zones of both Texas and Louisiana indicate that TDS values from less than 20,000 ppm to as much as 345,000 ppm may be expected. Figure 8 illustrates analyses of geopressured fluids from 37 wells along the Gulf Coast.

The concentrations of major dissolved ions in geopressured water are compared to the concentrations of ions in normal sea water (Gulf of Mexico) (fig. 8). For geopressured fluids $Na^{+}$, $Cl^{-}$, $Ca^{++}$, $HCO^{3-}$, $B^{+++}$ ions have been recorded in concentrations of up to 1 order of magnitude greater than sea water with $Ca^{+++}$ ion concentrations sometimes an order of magnitude less than sea water. $K^{+}$ and $Br^{-}$ ion concentrations bracket their concentrations in sea water and occur in concentrations as much as one half order of magnitude more or less than their normal sea water concentrations. The normal concentration of $SO_4^{--}$ ions range from an order of magnitude less than sea water to missing altogether. Data on trace elements in geopressured fluids

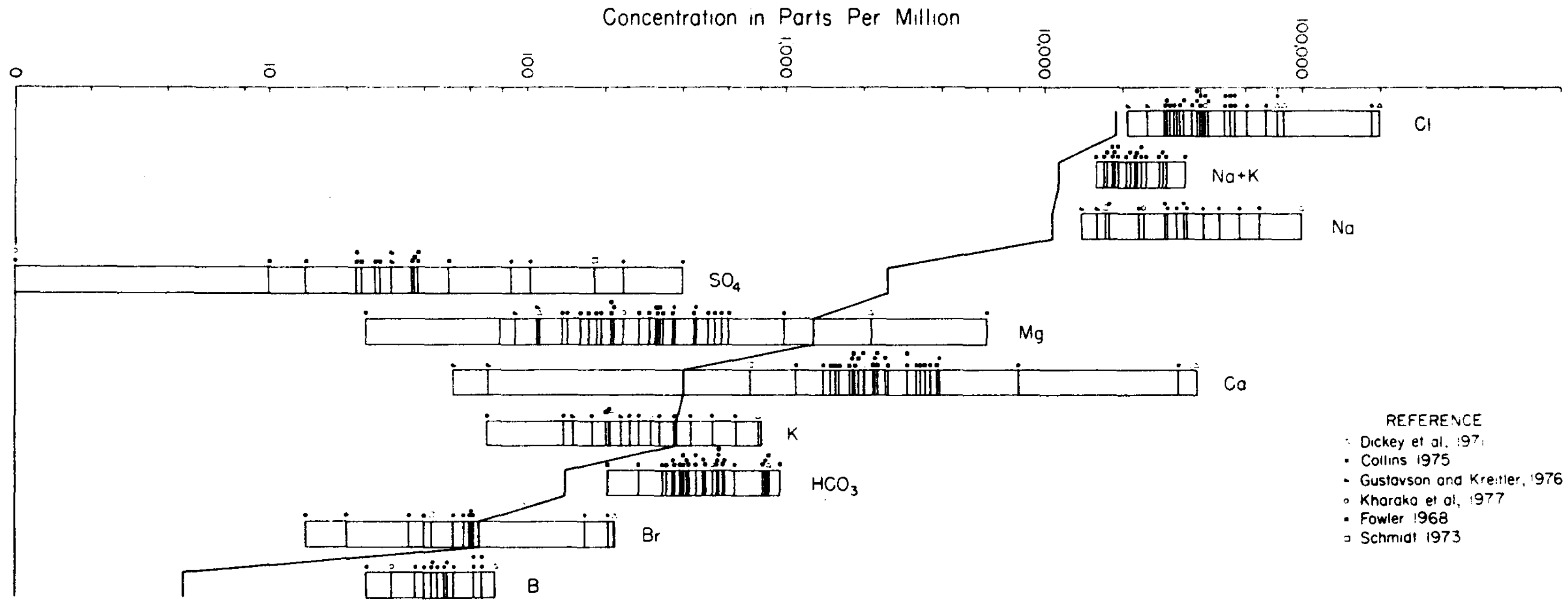


Figure 8. Geothermal brine concentrations.

are very limited although Gustavson and Kreitler (1976) report traces of beryllium, copper, iron, and strontium in formation fluids from the Chapman Ranch Field south of Corpus Christi. Kharaka and others (1977, 1977a, and 1978) report traces of hydrogen sulfide and ammonia from several Texas fields.

Geopressured fluids are not concentrated sea water with a regular and systematic increase in all dissolved ions, but are complex solutions that are in part the result of fluid and ion migration and chemical reactions that accompany the burial of sediment and its subsequent diagenesis. Therefore, in the event that geopressured fluids are released into bays, lagoons, or the Gulf of Mexico the fluid release cannot be simply equated to an input of concentrated sea water, for the balance of ions in geopressured fluids differs markedly from the ionic balance of normal sea water. Possible air contaminants derived from the release of geothermal fluids are methane ($CH_4$), non-methane hydrocarbons ($C_NH_N$), hydrogen sulfide ($H_2S$), and ammonia ($NH_3$) (Kharaka and others, 1977). If extracted hydrocarbon residues and non-condensable gases are flared, other carbon and sulfur compounds may be released to the atmosphere.

Surface disposal of geopressured-geothermal fluids

Geothermal fluids could be disposed of into surface water bodies or they could be injected into the subsurface. Disposal into surface waters would be by pipeline exposed near the bottom of a water body and should cause rapid and effective mixing with ambient waters. Disposal of large volumes of brine into surface waters or temporary storage in holding ponds is, however, likely to result in significant environmental impacts.

Gustavson and Kreitler (1976) describe the impact to Chiltipin Creek of salts that are aparently the residual of oil brines previously stored in evaporation ponds. Salinity of Chiltipin Creek waters has exceeded 35,000 ppm several times a year since 1969, effectively destroying the natural environments of the stream. In the wetlands and estuary systems of the Coastal Zone, a delicately balanced, broad-mixing gradation of fresh to salt water exists and direct disposal or accidental release into these waters can have a number of significant negative consequences. Mixing occurs as fresh-water discharge from streams intermingles with marine waters moving landward through tidal inlets and passes, and by storm inundation. The primary effects will be the degration of vegetation and aquatic fauna intolerant to rapid salinity or temperature changes resulting from geothermal fluid releases. In addition, boron and toxic elements contained in geothermal waters may be sufficient to produce harmful effects to biota.

Operating thermal effeciency in most types of generating facilities today is less than 50 percent. Most of the energy is lost or dissipated as low-grade waste heat additions into the environment. The discharge of heat to a body of water can cause various physical, biological, and chemical effects. With increasing water temperature, the oxygen-holding capacity of the water decreases, density changes may cause stratification, evaportation is increased, chemical, biological, and physical reaction rates increase, and viscosity decreases. Surface waters of the Texas-Louisiana Coast cover a whole spectrum of different types of water bodies and water chemistries from open marine to fresh water pond, in arid to semi-tropical environments. If surface waters are used in a cooling system or for disposal of geothermal waters, effects of geothermal heat discharge will be dependent on plant site location and proximity to and use of water bodies.

Subsurface disposal of geopressured-geothermal fluids

Disposal of geothermal fluids into the subsurface will result in substantially less effect on the environment than would surface disposal. Twenty or more injection wells may be needed to dispose of the 64,800 $m^3$ (400,000 bbl) of spent fluid from a single 25 mw power plant: the number of wells is dependent upon the rate of disposal per well. In the absence of an accidental release of brines, the major potential impacts resulting from the reinjection of geothermal brines would be (1) possible upward migration of the base of fresh ground water that would overlie the area of the disposal field, or perhaps leakage of brines along faults and (2) induced movement along faults.

Accidental spills

From the complex network of production wells, pipelines, power plants, and disposal wells that will comprise a geopressured-geothermal electrical generating plant, an accidental release of hot brines is possible. Spills are most likely to happen in the process of drilling the well--a blow-out, during normal maintenance procedures of an operating well, or as a breach in the pipeline that will carry the geothermal water from production well to generators to disposal well. Geothermal fluids released on land would harm vegetation and small animals, and would temporarily increase soil salinity. Sustained releases on land could increase soil salinity to the point where the soil would no longer support non-salt tolerant vegetation. Large spills or sustained releases could also contaminate shallow ground water and streams.

## Commercial development scenarios

The commercial development of geothermal resources can be described in terms of three location scenarios:

1. The first scenario places production generating and disposal facilities on coastal low-lands or uplands accessible by roads. The power plant will occupy a relatively small area within a network of production wells, and spent fluids will be disposed via reinjection wells. In this scenario a minimum of land area would be directly affected as well sites, pipelines, and access roads to the well sites, storage ponds, and generating plant site.

2. The second scenario places generating production and disposal facilities on low-lying coastal marsh lands that occur primarily in Louisiana. Under these circumstances production and disposal-well sites would be accessible primarily by dredged canal. The generating plant would be placed on a pad of made land constructed from dredge spoil. Access to the generating facility would require either dredging a canal or dredging material to support a road. Substantial dredging would be required to open canals to move heavy equipment to and from drill sites and the generating facility and to construct and maintain pipelines.

3. The third scenario requires that production facilities be located offshore in estuaries, bays, lagoons, coastal lakes, or the Gulf of Mexico. Under these circumstances production facilities may consist of a network of wells in the water body or of groups of directionally drilled wells that may be serviced from one or two production platforms. In this case a gathering facility and the array of injection wells would be located on land and connected to the production platforms by pipeline.

Of the three scenarios, development on coastal lowlands would result in the least harm to the environment while development in coastal marshlands would result in severe environmental disruption.

Power plant systems

For each location scenario, two possible power plant systems may apply: two-staged flashed steam and secondary working fluid systems. The fundamental difference between the flash method and secondary working fluid method (binary) in terms of environmental impact is that the flash method allows noncondensable gases to be passed to the atmosphere, or flared if combustible.

Approximately 10 to 12 production wells (at a flow rate of $6560 m^3$/day/well 40,000 bbl/day well) would be required to supply geothermal fluids to a 25 mw flash plant. Twenty to twenty-four injection wells with injection rates of 985 $m^3$/day (6,000 bbl/day) would be required to dispose of the spent geothermal fluids for a facility of this magnitude. At half-mile spacings the well fields would require seven to ten $mi^2$.

Land surface disturbance

Intense development will occur only at the power plant site where the construction of roads, temporary holding ponds, power transmission lines, and the power plant will require the use of a minimum of 10 acres. The major impact here is that the area of the development site is withdrawn from the natural system. Disposal and production wells will be accessibly by a network of unimproved dirt roads whose effect on upland area development will be minor. The construction of roads or canals in wetland areas would, however, severely impair the local environment.

## Pipelines

A system of pipelines will be necessary to collect and carry geothermal fluids from production wells to the power plant site and later to the disposal facilities. Current practice on land is to bury pipelines. The environmental impact of burying a pipeline on land is relatively minor, consisting of disturbed soil and vegetation along the route of the pipeline. Vegetation can be reestablished along the pipeline generally within a few months. The construction of pipelines or canals through wetlands, bays, estuaries, or the Gulf of Mexico, however, is likely to result in significant local environmental disturbance. Loss of habitat and vegetation in areas occupied by spoil piles, levees, and canals will result. Reduction of water quality will probably result from the redistribution of heavy metals, pesticides, sulfides, and particulate matter contained in the dredged spoil. Canals and levees serve to interrupt natural drainage of marsh areas and can locally raise or lower water levels.

## Noise

The development of geopressured-geothermal resources under all three scenarios will result in similar elevated noise levels. Temporary noise-level increases will result from the construction of each drill site and from well drilling. The drilling operation, involving the use of heavy equipment and large diesel engines, occurs 24 hours a day for several weeks or longer and noise levels of 80 to 90 dBA on the derrick floor can be expected. The construction of pipelines and the power plant will also result in temporarily increased local noise levels largely due to the operation of construction equipment. The effects of elevated noise levels on animal life are not clearly understood, but do not appear to be of major significance.

Cooling towers

Many methods of condenser cooling are possible in the coastal region and each method employs treatments or induces some chemical and physical changes on the cooling waters. Chlorine may be added to prevent fouling of condensers by untreated natural water. Additional algicides, biocides, and corrosion and scaling inhibitors are added to recirculating cooling systems and these chemicals can become concentrated by evaporation in draft towers or holding ponds. Furthermore, these cooling fluid additives are carried into the atmosphere and to the surrounding landscape in water vapor droplets.

## PROGRAM GOALS

This document defines a program to assess aspects of environmental quality within the Texas Outer Coastal Zone that may be affected by geopressured-geothermal resource development including:

1. Land subsidence and fault activation
2. Effects of spent geothermal fluid disposal
3. Ecosystem quality
4. Water quality
5. Air quality
6. Social impacts of geothermal development on communities

The broad goals of this program are identical to those expressed by Anspaugh and others (1977), namely to

> ...ensure that large-scale geothermal development proceeds in an environmentally sound manner, that major problem areas are anticipated, and that necessary feedback to those concerned with technology development exists so that appropriate control

measures may be instituted if justified. In order to achieve these broad, problem-oriented goals, the program must maintain a high degree of flexibility so that the main emphasis can constantly be focused on the most important, unresolved issues. These issues may well change as the program develops. A major effort will also be required to achieve a high degree of coordination and information transfer among many organizations including the technology developers and users and the various federal, state, and local government agencies responsible for regulatory aspects of geothermal development. A secondary goal of the program will be to accumulate sufficient data so that any problems associated with the development of geothermal resources may be readily distinguished from those due to other causes.

## RECENTLY COMPLETED AND ONGOING ENVIRONMENTAL RESEARCH

The Bureau of Economic Geology has recently completed several environmental studies aimed specifically at delineating the potential environmental concerns that could arise from development of geopressured-geothermal energy:

1. Geothermal Resources of the Texas Gulf Coast: Environmental Concerns Arising from the Production and Disposal of Geothermal Waters.
   U.S. Energy Research and Development Administration Contract #AT-(40-1)-4900, 1976.
2. Ecological Implications of Geopressured-Geothermal Energy Development, Texas-Louisiana Gulf Coast.
   U.S. Department of the Interior, Fish and Wildlife Service Contract #14-16-0008-2141.
3. Preliminary Environmental Analysis of Geopressured-Geothermal Prospect Areas, Brazoria and Kenedy Counties, Texas.
   U.S. Department of Energy Contract #EG-77-S-05-5401.

We are currently performing environmental baseline and monitoring studies in the vicinity of a geopressured-geothermal test well site in Brazoria County, Texas. Monitoring includes:

1. Faulting and subsidence--liquid tiltmeter survey, annual first-order leveling survey, and microseismicity survey
2. Air quality
3. Water quality
4. Noise
5. Archeological resources

We are also completing the preliminary environmental analysis of geopressured-geothermal prospect areas in Colorado and DeWitt Counties, Texas (U.S. Department of Energy Contract #EG-77-S-05-5401).

## AIR QUALITY

### Introduction

Human activity on the Texas Gulf Coast has resulted in severe local degradation of air quality. Several air quality regions along the coast do not meet current Federal air quality standards for ozone, non-methane hydrocarbons, sulfur dioxide, and particulates (Texas Air Quality Control Board, 1976) (tables 3, 4). The development of geopressured-geothermal resources which may contain both $H_2S$ and hydrocarbons could, under certain conditions, contribute to further degradation of air quality.

### Air Pollutants in Geopressured-Geothermal Fluids

The chemistry of formation fluids from geopressured-geothermal horizons is incompletely known, since only a few detailed analyses are available.

Kharaka and others (1977, 1977a, 1978) have shown that small but variable amounts of hydrogen sulfide ($H_2S$) (0.04 to 1.4 mg/l) and ammonia ($NH^+_4$) (4.2 to 100 mg/l) may be present in fluids from the geopressured zone in certain areas of the Gulf Coast (table 3). This data and data from South Texas (Gustavson and Kreitler, 1976), show the variable chemistry of geopressured formation fluids. From available data it is impossible to estimate with assurance either the presence of potential air pollutants or their concentration for any geothermal prospect areas before formation fluids are available for analysis. It is generally thought, however, that brines from geopressured horizons are saturated, or nearly so, in methane and other hydrocarbons. Non-methane hydrocarbons will only amount to approximately 5.0 percent by volume of the total hydrocarbon load.

Commercial utilization schemes will require either flashed stream, total flow or secondary working fluid systems to convert geothermal heat and mechanical energy to electrical energy. In each of these systems gas separators will be used to strip off methane from the geothermal fluids. If the methane contains $H_2S$ or other unwanted gases these will be scrubbed and flared to the atmosphere. Non-condensable gases from the cooling processes associated with the flashed stream or total flow systems will also be flared or released to the atmosphere.

The possible air contaminants from vents, leaks, or from incomplete combustion in flares would include methane ($CH_4$), non-methane hydrocarbons ($C_nH_n$), hydrogen sulfide ($H_2S$), and ammonia ($NH_3$) (Gustavson and others, 1978). Sulfur dioxide, a product of the oxidation of $H_2S$, is also a probable air contaminant.

Table 3

- 1978 -

Comparison summary of CAMS (continuous air monitoring stations) data

with ambient standards

| Air Quality Control Region Number | Station Location | CAMS Number | Ozone-Second Highest Hour | Ozone-Percent of Time 0.12 ppm | Carbon Monoxide 2nd Highest Hour | Carbon Monoxide 2nd Highest 8 Hrs. (non-overlapping) | Nonmethane Hydro-carbons 6-9 AM 2nd High | Sulfur Dioxide 2nd Highest 24 Hrs. | Sulfur Dioxide Annual Mean | Sulfur Dioxide 2nd Highest 3 Hrs. (Non-overlapping) | Nitrogen Dioxide Annual Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Maximum Allowable by Ambient Air Standards (parts per million | | | 0.12 | 0.0 | 35 | 9 | 0.24 | 0.14 | 0.03 | 0.50 | 0.05 |
| 10 | Nederland | 2 | 0.19 | 0.5 | 2.3 | 1.1 | 4.2 | 0.02 | 0.00 | 0.10 | 0.01 |
| | West Orange | 9 | 0.17 | 0.5 | 4.2 | 3.0 | 2.9 | 0.05 | 0.00 | | 0.01 |

Table 3 (continued)

- 1978 -

Comparison summary of CAMS data with ambient standards

| Air Quality Control Region Number | Station Location | CAMS Number | Ozone-Second Highest Hour | Ozone-Percent of Time 0.12 ppm | Carbon Monoxide 2nd Highest Hour | Carbon Monoxide 2nd Highest 8 Hrs. (Non-overlapping) | Nonmethane Hydro-carbons 6-9 AM 2nd High | Sulfur Dioxide 2nd Highest 24 Hrs. | Sulfur Dioxide Annual Mean | Sulfur Dioxide 2nd Highest 3 Hrs. (Non-overlapping) | Nirtogen Dioxide Annual Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Maximum Allowable by Ambient Air Standards (parts per million) | | 0.12 | 0.0 | 35 | 9 | 0.24 | 0.14 | 0.03 | 0.50 | 0.05 |
| 5 | Corpus Christi, Urban | 4 | 0.16 | 0.2 | 9.3 | 3.7 | 3.5 | 0.03 | 0.00 | 0.15 | 0.01 |
| | Corpus Christi, Downwind | 21 | 0.14 | 0.1 | - | - | - | 0.01 | 0.00 | 0.08 | - |
| 7 | Houston, East | 1 | 0.21 | 0.6 | 11.8 | 5.9 | 4.6 | 0.03 | 0.00 | 0.04 | 0.03 |
| | Harris County, Aldine | 8 | 0.21 | 1.5 | 10.6 | 5.6 | 4.2 | 0.02 | 0.00 | 0.03 | 0.02 |
| | Texas City | 10 | 0.29 | 0.9 | 4.8 | 2.4 | 2.2 | 0.01 | 0.00 | 0.04 | 0.02 |
| | Clute (Freeport) | 11 | 0.16 | 0.4 | 6.4 | 2.8 | 2.6 | - | - | - | 0.02 |
| | Seabrook | 20 | INSUFFICIENT DATA NOTE 1 | | | | | | | | |

Under normal operating conditions methane will be stripped from geothermal fluids and sold. Gaseous non-methane hydrocarbons (5 percent by volume) will be removed from the brine with the methane and thus will probably not be present in volume large enough to be significant air contaminants. $NH_3$ and $H_2S$ will be flared or released to the atmosphere. Furthermore, it does not appear that significant amounts of $H_2S$ will be found in geopressured-geothermal fluids. However, because the chemistry of geopressured formation fluids is variable and poorly understood, the effects of gases contained in these fluids on potential air quality are also poorly known. Therefore, until better knowledge of formation fluid chemistry is available, air quality should be monitored at each geopressured-geothermal test well site.

Commercial operations or possibly advanced testing phases will require cooling and condensing of spent geothermal fluids prior to reinjection. Biocides such as sodium chromate and sodium pentachlorophenate may be introduced to the waters in the cooling tower to prevent the growth of algae (Muehlberg and Shepard, 1975). Triethylene glycol is used in the process of removing water vapor from methane. These substances, such as boron, that are highly toxic to plants may be present in cooling tower and dehydrator exhaust and may be carried to surrounding vegetation along with natural substances in the geothermal fluids by wind drift.

## CLIMATE

The climatic regions of the Texas Gulf Coast approximately coincide with boundaries of the Air Quality Control Regions along the coast (fig. 9). The climatic regions are based on characteristic annual distributions of rainfall,

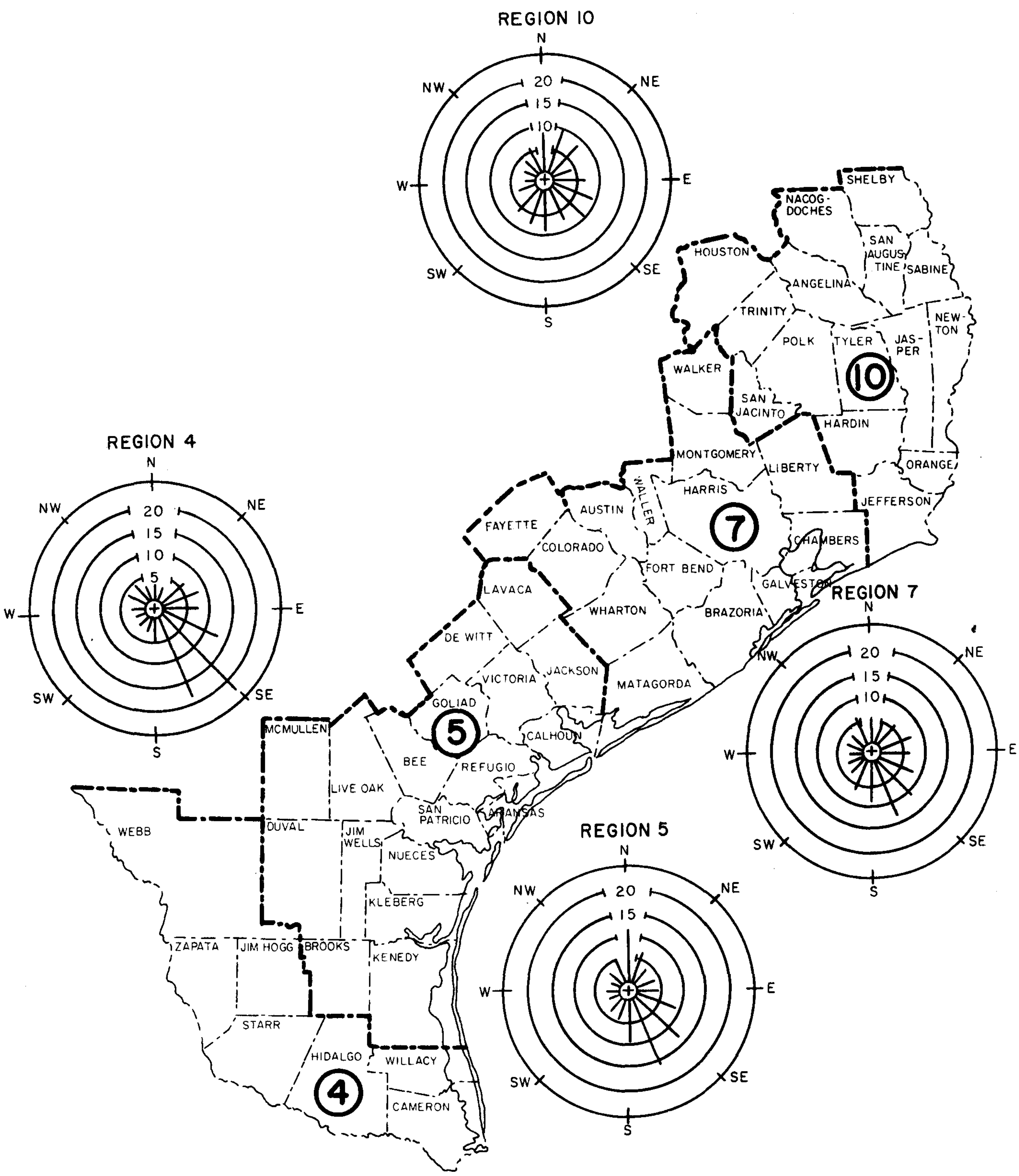


Figure 9. Air quality regions and wind roses.

with the lower coast (Air Quality Regions 4 and 5) receiving maximum precipitation during May and September and the upper coast receiving maximum precipitation during the summer months.

It is difficult to generalize about the climate of the Texas coast. For example, yearly precipitation is likely to vary from the mean annual precipitation by 25 percent during any given year. Furthermore, the mean annual preciptation for the Houston-Galveston area is nearly twice that of far South Texas and the Rio Grande.

The coastal climate, however, is characterized by southerly and southeasterly breezes. It is warm throughout, humid in the north but becoming increasingly drier to the south. Outbreaks of cold polar air occur from September to May, although they occur more frequently during the winter months. These frontal systems, "northers," bring strong northerly winds, dry air, and cold temperatures, although passage of the fronts may generate substantial rainfall. It is these inflexes of cold polar air that account for the few episodes of freezing weather that occur on the Texas coast. The Texas Gulf Coast is also subject to hurricanes and tropical storms from midsummer through the fall. Storms with hurricane force winds strike the Texas coast about once in every 1.5 years. Carr (1967) and Orton (1964, 1969) provide excellent general discussions of aspects of the Texas coastal climate.

Air Quality Control Region 4 encompasses the counties that comprise the lower Rio Grande Valley. The climate is warm and dry with annual mean temperature extremes that range from 48°F (9°C) (January) to 97°F (36°C) (July). Mean annual rainfall ranges from 24 to 28 in (61 to 71 cm). Prevailing wind directions are shown in figure 9. As is true with the entire

Texas coast gentle southeasterly onshore breezes occur most of the time. However, the wind roses of figure 9 do not adequately show the second dominant wind direction. North, northwest, and northeasterly winds associated with the southward passage of cold air masses ("northers") have a strong influence on many aspects of the Texas coast in addition to climate and air quality.

Air Quality Control Region 5 occurs from Kenedy County northeastward to Jackson and Lavaca Counties. Along the coast the climate is warm and humid and mean temperature extremes range from 46°F (8°C) in January to 95°F (35°C) in July. Mean annual precipitation ranges from 23 to 40 in (58 to 101 cm), with precipitation maximums occuring during May and September. Prevailing wind directions are south-southeast (figure 9).

Air Quality Control Region 6 extends along the coast from Matagorda County to Chambers County. Climate here is warm and humid. The mean annual minimum, 44°F (7°C), occurs in January and the mean maximum temperature, 93°F (34°C), occurs in July. The mean annual rainfall ranges from 40 to 50 in (102 to 127 cm), with maximum monthly rainfalls occurring during the summer.

Region 10, the northernmost coastal air quality region, is also the wettest, receiving more rainfall than any other area of the State, more than 50 in (127 cm). Climate is hot and humid with temperature ranging from the mean minimum of 40°F (4°C) in January to the mean maximum of 93°F (34°C) in July. Winds are variable with southerly and southeasterly sea breezes dominant. Northeasterly winds are important during the passage of cold fronts during the cooler months. A wind rose is shown in figure 9.

## Temperature Inversions

Air temperature normally decreases with elevation above the land surface. When the reverse is true for a layer of air, a condition of temperature inversion exists. A low-level inversion or isothermal layer results in stable air structure and tends to suppress air turbulence or mixing and holds down wind velocities near the earth's surface. Thus, temperature inversions tend to prevent dispersion of air pollutants. Table 4 gives the percentage of frequencies of inversions below 500 ft (152 m) for a portion of the Texas Gulf Coast. The data, although limited, are characteristic of the coast and suggest that air stability decreases rapidly during the daylight hours and only rarely do stable air masses, temperature inversions, exist by late afternoon. Temperature inversions are least common during the summer months and most common during the winter months.

## Low-level Air Turbulence and Mixing Depths

Two forms of turbulence are important on the Texas Gulf Coast, "mechanical turbulence" produced by shear and "convective turbulence" produced by hydrostatic instability. If the vertical temperature distribution is stable, turbulence is suppressed, but if temperature stratification is unstable, as is usually the case along the Texas Coast, turbulence is increased.

As air is heated during the day, temperature stratification becomes neutrally stable or unstable. This condition favors vertical convective mixing of the lower portions of the atmosphere. The heights to which mixing occurs along the coast are given in Table 5 and are indicative of the air layer through which pollutants can be mixed. Vertical mixing heights are greater in summer (3,940 to 4,590 ft; 1,200 to 1,400 m) along the coast and less during the winter (1,600 to 2,460 ft; 600 to 750 m) (Holzworth, 1962). Visual evidence of low-level turbulence in the form of vertical convection is given by the presence of cumulus clouds.

Table 4

Percentage frequencies of inversions and/or

isothermal layers based below 500 ft.

| STATION | SEASON | 2100 | 0900 | 1800 | 0600 | PERIOD OF RECORD USED | |
|---|---|---|---|---|---|---|---|
| | | | | | | For 03Z and 15Z OBS. | For 00Z and 12Z OBS. |
| San Antonio WBAS | Winter | 54 | 34 | 9 | 47 | June, 1955 - May, 1957 | June, 1957 - May, 1959 |
| | Spring | 27 | 6 | 2 | 43 | | |
| | Summer | 8 | 0 | 2 | 26 | | |
| | Fall | 46 | 15 | 6 | 45 | | |
| Brownsville WBAS | Winter | | 51 | 7 | 66 | June, 1955 - May, 1957 | June, 1957 - May, 1959 |
| | Spring | | 11 | 1 | 52 | | |
| | Summer | | 2 | 2 | 63 | | |
| | Fall | | 23 | 4 | 71 | | |

Seasons:

- Winter: December, January, February
- Spring: March, April, May
- Summer: June, July, August
- Fall: September, October, November

Table 5

Estimates of mean maximum mixing depths (feet above surface).

| Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Region 4 | | | | | | | | | | | |
| 2100 | 2720 | 2620 | 2890 | 3180 | 3970 | 4200 | 4490 | 4070 | 3940 | 2920 | 1940 |
| Region 5 | | | | | | | | | | | |
| 1840 | 2620 | 2620 | 3120 | 3280 | 3940 | 4270 | 4590 | 4100 | 3940 | 2690 | 1940 |
| Region 7 | | | | | | | | | | | |
| 1640 | 2490 | 2790 | 3350 | 3770 | 4270 | 4590 | 4590 | 4270 | 4000 | 2760 | 1900 |
| Region 10 | | | | | | | | | | | |
| 1710 | 2460 | 2790 | 3280 | 3610 | 3940 | 3940 | 4100 | 4100 | 3940 | 2620 | 1900 |

(Modified from Texas Air Control Board, 1974)

Mechanical turbulence, as evidenced by strong low-level winds, occurs with moderate frequency in the coastal areas of Texas. These cases are limited largely to the passage of polar air masses with large pressure gradients during the winter months.

During the summer months weather is dominated by the tropical maritime air mass extending westward from the Bermuda high-pressure cell. Southeasterly winds prevail throughout the year, although they occur more frequently during the summer months. Velocity of these winds is most frequently 8 to 18 miles per hour (12.9 to 30 km/hr).

Along the Texas coast temperature inversions are rare during the summer (table 4). Convective mixing is common and mixing heights reach over 4,000 ft (1220 m). Strong prevailing southeasterlies combine with unstable air to encourage vertical mixing. In winter stable conditions occur infrequently and these are partly mitigated by the passage of cold fronts and associated strong northerly surface winds.

Thus the conditions that prevail along the Texas coast are excellent for both horizontal and vertical dispersion of pollutants: conditions do not favor the accumulation of air pollutants.

## CURRENTLY AVAILABLE AIR QUALITY DATA

The Texas Air Quality Control Board maintains an extensive network of air monitoring and sampling equipment along the Texas Gulf Coast. In conjunction with this are the National Air Surveillance Network (NASN) and the City-County Network of sampling sites. Through 1977 a total of 139 High-Volume air sampler and 104 gas bubbles were in use for non-continuous air sampling (table 6). At the same time 36 continuous monitoring vans are distributed along the coast (see figs. 10 and 11).

Table 6

Air quality surveillance system regional equipment.

| Region | Hi-Vols | Gas Bubblers | Continuous Monitoring Trailers |
|---|---|---|---|
| IV | 8 | 8 | 3 |
| V | 19 | 18 | 6 |
| VII | 34 | 29 | 21 |
| X | 11 | 12 | 6 |
| SUBTOTAL: | 72 | 67 | 36 |
| *NASH and City-County Network | | | |
| IV | 11 | -- | -- |
| V | 10 | 1 | -- |
| VII | 37 | 34 | -- |
| X | 9 | 2 | -- |
| SUBTOTAL: | 67 | 37 | -- |
| TOTAL: | 139 | 104 | 36 |

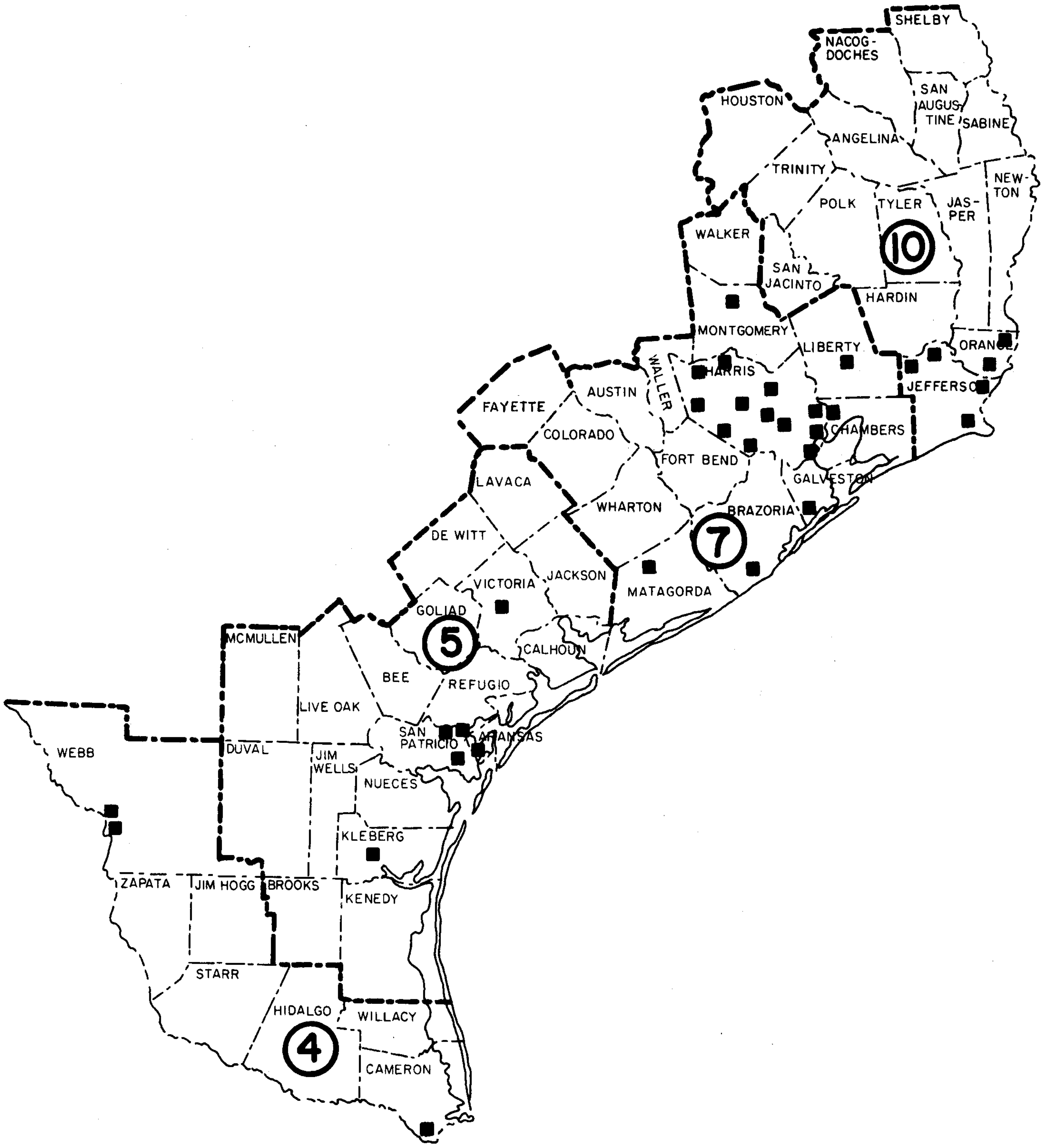


Figure 10. Locations of continuous air quality monitoring vans.

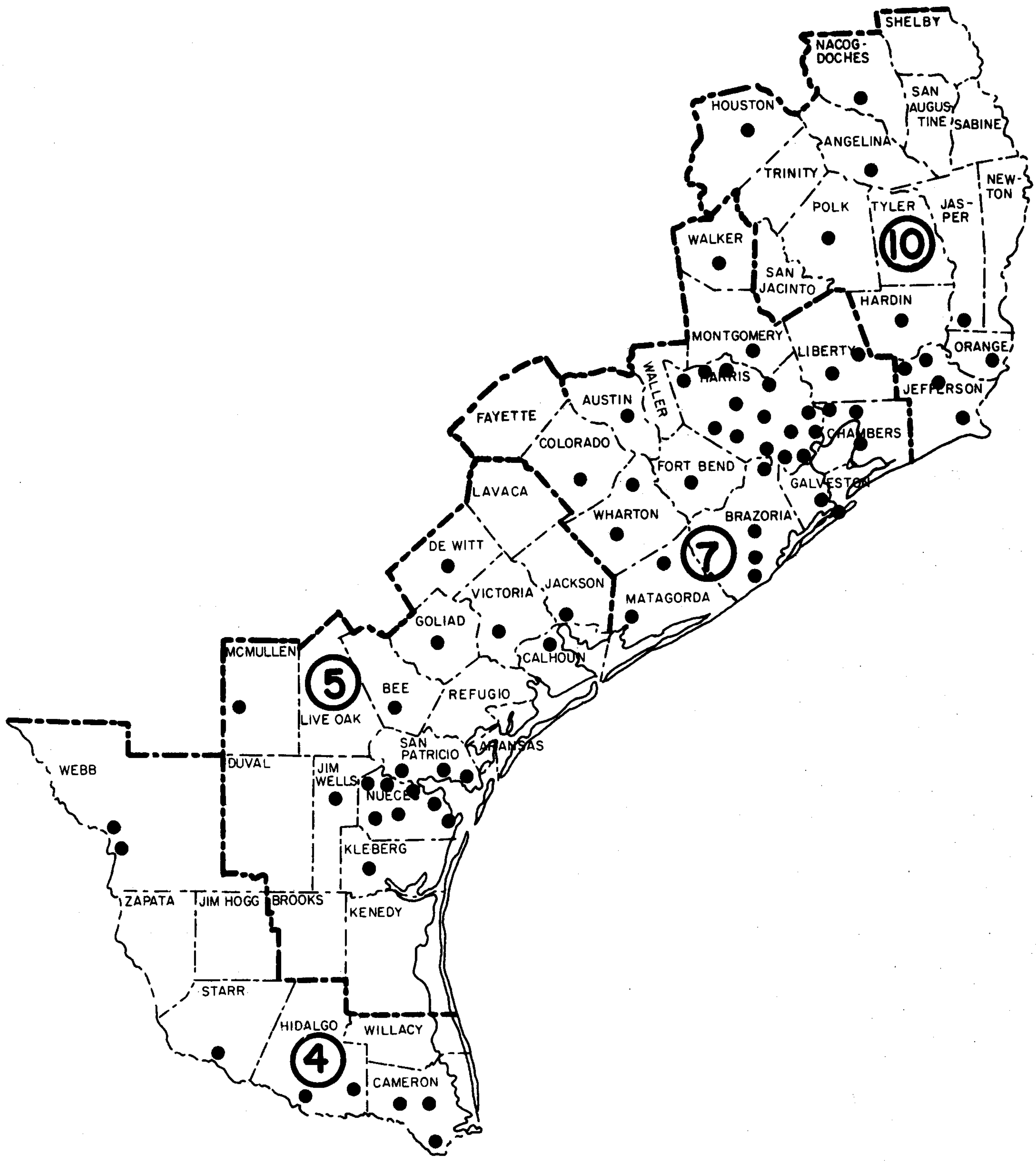


Figure 11. Locations of high-volume air samplers.

The high-volume air samplers are designed to provide data on total suspended particulates, benzene solubles, sulfates, nitrates, heavy metals, and trace elements. X-ray fluorescence is used to identify specific elements and types of particulate matter. Gas bubbles provide data on $SO_2$, $NO_2$, $NH_3$, total oxidants, aldehydes, mercury vapor, hydrogen sulfide, and fluorides. Continuous monitors collect data on CO, $HC_4$, THC, $SO_2$, $H_2S$, TS, $O_3$, NO, $NO_2$, temperature, wind speed and direction, solar radiation, and miscellaneous inputs. All data are stored and available at the Texas Air Quality Control Board, Austin, Texas.

### Air Quality in the Texas Coastal Zone

Table 7 summarizes National Air Quality standards and outlines those regions that do not meet these standards. Regions 5, 7, and 10 do not meet national standards for particulates, sulfur dioxide, photochemical oxidants, and non-methane hydrocarbons. Region 4 does not meet national standards for particulate matter. Additional data are available from the Continuous Monitoring Data Summaries of the Texas Air Quality Control Board (1975, 1976).

## AIR QUALITY DATA ACQUISITION PLAN

### Baseline Air Quality Monitoring

The available ambient air quality data on the Texas coast are sufficient to characterize baseline air quality within the urbanized and industrialized areas of the coast. The density of monitoring and sampling stations is much less in rural areas than it is in industrialized or urbanized areas. Nevertheless, sufficient data are probably available to characterize regional ambient air quality in rural areas. Furthermore, only a limited number of widely spaced geopressured-geothermal fairways have been identified along the

Table 7. National air quality standards and maximum recorded air pollution levels for Texas air quality regions.

| POLLUTANT | READING: Type or Time | PRIORITY CLASSIFICATION: I | II | III | STANDARDS: National Primary | National Secondary | PRIORITY OF REGIONS |
|---|---|---|---|---|---|---|---|
| Particulate Hg/M$^3$ | AGM<br>24 hr. max. | 95<br>325 | 60-96<br>150-325 | 60<br>150 | 75<br>260 | 60<br>150 | I 5, 7<br>II 10<br>III 4 |
| Sulfur Dioxide Hg/M$^3$ (PPM) | AAM<br>24 hr. max.<br>3 hr. max. | 100 (.04)<br>455 (.17) | 60-100 (.02-.04)<br>260-455 (.10-.17)<br>1300 (.5) | 60 (.02)<br>260 (.10)<br>1300 (.5) | 80 (.03)<br>365 (.14) | 1300 (.5) | I 7. 10<br>II 5<br>III 4 |
| Carbon Monoxide mg/M$^3$ (PPM) | 8 hr. max.<br>1 hr. max. | 14 (12)<br>55 (48) | NA | Less than for I | 10 (9)<br>40(35) | 10 (9)<br>40(35) | III All Regions |
| Photochemical Oxidants Hg/M$^3$ (PPM) | 1 hr. max. | 195 (.10) | NA | Less than for I | 160 (.08) | 160 (.08) | I 5, 7, 10<br>III 4 |
| Hydrocarbons (nonmethane) Hf/M$^3$ (PPM) | 3 hrs. max. 0600-0900 | 195 (.29) | NA | Less than for I | 160 (.24) | 160 (.24) | I 5, 7, 10<br>III 4 |
| Nirtogen Dioxide | AAM | 110 (.06) | NA | Less than | 100 (.05) | 100 (.05) | III All Regions |

Revised 4/15/75

(Modified from Texas Air Control Board, 1974)

Texas coast (fig. 2). Because of the available data and because of the distribution of potential goepressured-geothermal production sites, no fixed-location monitoring stations in areas other than geopressured-geothermal production or test sites are needed.

## Current Air Quality Monitoring

Air quality and meteorological data are currently being collected at the first geopressured-geothermal test well, the Pleasant Bayou #1, near Alvin in Brazoria County, Texas. Through a subcontract with The University of Texas at Austin, Radian Corporation has been monitoring air quality since March 1978. Since the test well will not begin production until late 1979, the data that have been accumulated since March 1978 will provide a suitable ambient air quality baseline.

## Site Specific Monitoring Stations

Until the potential impacts of geopressured-geothermal development on ambient air quality are thoroughly understood each geopressured-geothermal site should be monitored for air quality. The pollutants of potential concern are methane, non-methane hydrocarbons, and ammonia, because these substances are known to occur in geopressured formation fluids. The oxidation of $H_2S$ produces $SO_2$, a pollutant of increasing importance on the Texas Gulf Coast. As other potential pollutants are recognized from analyses of geopressured-geothermal or from substances such as corrosion inhibitors and biocides introduced into cooling tower waters additional parameters may be added to the list. Meteorological data should be collected concurrently with air quality data.

All air quality monitoring should conform to Environmental Protection Agency Quality Assurance procedures and should meet or exceed all Federal performance and dimensional specifications including those in the Federal Register (1971).

Estimated Cost for Site Specific Air Quality Monitoring

Methane

Non-methane hydrocarbons

Sulfur dioxide

Hydrogen sulfide

Ammonia

Meterological data

Total Cost $125,000/year

Proposed Air Quality Monitoring

The first geopressured-geothermal test well site is currently monitored for air quality. Within the next two years, three additional sites may be considered for testing: Kenedy, Colorado, and DeWitt Counties. If these tests occur, funding required for air quality monitoring may exceed $350,000 per year.

## ECOSYSTEM QUALITY

### Introduction

The following discussion of ecosystem quality and of the kinds of changes in the ecosystem that may occur as a result of development of geopressured-geothermal resources along the Texas Gulf Coast is based on documents previously prepared by the Bureau of Economic Geology. These documents include: "Ecological

Implications of Geopressured-Geothermal Energy Development, Texas-Louisiana Gulf Coast," (Gustavson and others, 1978); "Environmental Analyses of Geopressured-Geothermal Prospect Areas," (White and others, 1978); and "Geothermal Resources of the Texas Gulf Coast: environmental concerns arising from the production and disposal of geothermal waters" (Gustavson and Kreitler, 1976).

Several potential effects on fish and wildlife resources have been recognized, based on analysis of information on the ecosystems concerned and the potential nature and extent of commercial exploitation of the geothermal resource. This evaluation considers stresses from geothermal activities and stresses from other sources, both man-induced and "natural." Such stresses include whole organism and biological-community responses to normal environmental regimes and altered responses to stressed regimes.

Three major biological issues pertinent to effects on fish and wildlife are addressed: (1) the adequacy of baseline data on kinds and quantities of organisms and on physical, chemical, and geological features of the Gulf Coast region; for example, can wetlands, marshes, productive estuaries, and critical game habitats be precisely located? (this information is critical to facility siting); (2) the status of predicting and identifying changes in ecological and physiological functions and processes anticipated from stress effects on geothermal exploitation; for example, are data available to allow accurate predictions of the effects of subsidence on ecosystems?; and (3) are adequate effects data available to determine the short-term and long-term impacts on ecosystems from surface releases of geothermal brines?

## Overview of the Texas Gulf Coast

The coastal region of Texas is ecologically diverse and complex, perhaps deceptively so, considering the lack of marked topographic relief in the area. The natural complexity is related not only to present climatic, geologic, and soil conditions, but also to the historical biogeography of the region.

The predominant factors responsible for the geographical pattern of change of terrestrial and freshwater biological diversity over the region are a climatic gradient of moisture and temperature and edaphic changes. Moisture decreases and temperature increases from northeast to southwest. The Texas coast can be divided into three climatic belts: a humid region from the Louisiana border to Galveston, a region ranging from wet subhumid near Galveston to dry subhumid near Corpus Christi, and a semiarid section from Corpus Christi to the Rio Grande. Average annual temperature ranges from 20°C at Sabine Pass to 24°C at Brownsville. Rainfall varies from 140 cm per year in the northern regions to 66 cm on the lower reaches of the coast.

Six different terrestrial ecoregions have been recognized for this area (Bailey, 1976). Three of these are humid forest zones including parts of the study area east of the Trinity River embayment. To the southwest of the mesic forest zones is a predominately oak (*Quercus* spp.)-bluestem (Poaceae) parkland section which gradually changes to a predominantly mesquite (Prosopis spp.)-acacia (*Acacia* spp.) section in the region of Calhoun County, Texas. Within this same area Bailey (1976) recognized two major marine and estuarine systems, a West Indian Province extending north from the Mexican border to Calhoun County and a Louisianian Province extending from there to the Mississippi River Delta region and beyond. Within each of these major ecological regions there are many different biological communities. Some of this variety results from the terrestrial-coastal surface.

The barrier islands along the Texas coast enhance the biological diversity of the region (table 8). The coast is characterized by a continuous series of bays, estuaries, and lagoons from Sabine Lake to Laguna Madre. The Texas Coastal Plain is drained by ten major river systems which enter the bays or discharge directly into the Gulf. The bays are normally headed by alluvial plains and deltas which usually support marshes. The seaward sides of bays are protected by barrier islands. The shores of many bays and both sides of barrier islands consist of many miles of fine sand beaches, tidal flats, or marshy areas. The Texas coastal system contains 398,080 acres of marsh and 1,344,000 acres of bays and estuaries.

The predominant human influence in the Gulf Coast region is commerical and agricultural. Seventy percent or more of the land is under commercial use of one sort or another. Because of the predominantly monocultural management practices of much of modern agriculture, many of the terrestrial biological communities of the region have been greatly simplified and therefore have probably become less ecologically stable than the natural communities which were once predominant. There are several major residential-industrial centers in the region, including Brownsville, Corpus Christi, Victoria, Houston, Galveston, and Beaumont.

The estuarine systems are some of the most productive in the world. They support large fisheries, provide a valuable recreational resource, and include habitats for a number of species threatened with extinction. Some of the major ecological conflicts in the region arise from the values of the above wetland-related activities and those of other, sometimes incompatible uses, such as those of heavy industry. The resolution of such conflicts in the future will tax the abilities of all of society (Blevins and Novak, 1975).

### Table 8. Biological assemblages of seven map units of coastal Texas as documented in the Environmental Geologic Atlas of the Texas Coastal Zone.*

| | Beaumont-Port Arthur | Houston-Galveston ‖ | Bay City-Freeport | Port Lavaca ‖ | Corpus Christi | Kingsville | Brownsville-Harlingen |
|---|---|---|---|---|---|---|---|
| Beach | + | + | + | + | + | + | + |
| Unvegetated coastal mud flat | + | − | − | − | − | − | − |
| Vegetated strandplain flat | + | − | − | − | − | − | − |
| Grass and locally scrub oak-covered ridges | + | − | − | − | − | − | − |
| Salt water marsh | + | + | + | + | + | − | + |
| Brackish water marsh | + | + | − | − | − | − | − |
| Brackish to fresh water marsh | + | + | + | + | + | − | + |
| Inland fresh water marsh | + | + | + | + | + | + | + |
| Prairie grasslands | + | + | + | + | + | + | + |
| Swamp | + | + | + | + | + | − | − |
| Frequently flooded fluvial areas | + | + | + | + | + | − | + |
| Fluvial woodland | + | + | + | + | + | + | + |
| Mixed pine and hardwood forest | + | + | − | − | − | − | − |
| Small prairies in forested uplands | + | + | − | − | − | − | − |
| Oak mottes and groves | + | + | + | + | + | + | + |
| Vegetated barrier flat | − | + | − | + | + | + | + |
| Sand flat | − | + | + | + | + | + | + |
| Barren land | − | + | + | + | + | − | − |
| Shell ramp barrier flat | − | − | + | − | − | − | − |
| Fluvial grassland | − | − | − | + | + | − | − |
| Berms | − | − | − | + | + | + | + |
| Washover channel and fan | − | − | − | − | + | + | + |
| Active dunes | − | − | − | − | + | + | + |
| Active clay-sand dunes | − | − | − | − | + | + | + |
| Poorly drained depressions | − | − | − | − | + | + | + |
| Loose sand and loess prairies | − | − | − | − | + | + | + |
| Brushland | − | − | − | − | + | + | + |
| Intense wind-deflation and wind-tidal activity | − | − | − | − | − | + | + |
| Fluvial brushland | − | − | − | − | − | − | + |
| Brush-covered bottom lands | − | − | − | − | − | − | + |
| Saline grasslands | − | − | − | − | − | − | + |
| TOTAL number of biotopes | 15 | 15 | 12 | 14 | 20 | 15 | 21 |

\+ *Biotope occurs in a particular mapping region.*

− *Biotope does not occur in a particular mapping region.*

‖ *Approximate coincidences with boundaries between biotic provinces as designated by Blair (1950): The boundary between the Houston-Galveston and the Bay City-Freeport sheets is somewhat south and west of the boundary between the Austroriparian and Texan biotic provinces. The boundary between the Port Lavaca and the Corpus Christi sheets lies southwest of the Texan/Tamaulipan boundary.*

* Source: Fisher *et al.*, 1972, 1973; McGowen *et al.*, 1976a, b; Brown *et al.*, 1976 and in press.

## Ecological Problems

Ecological problems associated with exploitation of major energy resources are summarized in table 9. Geothermal resource exploitation shares many of the ecological problems of other energy systems and has some unique ones. Problems shared with petroleum-based resources include fluid spills, road construction, possible dredging and filling in wetland areas, drilling fluids and rockcuttings disposal, noise, power transmission lines, pipelines, and land areas affected by production and injection wells. Total land surface area compared to other power generating methods may be very limited principally because of the number of fields with geological characteristics suitable for exploitation. It may be necessary to construct water towers for cooling purposes, thus including aerosol drift of treatment compounds (biocides) and/or geothermal fluids to surrounding areas. Depending on the exploitation scenario, structures may be located offshore in the Gulf, in bays and estuaries, and/or on land. Solid wastes, organic pollutants, and heat and noise common to other industrial complexes will undoubtedly occur.

Unique problems associated with exploitation of geopressured-geothermal resources involve the handling of huge quantities (as much as 50,820 $m^3$/day 310,000 bbl/day) of geothermal fluids at very high temperatures (150$^{\circ}$C). Land subsidence and surface faulting may result from withdrawal of these fluids. Fluids may be very saline and possess ionic proportions different from that of seawater. In addition, the brines may contain toxic substances such as ammonia, boron, and hydrogen sulfide. The large quantities of fluids withdrawn may require that extensive surface holding ponds be constructed capable of temporarily storing fluids in the event of: (1) blowouts during drilling or well maintenance, (2) possible pipeline breaks or leaks, and (3) shutdown of generating facilities during which time brine flow might continue.

If injection of geothermal effluents is feasible, and uncontrolled spills can be prevented, then ecological impacts of geopressured-geothermal exploitation may be minimized compared to other currently effective electrical energy conversion systems, with the possible exceptions of hydroelectric and cogeneration. It appears that geopressured-geothermal energy production may be a small and relatively short-term energy source resulting in environmental problems much like those of fossil-fuel systems.

## ECOLOGICAL RESOURCES OF THE GULF COAST

The following is a summary of ecological resources of coastal Texas. These resources include both human systems and the natural ones on which they depend. Both could be affected by exploitation of geopressured-geothermal energy resources.

### Current Land Use

The predominant use of land in this coastal region is related to agriculture, petrochemicals, tourism, ports and other transportation, and manufacturing. Agriculture and related industries account for 70 to almost 100 percent of the principal land commitment. The types of agriculture vary, reflecting partially the natural ecological resources in the region. Grazing and croplands are extensive. Forestry is important inland from the Upper Texas Coast. Oil and gas fields are common throughout this zone, and major refining and distribution centers are located near Corpus Christi, Houston-Galveston, and Beaumont-Port Arthur. Corpus Christi and Houston-Galveston are important ports and Houston is a major distribution point for air traffic. Tourism is extensive, particularly on the beaches of the barrier islands of the Texas coast. The Houston-Galveston area in particular has become an important manufacturing center for a diversity of products besides petrochemicals including foods, sulfur, wood products, and other construction materials. For detailed land use maps of this region and tabulations of acreages under different uses, see Fisher and others, (1972, 1973); General Land Office of Texas, (1975); McGowen and others, (1976a) and Brown and others, (1976 and in press). Figure 7 is a generalized land use map of the Texas Coastal Zone.

## Current Aquatic Usage

The coastal waters of the Texas area form an important natural resource base for economic activities. Three economic sectors depend directly upon coastal waters: waterborne transportation, commercial fisheries, and recreation and tourism (General Land Office of Texas, 1976).

The commercial fishing industry on the Texas coast produced almost 40.14 million kilograms (88.5 million pounds) of finfish and shellfish in 1975 with a market value of $93 million (U.S. Department of Commerce, 1976). The indirect effects of this production throughout the State and the Nation total nearly $350 million per year.

## Natural Ecological Systems of the Texas Gulf Coast

Many attempts have been made at classifying ecological systems by energy relationships, environments, and biotypes (Bailey, 1976; Ketchum, 1972; U.S. Fish and Wildlife Service, 1976a). Among the most notable for the Gulf Coast are those of the Bureau of Economic Geology (Fisher and others, 1972, 1973; McGowen and others, 1976, 1976a; Brown and others, 1976 and in press), and General Land Office of Texas (1976, 1975). The study area includes four major terrestrial and fresh-water ecological and biogeographical zones (fig. 12). These zones reflect not only the present ecological distributions of species, but also their evolutionary history. The patterns are evident from studies of plants (Tharp, 1939), historic American Indian groups (Kroeber, 1939), other terrestrial vertebrates (Blair, 1950), and freshwater fishes (Hubbs, 1957). Three major North American biotas are represented. Many of the plants and animals characteristic of the New World tropics enter the southern area on the Rio Grande plain. Species characteristic of the arid southwestern deserts are present in the extreme southwestern part of the study region. Plants and animals of the eastern humid coastal plain forests occupy the eastern section. These biotas interdigitate and intermix in characteristic groupings across the study area.

Parts of four biotic provinces recognized by Blair (1950) are represented (fig. 12). The Chihuahuan province is barely represented in southwestern Starr County, Texas. It includes species that are widely distributed in the deserts of southwestern North America. The Tamaulipan is subhumid subtropical prairie brushland dominated by mesquite (Prosogis spp.) and acacia (Acacia spp.) that includes the Gulf Coastal Plain extending approximately from Mexico to Calhoun County, Texas. The Texas province to the north is a broad ecotone (transitional ecological zone) which is subhumid subtropical prairie parkland characterized by oak (Quercus spp.) and bluestem (Poaceae). It is a transition area between the semiarid grasslands to the west and the eastern mesic forest. The Austroriparian province includes humid subtropical forests of East Texas and southern Louisiana. Most of the species of this coastal plain forest region extend eastward to the Atlantic.

The above distributional pattern is exhibited by most species of fresh-water fishes. There are two major exceptions: (1) those species limited by stream divides, and (2) associations of marine and freshwater forms living in freshwaters near the coast (Hubbs, 1957). The major stream divides, which affect 35 species of fresh-water fishes in Texas, are the Rio Grande-Nueces, Nueces-Guadalupe, Brazos-Trinity, Trinity-Neches, and the Neches-Sabine.

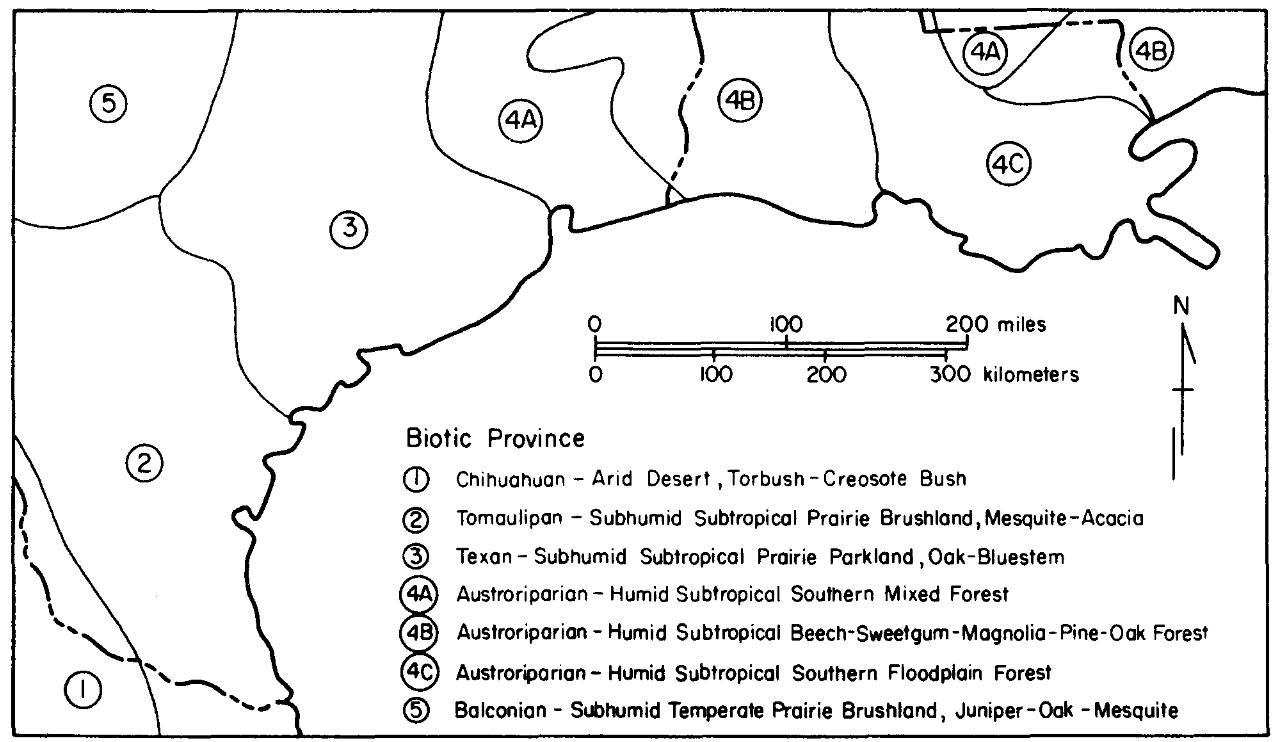


Figure 12. Biotic provinces of the northwestern Gulf Coast.

The broad biogeographic patterns illustrate not only differences in the ecological characteristics of the environments, but also genetic differences of the populations inhabiting them. When making predictions of possible environmental modifications such as those associated with energy exploitation strategies, these different areas must be considered separately. Hubbs (1957) notes that the agreement between distributions of aquatic and terrestrial species is probably based on climatological and geological factors which probably determine the properties of water. He mentions difficulties in rearing Austroriparian fishes in waters of Balconian origin which have moderate amounts of dissolved salts and proportionally more calcium, magnesium, and carbonate ions. There are similarly high mortalities of Balconian species in waters of low pH. This illustrates not only differences in ecology and physiology of species from different biogeographic areas but also the importance of ionic composition of water for fish.

## Community and Habitat Diversity

Within each of the broad ecological zones discussed, there is a considerable diversity of habitat types and biological communities. The recently published or soon to be published maps of "biological assemblages" included in the Environmental Geological Atlas of the Texas Coastal Zone include 30 different physiographic types based primarily on plant associations and geological features (Fisher and others, 1972, 1973; McGowen and others, 1976 and in press). Between 12 and 22 different "subaerial" biotypes are indicated for each of 7 mapped areas. The numbers and kinds of biotypes from the different areas may be compared in table 9. This table illustrates the relationship of this variation to the biotic provinces included. Harcombe (1974) discusses communities of Chamber County, Texas. Watson (1975) gives an account of 9 biological communities for parts of East Texas included in the Big Thicket National Preserve. Johnston (1955) contains much information on the plant associations of the southern coastal plain of Texas.

## Special Biological Resources of the Texas Coastal Zone

### Aquatic Resources

The major fish resources of the Texas Coastal Zone are described by Gustavson and others (1978). The freshwater streams, lakes, and ponds of the Texas Coastal Zone produce a wide variety of important sports fishes. The estuarine sports fishery is also an extensive and year-round activity along the Gulf Coast. It is difficult to present actual numbers for this fishery because production from coastal waters is not distinguished on the basis of catch area. Fish caught offshore, nearshore, and in the estuaries are all considered part of the coastal catch.

The commercial fishery in the estuarine waters produces mostly shellfish. Shrimp, oysters, and crabs are taken in large quantities all along the coast. Controlled fish netting (gill and trammel nets) and troutline sets are allowed in most areas and produce moderately large quantities of redfish, speckled trout, flounder, and several nongame species. Gunter (1967) states that estuarine-dependent species make up 97.5 percent of the total commercial catch of the Gulf states, and this has resulted in the regulation of fishing methods (both sport and commercial) that might result in harm to the overall fishery.

The industrial fish populations of the Gulf of Mexico have produced some of the largest landings in North America, a substantial portion of which have come from the waters of Texas. The most important of the products in terms of dollar value are the shrimp. Table 9 gives an indication of the total nursery areas contained in the Gulf Coast by state and the average annual shrimp catch. Shrimp productivity is dependent on the availability of coastal marshes which function as a nursery, refuge, and food source. The habitat requirements of juvenile shrimp have been discussed by Gunter (1961), Barrett and Gillespie (1975), and Gaidry and White (1973). The importance of salinity and freshwater runoff in the production of penaeid shrimp are reviewed by Gunter and Edwards (1969), Gunter and others, (1964), Zein-Eldin and Griffith (1969) and Copeland and Bechtel (1974). Aldrich (1964), Zein-Eldin and Griffith (1969), Williams (1960), and Copeland and Bechtel (1974) have discussed the temperature relationships for penaeid shrimp.

The major finfish exploited commercially is the Gulf menhaden (Brevoortia partonus). It has been reported to support the largest commercial fishery in North America (Reintjes and Pacheco, 1966). Gunter and Christmas (1960) reviewed the Menhaden fishery and found that approximately 30 percent of the production came from Texas. In addition to the Menhaden fishery there is an industrial bottom fishery which is relatively new to the northern Gulf (Thompson, 1959a, 1959b, 1959c, and Roithmayr, 1965). Dunham (1972) conducted a study of commercially important estuarine-dependent industrial fishes. It has been estimated that over 90 percent of the total commercial catch of finfish and shellfish in the Gulf of Mexico is estuarine-dependent (Louisiana Wildlife and Fisheries Commission, 1971).

Terrestrial Resources

Terrestrial biologic resources along the Texas Coast, including upland game birds, migratory water fowl, marsh birds, non-game birds, game animals,

Table 9. Acres of marshes, estuarine waters, and shrimp catch (heads-on) by states.*

| | *ACRES* | | | *POUNDS* |
|---|---|---|---|---|
| | *Estuarine Waters* | *Coastal Marshes* | *Mangrove Swamps* | *Average Annual Shrimp Catch 1965-1974* |
| **West coast of Florida** | 2,081,525 | 528,528 | 393,160 | 26,578,000 |
| **Alabama** | 397,353 | 34,614 | -- | 14,035,000 |
| **Mississippi** | 500,379 | 66,933 | -- | 8,063,000 |
| **Louisiana** | 3,378,924 | 3,900,000 | -- | 73,547,000 |
| **Texas** | 1,344,000 | 486,400 | -- | 83,744,000 |

*From Barrett and Gillespie (1975).

and fur-bearers are described by Gustavson and others (1978) and by Wolfe and others (1974).

## Unique, Rare, or Endangered Species

There are 228 species of plants and animals known from the coastal region which are rare and/or in danger of extinction. These include 154 plant species and 74 species of vertebrates (Blevins and Novak, 1975; Rare Plant Study Center, 1974; Texas Organization for Endangered Species, 1975).

## Data Sources for Biological Resources

Adequate, good-quality data describe current land use, aquatic usage, natural ecological systems, biotic provinces, habitats, biological communities, aquatic resources, terrestrial resources and unique, rare, or endangered species of the Gulf Coast. Some of the data, however, are regional in scope and may not be exactly suited to site specific studies.

For example, biologic-assemblage maps are available from the Bureau of Economic Geology, but they are published at a scale of 1:250,000. Consequently, they serve as excellent guides to the biologic assemblages of a site but are not intended to replace on site mapping of habitats and biologic assemblages. Several lists of rare, endangered, or unique species are available, but species are listed by counties. Maps of their preferred habitat and known range, especially for the smaller species, are not available.

Data pertaining to local biological resources should be obtained from each geopressured-geothermal test site. These efforts are currently under way or completed for four geopressured-geothermal test well site in Brazoria, Kenedy, DeWitt, and Colorado Counties in Texas (White and others, 1978; Gustavson and others, in preparation).

# POTENTIAL EFFECTS OF GEOTHERMAL ENERGY EXPLOITATION ON THE ECOLOGY OF THE TEXAS-LOUISIANA GULF COASTAL REGION

Consideration of possible environmental impacts of geopressured-geothermal energy exploitation at this time is somewhat speculative because of several unknown or undecided factors. Complete water analyses are not available for geopressured fluids, several potential locations of fields in different coastal environments are being considered, and several alternative thermal-electric conversion technologies are possible.

## Geothermal Exploitation Activities Likely to Cause Alteration or Destruction of Habitats

Many different activities associated with exploitation of geopressured-geothermal resources can potentially alter or destroy habitats. These include the construction and maintenance of industrial facilities, waste management activities, secondary energy-use facilities, land subsidence (unintentional), and several possible unusual hazards. These activities are briefly described in the introduction and more completely described in Gustavson and others, (1978).

### Construction and Maintenance of Facilities

All of these structures replace whatever habitat existed prior to their construction.

#### Cooling Systems

Effects of cooling systems on ecosystems may result from release of chemical effluents, demands on local water supplies, release of heat, release of water vapor, and the construction of canals, pipelines, or cooling structures (Shinn, 1976).

Large withdrawals of fresh, brackish, or sea water from natural sources for use in cooling structures could interfere with habitat requirements such as patterns of flow, water depth, or temperature, and might result in increased salinities in down-drainage water resource areas (Copeland, 1974). Brungs (1976) contains extensive information on the effects of chlorinated cooling water on aquatic life.

Spill holding ponds

Even though deep-well injection of spent geopressured fluid wastes may be feasible, it appears that it would be necessary to construct holding ponds capable of retaining up to 5,000 $m^3$ (30,000 bbl/day) to mitigate effects of an uncontrolled flow which might result from a blowout or breakdown of the pipeline or injection system. The amount of time that might be required for a shutdown of the geopressured fluid flow during a system failure or a large-scale uncontrolled spill is not known.

Waste Disposal Problems

Geothermal brines

The chemical composition of geopressured-geothermal brines is not completely known. The problems of understanding the effects of geothermal brines released to the ecosystem cannot be fully understood until complete analyses of geothermal brines are available. Analyses of fluids from geopressured sediments are now in progress at the U.S. Geological Survey, Menlo Park, California (Kharaka, personal communication) and the Bureau of Economic Geology, The University of Texas at Austin. A general knowledge of the concentrations and distributions of major ions is available (fig. 8). It should be noted that these concentrations and distributions will probably vary from site to site, and possibly from well to well, along the Gulf Coast. Except for the data of Kharaka and others (1977), and Gustavson and Kreitler (1976), we have only limited analyses of trace elements for geopressured waters (table 10).

The most probable method of disposal of geopressured-geothermal waters is injection into deep permeable geological formations. There are few data available on the capacity of such reservoirs to accept large-scale long-term injection of such fluids (Underhill and others, 1976; Gustavson and Kreitler, 1976). Wood (1973) stated that the use of waste-injection wells is a much smaller threat to the environment and to ground water than is the improper surface disposal of such wastes. Problems that may arise as a result of injection procedures include the displacement of brines already present in the formation which may flow to the surface or to fresh aquifers along faults or through abandoned test holes or old wells that have been destroyed by corrosion. Also, excessive injection pressure may fracture confining beds and permit geothermal waste fluids to flow into other aquifers (Wood, 1973). These problems have been addressed by Muehlberg and Shepard (1975) in their consideration of a possible geopressured site in Willacy County, Texas.

The possible release of brines into surface environments is a major concern, although the probability of a large, long-term release is very slight. Release of brines could occur from a variety of sources including flooding of canals that might be used to transport waste effluents; leakage, rupture, or overflow of brine holding ponds; leakage or blowouts from production wells; spills associated with various types of failure of the electrical generating system; failure associated with technology used to remove methane from brines; spills associated with injection wells;

## Table 10. Chemical composition of selected formation waters from the Texas Gulf Coast.*

| | Sample Number 76GG17 | 76GG58 | 76GG63 |
|---|---|---|---|
| Well number | Gardiner #1 | May Owens #1 | Portland #A-3 |
| Field | Chocolate Bayou | East White Point | Portland |
| County | Brazoria | San Patricio | San Patricio |
| Production zone | Lower Weiting | Owens | Morris |
| Perforation interval *m* | 3,588-92 | 3,138-55 | 3,511-6 |
| **Fluid production rates** | | | |
| Oil and condensate *$m^3$/day (barrels/day)* | 2.1 (13) | 3.0 (19) | 4.8 (30) |
| Water *$m^3$/day (barrels/day)* | 48 (301) | 1.3 (8) | 7.5 (47) |
| Gas *1,000 $m^3$/day (1,000 $ft^3$/day)* | 2.7 (96) | 14.5 (513) | 25 (882) |
| **Temperature** | | | |
| Measured °C | 129 | 112 | 126 |
| Quartz °C | 128 | 84 | 130 |
| Na-K-Ca °C | 124 | 100 | 120 |
| Original bottom hole pressure *$10^6$ kn/$m^2$ (psi)* | 172 (7,589) | 188 (8,333) | 191 (8,455) |
| **Chemical composition** *mg/l* | | | |
| TDS *calculated total dissolved solids* | 68,000 | 24,900 | 17,800 |
| Na | 24,000 | 9,250 | 6,500 |
| K | 300 | 70 | 68 |
| Rb | 0.80 | 0.30 | 0.30 |
| $NH_3$ | 26 | 11.0 | 5.8 |
| Mg | 235 | 31 | 15 |
| Ca | 2,000 | 200 | 89 |
| Sr | 380 | 25 | 7.0 |
| Fe | 8.0 | 70 | 2.3 |
| Mn | 2.7 | 1.4 | 0.16 |
| Cl | 40,500 | 14,000 | 9,270 |
| $HCO_3$ *field titrated alkalinity* | 520 | 1,200 | 1,600 |
| $SO_4$ | 0.6 | 22 | 84 |
| $H_2S$ | 0.32 | -- | -- |
| $SiO_2$ | 87 | 34 | 93 |
| B | 30 | 24 | 62 |
| pH | 6.3 | 6.7 | 6.8 |

*From Kharaka, Callender, and Wallace (1977).

discharge of cooling water (if geothermal water were used as a coolant); discharge of brines into terrestrial, fresh-water, estuarine, or marine systems; or problems associated with the disposal of pipeline scalings.

Even with injection, the possibility of spills exists. Temporary surface storage may be necessary at various times during the normal plant operations or during an injection system shutdown. During these periods, geothermal brines would be retained in holding ponds.

Potential biological effects of brines

Potential problems associated with storage of the spent fluids in holding ponds include damage to local terrestrial plant life and disruption of animal behavior patterns in the immediate area. Marked effects might result from spills outside holding pond areas (e.g. pipeline ruptures). If brines escaped to fresh-water areas, there might be severe salinity problems for organisms intolerant of increased salinity, and toxic compounds may also be present (boron, ammonia, etc.). Downstream drainage areas may be affected, including estuarine and marsh habitats (especially those that contain important nursery grounds for sensitive juvenile stages of organisms). Included in these salinity problems are unusual ionic ratios. Critical aspects of a brine spill are its location and the amount of time required to shut down the system.

The impacts of a geothermal brine spill may include an initial kill of local aquatic life because of osmotic, thermal, or other toxic stress, followed by long-term, possibly chronic effects of gradual dissipation of elevated levels of salinity, heavy metals, and other geothermal compounds. Natural ecological systems that receive such brines are modified in a number of ways which affect water circulation systems, osmotic regulation of aquatic organisms, water stratification, specific heat, hydrogen ion balance, buffer systems, solubility of oxygen, turbidity, and ion balance. Such changes result in low species diversity and in destruction of bottom communities and soil structure (Moseley and Copeland, 1974). Effects of brine pollution are beginning to be understood from studies of salinas, natural hypersaline lagoons, and brine polluted communities. Very few organisms are capable of adapting to the high salinities, strange chemical balances, and varying inputs of brine waters.

Effects of salinity on organisms

Even the most tolerant plant species are able to withstand natural marine salt concentrations of only about 50,000 ppm. Fresh-water marsh species have much lower tolerances. Tables 11 and 12 indicate some of the tolerance ranges of typical plant species found in coastal Texas and Louisiana. The upper limits of salinity that halophytes can tolerate vary with rapidity of the change, duration of change, and temperature factors (Waisel, 1972). Hoese (1967) states that the Gulf salt marsh system based on Spartina alterniflora would probably be destroyed by salinities which approached or exceeded 50,000 ppm. In addition, plant species are extremely sensitive to ionic imbalances. Effects of a geopressured brine spill on terrestrial plant communities, natural or agricultural, could be severe. Although we know of no research on the effects of geopressured brines per se, there is considerable literature on the effects of general salinity and of particular substances present in geopressured fluids on terrestrial plants. (Effects of ions, elements, and compounds know to occur in geopressured fluids are summarized in Gustavson and others, 1978.) Studies of salinity effects on terrestrial plants and soils have been concerned principally

Table 11. Salinity tolerances of some typical plant species found in coastal Texas and Louisiana. Plant salinity ranges from Palmisano (1970) unless noted otherwise.*

| Species | Common name | Bay or marsh type where normally found | Salinity Low | Salinity High | Average |
|---|---|---|---|---|---|
| *Halodule Wrightii* | Shoal-grass | Brackish-Hypersaline | 1,000[1] | 60,000[1] | -- |
| *Ruppia maritima* | Widgeon-grass | Brackish-Hypersaline | 0[2] | 45,000[1] | 25,000[3] |
| *Cymodocea filiformis* | Manatee-grass | Salt; Brackish | 10,000[2] | 40,000[2] | -- |
| *Thalassia testudinum* | Turtle-grass | Salt; Brackish | 10,000[2] | 50,000[2] | 30,000[4] |
| *Halophila Engelmannii* | Halophila | Salt; Brackish | 23,000[5] | 37,000[5] | -- |
| *Spartina alterniflora* | Cordgrass | Salt | 5,500 | 40,000 | 16,100 |
| *Distichlis spicata* | Saltgrass | Salt; Brackish | 5,000 | 50,000 | 14,200 |
| *Juncus Roemerianus* | Black Rush | Salt; Brackish | 1,000 | 45,000 | -- |
| *Scirpus robustus* | Salt-marsh Bulrush | Brackish | 6,000 | 39,000 | -- |
| *Spartina patens* | Saltmeadow cordgrass | Intermediate; Brackish | 0 | 39,000 | 9,600 |
| *Scirpus Olneyi* | Olney Bulrush | Intermediate; Brackish | 5,000 | 17,000 | 9,200 |
| *Alternanthera philoxeroides* | Alligator-weed | Intermediate | 0 | 15,000 | 1,400 |
| *Phragmites communis* | Common Reed | Intermediate; Fresh | 0 | 20,500 | -- |
| *Vigna repens* | Wild Cowpea | Intermediate; Fresh | 2,000 | 12,000 | -- |
| *Sagittaria falcata* | Sythefruite Arrowhead | Intermediate; Fresh | 0 | 9,500 | 2,300 |
| *Cladium jamaicense* | Jamaica Saw-grass | Fresh | 0 | 3,000 | -- |
| *Panicum hemitomon* | Maidencane | Fresh | 0 | 1,000 | 900 |
| *Eichornia crassipes* | Water-hyacinth | Fresh | 0 | 500 | -- |

[1] Simmons (1957) [3] McMillan and Moseley (1967)
[2] McMillan (1974) [4] Zieman (1975)
[5] Approximate averages from various literature

*Names after Correll and Johnston (1970).

**Table 12. Soil moisture salinity tolerances of various agricultural crops.***

| Crop | Year Mg/l (ppm) 1946 | 1947 | 1948 | Future limit |
|---|---|---|---|---|
| Spring barley (grain) | 13,300 | 3,200 | 15,000 | 10,000 |
| Sugarbeet (sugar) | 7,300 | 1,500 | 9,000 | 7,000 |
| Mangels (dry substance) | -- | 2,500 | 7,500 | 6,500 |
| Oats (grain) | 10,600 | 2,200 | 6,000 | 6,500 |
| Lucerne | > 3,000 | -- | -- | 6,000 |
| Spring wheat (grain) | 8,300 | 2,600 | 3,200 | 4,000 |
| Flax (straw) | 2,500 | -- | 4,800 | 4,000 |
| Potatoes | 3,100 | 1,100 | 4,200 | 3,000 |
| Onions | 2,500 | -- | 3,200 | 2,500 |
| Horse beans (seed) | < 3,000 | 3,400 | 3,100 | 2,000 |
| Poppy (seed) | 2,000 | 1,000 | -- | 1,500 |
| Peas (seed) | 600 | 600 | 600 | 600 |
| Beans–brown (seed) | 400 | 500 | 400 | 500 |
| Beans–white (seed) | -- | 400 | 400 | 400 |

*Data are for the crops grown on drained land in the Netherlands which had been flooded by marine water during World War II. The soil could be considered a light marine clay containing 0 to 6% $CaCO_3$ and a little humus (2-4%). The water table was about 1 meter below the soil surface. NaCl was measured in soil moisture in the 5-20 cm layer at the time of the sowing period in spring and from which at least 75% of a normal yield was obtained.*

*Modified from Berg (1950).

with soluble seawater-derived salts of which the main ionic constituents are chloride, sodium, sulfate, magnesium, calcium, potassium, bicarbonate, and bromide (table 12). Salinity tolerances of several common Gulf Coast animals are given in table 13.

The concentrations of 20 substances in geopressured brines and suggested ambient limits of concentration in biological and industrial environments are summarized in table 14. The concentration of at least 13 of these substances are above recommended standards for drinking water in at least one of the geopressured samples: silica, calcium, magnesium, strontium, copper, iron, manganese, sodium, potassium, ammonia, bicarbonate, chloride, and lead. Sixteen exceed standards for some terrestrial freshwater or marine organisms including beryllium, boron, cadmium, hydrogen ion (pH), and hydrogen sulfide in addition to the above substances, except perhaps strontium and lead. Concentrations of at least eight substances exceed some maximum industrial economic limits: silica, calcium, manganese, strontium, sodium, bicarbonate, sulfate, and chloride. These limits are suggested by the U.S. Environmental Protection Agency (EPA, 1976) and/or McKee and Wolf (1963). Concentrations for geothermal water samples refer to undiluted wellhead concentrations--not to concentrations that might result from processing dilution, concentration, or mixing after potential release to natural bodies of water.

We have no specific data on organic compounds present in geopressured fluids other than methane ($CH_4$). Future analyses should include organics--particularly the cyclic compounds and other toxic substances known from crude oil such as ethylene sulfide.

Table 13. Natural salinity tolerances for some species of coastal Texas and Louisiana animals. Some of the figures may represent salinity preferences rather than tolerances.

| Species | Common Name | Salinity Range (ppm) Low | High | Preference | Source |
|---|---|---|---|---|---|
| *Menippe mercenaria* | Stone Crab | | 35,000 | | Simmons (1957) |
| *Rangia cuneata* | Marsh Clam | 0 | 24,900 | | Perret *et al* (1971) |
| *Crassostrea virginica* | American Oyster | 10,000 | 30,000 | | Gunter (1967) |
| *Thais haemastoma* | Oyster Drill | 1,700 | 25,900 | >15,000 | Perret *et al* (1971) |
| *Penaeus setiferus* | White Shrimp | 25,000 | 45,000 | <45,000 | Simmons (1957) |
| | | 0 | 30,000 | | Lindall *et al* (1972) |
| | | 15,000 | 30,000 | | Gosselink *et al* (1976) |
| *Penaeus duorarum* | Pink Shrimp | | 69,000 | | Simmons (1957) |
| | | 15,000 | 25,000 | | Gosselink *et al* (1976) |
| *Penaeus aztecus* | Brown Shrimp | 0 | 69,000 | | Lindall *et al* (1972) |
| | | 15,000 | 28,000 | | Gosselink *et al* (1976) |
| *Palaeomonetes vulgaris* | Grass Shrimp | 25,000 | 45,000 | <45,000 | Simmons (1957) |
| *Palaeomonetes pugio* | Grass Shrimp | 25,000 | 45,000 | | Simmons (1957) |
| *Palaeomonetes intermedius* | Grass Shrimp | 20,000 | 60,000 | | Simmons (1957) |
| *Callinectes sapidus* | Blue Crab | 20,000 | 60,000 | | Simmons (1957) |
| *Brevoortia patronus* | Largescale Menhaden | 20,000 | 60,000 | | Simmons (1957) |
| | | 500 | 54,300 | | Renfro (1960) |
| *Dorosoma cepedianum* | Gizzard Shad | 100 | 41,300 | | Renfro (1960) |
| *Anchoa mitchelli* | Bay Anchovy | | 80,000 | <50,000 | Simmons (1957) |
| | | 6,000 | 30,000 | | Gosselink *et al* (1976) |
| *Cyprinodon variegatus* | Sheepshead Minnow | 5,000 | 75,000 | | Simmons (1957) |
| | | 5,000 | 28,000 | | Gosselink *et al* (1976) |
| *Cynoscion arenarius* | Sand Trout | | 45,000 | <45,000 | Simmons (1957) |
| | | 15,000 | 26,000 | | Gosselink *et al* (1976) |
| *Cynoscion nebulosus* | Spotted Seatrout | 25,000 | 75,000 | <60,000 (young) | Simmons (1957) |
| | | 19,000 | 27,000 | | Gosselink *et al* (1976) |
| *Leiostomus xanthurus* | Spot | | 60,000 | <50,000 | Simmons (1957) |
| | | 8,000 | 27,000 | | Gosselink *et al* (1976) |
| *Micropogon undulatus* | Atlantic Croaker | | 70,000 | | Simmons (1957) |
| | | 15,000 | 30,000 | | Gosselink *et al* (1976) |
| *Mugil cephalus* | Striped Mullet | 1,400 | 75,000 | <45,000 (spawn) | Breuer (1957) |
| | | 15,000 | 27,000 | | Gosselink *et al* (1976) |
| *Mugil curema* | White Mullet | 25,000 | 50,000 | <40,000 | Simmons (1957) |
| | | 25,000 | 36,000 | | Moore (1973) |

Table 14. Concentrations of 20 substances in geopressured brines and suggested ambient limits in biological and industrial environments.*

| Element, ion, or compound | *Geopressured formation waters*: Gardiner Well #1 | Mayo Owens Well #1 | Portland Well #A3 | W.F. Lehman Well #1a | Lehman Gas Unit #1a | LR-67-01-802 | Maximum safe limit in domestic water supplies | Maximum economic limit in industrial water supplies *(ppm)* | Maximum safe limit in irrigation water supplies or aquatic environments |
|---|---|---|---|---|---|---|---|---|---|
| Silica ($SiO_2$) | 87 | 34 | 93 | 68 | 71 | | 50 (turbidity problems) | 0.3-40.0 (boiler feed); 0.1 (turbine blades); 20-100 (pulp and paper mills) | 10-50 suggested limit |
| Calcium (Ca) | 2,000 | 200 | 89 | 71 | 52 | | 30 (drinking and cooking) 75-200 maximum limit | 10-500 | Often desirable for irrigation, depending on soil type |
| Magnesium (Mg) | 235 | 31 | 15 | 90 | 110 | | 30-125 0.05 mg/l recommended | 5-300 | 24 to protect underground water basins |
| Strontium (Sr) | 380 | 25 | 7.0 | 126-252 | 38-72 | 95 | ~30 (drinking and cooking) 75-200 maximum limit | ~10-500 | |
| Copper (Cu) | | | | 0.17-0.38 | 0.11-930 | 0.01 | 1.0 | | 0.0018-7.5 depending on species and conditions |
| Iron (Fe) | 8.0 | 70 | 2.3 | 8.4-16.8 | 2.7-3.8 | 16 | (0.3)[1] | | 1.0 freshwater |
| Manganese (Mn) | 2.7 | 1.4 | 0.16 | ND | ND | <0.02 | (0.05)[1] | | 0.2 for irrigation water on acid soils 0.1 for protection of consumers marine molluscs |
| Sodium (Na) | 24,000 | 9,250 | 6,500 | 16,000 | 14,000 | | Harmful to humans suffering from cardiac, renal and circulatory disease 10-115 is conservative limit | 50 | 106-212 in sprinkler irrigation may cause serious foliage damage Cumulative deterioration of soil likely 2,000 limit for livestock water |
| Potassium (K) | 300 | 70 | 68 | 230 | 150 | | 1,000-2,000 extreme limit for drinking | | Essential in small quantities for stock and plant nutrition |
| Rubidium (Rb) | 0.80 | 0.30 | 0.30 | | | | | | 1.4-100 freshwater |
| Ammonia ($NH_3$) | 26 | 11 | 5.8 | | | | | | Toxic to fish 0.02 freshwater |
| Bicarbonate ($HCO_3^-$) | 520 | 1,200 | 1,600 | 526 | 581 | | 0-150 desirable or permissible | 100-200 | 200 causes decline of sugar in apples and pears |
| Sulfate ($SO_4^=$) | 0.6 | 22 | 84 | 30 | 30 | | 200-400 | 20-300 | 576-960 maximum limit may cause precipitation of calcium and, thus, toxicity |
| Chloride ($Cl^-$) | 40,500 | 14,000 | 9,270 | 25,000 | 21,000 | | Harmful to humans with heart and kidney disease; 5-600 depending on climate and other factors USPHS recommended limit is 250 | 20-1,500 | 1,500-3,000 limit for livestock watering |
| Beryllium (Be) | | | | 0.13-0.26 | 0.11-0.22 | | ? | | 0.011-1.100 freshwater; 0.1-0.5 for irrigation depending on soil type |
| Boron (B) | 30 | 24 | 62 | | | | Total at 5-45 grams in drinking water OK | | Deleterious for certain crops at the following concentrations: • In excess of 0.5: pecans, artichokes, plums, pears, apples, cherries, grapes, peaches, oranges, avocados, grapefruit, and lemons • 1.0-2.0: potatoes, tomatoes, peas, wheat, corn, oats, and lima beans • 2.0-4.0: asparagus, date palms, sugar beets, alfalfa, onions, turnips, cabbages, lettuce, and carrots |
| Cadmium (Cd) | | | | | | 0.008 | 0.01 | | 0.0004-0.012 freshwater; 0.005 marine |
| Lead (Pb) | | | | | | <0.2 | 0.05 | | 0.0052-560.0 fish, depending on species and conditions |
| Hydrogen sulfide ($H_2S$) | 0.32 | ND | ND | | | | | | 0.002 freshwater and marine |
| pH (acidity) | 6.3 | 6.7 | 6.8 | | | | 5-9 | | 6.5-9.0 freshwater; 6.5-8.5[2] marine |

[1] based on aesthetic criteria [2] . . . but not more than 0.2 units outside normally occurring range.

*Data on brines are from Kharaka, Callender and Wallace (1977), Gustavson and Kreitler (1976), and unpublished data of the Bureau of Economic Geology, University of Texas. Suggested ambient units are from McKee and Wolf (1963) and U.S. Environmental Protection Agency (1976).

Data availability on effects of geothermal brines

Gustavson and others (1978) have reviewed the known effects of specific components of geopressured brine and of total salinity on organisms. The literature that deals with these subjects is substantial. What is not clearly understood are the synergistic effects that may result when organisms are placed in contact with brines containing all of these components in a variety of concentrations. Furthermore, little is known of how toxic trace elements are transmitted through the food networks of the Gulf coastal region.

Thermal Discharge

Like all other thermal electric generating plants, geothermal power plants produce large amounts of hot wastewater. Geothermal generating plants yield a greater amount of waste heat per unit of electrical energy produced than do fossil-or nuclear-fueled plants because the temperature and pressure (hence the enthalpy) of natural steam is much lower than that of steam produced in a boiler (U.S. Department of the Interior, 1976). If spent geothermal brines are discharged into holding ponds, a large amount of additional heat may be added to the local environment.

Heat affects the physical properties of water such as density, viscosity, vapor pressure, and solubility of dissolved gases. Consequently, such processes as settling of particulate matter, stratification, circulation, and evaporation can be influenced by changes in temperature. Because solubility of oxygen in water decreases as temperature increases, thermal pollution reduces the oxygen resource. Clark (1974) has stated the following areas of concern for thermal pollution in coastal environments:

(1) Heat affects the rate at which chemical reactions progress, and it can speed the formation of undesirable compounds or change dynamic equilibria. It affects biochemical reactions, and higher biochemical rates can result in a more rapid depletion of the oxygen resource.

(2) Physiological processes such as reproduction, development, and metabolism are temperature dependent. The geographic ranges of many species of fishes and the species composition of communities are governed to a great extent by environmental temperature. Temperature anomalies also can block passage of anadromous fish, greatly reducing future populations.

(3) Thermal pollution affects other aquatic organisms such as plants, the benthos, and bacterial populations. Increased temperatures may reduce the number of species to nuisance conditions.

Potential effects of discharge of geothermal heat into the atmosphere and surface waters of Texas are of concern. Greatest impacts would be on the aquatic ecological systems. Since these systems have been studied extensively, no additional impact studies are recommended. Effects on terrestrial systems are not as well-documented, possibly because of the subtle nature of these impacts. An obvious possible effect of thermal pollution is an immediate kill, but less obvious sublethal effects may pose greater risks because they can have far-reaching effects on entire populations. These include seasonal distribution patterns, growth effects, reproductive timing and success, metabolic regimes, and so forth. Holland and others (1971) found that mortality in blue crabs (Callinectes sapidus) was directly related to temperature above 30°C, and the upper incipient lethal temperature for juveniles was 33°C. Galloway and Strawn (1975) found that fish diversity indices in a hot-water discharge area of an electric generating station in Galveston Bay, Texas, declined above 35°C. Temperatures lower than lethal levels may result in stimulation of growth and reproduction in the cooling system and thermal plume of a power plant during the seasons when ambient water temperature is less than optimum, but growth, reproduction, and survival are reduced when the elevated temperatures become excessive. Additional problems may arise when organisms are utilizing the warm waters during the cold months and the effluent is shut down. The refuge becomes a death trap under these circumstances (Lauer and others, 1975).

Edwards (1969) states that temperature appears to be of primary importance in the seasonal distribution of Texas benthic marine algae, and Thorhaug (1976) found temperature to be a critical factor in the growth and survival of the seagrass community. Subtle effects of increased temperature may be expressed as reduced ability to cope with additional stresses. Wohlschlag and others (1968) found that scope for routine activity declines at higher temperatures (near 30°C) for the pinfish (Lagodon rhomboides). In this case, if the fish were presented with an additional stress, such as an industrial effluent from which they could not escape, they might die.

Research on the effects of elevated water temperature on organisms documents the consequences that might result from release of geothermal brines.

Availability of data on thermal discharges

The literature review suggests that the effects of thermal discharges are fairly well known. Studies dealing with thermal discharges are sufficient to assess accurately the effects on the ecosystem that may result from releases of geothermal fluids.

### Subsidence

The problem of subsidence is discussed specifically elsewhere in this report. Development of the geothermal resource requires that large quantities of fluids be removed from the subsurface for utilization and disposal. Fluid removal from geopressured formations could result in formation compaction and subsidence of the land surface.

Subsidence may occur while the elevation of the ground-water table remains unchanged and would result in a relative rise in the water table. If the root systems of surface vegetation are above the water table, such changes in ground-water level can also produce changes in plant communities. Subsidence in or near coastal wetlands could result in significant environmental alterations because slight changes in land elevation lead to extensive lateral shifts in both salinity and wetland vegetation zones. Fault planes, in part at least, may control or limit subsidence (Gustavson and Kreitler, 1976). Resulting effects on natural or man-made levees could alter the normal pattern of salt-water intrusion into coastal marshes and estuaries where nursery areas may become unsuitable for species that are dependent upon fresh-water input.

## Recommended Research, Current Research and Monitoring, and Plan for Data Acquisition on Ecosystem Quality

Environmental studies dealing with the development of geopressured-geothermal resources in the Texas Coastal Zone have predicted that the major impacts to the ecosystem are likely to arise from surface disposal or accidental release of geothermal fluids, surface subsidence induced from fluid withdrawal, and from habitat loss resulting from the construction of the power plant and well field.

In view of this, the following site specific and general environmental studies are recommended. Some of these studies are already underway in Texas.

1. Site specific baseline investigations should be conducted to include habitat mapping. Down-drainage regional baseline investigations should be conducted in the general area of the site.

2. The status of endangered species at the site should be determined. These studies should include special requirements and mapping habitats.

3. Studies 1 and 2 should be repeated at reasonable intervals and all specimens, of plants, animals, etc. collected during these studies should be documented, sorted, and catalogued in museums or herbaria for future reference.

4. In addition to site specific studies, certain generic studies should be considered. Most important among these are determining the stresses placed on an ecosystem from exposure to geopressured-geothermal fluids in terms of both responses to single ions and the synergistic effects within the effluent (including ionic imbalances). Sublethal stresses are of particular importance because they may result in subtle population or community changes as well as changes in the individual organism.

5. For specific toxic trace elements an understanding of how the toxic element is transmitted through the food network or chain is necessary. A thorough understanding of where toxic elements are stored in the ecosystem should be achieved prior to disposal of geothermal fluids.

6. For wetland areas it is necessary to understand the impacts of relatively rapid subsidence potentially induced by withdrawal of geothermal

fluids. What are the kinds and rates of change that are forced on an ecosystem that is exposed to permanent increases in water depth, or that is newly exposed to temporary inundation?

Current research and data availability

The distribution of biological assemblages in the Texas Coastal Zone and South Texas is relatively well known (Fisher and others, 1972, 1973; Brown and others, 1976, 1977; McGowen and others, 1976a, b; Wermund and others, Gustavson and others). Several current or recently completed projects at the Bureau of Economic Geology provide additional information on the distribution of biological assemblages:

1. The geology of state-owned submerged lands. These lands include all coastal bays, estuaries, and lagoons from the shoreline seaward for 10.2 miles. Over 6,000 bottom samples were collected on a 1-mile grid and stained and preserved. Analyses of these samples and of 3,500 miles of high resolution seismic reflection profiles have resulted in a comprehensive series of maps of geologic structures, sediment type and size distribution, biologic assemblage distribution, organic carbon, and trace element distribution.
2. An inventory of wetlands.
3. An analysis of the historical changes of the Texas Gulf shoreline.
4. An assessment of the ecological implication of geopressured-geothermal energy development on the Texas-Louisiana Gulf Coast.

Research Plan

Site Specific Studies

Recommended site specific data acquisition for the assessment of potential environmental impacts on ecosystem quality is already underway in several areas of interest in Texas. Baseline environmental assemblages or habitat analyses and mapping have been completed for the 50 $mi^2$ areas that contain the Brazoria County and Kenedy County geopressured-geothermal fairways. Habitats of rare or endangered species have also been mapped. Additional analyses and maps describe current land use, subsidence and faults, flood potential, lithology and soils, water resources, and meteorological characteristics. As testing of these areas continues and as additional development occurs, analyses of impacts to ecosystem quality will be updated. During 1979 two additional test sites are contemplated for prospect areas in the Wilcox Formation geopressured-geothermal fairways. The environmental studies that will be performed for these areas also include habitat mapping, with special attention paid to the habitats of rare or endangered species.

Until additional test sites are identified no new site specific studies are contemplated and no additional funds are needed.

General Studies

The major problems that remain need to be addressed prior to large-scale development of geopressured-geothermal resources:

I. Brine effects on wildlife, including shell- and finfish. Determine the long-term potential for degradation of fish and wildlife populations if geopressured-geothermal fluids are released into the Gulf of Mexico. Although onshore disposal of geothermal fluids by injection is contemplated, the high cost of injection makes disposal into the Gulf of Mexico attractive, especially for near-shore or off-shore developments. Surface disposal or accidental release of geopressured-geothermal fluids is likely to degrade surface water and is likely to result in displacement, mortality, or reduced population vitality of certain species due to the uptake of heavy metals.

II. Effects of Subsidence. Determine the long-term effects of subsidence, especially in sensitive transitional environments that directly affect the fin- and shellfish industry and tourism. These are the major spawning areas for fin- and shellfish, and salt marshes which produce or feed much of the biomass along the Gulf Coast. What are the effects of increased inundation or increased water depth on these habitations? How do organisms respond to these changes in the Gulf and at what rates? A natural laboratory exists in the Gulf to study some of these effects because both areas of slow natural subsidence and rapidly man-induced subsidence have been identified.

III. Trace Element Effects on Aquatics, Fish and Wildlife. Determine the significance of trace elements including but not limited to Cu, Fe, Mn, Be, B, Cd, Pb, Zn, and As in aquatic food nets, fish, and wildlife in terms of origin, methods of transport, concentration factors, transfer rates, and the eventual storage site at each trophic level.

Cost Estimate for General Tasks--1979

| | Equipment | | Operating fund | |
|---|---|---|---|---|
| 1. Brine effects on wildlife, shell- and finfish | $ 15,000 | $ 5,000 | $ 110,000 | $ 120 |
| 2. Effects of subsidence | 10,000 | 3,000 | 60,000 | 66 |
| 3. Effect of trace elements to aquatics and wildlife | 15,000 | 5,000 | 100,000 | 120 |
| | $ 40,000 | $13,000 | $ 280,000 | $ 306 |

## SOCIOECONOMIC AND CULTURAL CONSIDERATIONS:
## IMPACTS ON COMMUNITIES

The outer Texas Coastal Plain is characterized by diverse geography, resources, climate, industry, and culture. It is richly endowed with extensive petroleum reserves, sulfur and uranium, deep water ports, an intracoastal waterway, mild climate, good water supplies, abundant wildlife, commercial fishing resources, unusual recreation potential, and large tracts of uncrowded land. The region within which geothermal or methane resources are likely to occur parallels the coast of Texas, extending inland from the coast approximately 100 miles, and covers approximately 60,000 $mi^2$. Included are approximately 2100 $mi^2$ of bays and estuaries and 325 m of beach along the Gulf of Mexico.

More than 25 percent of the State's population and more than 33 percent of its economic resources are concentrated in the outer Coastal Plain, an area including only approximately 15 percent of the State's land area. This section describes the population patterns and resources of the outer Coastal Plain and the effects on communities that are likely to result with the development of geopressured-geothermal resources. Gustavson and Kreitler (1976); Gustavson and others (1978); and White and others (1978) describe potential impacts on socioeconomic cultural resources that are likely to arise from the development of geothermal resources. Lopreato and Blisset (1977) described citizen reaction to the possibility of geothermal development and related industrial development in the Brazoria County area. Letlow and others (1976) discuss the key socioeconomic and demographic variables that may be affected by development of the resource. Adams and Holloway (1974), Barnstone and others (1974), and Blaylock and Jones (1973) describe the economic-environmental impacts of industrial expansion in South Texas.

Essentially all of the results of geothermal energy development will be similar to those experienced in conjunction with development of oil and gas resources. Major changes may arise from site preparation and development; production, transportation, storage, and disposal of fluids; production and transmission of electrical energy; and production, storage, and transportation of methane. By far the most serious environmental impacts will be from surface subsidence and fluid disposal. Positive social advantages may include expansion of the local skill levels, wages, tax base, and social infrastructure. For detailed descriptions of the Texas Gulf Coast demographic and socioeconomic variables see Pan American University (1973); Governor's Office of Information Services (1974), and Arbingast and others (1973).

Surface subsidence and faulting may have far-reaching effects on land use, man-made structures, flood potential, and marine biological communities. Differential subsidence may be expressed as surface faults and could severely damage both surface structures and buried pipelines. Low-lying coastal areas may be inundated permanently or subjected to more frequent stream and hurricane surge flooding (Brown and others, 1974). Shallow water marine and salt marsh communities may be severely stressed or eliminated locally as they become exposed to deeper water. Changes in marine, estuarine, and salt marsh ecosystems may result in serious local effects on major income sources on the Texas Gulf Coast--shell- and fin-fishing and recreational fishing.

Subsurface disposal of geothermal fluids will minimize environmental damage. However, because of our limited knowledge of the hydrology and geology of disposal aquifers the possibility of two severe impacts cannot be eliminated. Disposal of geothermal fluids into a salt-water aquifer will displace formation waters (brines) already in the pores of the rock. Displaced formation waters may then migrate up abandoned and improperly plugged wells, or up fault plains to contaminate fresh ground-water resources. Accidental releases of geothermal brines at the surface could damage surface fresh-water and coastal marine ecosystems and shallow ground-water resources.

Physical and biological alterations listed here are described in detail elsewhere in this document. However, because they have direct effects on the economy and on the "quality of life," physical and biological considerations are difficult to separate from the community concerns discussed below.

Potential effects on the community arising from geopressured-geothermal energy development are defined by Lopreato and Letlow (1976). They suggest that increasing demands will be put on the local work force, housing, schools, hospitals, and other services. The nature and pattern of existing land use could also change. The key to dealing with these problems will be community adaptability and attitudes. "Is the community"... in fact "willing to commit itself to expansion in services, to adjustment to zoning laws, to some short-term crowding of facilities, and to potential growth in general"? (Lopreato and Letlow, 1976). Although Lopreato's and Letlow's (1976) studies are not definitive, they do suggest that geothermal development in the early stages of exploration and testing will produce few positive or negative effects on the Gulf Coast communities where development occurs. They also caution that if large-scale industrial growth occurs later as a result of geothermal development, changes in the community would be large, especially in less developed areas.

## Baseline Information Sources

### Land use

Land use in the Coastal Plain of Texas has been primarily agricultural. Agriculture is highly diversified with vegetables, cotton, peanuts, flax, citrus, grain sorghum, timber, cattle, and poultry being the most important products. Production of some of these commodities is controlled by climate and soil development. Rice, which requires large quantities of water, is produced only in the eastern half of the State where precipitation is relatively heavy. Timber products are also produced in the eastern quarter of the area where soils are relatively acid and where precipitation is sufficient to support heavy timber growth. Citrus products, on the other hand, are produced only in the valley of the Rio Grande where water is available for irrigation and where the growing season is 365 days a year. Industrial development along the Gulf Coast has expanded rapidly since the discovery of petroleum early in this century. The Texas Gulf Coast contains the largest concentration of petroleum and petrochemical production and refining facilities in the country. People have caused major alterations in the natural environments of the Coastal Plain by building communities, industries, and transportation systems, by clearing and plowing land, by damming the major rivers for flood control and water storage, and by dredging natural inlets, bays, and estuaries.

Recognizing that natural resources in the Texas Coastal Plain were finite and that certain current and planned land uses within the Coastal Plain might be inappropriate, several Texas state agencies began to inventory the natural resources of the Coastal Plain. The Bureau of Economic Geology (Brown and others, 1976, 1978, in press; Fisher and others, 1972, 1973; McGowen and others, 1976a and b; Kier and others, 1977; and St. Clair and others, 1975) in part supported by the General Land Office of Texas, the Department of Water Resources, and the Houston-Galveston Area Council has provided detailed catalogues of the Land and Water Resources of the Texas Coastal Plain. The Coastal Zone Management Program developed by the General Land Office of Texas (1975) also provides a regional catalogue of physical and cultural resources of the Texas coastal region. The Texas Parks and Wildlife Commission has developed an Outdoor Environmental Plan for a major portion of the Texas coast. The Bureau of Economic Geology, under contract to the United States Fish and Wildlife Service, has provided an inventory of the biological resources of the Texas and Louisiana Gulf Coast (Gustavson and others, 1978). The Bureau of Business Research Atlas of Texas provides an inventory of industrial, agricultural, economic, and population data for the State. Because of these programs the regional distribution of physical and cultural resources on the Texas Gulf Coast is well understood.

Population

Approximately 3,860,000 people or 32 percent of the State's population live in the area of interest (U.S. Bureau of the Census, 1970, 1972). This portion of the Gulf Coastal Plain covers 44,238 $mi^2$ or approximately 16 percent of the State's area. The population origin groups in this area are basically Spanish surnamed south of Corpus Christi and old stock Anglo-American northeast of Corpus Christi. In a number of areas northeast of Corpus Christi population origin groups of Swedish, Wendish, Polish, Irish, Danish, and Afro-Americans are important. Population densities range from over 1500 persons per square mile in Harris County to less than 5 persons per square mile in Kenedy, Jim Hogg, Zapata, McMullen, and LaSalle Counties (Arbingast and others, 1973). Other important socioeconomic trends are distinguished along the coast; per capital income increases from less that $2000 near the Rio Grande to from $2500 to over $4000 in some counties in the Houston-Beaumont area. Median age increases from 20 to 25 years in the southern part of the area to 25 to 30 in the northeastern part of the area. Major growth areas along this portion of Texas are identified as Standard Metropolitan Statistical Areas: Brownsville-Harlingen-San Benito, McAllen-Pharr-Edinburg, Laredo, Corpus Christi, Galveston-Texas City, Houston, and Beaumont-Port Arthur-Orange. In the counties outside these SMSA's population has changed only slowly since the turn of the century, locally increasing or decreasing (Arbingast and others, 1973).

In the area of interest, petroleum exploration, production, and refining are major sectors of employment. The production of plastics, fertilizers, insecticides, and other organic chemicals from hydrocarbons produced along the Gulf Coast also employs substantial numbers of workers. Thus a substantial labor force with expertise in the production of hydrocarbons and its by-products exists along the Gulf Coast. Since nearly all of the activities associated with production of geothermal resources are the same as or similar to activities associated with production of oil and gas, a labor pool with ample expertise exists to produce geopressured-geothermal resources in the Coastal Plain area.

Industrial activity

Areas of major industrial activity on the Texas Coastal Plain are closely associated with major metropolitan areas; Beaumont, Port Arthur, Orange, Houston, Texas City, Galveston, Freeport, Victoria, Corpus Christi, Brownsville, Harlingen, and McAllen. Other areas along the coast support moderate but diverse industrial development. This is probably due to locally available agricultural products, livestock, poultry, fish, and energy and chemical feedstocks. The diversity of industrial development in the area of potential geopressured-geothermal resource development is shown in table 15. Many of these industries can utilize directly either the heat energy or the methane produced from geothermal resources, and all utilize electrical energy.

The contribution of some of these industries, especially smelters, refineries, and chemical plants, to air pollution in the outer Coastal Zone is significant and has resulted in most of the outer Coastal Plain being classified as regions of air quality non-attainment (see Air Quality Section).

### Agriculture

Agriculture is a major economic activity in all but 7 of the counties in the study area (Arbingast and others, 1973), the major agricultural regions of the Texas Coastal Plain. Vegetables, livestock, cotton, and flax are important commodities in the South Texas Plain. Cotton, vegetables, grain sorghum, and livestock are the major products in the Coastal Bend area. Cotton and livestock are important in the Blackland Prairie and in the Post Oak region. In the East Texas timber region timber products, poultry, and livestock are the major commodities. Along the Coastal Prairie rice, cotton, and cattle are the major agricultural products.

### Recreation

Gustavson and others (1978) report that the large coastal tourist industry depends not only on the diversity of fish and wildlife, but also on scenic views, open beaches, wetlands, and clean air and water. It has been estimated that some 750,000 Texans currently engage in recreational fishing in Texas

Table 15

Industrial plants in the outer Gulf Coastal Plain employing more than 50 workers (Arbingast and others, 1973).

| Product | Number of plants |
|---|---|
| Food and related products | 98 |
| Beverage plants | 15 |
| Breweries | 3 |
| Dairy products | 12 |
| Textile plants | 7 |
| Flour and grain mills | 18 |
| Apparel plants | 38 |
| Lumber and wood products | 46 |
| Furniture and fixtures | 25 |
| Chemicals | 162 |
| Petroleum refineries | 20 |
| Cement plants | 6 |
| Gypsum plants | 1 |
| Glass plants | 4 |
| Smelters and refineries | 9 |
| Metal can plants | 5 |
| Bottle plant | 1 |
| Non-electrical machinery | 166 |
| oil field machinery and equipment | 59 |
| Electrical equipment | 51 |
| Mobile home plants | 2 |
| Boat- and ship- building yards | 16 |
| Aircraft and parts | 7 |

coastal waters. Texans catch over 18 million kg (40 million pounds) of speckled trout (Cynoscion nebulosus), redfish (Sciaenops ocellata), drum (Pogonias cromis), and shrimp (Penaeus spp.) estimated to produce "net economic benefits" to Texas of over $19 million annually. Gunter (1967) has estimated the annual sport fishing catch of estuarine fishes of the Gulf Coast to be at least 45 million kg (100 million pounds) and perhaps greater. In addition to the sports fishery, the Texas coastal region is located in the heart of the Central and Mississippi Flyways used by a large variety of migratory birds. Fish, waterfowl, and other game animals attract thousands of hunters and sports fishers to the Gulf Coast every year. Recreation and tourism are estimated to generate $585 million annually in Texas alone.

The rivers, lagoons, bayous, estuaries, and bays of the Coastal Zone are used for surfing, sailing, swimming, sunbathing, scuba diving, water skiing, sport fishing, and motor boating. Marine recreation and tourism had an estimated 1970 market value of $14.5 billion and by far exceeded fishery and mariculture ($3.1 billion), oil and gas ($5.0 billion), and the chemical and mineral industries ($0.4 billion). Economists anticipate an increase of at least $100 million a year in national expenditures for marine recreation over the next two decades (Committee on Oceanography, 1964).

Renewable resources

The chief renewable resources in the Texas Gulf Coast are finfish, shellfish, game, fowl, and wetlands, all of which are described in the section that deals with ecosystem quality.

Nonrenewable resources

The chief nonrenewable resource of the Texas Gulf Coast is its mineral wealth. These minerals include oil and gas, uranium, lignite, sand and gravel, sulfur, salt, gypsum, and shell (St. Clair and others, 1978). Geopressured-geothermal energy in its several components--heat, pressure, and methane--may be a significant addition to the State's nonrenewable resources. As a new alternative energy resource it is of particular importance in the Gulf Coast because the oil and gas reserves there are rapidly declining.

In summary, information dealing with land use, population, employment, industry, agriculture, recreation, and natural resources along the Texas Gulf Coast are sufficient to provide a regional baseline. Letlow and others (1976) have also completed a description of the area to be affected by geothermal development and have included an analysis of baseline social and demographic data.

## Recent Socioeconomic and Demographic Research

Letlow and others (1976) have provided an analysis of baseline social and demographic data for the Texas Gulf Coast. They describe the potential local community impacts of exploration, development, and production of geothermal resources. They also survey the institutions and political groups that would be interested in or have jurisdiction over some phase of geopressured-geothermal energy development. In 1977, Lopreato and Blissett developed the methodology for and completed an attitudinal survey of citizens in the Brazoria County area where the first geopressured-geothermal test well was eventually spudded. The major results of this survey were that area residents were in favor of the development of geothermal energy. In addition, the need to provide an efficient channel to disseminate relevant information on geothermal energy development to area residents was identified.

## Future Research

Our recommendations for research and service follow the recommendations and conclusions of Letlow and others (1976) and Lopreato and Blissett (1977).

Letlow and others (1976) have concluded that initial exploration and testing phases of geothermal development are likely to produce few positive or negative effects on Gulf Coast communities. Lopreato and Blissett (1977) confirmed the need for attitudinal surveys at potential sites and for additional communication to area residents. For these reasons and because large-scale industrial utilization of geothermal energy is not likely to occur until geothermal energy becomes a proven economical resource at some future time, only two social research tasks are recommended at this time.

1. Attitudinal Survey at Site

> Before the test-bed site is finally determined, a random survey of citizens in the potential site area should be conducted. This survey would identify attitudes toward and expectations of the resource development. Public expectations of great economic benefits at little environmental cost could impede continued demonstration of geopressured-geothermal energy if the public comes to feel at some point that it has been misled. The public must understand that beneficial and detrimental aspects of the development of this alternative energy resource, including the range of possible environmental hazards. The only credible means of knowing public perception is through survey analysis......The data would allow planners to understand better the needs and orientations of the community and the constraints and limitations within which development will occur. <u>It is absolutely essential that an initial survey be conducted before announcement is made of definite site selection</u>.
>
> Following the initial baseline survey, a series of additional samples would be drawn to determine changing public perceptions as the resource is developed. Estimated time requirement for initial survey is 6 months (Lopreato and Blissett, 1977).

2. Citizen Conference

During the period when an environmental report is being conducted for the test site, a Citizens' Conference on Geothermal Development should be held in the area. All geothermal research groups might be involved as informants, with the sociocultural and institutional groups working most closely on conference organization with the citizens. A variety of interest groups should be represented, and the conference should be open to the area public. The conference would provide a mechanism for disseminating information to the public body likely to be most affected by early resource development and would offer an opportunity for input from the populace. Professional input should be energetic and yet simple enough for the layman to grasp basic technical, legal and institutional issues surrounding the potential development. An educated and involved public will be less likely to respond negatively to an innovative energy resource than would be an uninformed group (Lopreato and Blissett, 1977).

Experience with public interest at the Brazoria County Test Well Site supports this observation.

Budget

I. Attitudinal survey

| | | |
|---|---|---|
| Single survey | | $30,000 |
| Surveys at Kenedy, DeWitt, and Colorado County sites | | 90,000 |
| | TOTAL | $120,000 |

II. Citizen conferences

| | |
|---|---|
| Conferences at Kenedy, DeWitt, and Colorado County sites | $ 500 |
| Costs are not predictable but could be limited to $500 per site | 500<br>500 |
| | $1,500 |

## Geothermal Fluid Disposal

Selection of disposal sites and methods of disposal for the enormous volumes of hot saline water that will result from geothermal production are two of the most perplexing problems that have arisen in the planning for geothermal resource development. Commercially viable generating facilities will have to be supplied by 5 to 10 wells, each capable of producing 3.8 $m^3$ per minute (1,000 gallons) or about 5,500 $m^3$ (34,000 barrels [bbls]) per day (approximately 170,000 to 340,000 bbls per day for a single generating facility). Although geothermal waters may be used by other industries for other purposes after passing through the generating facility, the problem of disposal is not lessened. The responsibility for disposal is simply transferred to others.

To determine the environmental impact of geothermal fluid disposal, the following questions need to be addressed: (1) What are the physiochemical characteristics of geopressured fluids? (2) What are the characteristics of the environments that will be degraded by contact with geothermal fluids through storage, transportation, or ultimate storage? (3) What are the characteristics of subsurface disposal sites? (4) What are the environmental problems and technical problems with high volume injection of spent geothermal fluids? and (5) What is the regulatory framework in which disposal must be considered? The resolution of these questions will help identify areas for future research.

### Physiochemical Characteristics of Geothermal Fluids

Water chemistry.--Using interpretations of electrical logs, Dorfman and Kehle (1974) suggest that salinities of geothermal reservoirs are comparatively fresh (total dissolved solids [TDS] <5,000 parts per million [ppm]) and could be used for irrigation and general use with minor desalination treatment. Dorfman and Kehle (1974) reasoned that diagenetic changes of montmorillonite to illite in deep Gulf Coast sediments allow as much as 15 percent of the water contained in the muds to be expelled as fresh water, thus decreasing the salinity of adjacent sandy aquifers.

More recently, analyses of water samples from below the top of the geopressured zone have become available for 13 wells throughout Aransas, Nueces, Refugio, San Patricio, and Brazoria Counties, and for 15 wells in Kenedy County. For the samples from Aransas, Nueces, Refugio, and the San Patricio Counties, TDS ranges from a minimum of 8,000 ppm to a maximum of 72,000 ppm (fig. 13). Chloride concentration ranges from 3,500 to 46,000 ppm and sodium-plus-potassium concentration ranges from 2,000 to 20,000 ppm. For the samples from Kenedy County, TDS ranges from 18,000 to 40,000 ppm (fig. 14). For these same waters, the pH varies from 4.9 to 10 (Taylor, 1975). If these water samples, all taken within 1 km (3,500 ft) of the top of the geopressured zone, are representative of geothermal fluids salinities within the geopressured zone, then produced geothermal waters will vary from moderately saline waters to brines.

Water samples from two wells in the geopressured Chapman Ranch field, south of Corpus Christi, Texas, were analyzed for major and minor chemical constituents. Formation waters were sampled at a depth of 3,350 m (11,000 ft); pore pressures were 668 $kg/cm^2$ (9,500 psi). The samples were classified as NaCl waters with TDS of approximately 40,000 milligrams per liter (mg/l) (table 16). Semi-quantitative spectrographic analyses of these geopressured waters show boron

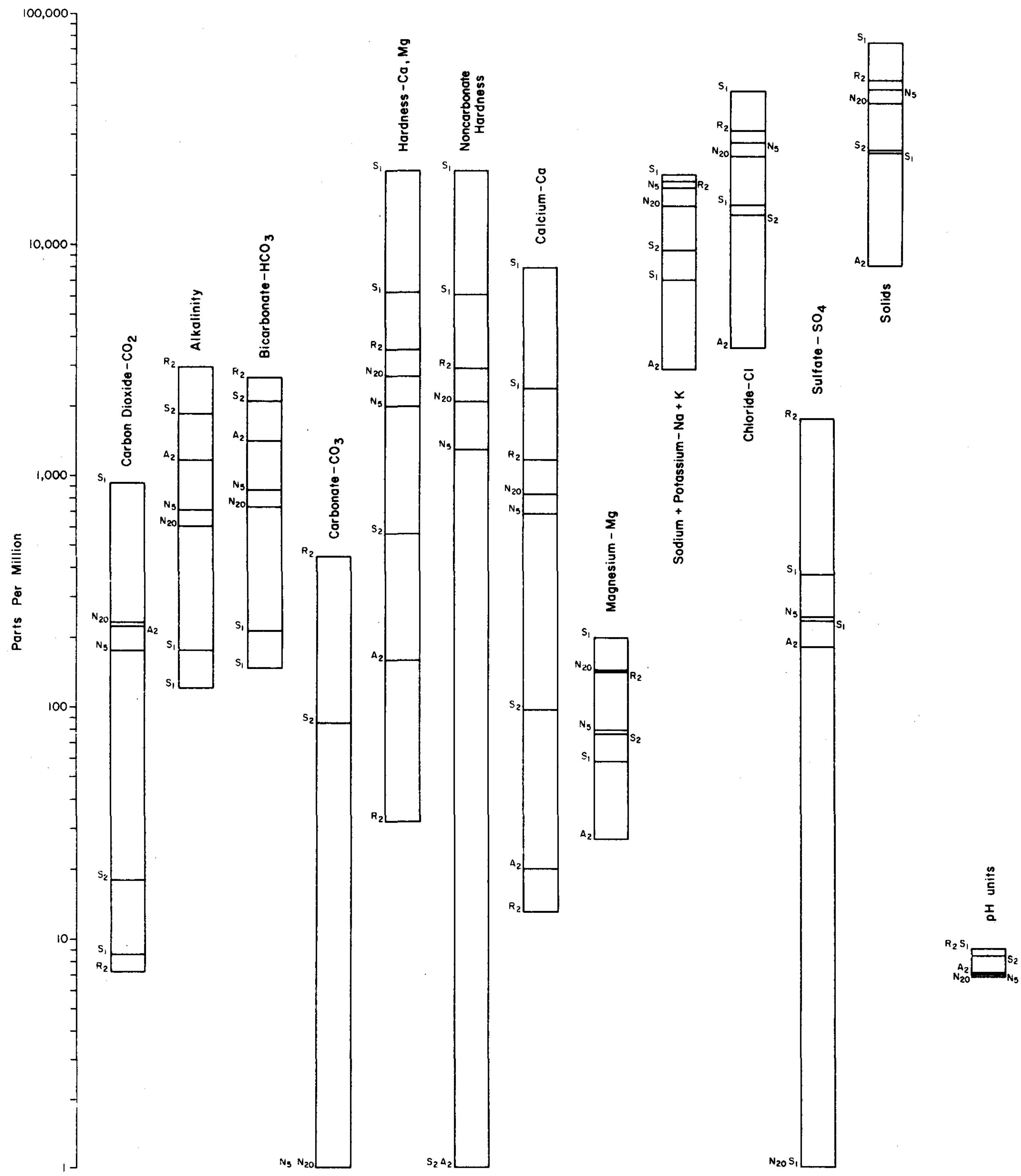


Figure 13. Analyses of waters from within the geopressured zone, (A) Aransas, (N) Nueces, (R) Refugio, and (S) San Patricio Counties (Data from Taylor, 1975).

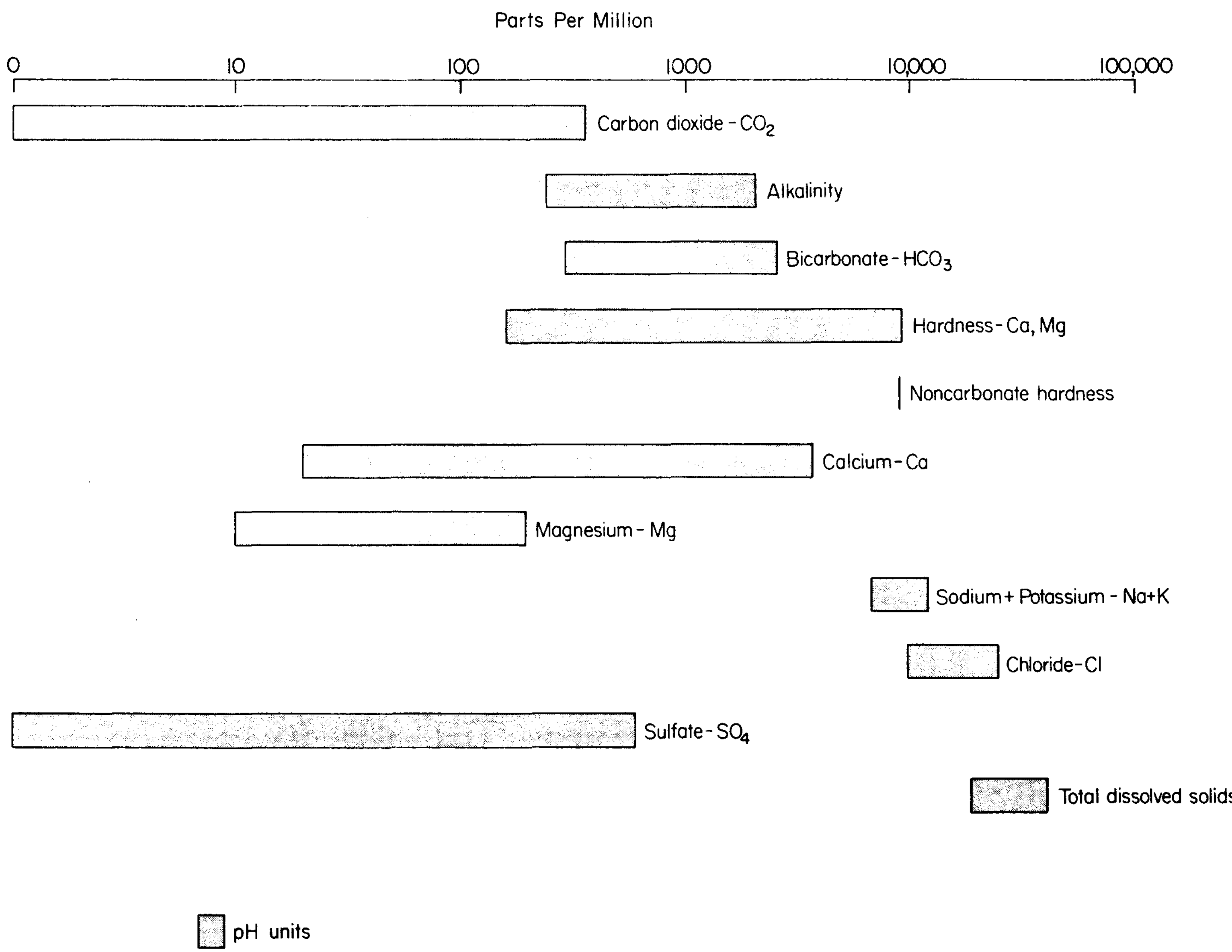


Figure 14. Analyses of water from within the geopressured zones, Kenedy County (data from Taylor, 1975).

Table 16. Chemical analyses of geopressured waters from six gas fields in Texas.

| Sample No.<br>Field<br>County | W.F. Lehman No.1<br>Chapman Ranch<br>Nueces<br>(Corpus Christi area) | Lehman Gas Unit No.1<br>Chapman Ranch<br>Nueces<br>(Corpus Christi area) | Mayo Owens #1*<br>E. White Point<br>San Patricio<br>(Corpus Christi area) | Portland No. A-3*<br>Portland<br>San Patricio<br>(Corpus Christi area) | Baer Ranch No.A-3<br>Baer Ranch<br>Matagorda | Gardener No.1*<br>Chocolate Bayou<br>Brazoria |
|---|---|---|---|---|---|---|
| TDS | 42,000 | 38,000 | 24,900 | 17,800 | | 68,500 |
| $HCO_3^-$ | 526 | 581 | 1,200 | 1,600 | 500 | 520 |
| $Cl^-$ | 25,000 | 21,000 | 14,000 | 9,270 | 21,200 | 40,500 |
| $SO_4$ | 30 | 30 | 22 | 84 | 100 | .6 |
| $Na^+$ | 16,000 | 14,000 | 9,250 | 6,500 | 13,000 | 24,000 |
| $K^+$ | 230 | 150 | 70 | 68 | 132 | 300 |
| $Ca^{++}$ | 71 | 52 | 200 | 89 | 688 | 2,000 |
| $Mg^{++}$ | 90 | 110 | 31 | 15 | 53 | 235 |
| $SiO_2$ | 68 | 71 | 34 | 93 | 132 | 87 |
| B | 25-42 | 19-38 | 24 | 62 | 97 | 30 |
| $NH_3$ | | | 11.0 | 5.8 | | 26 |
| pH | 6.3 | 6.5 | 6.7 | 6.8 | 6.0 | 6.3 |

*from Kharaka and others (1977)

concentrations ranging from 19 to 42 mg/l. These concentrations are similar to those found by Kharaka and others (1977) in other geopressured fields in Texas and Collins (1975) for Tertiary Formation waters from Louisiana. If high boron concentrations are characteristic of geopressured waters throughout the Texas coast, then this constituent alone will prevent their use in irrigation and may prevent their disposal into marine waters. Even the most boron-tolerant plants need irrigation waters with less than 3.8 mg/l boron (Richards, 1954). Trace quantities of aluminum, beryllium, copper, and iron were found in the Chapman Ranch geopressured waters. Tables 16 and 17 show the elements analyzed and their individual detection limits.

Kharaka and others (1977) observed high concentrations of boron (42-62 mg/l) and ammonia (9.8 to 26 mg/l), and moderate TDS values (17,800 to 68,500 mg/l) from geopressured horizons in the Chocolate Bayou, and E. White Point, and Portland fields.

In Louisiana, geopressured waters of the Manchester field are moderately saline (16,000 to 26,000 mg/l TDS), but less saline than overlying normally pressured waters (60,000 to 180,000 mg/l TDS) (Schmidt, 1973). In Hidalgo County in South Texas, the average salinity for a geopressured reservoir is about 25,000 mg/l TDS (Papadopulos, 1975).

Geothermal Fluid Temperatures.--The temperature distribution of fluids within the geopressured zone is imprecisely known. Data are usually limited to a single bottom-hole temperature for each well. Isothermal maps of the middle and southern Gulf Coast (Bebout and others, 1975a, 1975b) are generally conservative because of the common practice of well-bore cooling, or even icing, prior to logging to protect temperature-sensitive electronic components

Table 17. Semiquantitative spectrophotometric analyses of evaporation residual.

| Element | Concentration Range[a] (mg/l) | | Lower Level of Detection[b] (mg/l) | |
|---|---|---|---|---|
| | W.F. Lehman No. 1[c] | Lehman Gas Unit No. 1[c] | W.F. Lehman No. 1 | Lehman Gas Unit No. 1 |
| Beryllium | 0.13 to 0.26 | 0.11 to 0.22 | 0.013 | 0.011 |
| Bismuth | ND[d] | ND | .34 | .30 |
| Boron | 25 to 42 | 19 to 38 | 1.3 | 1.1 |
| Cadmium | ND | ND | 21.0 | 19.0 |
| Chromium | ND | ND | .021 | .019 |
| Cobalt | ND | ND | .13 | .11 |
| Copper | 0.17 to 0.38 | 0.11 to 930 | .034 | .030 |
| Gallium | ND | ND | .084 | .076 |
| Iron | 8.4 to 16.8 | 2.7 to 3.8 | .25 | .23 |
| Lead | ND | ND | .84 | .76 |
| Manganese | ND | ND | .63 | .57 |
| Molybdenum | ND | ND | .13 | .11 |
| Nickel | ND | ND | .13 | .11 |
| Silver | ND | ND | .042 | .038 |
| Strontium | 126 to 252 | 38 to 72 | .042 | .038 |
| Tin | ND | ND | .63 | .57 |
| Titanium | ND | ND | 1.3 | .1 |
| Vanadium | ND | ND | .21 | .19 |
| Zirconium | ND | ND | .29 | .27 |

[a]Concentration range calculated from weight percent of ROE.

[b]Lower level of detection calculated from percent sensitivity in sodium potassium matrix. (Harvey, 1964, table 2, p. 58) in ROE.

[c]Sample from portable separator at well head. Samples acidized with concentrated $HNO_3$.

[d]Not detectable.

of electrical logging sondes. Reported fluid temperatures in geothermal fairways, nevertheless, are locally in excess of 194° C (300° F). Maximum recorded bottom-hole temperatures of the Texas Gulf Coast exceed 288°C (520°F).

Geothermal fluids will probably lose only a moderate amount of heat energy while passing through the generating facility. The temperature of the disposal water will be dependent on the residence time of the fluid in storage. The longer the storage, the closer the fluid temperature will approach ambient air temperature. This temperature will be particularly important if waste waters are disposed in surface water bodies.

## Water Quality Concerns

In the process of developing geothermal resources contamination of surface-water and fresh ground-water resources must be prevented.

### Surface water hydrology

Surface water bodies constitute both fresh and saline water bodies. Contaminants are both the waste heat of the geothermal fluids and their chemical composition. Water quality in most fresh-water bodies (rivers or streams, lakes or ponds) in the Texas Coastal Zone is suitable for irrigation or human consumption after treatment. For the Nueces River total dissolved solids generally are less than 500 ppm and for the Colorado River, the TDS is generally less than 300.

Historically the storage and disposal (in evaporative pits) of saline waters from oil production has polluted surface waters in several areas of the Texas Coastal Zone. Chiltipin Creek, which drains a small basin into Copano Bay, exemplifies oil field brine contamination of a freshwater body. The creek waters contain high concentrations of calcium, magnesium, sodium, and chloride ions, with TDS as high as 39,000 ppm (fig. 15). Salinities of the creek waters vary inversely with discharge and thus are high during periods of low discharge and low during periods of high discharge; rainwater dilutes the salt concentration of waters that are apparently percolating into the stream. The pollutants in Chiltipin Creek are attributed to salt-water disposal associated with petroleum production. Chloride content fluctuates inversely with discharge, suggesting that the chloride is coming from low-flow ground-water discharge. The only recognizable source of chloride ion is abandoned salt-water evaporation pits that lie in the Chiltipin Creek drainage basin. Although the use of evaporation pits to dispose of salt water has been disallowed by the Texas Water Quality Board since January 1, 1969, water pollution has continued for 6 years since the pits were abandoned.

Other incidences of pollution of shallow ground water and streams from salt-water evaporation pits have been observed in Matagorda County (Hammond, 1969) and in the Hamlin, Texas area (William A. Trippet II, personal communication, 1975). The material lining these pits did not prevent percolation of large volumes of salt water into the substrate.

The disposal of geothermal fluids into coastal bays, estuaries, or the Gulf of Mexico has been a proposed alternative to deep well injection. The salinity of produced geothermal waters does not preclude their disposal into marine waters of the Gulf of Mexico or into certain coastal waters. Coastal waters are characterized by highly variable salinities, ranging from fresh water to hypersaline (Parker, 1960; Brown and others, 1976; Brown and others,

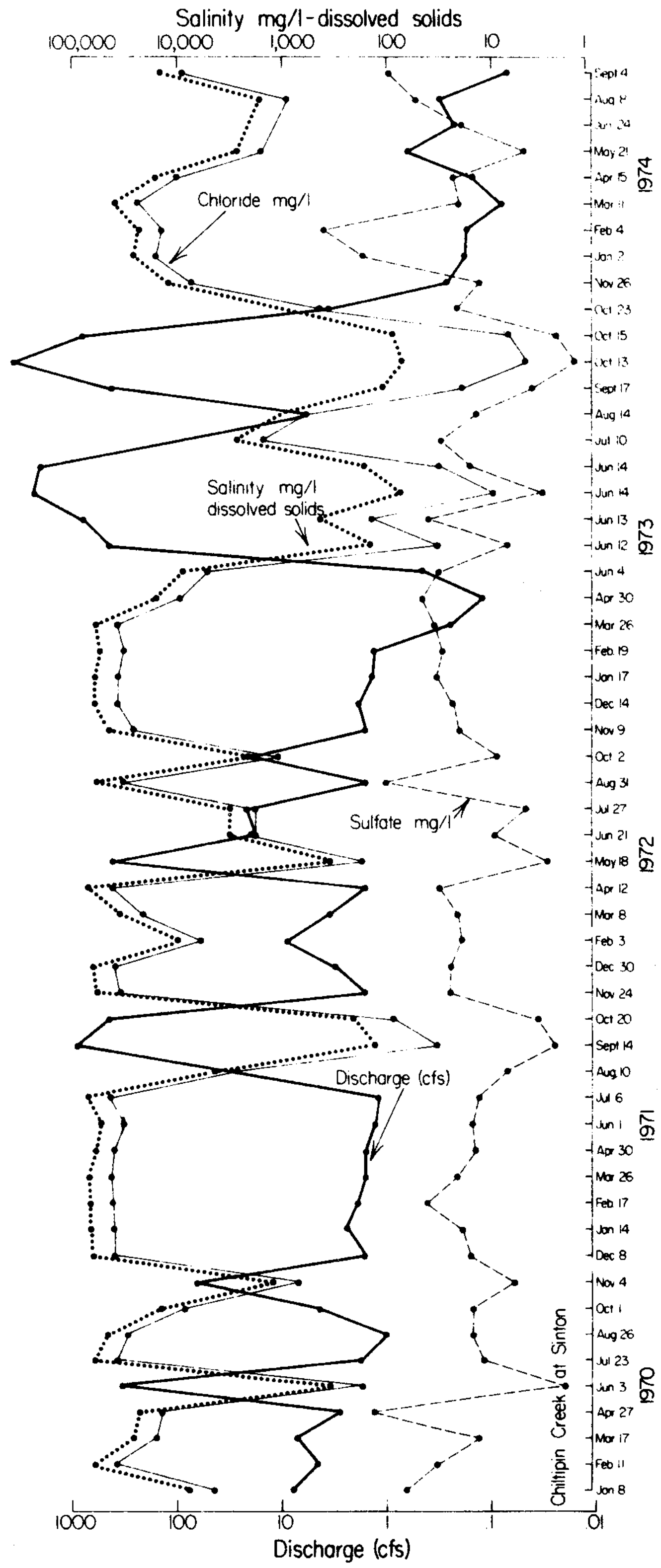


Figure 15. Chiltipin Creek contamination.

in press; McGowen and others, 1976). If saline fluids were adequately mixed in coastal water, they could have little effect on the overall salinity of the bays, lagoons, or estuaries because of the vastly greater volume of bay, lagoon, or estuarine water. Furthermore, periodic freshening of bays and estuaries by flood waters would not be significantly diminished by geothermal fluid disposal.

Though the salinities of the geopressured fluids may not be significantly different from that of sea water, the geopressured fluids may be detrimental to aquatic ecosystems because of (1) increased concentration of specific common ions, (2) increased concentrations of trace elements, and (3) differing ion ratios from sea water. For geopressured fluids $Na^+$, $Cl^-$, $Ca^{++}$, $HCO^{3-}$, $B^{+++}$ ions have been recorded in concentrations of up to 1 order of magnitude greater than sea water with $Ca^{++}$ ion concentrations sometimes an order of magnitude less than sea water. $K^+$ and $Br^-$ ion concentrations bracket their concentrations in sea water and occur in concentrations as much as one half order of magnitude more or less than their normal sea water concentrations. The normal concentration of $SO_4$-- ions in sea water is nearly 2450 ppm. In geopressured fluids concentrations may be two orders of magnitude less; several analyses indicate that $SO_4$-- ions are missing altogether (Gustavson and Kreitler, 1976).

Data on trace elements in geopressured fluids are very limited although Gustavson and Kreitler (1976) report beryllium, copper, iron, and strontium in formation fluids from the Chapman Ranch field south of Corpus Christi. Kharaka and others (1977) report traces of sulfate ion, hydrogen sulfide, rubidium, and ammonia from the Chocolate Bayou field in Texas.

Geopressured fluids are not concentrated sea water with a regular and systematic increase in all dissolved ions, but are complex solutions that are in part the result of fluid and ion migration and chemical reactions that accompany the burial of sediment and its subsequent diagenesis (Kharaka and others, 1978). Therefore, in the event that geopressured fluids are released into bays, lagoons, or the Gulf of Mexico, the fluid released cannot be simply equated to an input of concentrated sea water, for the balance of ions in geopressured fluids differs markedly from the ionic balance of normal sea water (Gustavson and others, 1978). May (1978) found that the poor survival of the Gulf Croaker (Bairdiella icistia) from the Salton Sea is related to the unusual ionic composition of that water body. The impact of effluent waters on different ionic composition and ion ratios on the Gulf's aquatic life is not known. Gustavson and others (1978) discuss these potential biologic impacts in detail.

The temperature in geothermal waters will probably be greater than 95°C (200°F) when discharged from the generating facility. These waters will require extensive cooling if they are to be disposed of into coastal waters or the Gulf of Mexico (Texas Water Quality Board, 1975). If geothermal waters are cooled to temperatures such that the maximum temperatures and temperature differentials attributable to the heated effluent remain within the regulatory guidelines, then environmental impact will be minimized. South Texas river, bay, estuarine, and Gulf waters are characteristically warm during the summer months. Surface-water temperatures can reach 43°C (111°F) in Laguna Madre and 35°C (95°F) in bays, lagoons, and estuaries (Parker, 1960). Natural temperatures of these waters equal or exceed the maximum ambient temperature, 32°C (90°F), suggested by the National Technical Advisory Committee for water-quality standards. Natural temperatures also equal or exceed the maximum ambient temperature, 35°C (95°F), suggested by the Texas Water Quality Board for tidal river reaches and bay and Gulf waters. High ambient air temperatures such as those occurring in the Corpus Christi fairway, which has a mean maximum July air temperature of 34.5°C (94°F) (Dallas Morning News, 1974), will increase the difficulty of cooling saline geothermal waters during the summer months. High ambient temperatures, suggested by regulatory agencies, will make disposal of hot saline fluids into coastal waters difficult unless they have been cooled to 35°C (95°F) or less.

The bay and estuaries of the Gulf of Mexico are the breeding grounds and nurseries for much of the fish and shellfish population of the Gulf of Mexico. The maintenance of these renewable resources is a critical environmental concern.

Potable ground water

Aquifers containing potable ground water in the Texas Coastal Zone are found in formations of Eocene to Pleistocene age and at depths shallower than 3,000 ft and more commonly less than 1,000 ft. The depth to the base of fresh water is greatest in the northeastern section of the Texas Coastal Zone and becomes progressively shallower toward South Texas (Wood and others, 1963). The waters commonly are sodium-bicarbonate waters. Wood and others (1963) and Baker (1978) have summarized the water resources of the Texas Gulf Coast. Individual county studies have been conducted by Wesselman (1971) for

Chambers and Jefferson Counties, Gabrysch (1972) for Harris and Galveston Counties, Sandeen and Wesselman (1973) for Brazoria County, Hammond (1969) for Matagorda County, Baker (1965) for Jackson County, Marvin and others (1962) for Victoria and Calhoun Counties, Woodman and others (1978) for Nueces, San Patricio, and Refugio Counties, Shafer and Baker (1973) for Kleberg, Kenedy, and southern Jim Wells Counties, and Baker and Dale (1964) for Willacy, Cameron, and Hidalgo Counties.

This ground water is used extensively for municipal, industrial, agricultural, and domestic use. Ground-water usage in the coastal plain is expected to increase. About a quarter of the population and a third of the economy of Texas is located in the Coastal Plain. The maintenance of a high level of water quality in the Gulf Coast aquifer, one of the largest in the country, is of paramount concern.

## Disposal Sites

Two environments have been considered suitable for disposal of saline fluids: marine waters (Gulf of Mexico or bay and estuaries) or saline aquifers.

Saline Surface Water: The disposal of geothermal fluids in saline surface waters is discussed more thoroughly in the previous section and in the Ecosystem section.

Saline Aquifers: The Railroad Commission of Texas permits well operators to dispose of saline water by injection into formations that contain mineralized water unfit for agricultural or general use and that do not contain oil, gas, or geothermal resources. Injection of spent geothermal fluids into saline aquifers is, in theory, the ideal method of salt-water disposal. This method limits surficial environmental hazards to the immediate areas of the geothermal wells, injection wells, and generating facility. As long as the geothermal fluids are adequately contained and insulated, hazards to plant and animal life should be minimal.

Although occurrence of sand bodies in the relatively shallow subsurface of the Texas coast is well-known, their suitability as disposal sites for large volumes of spent geothermal fluids is not completely understood. The shallowest, thick and laterally extensive sands that might be suitable to accept large volumes of spent geothermal fluids, are the basal Miocene sands that lie above the Anahuac Shale. In the Frio geothermal fairways the depth to this unit exceeds 5,000 ft. In the Coastal Zone, the depth to the base of fresh (<1000 ppm TDS) to slightly saline (<3000 ppm TDS) ground water is relatively shallow. The interbedded sands and shales between the basal Miocene Sand the base of the fresh to slightly saline ground-water zone are probably sufficiently thick to prevent contamination of shallow ground water by geothermal fluids. There has been only limited mapping of sand thickness and geometry of disposal reservoirs. The only completed study has been of the depositional patterns of the Miocene facies of the Middle Texas Coastal Plain (Doyle, in press). Nothing has been done on sand distribution in either the Upper or Lower Texas Coastal Plain, nor on the hydrologic properties of these sediments in any of the Coastal Zone.

Knutson and Boardman (1978) summarized deep well injection of brines from petroleum operations. Disposal depths are generally less than 6000 ft. In Brazoria County disposal generally occurs between 4,000 to 6,000 ft whereas in Matagorda County disposal depths range from 2,000 to 3,000. The thickness of the disposal interval shows considerable variation. In Brazoria County 66 percent of the disposal intervals are greater than 2000 ft thick, whereas in

Matagorda County about 68 percent are less than 500 ft. The disposal rate was 34,000 bbl/day. The maximum average rate, however, is only 8,000 bbl/day.

In 1961, 93 percent or approximately 2,381,000 $m^3$ (15,000,000 bbls) of saline oil field waters produced in Matagorda County was disposed of by deep subsurface injection wells (Hammond, 1969). This is approximately the projected monthly production for a single geothermal electrical generating site. Injection zones for 43 wells in the county range from 451.2 m to 2,165.3 m (1,480 to 7,102 ft) below land surface with injection pressures ranging from 0 (gravity flow) to 70.4 $kg/cm^2$ (1,000 psi). Of these wells, only two have high rates of disposal: one at a rate of 952.4 $m^3$ (6,000 bbls) per day under a surface pressure of 56.3 $kg/cm^2$ (800 psi) and another at 1, 587.3 $m^3$ (10,000 bbls) per day under a surface pressure of 21.1 $kg/cm^2$ (300 psi). Many of the injection wells require high surface pressures to dispose of relatively small volumes of water. For example, the no. 1 J. B. Beld injection well (Hammond, 1969) requires surface pressures of 56.3 $kg/m^3$ (800 psi) to dispose of only 23.8 $m^3$ (150 bbls) per day. The limited data that are available regarding rates of injection and the surface pressures required for injection suggest that the capacity of formations to take up disposed fluids is highly variable. Most disposal rates are usually less than 158.7 $m^3$ (1,000 bbls) per day even though surface pumping pressures range upward to 70.4 $kg/cm^2$ (1,000 psi). At disposal rates of 1,587.3 $m^3$ (10,000 bbls) per day, the highest reported disposal rate, 20 to 40 disposal wells per generating site will be needed. Deep-well injection into saline aquifers is an established technique. The previous injection rates or quantities are not as great as the expected volume of fluid (300,000 - 400,000 bbl/day) from a 25 MGW plant. Herein lies a critical environmental problem for fluid disposal for geothermal-geopressured energy production.

The injection of large volumes of fluids into subsurface reservoirs has the potential for inducing seismicity. The Texas Gulf Coast Geosyncline is interlaced with thousands of miles of active growth faults, which are presently moving from natural and man-induced causes. This movement has not generated measurable seismicity because the sediments are continuously deforming plastically. Increased pore pressures along the fault surface from fluid injection may decrease the frictional strength of the fault and subsequently permit increased fault movement and the generation of seismic energy.

Induced seismicity has already occurred in Texas. On August 14, 1966, an earthquake (intensity 4-5) occurred near Kermit, Texas (West Texas). At least eleven aftershocks occurred in the area. Subsequent earthquakes occurred in 1971. Shurbet (1969) attributed this earthquake and its aftershocks to waterflooding of a oil and gas field in the area.

Induced seismicity from deep well injection has been carefully documented in Denver, Colorado (Healy and others, 1968), and Rangely, Colorado (Raleigh and others, 1976). Earthquakes with Richter magnitudes of 3 to 4 were recorded in the Denver area from 1962 through 1967. Fluid injection of chemical wastes at Rocky Mountain Arsenal decreased shear strength on a weak pre-existing fault surface and led to the seismic events (Healy and others, 1968). To validate the concept that increased pore pressures were decreasing effective stress and permitting faults to move, a fluid injection/seismic monitoring experiment was conducted in the Rangely oil field. The result of that investigation showed conclusively that induced seismicity by deep well injection was occurring (Raleigh and others, 1972).

Fluid injection along fault surfaces may cause a decrease in the frictional strength of a fault. Increased pore pressures drop the effective stresses that prevent a fault from moving. The concept was originally proposed by Hubbert and Rubey (Hubbert and Rubey, 1959, and Rubey and Hubbert, 1959). Whether seismicity could occur in the Gulf Coast because of deep-fluid injection is dependent on whether there is a strain accumulation in the fault zones. If the faults lock at depth, then increased pore pressure on the faults would permit movement. If fault movement is by continual creep, then induced seismicity is probably not a problem. To date there has been no recorded induced seismicity in the Gulf Coast from fluid injection. It is also expected that pressures of fluid injection will be significantly lower than in the Rangely experiment. The potential for seismicity should likewise be reduced.

Injection programs should follow a four-step operation: (1) evaluate the geology and hydrology of the potential injection reservoirs, (2) design and construct suitable wells for high pressure, high volumes, high flow rates, and chemical compositions of injected fluids, (3) develop surface facilities (a) for injecting a clean fluid to prevent well clogging and (b) to replicate critical operations such that breakdowns do not create production or storage problems; and (4) operate and monitor (Knutson and Boardman, 1978).

Geologic and gydrologic evaluation of injection sites characteristically entails a study of the immediate vicinity of the injection well or injection field. Because of the extremely large volumes of fluids (400,000 bbl/day) that could be injected into the subsurface, studies of a larger scope should be considered. Regional sand geometry of the saline aquifers needs to be known. This should include studies of thickness, orientation, and continuity of sand packages and the occurrence of faults acting as barriers to fluid migration. The continued long-term injection of fluids may change the potentiometric distribution between saline ground water and fresh shallow ground water. The elevation of interface between these two water bodies is controlled by the balance of head potentials in both aquifers. Increase the pressure in the underlying saline aquifer, then the interface between the two bodies of water will rise. Growth faults or abandoned leaky oil wells may be preferential pathways for saline water escape.

Well design and construction have to be suitable to carry large volumes of disposal water, not have leaks into fresh ground, not have formation plugging problems nor cause fracturing of the aquifer. Well design and construction are primarily technical problems. They are of environmental concern because well failure could lead to leakage in fresh water aquifers or result in surface storage problems which may not be environmentally acceptable.

Necessary surface facilities are needed for storage of brines prior to injection and for treatment of the injected fluids so that they will not clog the formation with suspended material or be chemically incompatible with the formation fluids. Storage facilities must be constructed and monitored such that leakage into shallow ground water cannot occur.

Monitoring injection operations is extremely difficult, because it requires the drilling of additional wells to monitor the migration of pressure and disposal fluids.

## Regulations Governing the Production and Disposal of Saline and/or Geothermal Fluids

Several State and Federal agencies, including the Railroad Commission of Texas, the Texas Water Quality Board, the Texas Air Control Board, the Texas Water Development Board, and the Environmental Protection Agency, have regulatory responsibilities that will directly or indirectly influence development of both a geothermal test well and, subsequently, a geothermal energy production/generation facility. Only those regulations that affect the production and disposal of saline water will be considered here. The Texas Air Control Board is charged under the amended Texas Clean Air Act of 1967 with safegarding the "air resources of the State from pollution by controlling or abating air pollution and emissions of contaminants..." (Texas Legislature, 1967). At this time, it is not known if geothermal fluids will contain potential air pollutants. The two most likely air pollutants will be volatile carbon compounds and hydrogen sulfide resulting from the production of gas that is expected to occur with geothermal fluids.

The primary environmental concern of the Railroad Commission and the Texas Water Quality Board with respect to geothermal development is the impact of the disposal of hot saline geothermal fluids. The Railroad Commission of Texas (1975) will regulate the drilling and operation of geothermal resource wells and the disposal of fluids from geothermal resource wells under rule 8 as follows.

(A) Fresh water, whether above or below the surface, shall be protected from pollution...

(B) ...[The operation of] geothermal well or wells drilled for exploratory purposes...shall be carried on so that no pollution of any stream or watercourse of this State, or any subsurface waters, will occur as the result of the escape or release or injection of geothermal resource or other mineralized waters from any well.

(C1)...[All operators conducting] geothermal resource development and production are prohibited from using salt-water disposal pits for storage and evaporation of...geothermal resource waters...

(C1b) Impervious collecting pits may be approved for use in conjunction with approved salt-water disposal operations...

(Clc) Discharge of...geothermal resource waters into a surface drainage watercourse, whether it be a dry creek, a flowing creek, or a river, except when permitted by the Commission is not an acceptable disposal operation and is prohibited.

(D1) The [well] operator shall not pollute the waters of the Texas offshore and adjacent estuarine zones (salt-water-bearing bays, inlets, and estuaries) or damage the aquatic life therein.

(D2)...Geothermal resource well drilling and producing operations shall be conducted in such a manner to preclude the pollution of the waters of the Texas offshore and adjacent estuarine zones.

(D2a) The disposal of liquid waste material into the Texas offshore or adjacent estuarine zones shall be limited to salt water and other materials which have been treated, when necessary, for the removal of constituents which may be harmful to aquatic life or injurious to life or property.

The Railroad Commission of Texas (1975) also regulates the injection of saline water under rule 9 as follows:

(A) Salt water...unfit for domestic, stock, irrigation, or other general use may be disposed of...by injection in the following formations: [rules listed].

(A1) All nonproducing zones of oil, gas, or geothermal resources bearing formations that contain water mineralized by process of nature to such a degree that the water is unfit for domestic, stock, irrigation, or other general use.

Water-quality standards developed by the Texas Water Quality Board were approved by the Environmental Protection Agency in October 1973 and were amended in 1975 (Texas Water Quality Board, 1975). These standards are in compliance with the Federal Water Pollution Control Act Amendments of 1972 (U.S. Congress, 1973). Under these standards, "it is the policy of the State... to maintain the quality of water in the State consistent with the public health and enjoyment, the propagation and protection of aquatic life, the operation of existing industries, and the economic development of the State..." Furthermore, "...no waste discharges may be made which will result in the lowering of the quality of these waters unless and until it has been demonstrated to the Texas Water Quality Board that the change is justifiable as a result of desirable social or economic development" (Texas Water Quality Board, 1975, p. 1).

The following suggested limitations to thermal pollution as outlined in the Texas Water Quality Standards (Texas Water Quality Board, 1975) are of interest:

1. 2.75°C (5°F) rise over ambient temperature for fresh-water streams.
2. 1.65°C (3°F) rise over ambient temperature for fresh-water impoundment.
3. 2.2°C (4°F) rise or a maximum temperature of 52.5°C (95°F) in fall, spring, and winter, and 0.85°C (1.5°F) rise or a maximum temperature of 52.5°C (95°F) in summer for tidal reaches of rivers and bay and Gulf waters.

The Texas Water Quality Board recognizes the salinities of estuaries are highly variable and that the dominant factor affecting salinity variations is the weather. Salinity standards are now incompletely defined but are under study.

The preceding review of the regulations and policies of the Texas agencies that apply to the disposal of salt water indicates that:

1. Temporary salt-water collecting or storing is permitted.
2. Salt water treated (including cooling) to remove harmful constituents may be released into bays, estuaries, and the Gulf of Mexico.
3. Under certain circumstances, the discharge of salt water into natural watercourses is permitted.
4. The reinjection of salt water into saline aquifers is permitted.
5. The lowering of standards for certain water bodies is permitted if sufficient need for economic development can be demonstrated.

Geothermal fluids therefore can be legally disposed of in two sites, saline water bodies or by deep-well injection. Injection into surface saline waters must guarantee that there will be no geologic degradation. Disposal into deep saline aquifers is acceptable if it does not impact fresh ground water nor interfere with oil and gas extractive operations or previously permitted injection wells.

## Summary of Environmental Problems from Fluid Disposal

Geothermal fluids can be disposed of in two ways: disposal into saline water bodies or deep-well injection. Surface disposal has to address two areas of concern: thermal impact on ecosystems and chemical impact on ecosystems. When the volume of fluids being disposed of is small, dispersion in a large body of water mitigates thermal and chemical contaminants. With disposal of large volumes of water, dispersion may be ineffective. The critical problem then becomes, can the ecosystems survive changes in environments?

A second problem arises with surface water disposal--the storage and transportation of fluids to the designated water body. Overland transport through canals or pipelines increases the potential for leakage in the shallow ground water and provides a barrier for seasonally migratory quadrupeds. Design criteria for the pipeline construction might incorporate bridge or tunnels in the same fashion as has been done along the Alaska Pipeline to guarantee the migratory pathways of the caribou.

Even though deep-well injection appears to be the most environmentally sound method of waste fluid disposal, certain environmental problems could arise. The development of wells and well fields capable of injection of large volumes of fluids is needed. There are few if any disposal operations in the Texas Gulf Coast that inject 300,000 to 400,000 bbl/day on a continuous daily basis.

Injected fluids from the oil and chemical industry miraculously disappeared into the subsurface saline aquifers. The disposal of large volumes of spent geothermal fluids may overpressurize these aquifers, causing leakage back into fresh ground water systems through abandoned leaky casings or up permeable fault zones or induce seismicity.

## Ongoing Programs

On-going programs addressing the problems of geothermal fluid disposal are limited to one program. Dr. Ben Caudle, Department of Petroleum Engineering, is delineating disposal sites for the Pleasant Bayou Prospect site in Brazoria County. He is developing a simulation model to determine injection requirements for the test well at Pleasant Bayou.

## Recommended Programs

The critical problems of geothermal fluid disposal are (1) if large volumes of fluid are disposed into surface saline waters what will be the impact on the ecosystems and (2) if large volumes of fluid are disposed into the subsurface, are the reservoirs hydrologically suitable to accept large volumes of fluid, will these fluids leak into fresh ground-water systems, and is there a potential for induced seismicity?

The research needs for critical areas are detailed in the Ecosystem section where this problem is addressed from the point of view of ecosystem studies.

Critical area (2), impact of deep well injection on the environment, studies in three areas need to be conducted: (1) reservoir suitability, (2) potential leakage, and (3) potential induced seismicity.

(1) Geometry, volume, orientation, porosity, permeability, and chemical interactions of the disposal reservoirs will determine reservoir suitability. The only regional study on disposal reservoirs that has been completed is a study of sand geometry of Miocene sands in the Middle Texas Coastal Zone (Doyle, in press). Sand geometry of Upper and Lower Texas Coastal Plain needs to be constructed. Studies on permeability, porosity, aquifer compressibility, water chemistry, clay mineralogy--all critical parameters for determining reservoir suitability--need to be initiated.

(2) Leakage of saline fluids into fresh ground-water aquifers may result from large-volume disposal of geothermal fluids. The interface between fresh ground water and saline ground water is not well understood. A genetic study is needed to explain the interaction between these two bodies of water and whether geothermal fluid disposal could cause significant contamination of fresh ground water.

(3) Induced seismicity may result from high volume, high pressure fluid injection. High resolution, low amplitude seismic monitoring is needed at the injection well for the test site or at a high volume injection well presently in operation to determine if full-scale injection operations may induce seismicity.

Cost Estimates for General Tasks-Water Quality-1979

| Task | Operating Funds |
| --- | --- |
| 1. Reservoir suitability | $ 50,000 |
| 2. Leakage | 50,000 |
| 3. Induced seismicity | 125,000 |
| | $ 225,000 |

## Subsidence and Faulting from Geothermal-Geopressured Energy Production

The Texas Coastal Zone is an area of multiple land uses. It supports intensive agricultural, industrial, and fishing industries. It is populated by both rural and metropolitan people. As a Coastal Plain its elevation in many localities is not significantly above sea level. Large scale subsidence and faulting could seriously impact this region. It is therefore necessary to address the problem of subsidence and faulting from geothermal-geopressured energy production. This chapter describes the geologic framework of the Cenozoic sedimentary wedge, the source of geopressuring, and the structural framework, the occurrences and causes of subsidence and fault activation, the potential for geothermal-geopressured energy production causing these phenomena, and the monitoring and research programs necessary to mitigate their potential occurrence.

## Geologic Framework of the Texas Gulf Coast

### Source of Geopressuring

The Texas Coastal Plain overlies a thick wedge of Cenozoic terrigenous sediments within the Gulf Coast basin. Over 50,000 feet (15,000 meters) of sediment has accumulated in some areas. Tertiary deltaic sediments, the primary Gulf Coast geopressured-geothermal reservoirs, include the Eocene Wilcox Formation, the Oligocene Vicksburg Formation, and the Miocene Frio Formation (Bebout and others, 1975, 1976, 1978).

Each depositional episode built further into the basin. Rapid sedimentation at the delta-front and prodelta section and concomitant growth fault movement rapidly buried thick sections of sand and mud. Rapid burial slowed dewatering of these sediments and the contained pore fluids became overpressured or geopressured. With each new period of sedimentation, a new geopressured section was developed and the geopressured section of the older units were buried more deeply (Fig. 16).

The geopressured zone has pore-water pressures which are abnormally high in comparison to pore-water pressures in other sediments that occur at equal depths. Under normal conditions, muds or mudstones undergo a decrease in porosity from greater than 50 percent at deposition to as little as 4 percent following burial, dewatering, and compaction in the normally-pressured sections. Porosity decreases logarithmically with depth under normal hydrostatic conditions (fig.17). Geopressured sediments, however, do not follow the smooth logarithmic compaction curves. Under hydrostatic conditions the pressure gradient is .465 PSI per foot. In the geopressured zone the pressure gradient can rise as high as 1.0 PSI per foot--over 2 times the normal pore pressure gradient (fig.18). At higher pore pressure gradients (than hydrostatic), the porosity loss with depth is offset (see fig.19). This occurs in the top of the geopressured zone, where porosities in both the shales and sands are higher than in the respective overlying normally pressured sediments. Deeper in the geopressured zone porosities continue to decrease with depth.

The source or cause of the high porosity and high pore pressures in geopressured sediments follows several schools of thought: rapid burial, mineralogic phase changes, shale diapirism, tectonic compression, osmotic and

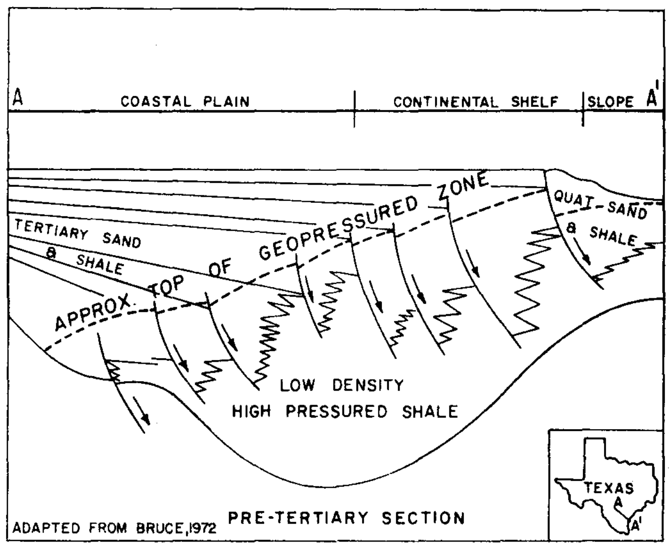


Fig. 16. Schematic representation of geopressured section (modified from Bruce, 1972).

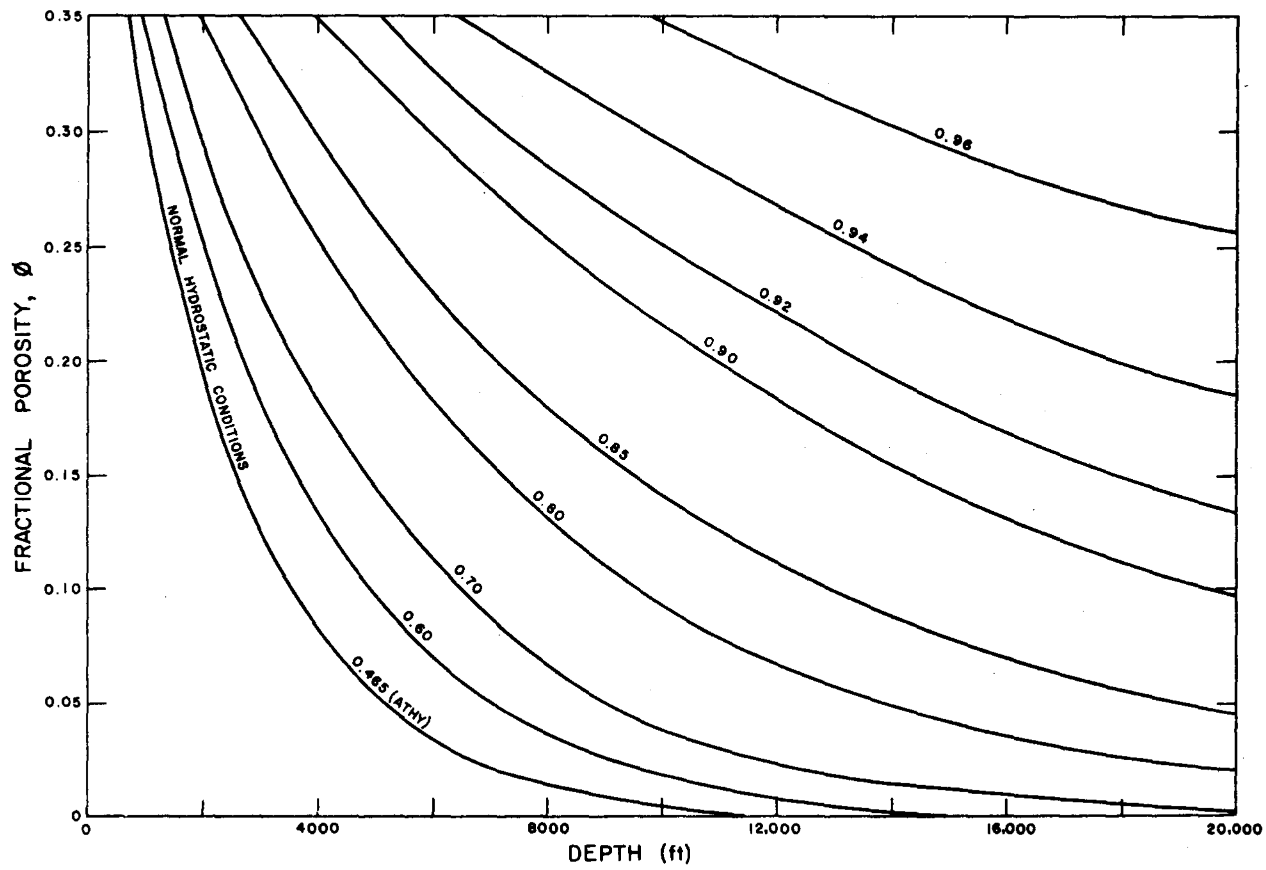


Fig. 17. Relationship between porosity and depth of burial for various values of λ (fluid pressure/overburden pressure) for an average shale or mudstone. Athy's curve (λ=046) is assumed to represent "compaction equilibrium" condition (After Rubey and Hubbert, 1959, p. 178, courtesy of the Geological Society of America Bulletin).

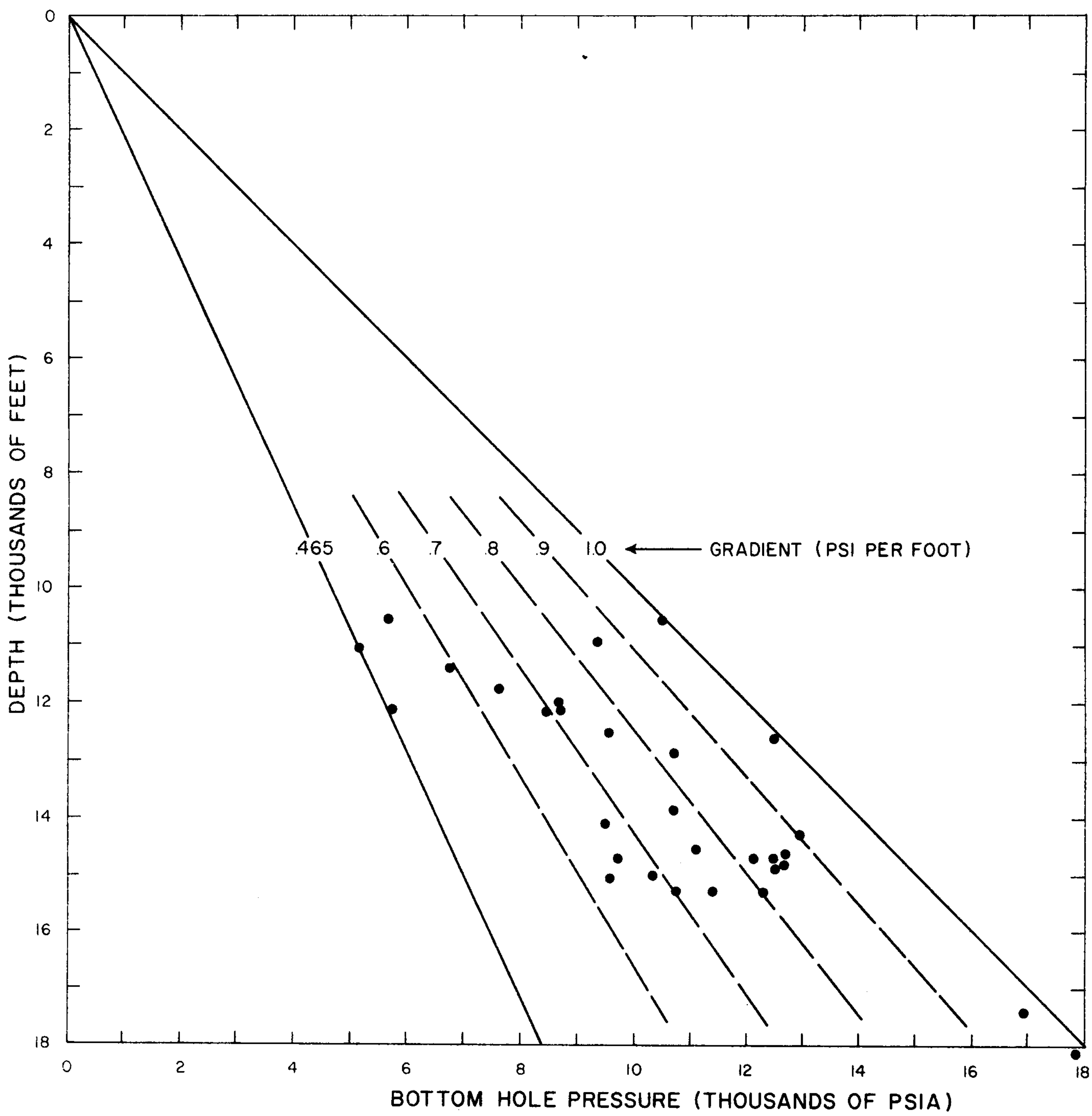


Fig. 18. Static bottom-hole pressures versus depth for a number of wells, Chocolate Bayou field, Brazoria County, Texas (from Bebout and others, 1978)

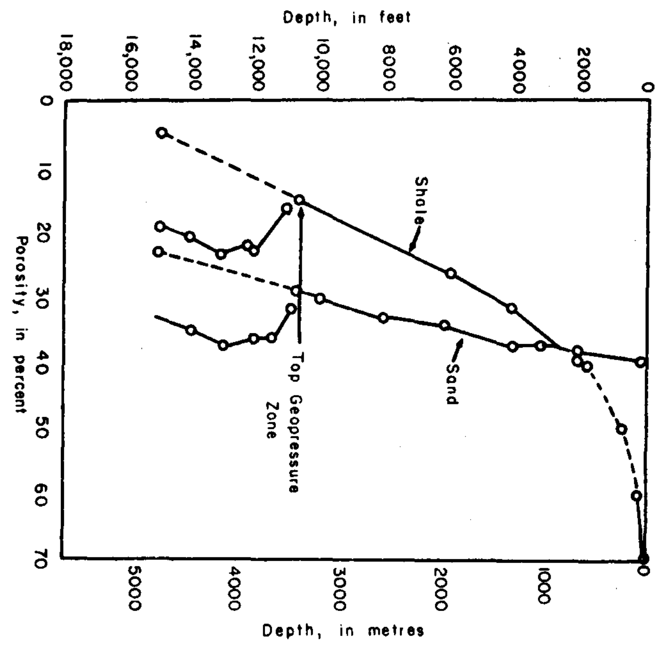


Fig. 19. Porosity versus depth of burial for Gulf Coast sediments. Note increased porosity for sandstone and shale at top of geopressured section (from Stuart, 1970).

diffusive gradients, and thermal expansion of fluids (Rieke and Chilingarian, 1974). The two mechanisms most commonly considered in the Gulf Coast are rapid burial or clay dehydration. Either geopressuring is related to rapid burial of sediments which have maintained the porosity and pore pressures from shallower depths or geopressuring has resulted from the water of clay dehydration during diagenesis.

Several researchers (Dickinson, 1953; Rubey and Hubbert, 1959; Bredehoeft and Hanshaw, 1968; Dickey and others, 1968; Schmidt, 1973; Chapman, 1972; Rieke and Chilingarian, 1974; Magara, 1975) suggest that geopressuring is the result of rapid burial, commonly on the coastward side of growth faults, and slow leakage of the pore fluids. With rapid burial, pore pressures, which were in equilibrium at shallow depths, become overpressured at greater depth.

Jones (1968; 1975) suggests that a significant part of the geopressuring results from the thermal diagenesis of clays. Montmorillonite is altered to illite and mixed-layer clays in the range of 6,000 to 12,000 feet (2,000-4,000 meters) with the release of free pore water (Powers, 1967; Burst, 1969). This release of water by clay diagenesis causes the overpressuring.

Structural Framework

Most of the geopressured-geothermal prospect areas are bounded by faults. The Kenedy and the Corpus Christi geothermal fairways and the Austin Prospect (Brazoria Fairway) are all structurally controlled. In the Brazoria Fairway (fig. 20) a relatively thin section of the Frio Formation expands to several thousand feet on the downthrown side of a growth fault (Bebout and others, 1978).

Growth faults are commonly associated with Gulf Coast sediments. The boundary between delta-front sands and thick, rapidly deposited prodelta mud facies is the principal zone of growth faulting. Rapid sedimentation of

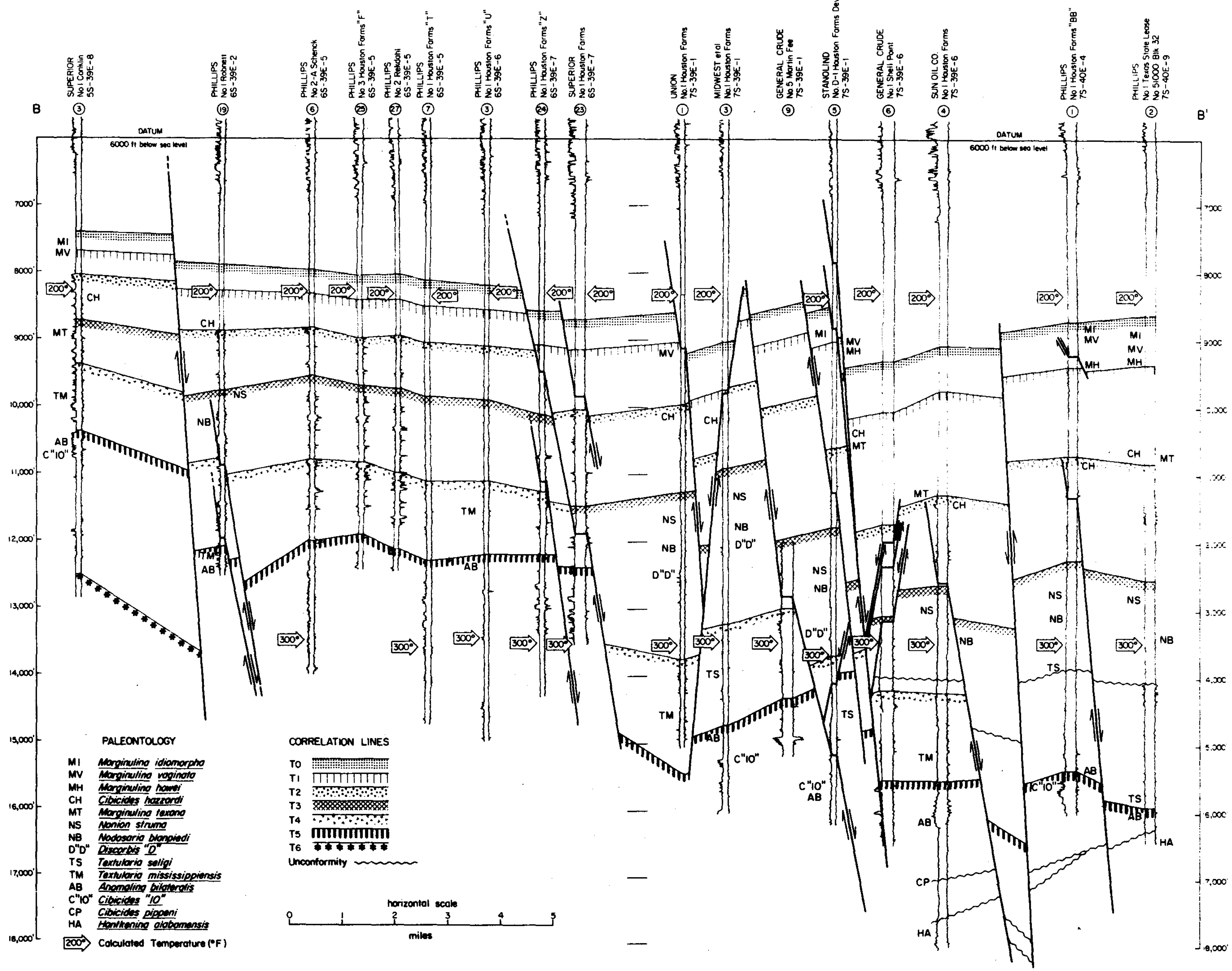


Fig. 20. Fault control of Frio Brazoria geopressured reservoir (Bebout and others, 1978). Note thickening of units across growth faults.

the thick, highly compressible mud is a significant factor in fault development. Stratigraphic thickness often increases across growth faults, indicating that sedimentation is contemporaneous with faulting (Carver, 1968). Growth faults may be reactivated with each new period of deposition where delta facies are superimposed.

Growth fault development in the Gulf Coast basin is enhanced by gulfward creep (landslide type of activation) of the entire sediment mass (Bornhauser, 1956; Bruce, 1972)(Fig. 16). Cloos (1968) showed experimentally that the growth faults of Tertiary section could develop by basinward, mass movement of sediments. When the Gulf Coast sedimentary mass is modeled as a large landslide, it has a factor of safety less than one and should theoretically be moving basinward (Reid, 1973). Faulting in the Gulf Coast basin may also be affected by regional basement tectonics (Bornhauser, 1956; Murray, 1961; Shelton, 1968).

Growth faults in the Gulf basin are characterized by seven common features (Carver, 1968):

(1) Fault traces on datum surfaces are arcuate and normally concave toward the coast.

(2) The average dip of the fault is approximately 45 degrees. The faults dip steeply near the surface and diminish to become bedding plane faults at depth (Hardin and Hardin, 1961; Murray, 1961; Ocamb, 1961; and Bruce, 1972).

(3) Faults are normal and are generally downthrown toward the coast (down to the coast). Cloos (1968) showed experimentally and Bruce (1972) documented with seismic profiles that the major growth faults should have associated antithetic faults (up-to-the-coast faults). The growth fault-antithetic fault pair will tend to form graben structures (Murray, 1961).

(4) Fault displacement tends to increase with depth to a maximum and

may then decrease at greater depths.

(5) Growth faulting produces rollover or reverse drag on the downthrown side.

(6) Progressively younger faults occur nearer the coast. As the major deltaic depocenters moved coastward, the growth faulting also moved in that direction.

(7) Growth faults are commonly associated with rapid increases in overall sediment thickness and a change from predominantly sand to mud facies on the downthrown side (Carver, 1968).

Faults are also associated with salt tectonism in the Gulf Coast sedimentary basin. Murray (1961) records seven distinctly different types of faults controlled by salt structures: normal faulting with single offset; normal faulting with multiple offset; grabens; horsts; radial faulting; and peripheral or tangential faulting; and reverse or thrust faulting. Quarles (1953) attributes the regional down-to-the-coast faults as well as a salt-dome faulting to salt tectonism rather than to depositional loading or landslide-type mass movements. The combination of faults caused by salt tectonism and faults generated by deltaic sedimentation and landslide mass movement dominates the structural framework of the Tertiary section of the Gulf Coast basin. Fault movement continued at least until the end of the Oligocene. Some faulting beneath the Coastal Plain, however, has continued through the late Tertiary (Miocene and Pliocene) and Quaternary (Kreitler, 1976).

Subsurface faults do not die out in the upper Cenozoic sediments but in many cases extend to the land surface. Their natural rate of movement, however, is so slow that their surficial expression is evident only through subtle geomorphic features such as lineations and rectilinear stream-drainage networks (Kreitler, 1976). Structural control of stream drainage is particularly evident in the Houston-Galveston area. Surface faults appear to control sections of Buffalo Bayou, Clear Creek, Highland Bayou, and Cypress Creek.

## Subsidence in the Texas Coastal Zone

Subsidence is occurring in most of the Texas Coastal Zone (Swanson and Thurlow, 1973; Brown and others, 1974) either as natural subsidence, subsidence from ground-water production, or subsidence from oil and gas operations. The separation of the three phenomena, particularly in the greater Houston area where there has been prolific hydrocarbon production as well as extensive ground water withdrawals, is extremely difficult. Concomitant with subsidence is active fault movement. (The causes for fault activation are the same for subsidence--natural activation, hydrocarbon production, and ground-water withdrawals.)

Natural subsidence and associated natural fault movement is occurring at an extremely slow rate. Swanson and Thurlow (1973) measured a natural subsidence of 0.5 to 1.2 cm/year and attributed much of the subsidence to increased sediment loading. These rates are high for natural subsidence. Holdahl and Morrison (1974) show subsidence rates approximately one half of those of Swanson and Thurlow (1974). These rates seem more reasonable. Measurable natural subsidence in the Coastal Zone has occurred primarily from the Lavaca River (Jackson County) north to Louisiana. There is little evidence for subsidence in South Texas (Brown and others, 1974). Holdahl and Morrison (1974) also indicate very low rates of subsidence in South Texas.

Though there is a component of natural subsidence in the Texas Coastal Zone, land-surface subsidence is primarily a consequence of ground-water pumping. Withdrawal began in the Texas Coastal Zone in the early part of this century and affects to varying degrees a substantial part of the Texas Coastal Plain. Most serious subsidence is in the greater Houston area, where some localities show recorded subsidence up to 8.5 ft (2.7 m). Significantly, both the rate of land subsidence, in terms of lost land elevation, and the area of impact are progressively increasing and have increased dramatically in the past three decades.

In 1943, when releveling recorded the first measurable subsidence, a little more than 140 $mi^2$ of land in the Houston region had subsided 1 ft (.3 m) or more, with maximum subsidence of about 1.5 ft (.45 m). By 1954, about 1,000 $mi^2$ (2600 $km^2$) of land had experienced subsidence in excess of 1 ft (.3 m) with maximum subsidence up to 4 ft (1.2 m). In 1964, more than 1,800 $mi^2$ of land had subsided more than 1 ft (.3 m) with maximum subsidence up to 6 ft (1.8 m). By 1974, more than 3,000 $mi^2$ (8,000 $km^2$) of land on the lower Texas coastal plain had undergone more than a foot of subsidence, and maximum subsidence had reached 8.5 ft (2.6 m). The area of lands impacted by subsidence of 1 ft (.3 m) or more has doubled approximately each decade for the past 30 years. At the present time, about 230 $mi^2$ (600 $km^2$) of land, centering on Pasadena, Texas, had subsided more than 5 ft (1.5 m).

Measurable subsidence, defined herein as 0.2 ft (6 cm) and greater, now impacts three areas of the lower Texas Coastal Plain: (1) an extensive area of the upper Texas Coastal Plain extending from Bay City northward into Louisiana and inland as much as 60 mi (100 km); this zone includes the critically impacted greater Houston area; (2) a large part of Jackson County; and (3) an area in Nueces and San Patricio Counties centered near the community of Odem (fig. 21).

Likewise, the cause of subsidence is well documented, primarily through the extensive monitoring of water-well levels, which was started in 1929 by the Water Resources Division of the U.S. Geological Survey. Comparison of areas of water level and piezometric decline with areas of land-surface subsidence clearly shows that they are coexistent. Results of monitoring by the U.S. Geological Survey have been reported in several papers; refer

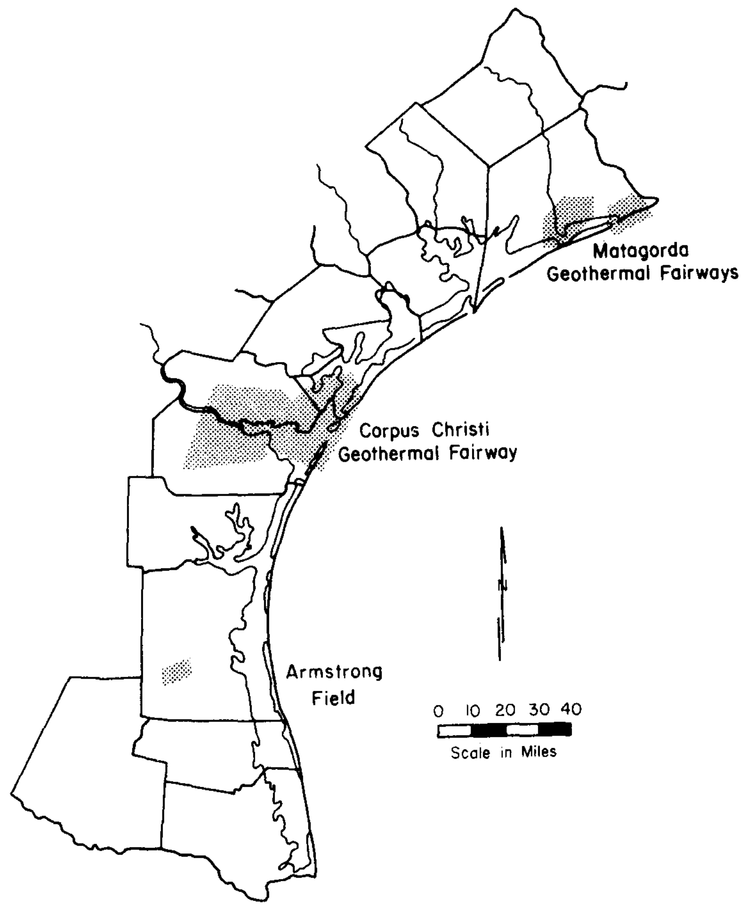


Fig. 21. Regions of land subsidence

especially to those reports by Gabrysch (1969, 1972), Gabrysch and McAdoo (1972), and Gabrysch and Bonnet (1974) as well as to reports by Marshall (1973) and Turner, Collie, and Braden, Inc. (1966).

Most of the ground-water production in the Texas Coastal Plain is from aquifers occurring from near the surface to depths as great as 3,000 ft (1,000 m). The geologic formations involved are composed of varying amounts of alternating sands (the aquifers) and interstratified clays. Geologists and engineers of the U.S. Geological Survey, who started monitoring water levels in Coastal Plain wells in 1929, have charted the long-term decline in the pressure levels. In 1943, maximum decline of the water level was about 150 ft. (45 m); by 1954, the piezometric level had dropped to about 300 ft (90 m); by 1964, it had declined to about 350 ft (106 m); and by 1974, it locally had declined to 400 ft (120 m).

The amount of subsidence that will occur is directly related to the decline in piezometric level, which is a function of the volume of water withdrawn from the aquifer. The amount of subsidence, however, will vary further depending upon the amount of clay within the aquifer section, the vertical distribution of the clay, the compressibility of the clay, and finally, the degree of undercompaction of the clay in its natural state. The amount of clay in the aquifer and the number of clay beds within the aquifer sands, as well as the compressibility of the beds, vary areally; certain areas may be more prone to subsidence than others, even with the same amount of ground-water withdrawal and comparable levels of peizometric decline.

Subsidence from hydrocarbon production also is an aerially-extensive problem in the Texas Coastal Zone. From Beaumont to Brownsville there are approximately 3,000 oil and gas fields that have produced over 10 billion bbl of crude oil and over 19,000 x $10^6$ mcf of natural gas. Production from these fields probably caused some subsidence over all of these fields. Land subsidence data over oil and gas fields in the Texas Coastal Zone is relatively limited. Subsidence has been measured over the Goose Creek field, Baytown, Texas (Pratt and Johnson, 1925), the Saxet oil and gas field, Corpus Christi area, the Chocolate Bayou field, Brazoria County (Kreitler, 1976), and five fields in the greater Houston area (table 1) (Kreitler, 1977).

Amounts of subsidence vary from 1 ft to over 3 ft (.3 m to 1 m). Subsidence over the Saxet field may be on the order of two meters or more based on the height of the Saxet fault scarp (Kreitler, 1977) (Fig. 22). Even though there are numerous fields in the Texas Coastal Zone, subsidence in most of the fields has not caused serious problems because subsidence has been minimal and its lateral extent has been limited to the field area. The subsidence impact from ground-water production appears more widespread.

Depths of hydrocarbon production and subsequent reservoir compaction that lead to land subsidence vary from relatively shallow in some fields (Goose Creek, less than 5000 ft [1500 m] or shallower, Saxet, 1000-8000 ft [300-2440 m]) to deep in fields such as Chocolate Bayou (oil production from 8000 to 12,000 ft (2400 m to 4000 m) and gas production from depths greater than 12,000 ft (3600 m) (Gustavson and Kreitler, 1976).

## Active Faulting in the Texas Coastal Zone

Many of the Tertiary faults in the Texas Coastal Zone extend upward to land surface, but few show evidence of recent movement. It is in the areas of extensive fluid withdrawal (water, oil, or gas) that these passive structural features become active faults. At least 150 mi (400 km) of active faults with topographic escarpments occur in Harris and Galveston Counties where more than 500,000,000 gallons (1,900,000 1) of water are pumped per day (Kreitler, 1976). Active faults in Baytown, Texas were recognized as early as 1926 by Pratt and Johnson (1926).

McClelland Engineers (1966) and Reid (1973) measured surface displacement

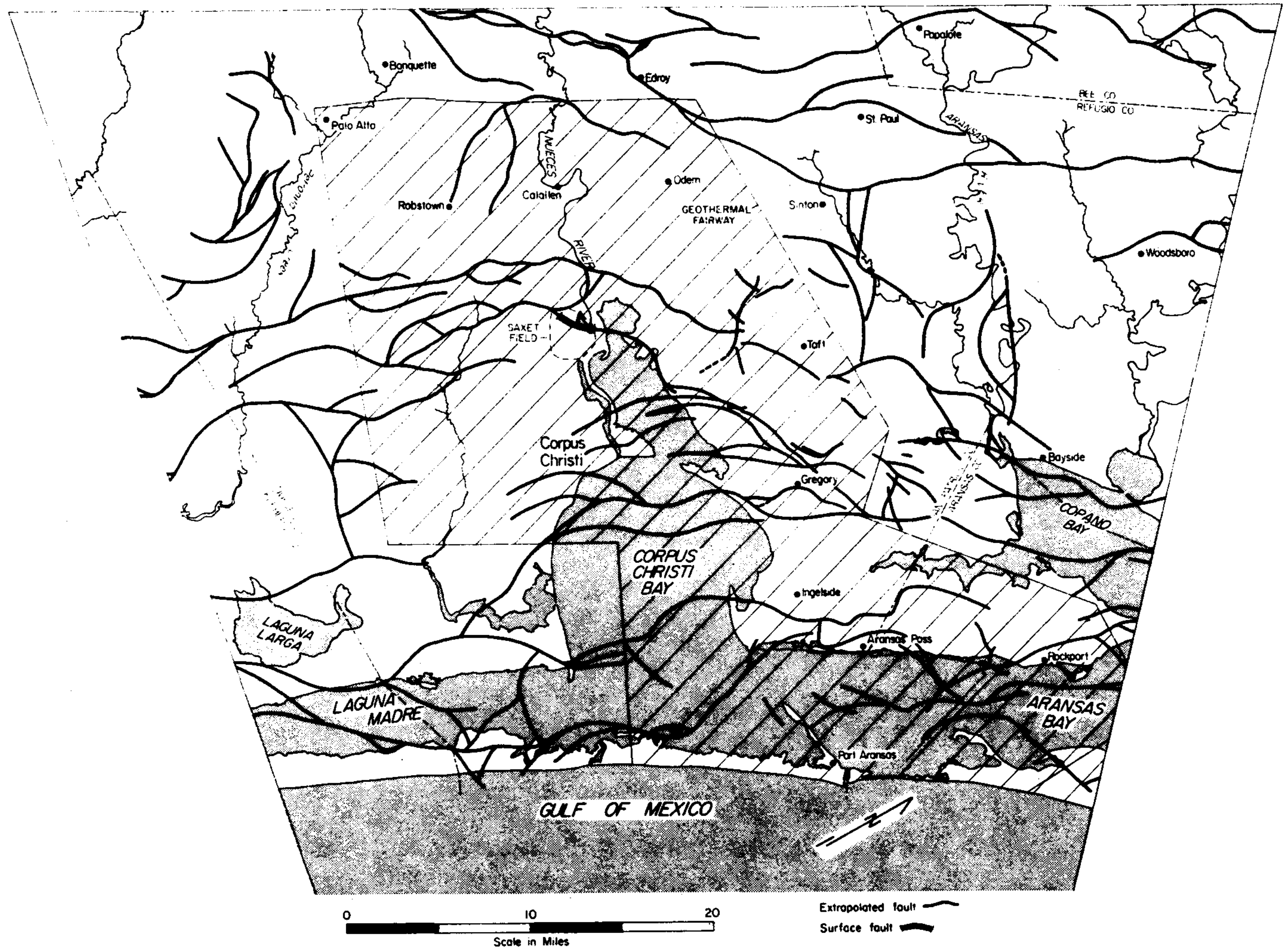


Fig. 22. Location of active fault over Saxet oil and gas field and coincidence to surface trace of extrapolated subsurface fault. Pattern area indicated Corpus Christi geothermal fairway.

of active faults from topographic profiles along highways. McClelland Engineers (1966) and Van Siclen (1967) suggested that faulting and subsidence were unrelated because the faults crossed the subsidence contours, and the strikes of the faults were not tangential to the regional subsidence bowl. Castle and Youd (1972) challenged Van Siclen's conclusions (1967) and suggested that radial-oriented strain from aquifer compaction was the mechanism for fault activation. Reid (1973) correlated horizontal fault displacement from two active faults in the western part of Houston with decline of the piezometric surface. Faults in the Houston-Galveston area may act as hydrologic barriers. Fluid production on one side of a fault causes piezometric surface declines and aquifer compaction on this side of the fault and not on the other. This differential sediment compaction is translated to the surface as differential land subsidence or fault movement (Kreitler, 1977a, b).

Fault activation is also attributable to oil and gas production. The Saxet oil and gas field (figs. 22, 23) best demonstrates the interrelationship of oil and gas production with faulting in the Texas Coastal Zone. In the Saxet field, a 6 ft (2 m) scarp has appeared along a segment of the surface extrapolation of a regional growth fault. The active segment of this fault lies almost exclusively within the Saxet oil and gas field (fig. 22). The topographic escarpment dies out along strike away from the field; natural, geologic activation, therefore, is not considered significant. Because there is no ground-water production in the area, ground-water withdrawals cannot be responsible for the movement. Fault movement has occurred since the onset of oil and gas production (W.A. Price, personal communication, 1975). Leveling profiles across the Saxet field show sharp increases in subsidence at the fault (fig. 23). Subsidence rates from 1950 to 1959, 0.22 ft (7 cm) per year, are approximately twice the rates from 1942-1950, 0.14 ft per year (4 cm per year). A rapid increase

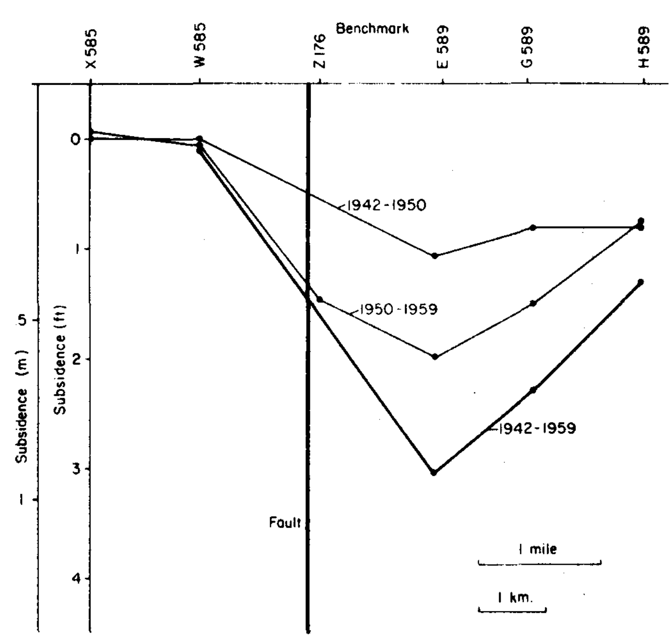


Fig. 23. Land subsidence over Saxet oil and gas field, Corpus Christi, Texas. Note fault control of subsidence between benchmarks W585 and Z176.

in gas production from shallow sands occurred from 1950 to 1959. Oil production, however, decreased during this period (Gustavson and Kreitler, 1976). Production of shallow high-pressured gas may have led to the compaction of the shallow gas sands on the downthrown side of the Saxet fault and subsequent differential land subsidence and fault activation.

In the Houston-Galveston area there is evidence of active faulting associated with at least six producing fields (Table 18). Detailed mapping of water well locations and approximate pumpage shows minimal shallow ground water production within the areas of these fields. Hydrocarbon production rather than shallow ground-water withdrawal therefore is considered the primary mechanism for fault activation (Kreitler, 1977b).

Even though extensive active faulting is occurring in the Texas Coastal Zone, there has been very limited occurrence of seismic activity. Seismic monitoring in Brazoria County has indicated no discernible seismic noise from fault movement (Teledyne Geotech, 1978a, b). Fault movement is considered to be slow but continuous, a creep-type movement, rather than discontinuous and rapid. This continuous movement prevents a strain build up along fault planes.

There are, however, two documented cases of seismicity associated with active faults in the Texas Coastal Zone. The first was associated with an active fault peripheral to the Goose Creek Oil Field, Baytown, Texas. Teacups on shelves rattled once in the 1920's (Pratt and Johnson, 1976); Yerkes and Castle (1976) attribute this minor earthquake to elastic rebound along the edge of the subsidence bowl. Some seismic activity may have been associated with fault movement peripheral to the Saxet oil and gas field. A man was supposedly knocked out of the barber's chair while getting a haircut (W.A. Price, personal communication, 1975). In both cases (Goose Creek and Saxet) fluids were being produced at high uncontrolled rates. At Goose Creek in the early days of production they produced more sand than oil. Rapid pressure

Table 18. Land subsidence and surface faulting associated with oil and gas fields, Harris Co., Texas.

| Field No. | Field Name | Producing Horizon (m) | Total Production ($10^6$ bbl) | Subsidence (m) | Faulting (m) |
|---|---|---|---|---|---|
| 1 | South Houston | 1,460[2] | 39.3 (1974)[2] | 0.3 (1942-1958)[4] | 0.45 (1972)[5] |
| 2 | Clinton | 915-2,134[2] | 2.7 (1974)[2] | 9 | 0.7 (1972)[5] |
| 3 | MyKawa | 1,483-2,645[2] | 4.1 (1974)[2] | 0.5 (1942-1973)[4] | 0.5 (1942-1973)[6] |
| 4 | Blue Ridge | 1,420-2,381[2] | 21.0 (1974)[2] | 0.2 (1942-1973)[4] | 0.15 (1966-1972)[5] |
| 5 | Webster | 1,481-2,564[2] | 41.3 (1974)[2] | 9 | 0.45 (1942-1975)[7] |
| 6 | Goose Creek | 1,490-1,310[8] | 60.3 (1926)[8] | 1.0 (1917-1926)[3] | 0.43 (1917-1926)[3] |

[1]See Figure 9 for field locations

[2]Texas Railroad Commission

[3]Pratt and Johnson (1926)

[4]National Geodetic Survey

[5]Reid (1973)

[6]Kreitler (1976)

[7]Clanton and Amsbury (1975)

[8]Minor (1926)

[9]not available

reductions and mining of the reservoir may have caused the reservoir to collapse.

Pressure declines in geopressured reservoirs may be large and rapid enough to generate seismic energy releases. Teledyne Geotech staff (1978a, b) predicted maximum shearing strain in a producing geopressured reservoir to be on the order of $10^{-4}$, which is within the range of non-elastic deformation. If the rocks at the depth of the reservoir are brittle, then seismic energy could be released during fluid production.

It appears that as long as the rocks and faults deform continuously there will be no strain build up. With significant pressure drawdowns and if the faults or sediments are brittle, then seismic energy releases are possible.

Environmental Impact of Subsidence and Fault Activation

The geographic location of fluid production controls the magnitude of the environmental impact of subsidence and faulting. Subsidence and fault activation are not critical problems until they adversely affect the quality of the present or future land use of a particular area. In Harris and Galveston Counties, fluid production has caused extensive land subsidence and has activated several surface faults. These faults intersect two airports, interstate highways at 11 different locations, railroad tracks at 28 locations, and pass through 11 communities in which more than 200 houses evidence fault damage. Land subsidence in Harris and Galveston Counties has greatly increased the area that may be affected by future hurricane flooding.

Each incremental loss of elevation subjects more coastal land along bays and estuaries to complete inundation from marine waters and intermittent inundation from hurricane surges and unusually high tides. In the Brownwood subdivision, Baytown, Texas, several houses stand in water. The United States Army Corps of Engineers (1975) estimated the minimum cost to relocate the residents of this community to be $16,980,000. Warren and others (1974) provide an estimate of the total property damage and loss from marine inundation caused by subsidence for 300 $mi^2$ of the Houston-Baytown area surrounding Galveston Bay: from 1943 to 1973, total estimated marine water damages from subsidence were $113 million. A six-ft (2 m) storm surge tide associated with tropical storm Delia in 1973 resulted in subsidence-related damages estimated at more than $53 million. Salt-water flooding in the Houston-Galveston area from hurricane storm surges is far more devasting than flooding from a six-ft tide, as discussed by Warren and others (1974). In 1961, Hurricane Carla with a peak flood surge of 16.4 ft (4.8 m) flooded 123 $mi^2$ (320 $km^2$) of Harris and Galveston Counties surrounding Galveston Bay. With the subsidence that has occurred between Hurricane Carla (1961 and 1973), an additional 25 $mi^2$ (64 $km^2$) of land can be expected to be flooded (an increase in the flooding area of about 20 percent) in a hurricane of the same magnitude and characteristics of Carla. The environmental impact of faulting and subsidence in Harris and Galveston Counties is high, because of their population density, low elevation, and proximity to the Gulf of Mexico.

Two recent legal decisions will probably have significance on the social and environmental impacts of subsidence in the coastal zone. In an attempt to control subsidence in the greater Houston area (Harris and Galveston Counties), the Texas Legislature in 1975 created the Harris-Galveston Coastal Subsidence District with the power to control well spacing and prevent excessive ground-water pumpage (Sec. 29, Ch. 284, Act 64, Leg. 1975). The district is presently trying to restrict ground water usage in the area but also to augment needed supplies by the importation of surface water.

The Supreme Court of Texas recently ruled (November 29, 1978) that ground-water producers could be legally liable for damages resulting from subsidence, if the landowner's production was negligent, willfully wasteful, or for the purpose of malicious injury (Supreme Court of Texas No. B-6682). Texas ground-water law had previously followed the doctrine of absolute ownership--landowners had absolute rights to ground water produced from their land regardless of the impact on surrounding owners (with the exception of wasteful use or an intent of malicious injury). Producers are now liable if their production can be shown to be negligent.

The ecological impact of subsidence in the Texas Coastal Zone is not known. Much of the zone is at an elevation relatively close to sea level. The shoreline is composed of bays, estuaries, and bayous. These water bodies are breeding grounds for finfish and shellfish populations in the Gulf of Mexico. Land subsidence in the greater Houston area should have impacted the aerial distribution of wetlands and open-water sections of Galveston Bay. The impact that subsidence has had on these biologic communities may be significant, but is not known.

## Potential Subsidence and Fault Activation from Geothermal-Geopressured Energy Production

Production of geothermal water from geopressured zones in Tertiary Gulf Coast sediments has potential for inducing surface subsidence and for fault activation. Estimates of potential fault movement and land subsidence can be made from simple mathematical models and by drawing analogies with subsidence and faulting attributed to production of oil, gas, and shallow ground water elsewhere in the Gulf Coast.

The high porosity (relatively speaking) of geopressured mudstones creates the potential for surface subsidence. Production of large quantities of water from geopressured sandstones may permit depressuring of intercalated or surrounding geopressured mudstones and a subsequent decrease in mudstone porosity. If pressure reduction occurs, the reservoir will undergo some compaction. Some of this compaction may be translated to land subsidence.

Where there are no lateral barriers to a geothermal reservoir, groundwater production may lead to reservoir compaction and subsequent land subsidence over an extensive area. Most geothermal reservoirs, however, will probably be located between major growth faults that may act as lateral permeability barriers. Geopressured-geothermal fluid production and subsequent pressure declines may be confined to reservoirs within fault blocks. Differential compaction of sediments within a fault block may then cause fault movement and differential subsidence at land surface.

In considering the potential impact of land subsidence and fault activation from geothermal production, three questions need to be addressed: (1) How much compaction of the reservoir will occur? (2) How much of the reservoir compaction will be translated to the land surface in the form of land subsidence and (3) What is the potential for fault activation?

## Potential for Reservoir Compaction

The potential for reservoir compaction can be evaluated using three different approaches (Gustavson and Kreitler, 1976). The first method estimates the probable compaction of reservoir mudstones ($\Delta m$) using equation 1 (modified from Domenico, 1972, p. 234). For a potential geothermal reservoir, probable mudstone compactions are calculated as the products of the estimated specific storage ($S'_s$), the known mudstone thickness (m), and various assigned pressure declines ($\Delta h$) (Equation 1).

$$\Delta m = S'_s h m$$

where

$m$ = clay thickness

$\Delta m$ = change in clay thickness

$S'_s$ = specific storage, $3.3 \times 10^{-4} m^{-1}$ (Papadopulos and others, 1975)

$\Delta h$ = pressure decline

Using equation (1), Gustavson and Kreitler (1976) calculated 5 ft to 100 ft (1.6 to 31 m) of potential compaction in the Armstrong field, a deep geopressured gas field.

The second approach in estimating potential compaction of geopressured mudstone is to multiply the thickness of mudstone in a reservoir by the long-term decrease in porosity caused by a decline of pore pressures (equation 2).

$$\Delta m = \Delta \phi m$$

where

$m$ = clay thickness

$\Delta m$ = change in clay thickness

$\Delta \phi$ = change in porosity

Using these porosity decreases, the mudstone thickness for the Armstrong wells, and equation 2, the calculated vertical compaction for the mudstone in the Armstrong Reservoir varies from 2.2 to 22 ft. (0.7 to 7 m). For details of these calculations see Gustavson and Kreitler (1976).

Geothermal ground-water production will probably cause mudstone compaction within geopressured reservoirs. The first and second approaches predict significantly different upper limits of compaction because of differences in the initial assumptions used in the calculations. Papadopulos (1975) estimated the compaction of a geopressured reservoir to be approximately 1 m by determining sandstone compressibility and mudstone compaction. His mudstone compaction was based on Hantush's (1960) leaky-aquifer theory. This theory provides a third, different estimate of reservoir compaction. A more accurate estimate for reservoir compaction will be known only when mudstone compressibilities can be determined experimentally with actual core material from a geopressured-geothermal reservoir. The different approaches, however, suggest that some mudstone compaction should be expected when pore pressures are lowered significantly within the reservoir.

White and others (1978), in an environmental assessment of the Brazoria County geothermal fairway, estimated surface subsidence to be 7 inches (17 cm) in the first 2 years and 12 inches (30 cm) after 5 years. These estimates are based only on sand compressibility and also represent the residual strain that has reached the land surface. Total compaction would therefore be expected to be greater.

## Potential for Surface Subsidence

The methods for estimating potential reservoir compaction are not directly applicable for estimating land subsidence because the translation of compactional strain at depth to land subsidence has not been considered. The resultant strain from reservoir compaction may be partially absorbed by overlying sediments. Geertsma (1973) and Finol and Farouq Ali (1975) have shown that for equal amounts of reservoir compaction, land subsidence will diminish as reservoir depths increase and as lateral dimensions of the reservoir decrease. Although they are deep, geothermal reservoirs are expected to have extensive lateral dimensions. The potential for land subsidence, therefore, needs to be considered.

Geertsma (1966, 1973) quantified the interaction of an isloated shrinking inclusion, the reservoir, and the overlying sediments. With Geertsma's (1966) theory of poroelasticity and Geertsma's (1973) tables, approximate values for land subsidence as a result of reservoir compaction can be calculated. For the Armstrong field, assumed to be a disk-shaped reservoir with a radius of

30 miles (4.8 km), approximately 37 percent of the compaction at the center of the reservoir could be translated into subsidence. The potential land subsidence can be evaluated by multiplying the reservoir compaction (first and second approaches) by this translation percentage. Land subsidence could vary from 1 foot (0.3 m) to more than 30 ft (10 m).

The percentage of compaction translated to the surface as land subsidence will probably be greater than predicted by Geertsma's (1973) equations because of structural control in the Gulf Coast. Geertsma's (1973) equations assume that the strain will be translated upward as an inverted cone. Because of the fault control of the reservoir and overlying sediments the translation of compaction strain upward may be restricted by the faults rather than spreading laterally in the inverted cone. A greater percentage of the compaction may therefore reach land surface.

One location where surface subsidence is associated with hydrocarbon production from deeply-buried sediments is the Chocolate Bayou field on the Gulf Coast (Gustavson and Kreitler, 1976). There has been more than 1 foot (0.3 m) of subsidence in the Chocolate Bayou oil and gas field, where production is at depths of 8000 to 15,000 ft (2,438 to 5,000 m). Oil production has been from deep normally pressured horizons (8,000 ft - 12,000 ft) (2,438 to 3,962 m) whereas gas production has been from the deeper geopressured zone. Periods of maximum rates of annual subsidence do not coincide with periods of maximum oil production but rather with periods of maximum gas production from geopressured horizons. If subsidence results from oil production, then there is a lag period during which strain is transmitted from the producing horizon 8,000 to 12,000 ft (2,438 to 3,962 m) to the surface. An additional unknown at Chocolate Bayou is the brine production. Water production did increase during the years of declining oil production (Grimsrud and others, 1978). If brine production was sufficiently high in later years there may not be an apparent lag between fluid production and subsidence. Sediment compaction from oil, brine, and gas production from the deep hydropressured or geopressured horizons appears to be the cause of land subsidence. Land subsidence over the Chocolate Bayou oil and gas reservoir further suggests that the possibility of subsidence from geopressured geothermal fluid ground-water production should be given serious consideration.

Surface faulting may accompany land subsidence from geothermal-geopressured energy production. The geothermal-geopressured fairways described by Bebout and others (1978) are fault controlled. It is expected that reservoir compaction will be fault controlled and differential reservoir compaction will be translated upward along the fault surface. This phenomenon is believed to be the mechanism causing surface faulting over actively producing oil and gas fields. Whether faulting will result from differential compaction in the geopressured reservoir is not known.

## Subsidence Monitoring Techniques

The potential of land subsidence and surface faulting is a major concern in large scale geothermal-geopressured fluid production. Understanding reservoir compaction and mechanisms of fault activation are important generic studies. They cannot, however, predict precisely where and how much subsidence will occur. Monitoring techniques for subsidence are the only approaches for accurately determining the impact that fluid production has had and will have at land surface. There are two basic approaches to surface monitoring (1) releveling of benchmarks by precise surveying techniques, and (2) strain meters.

Regional and Local Leveling Networks

A precise leveling network is a series of benchmarks that are tied to a datum point of known elevation. The amount of subsidence (or rebound) is determined by multiple determination (at different times) of the precise elevation of each benchmark. The difference in elevation represents the amount of subsidence that has occurred between measurements. Leveling surveys generally are one of two types: (1) regional surveys that cover large geographic areas and are designed to measure absolute elevations, and (2) local nets which cover smaller areas with a greater density of benchmarks but are designed to indicate relative elevations because they are only tied to one benchmark of a regional network whose absolute elevation may not be known at the time of measurement.

Throughout the Texas Coastal Zone, the National Geodetic Survey (NGS) has maintained an extensive regional network of first-order and second-order surveys. The first leveling program was a first-order line from Smithville to Galveston surveyed in 1905 and 1906. In 1918, a first-order line was established from Sinton, Texas, to New Orleans, Louisiana. During the period between 1932 and 1936, several other first- and second-order lines were established, and the two original lines were releveled. In 1942 and 1943, a large number of second-order lines were established and most of the older lines were releveled. Following the leveling program of 1942-1943, subsidence in the Houston area was first documented. Subsequently, releveling surveys were completed in 1951, 1953-54, 1958-59, 1964, and 1973. These surveys clearly establish the extent and amount of subsidence in the lower Texas coastal plain. Additional surveying has been done by the U.S. Geological Survey, various agencies in the Houston area, and the Texas Highway Commission in the Kingsville, Texas area (Lofgren, 1977). The most recent regional leveling program was conducted by the National Geodetic Survey (for U.S. Department of Energy) from Houston to Corpus Christi. This benchmark network was to establish absolute elevations over all prospective geothermal-geopressured fairways in the Texas Coastal Zone.

A critical problem with regional leveling networks is tying the regional network to a datum where the absolute elevation is known. For the most recent NGS leveling in the Texas Coastal Zone (1978) the survey was tied to Austin, Texas for a stable benchmark. Lofgren (1977) suggests that leveling surveys could frequently tie to tidal benchmarks and this might alleviate the problem of tying to stable benchmarks far from the area of interest. In the Texas Coastal Zone there are over 100 tidal stations. Robert Gabrysch (USGS Water Resource Division, Houston, Texas) is investigating the use of tidal gauges as controlled datum points. Precision is expected to be within 0.1 ft (3 cm). This precision may be sensitive enough for subsidence studies in the greater Houston area, but may not be sufficient for base level subsidence or subsidence from a geothermal-geopressured field where amounts of subsidence are expected to be less than in the Houston area.

General locations of tidal stations and NGS benchmarks are provided by Lofgren (1977). Van Til (1978) describes in detail techniques for establishing releveling networks for subsidence resulting from geothermal operations.

## Other Surface Monitoring Techniques

Benchmark releveling networks are very worthwhile but do have their limitations. They are expensive, provide a limited amount of data, and can only be resurveyed every couple of years. If significant detrimental subsidence results from fluid production, a releveling program measures what has already occurred and in some cases after the environmental damage has resulted. In environmentally sensitive areas more rapid response monitoring techniques are needed. Tiltmeters and strain gauges may be the most suitable alternative to benchmark releveling techniques.

Strain gauges (tiltmeters and horizontal strain gauges) measure rotations or tilts of the land surface. Subsidence generally is not uniform over a fluid-producing, compacting reservoir. Sensitive tiltmeters are capable of measuring very slight variations of subsidence as land tilt. Tiltmeters can measure rotations as sensitive as approximately 1 second of arc (Van Til, 1978). Davis and others (1969) have shown excellent correlations between head decline from shallow pumping wells and surface strain gauges measuring land tilt. Small tiltmeters and strain gauges, which measure tilt in a relatively small area (a few meters), have intrinsic problems that may be unacceptable to monitoring subsidence from deep geothermal-geopressured fluid production. Most electronic surface strain gauges have a problem of electronic drift (i.e. the meter over time indicates movement although there is none). The translation of strain from a deep compacting geopressured reservoir to the surface probably will not be instantaneous. The use of surface strain meters devices that have electronic drift would unduly complicate monitoring. Also, compaction at depth of geopressured reservoir may not translate to the land surface as differential subsidence in the small area being monitored by the meter. The differential subsidence will probably occur over a large area and not be detected by the meter.

Multiliquid tube tiltmeters may resolve the previously stated problems. Liquid tube tiltmeters are non-electric and therefore do not have the electronic drift problem. The multiliquid approach provides a correction for ambient temperature gradients along the tubes (Huggett and others, 1976). The length of the tubes can be up to 1 km long. Differential subsidence should be measurable in that distance. A multiliquid tiltmeter has been installed at the Pleasant Bayou test site and is discussed in more detail under Ongoing Programs.

Ongoing Programs Related to Geothermal-Geopressured Fluid Production

Three current research programs at The University of Texas address environmental problems associated with the development of geopressured-geothermal energy. The Bureau of Economic Geology is monitoring subsidence, air and water quality, noise, ecosystem quality, and microseismicity at the Pleasant Bayou No. 1 geopressured-geothermal test well in Brazoria County. BEG is also preparing to undertake environmental analyses of two potential test well sites in DeWitt and Harris Counties.

(1) Subsidence Monitoring Program

The National Geodetic Survey in 1978 completed a leveling network of benchmarks from Houston to Corpus Christi. This benchmark network crosses several geothermal fairways, Pleasant Bayou fairway, Matagorda fairway, Corpus Christi fairway, and the Chocolate Bayou field. The level lines across the geothermal fairways are located along lines where there had been previous surveys. Estimates of levels of non-geothermal induced subsidence are being determined.

(2) Pleasant Bayou Environmental Monitoring

The Pleasant Bayou monitoring study is designed to address all major environmental impacts that may arise from production tests at the drill site. The study is developing base-line data banks for air and water quality (both surface and ground water), noise, subsidence, and microseismicity.

The National Geodetic Survey has recently completed a releveling of vertical control benchmarks in the Pleasant Bayou area and has tied their lines to benchmarks at the test well site. Teledyne Geotech has completed a regional loop (18 miles) and a closely spaced net of level lines around the well site. Additional releveling surveys will follow after fluid production begins.

Dr. James Dorman, Geophysical Laboratory, The University of Texas at Galveston, will install a 1 km long multiliquid tube tiltmeter on a radius outward from the test well. Sensitivity of the instrument is expected to be in the order of 1 mm. Differential subsidence or tilt of the land surface will be recorded, if it occurs.

Teledyne Geotech is conducting microseismic surveys of the test well area. Using a network of five geophones, events of magnitude 0.25 to 0 are currently recognized. To avoid surface noise from traffic and pipelines, the next generation survey will have geophones at the bottoms of 30 m deep holes. In this configuration the monitoring network will detect events of magnitude -0.25 to -0.5.

(3) Compaction Measurements on Texas Gulf Coast Sandstones and Shales

The purpose of this study is to evaluate the effect of pore pressure declines from geopressured-geothermal water production on porosity and permeability of the shales and sandstones associated with a producing reservoir. Potential problems generated with a loss of porosity and permeability are (1) decreased reservoir efficiency, (2) non-uniform deformation of the overburden that will induce shear stresses and may reactivate growth faults, and (3) land surface subsidence.

Deformation of geopressured shales and sandstones will be accomplished through a series of triaxial and hydrostatic tests at varying temperatures and pore pressures in an attempt to simulate geopressured-geothermal conditions. Core from the Pleasant Bayou test well will be used to evaluate rock compressibility. This work is being conducted by Dr. Ken Gray and Dr. William Thompson of the Center for Earth Sciences and Engineering of The University of Texas at Austin.

(4) Compaction and subsidence modelling on Texas Gulf Coast geopressured sediment

Compressibility data obtained in the compaction program previously discussed will be input into a modelling effort to predict compaction and subsidence at the Brazoria Fairway test well site. This work is being conducted by Dr. Ken Gray and Dr. William Thompson of the Center for Earth Sciences and Engineering.

## Project Plan

Programs to more definitively evaluate potential environmental problems of subsidence and faulting resulting from geothermal-geopressured energy production are categorized into the following six groups: (1) Subsidence monitoring, (2) seismicity monitoring, (3) mechanisms of subsidence and faulting, (4) impacts of subsidence on biologic systems, (5) impacts of subsidence on economic and social systems, and (6) methods of measurement of crustal elevation change and reservoir compaction.

(1) Subsidence Monitoring

Benchmark monitoring to determine background, non-geothermal, subsidence, and benchmark monitoring over producing geothermal-geopressured reservoirs are the most critical aspect of subsidence/faulting aspects of the environmental plan. Ongoing programs are presently identifying the regional component of subsidence. A high density network of benchmarks at the Pleasant Bayou prospect have been installed and leveled. After fluid production at the test well has been operational for approximately 1 year, the benchmarks over the field should be relevelled. If other fairways are considered, the testing or full scale production benchmark networks need to be established.

(2) Seismicity Monitoring

Continued monitoring of microseismicity at test well sites and other localities is needed. Additional information is needed to determine whether there is presently any natural seismic activity in the Gulf Coast. Deep oil and gas field and large fluid injection programs should be monitored to determine if microseismicity is associated with these operations. Microseismicity needs to be monitored at all test well operations.

(3) Mechanisms for Subsidence and Faulting

The potential of land subsidence from geopressured-geothermal energy production is conjecture at this time. There is presently no large-scale water production from the geopressured zones. Subsidence measurements over geopressured gas fields are complicated by oil and formation-water production from the hydropressured zone (e.g., Chocolate Bayou field). There is no definitive case of known subsidence from the fluid production from the geopressured zone. Three approaches can be taken to evaluate the problem: (1) construct a high-yield well in the geopressured zone, produce it to see if subsidence results, (2) conduct compressibility studies of sediments from geopressured zone, and (3) draw analogies to subsiding areas resulting from fluid production.

All three of these approaches have been or are being used in evaluating subsidence potential in the Texas Gulf Coast. (1) A well has been drilled at the Pleasant Bayou site and land surface is being monitored for crustal elevation changes. (2) The Center for Earth Sciences and Engineering is conducting compressibility tests on core from the Pleasant Bayou site and predicting subsidence, and (3) studies of analogous subsidence from ground water, and oil and gas production have been made (e.g., Gustavson and Kreitler, 1976). These studies hopefully will resolve the major questions.

(4) Impact of Subsidence on Surface Ecosystems

The geothermal-geopressured fairways in the Frio underlie bays, estuaries, and bayous of the Texas Gulf Coast. The bays and estuaries are the breeding grounds and nursery for the fish and shellfish populations in the Gulf of Mexico. Much of the subareal land has an elevation below 15 ft (5 m). Broad, regional land subsidence from geothermal-geopressured water production could significantly alter the ecosystems in these low-land areas. Biologic assemblages may have adapted to certain depth ranges. Optimum circulation of nutrients in bays and lagoons may be controlled by bay depth. Regional changes of elevation could significantly alter the ecosystems in these low-lying areas, particularly for the short-term and possibly for the long-term.

Two research programs are recommended. The impact of the subsidence on coastal ecosystems can be determined by (1) ecosystems studies of coastal water bodies in areas of severe subsidence and (2) by determining the geographic area affected. The land around Clear Lake on the county line between Harris and Galveston Counties, Texas and Galveston Bay in the Baytown, Texas, area have both subsided over four feet in the last thirty years. These areas would be optimum field areas to study ecosystem changes resulting from subsidence. Critical questions to be addressed are (1) how have biological communities responded to depth of water changes? and (2) what are the short-term versus long-term effects? The geographic area of low-land ecosystems also needs to be determined. If the amount of wet-lands to be impacted is relatively small, the regional impact is small. If the area is large, the regional impact may be significant. A quantitative study of the amount of land that would change ecosystems from given amounts of subsidence is needed. How much land with a given amount of subsidence would convert from coastal prairie to wet-land or how much wet-land to bay and estuary. These are critical problems that could affect the gross productivity of these low lands.

(5) Economic Impacts From Subsidence

Few studies have been made that document the social and economic effects of subsidence in the Gulf Coast. The work of Warren and others (1974) documented the costs of one small area from one small storm in the Galveston Bay area. Kreitler (1977) calculated the area that would be inundated by a hurricane flood surge. Kreitler and McKalips (1978) counted the number of houses damaged by active surface faulting. No attempt has been made to calculate the financial impact of subsidence in the greater Houston area. Calculations of this type need to include loss of land values due to complete inundation and intermediate damage, loss of structures (houses, buildings, bridges, etc.) and the cost to local, state, and federal governments.

(6) Indirect Measurements of Reservoir Compaction

Reservoir compaction is the prime unknown which will determine if subsidence will be a critical problem. Potential compaction can be estimated by compressibility testing of core samples. Actual compaction will be measured at the borehole through radioactive bullet studies. Indirect geophysical measurements provide a third approach at measuring compaction/subsidence. Releveling networks and tiltmeters (as described in "Ongoing Research") measure the end product of compaction, subsidence.

Gravity surveys may be an additional approach to studying compaction in geothermal-geopressured reservoirs. In areas of fluid withdrawals, changes in gravity measurements may result from either fluid withdrawal and compaction or land subsidence. Gravity measurements will decrease with compaction and increase with subsidence. Gravity is capable of measuring subsidence on the order of a few centimeters. Gravity measurements at Wairakei geothermal field, New Zealand, have shown significant negative gravity changes beneath the subsidence bowl (Hunt, 1970).

It is recommended that a gravity study be initiated for the Pleasant Bayou geothermal-geopressured test site. A two-phase program should be instituted: (1) Review old gravity surveys through the Pleasant Bayou area and possibly other oil production areas where there have been multiple surveys. (2) Conduct gravity surveys before and after test production at the Pleasant Bayou site. Before phase 2 is conducted, the applicability of this technique for evaluating mass changes from deep geopressured production should be evaluated. A gravity measurement is an averaged value of gravity for the sedimentary column beneath the meter. The gravity change from one meter of compaction at 15,000 ft (5000 m) may be below the sensitivity of the gravity meter.

Cost Estimates for General Tasks

| | |
|---|---|
| 1. Subsidence Monitoring (detailed network over one field with survey before and after production) | $ 75,000 |
| 2. Seismic Monitoring (detailed microseismic monitoring one field for one year) | 125,000 |
| 3. Gravity Measurements (detailed network over one field with survey before and after production) | 50,000 |
| 4. Subsidence Impact on Ecosystems | 75,000 |
| 5. Economic Impacts | 100,000 |

## Ecosystem and Air Quality Workshop

The purpose of the Ecosystem and Air Quality Workshop was to discuss the potential environmental impact from geothermal-geopressured fluid production and disposal and the monitoring programs necessary to insure environmental quality.

Potential air quality problems are releases of $H_2S$ and its subsequent oxidation to $SO_2$ and $NH_3$ releases. It was felt that fluid reinjection would reduce potential for releases. Because of the variability of water quality from geopressured reservoirs, it is impossible to predict what air quality problem will result from a specific operation. Also the establishment of additional air quality networks in the Texas Coastal Zone for monitoring ambient conditions is not needed because of a satisfactory network already in operation. At each test facility an air quality monitoring station should be established.

The panel agreed that major ecosystem problems could result from land subsidence and the surface release of disposal fluids. Subsidence could alter shorelines, cause changes in wetland areas, changes in circulation patterns in the bays, and convert prairie land to marsh land.

Surface disposal of geothermal fluids could significantly impact the ecosystems into which the fluid is disposed. Altering the temperature and salinity regime of a lagoon or estuary would impact the ecosystem. The input of trace toxic elements might be fatal to specific species. Long-term inputs of sublethal concentrations might impact the overall ecosystem by affecting reproductivity, growth rates, and general vigor of different species.

It was concluded that reinjection of spent fluids was environmentally far more acceptable than surface disposal. The following list includes the participants in the Ecosystem and Air Quality Workshop.

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## Subsidence, Faulting, and Seismicity Workshop

The purpose of the Subsidence, Faulting, and Seismicity Workshop was to discuss the potential of these phenomena resulting from large-scale geothermal-geopressured energy production. The following outline summarizes the areas of discussion.

A. Nature and extent of potential geothermal-geopressured energy development in Texas Gulf Coast

B. Environmental Impacts
   1. Subsidence
   2. Faulting
   3. Seismicity

C. Mechanisms of Subsidence, Faulting, Seismicity
   1. Subsidence
      a. compaction
      b. translation of compactional strain to land surface
   2. Faulting
      a. geologic mechanisms of movement
      b. man-induced mechanisms of movement
   3. Seismicity
      a. natural seismicity
      b. man-induced seismicity
      c. monitoring techniques

D. Legal and regulatory considerations

Several general conclusions were reached. The potential for subsidence from large-scale geothermal-geopressured fluid production is very real. The location of geothermal-geopressured fairways in environmentally sensitive coastal areas makes the environmental problems more critical.

The behavior of shales and sands composing the reservoirs are not understood. The problem of whether shale compaction will occur is dependent on their porosity and whether there will be adequate drainage of the shales once there are significant pressure declines in the reservoir sands. It was suggested that microfracturing of the shales (by hydrofracting) would permit drainage of the shales. Several participants commented that we don't understand the rheological character of sediments at these temperatures and pressures. Rock samples at the surface may be rigid and brittle but in places (at several thousand feet below land surface) they may deform plastically. Because of this difference in the rheological character of deeply buried sediments, the comparison of subsidence potential of geopressured reservoirs to shallow ground water aquifers or deeper oil and gas fields may not be analogous.

Seismicity from either large-scale production or reinjection of geothermal fluids was considered as a definite possibility. Depressuring of the reservoir may alter the rheological nature from being able to deform plastically to rigid sediments, which would deform by brittle failure. It was felt that reinjection might increase pore pressures on fault zones and subsequently cause fault movement.

It was agreed that the best safeguards from environment damages resulting from subsidence, faulting, and seismicity were surface monitoring programs. It is critical that adequate subsidence monitoring and seismic monitoring programs be maintained in the geothermal production areas. The following list includes participants in the Subsidence, Faulting, and Seismicity Workshop.

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