Title

A PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPMENT. EDAW-ESA

Permalink

https://escholarship.org/uc/item/8sz6n4hq

Authors

Inc., EDAW
Division, EarthSciences

Publication Date

1980-12-01

561
5-14-81

R4306

Dr. 2643

LBL-12392
UC-66e
GSRMP-10

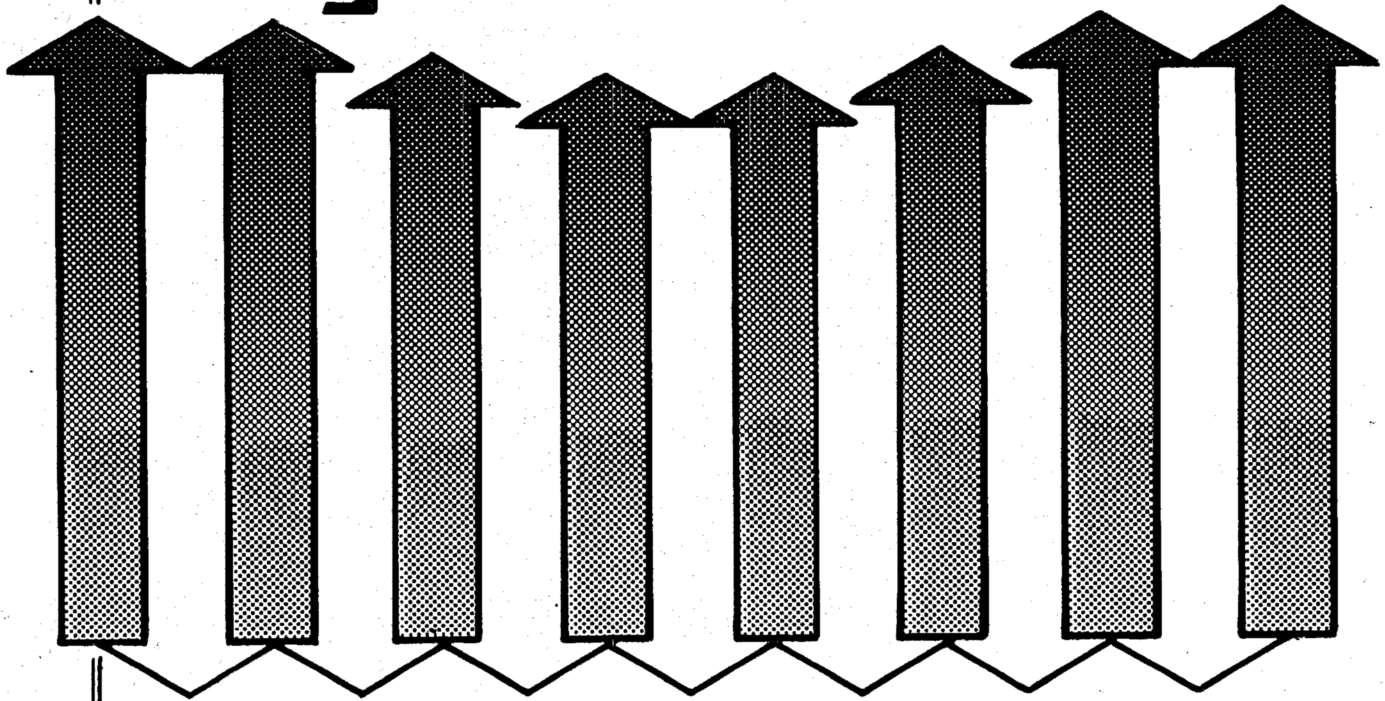
A Problem Definition Study of Subsidence Caused by Geopressured Geothermal Resource Development

EDAW-ESA,
a Joint Venture of EDAW Inc.
and Earth Sciences Associates

701 Welch Road
Palo Alto, California 94304

December 1980

Geothermal Subsidence Research Management Program



Earth Sciences Division
Lawrence Berkeley Laboratory
University of California

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A10

EDAW·ESA

LBL-12392

GSRMP-10

A PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPMENT

9513318

EDAW-ESA, a Joint Venture
✓ of EDAW Inc. and Earth Sciences Associates, 9509668
701 Welch Road
Palo Alto, California 94304

Prepared for:

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

December, 1980

This work was supported by the Assistant Secretary for Resource Applications, Office of Industrial and Utility Applications and Operations, Geothermal Energy Division of the U. S. Department of Energy under Contract W-7405-ENG-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ZB

FOREWORD

This report was prepared by EDAW-ESA under Lawrence Berkeley Laboratory Purchase Order 4501810 during the contract period of October 1, 1979 to September 30, 1980. EDAW-ESA is a joint venture of EDAW Inc., an environmental planning firm, and Earth Sciences Associates (ESA), a geotechnical consulting firm. General responsibilities for various phases of this work were as follows:

Project Management: EDAW-ESA, a joint venture. Richard C. Harding, Principal-in-Charge: Barbara Turner and Linda Lee, Project Managers.

Environmental Studies: EDAW, Inc., Alison Massa, Project Manager.

Development Scenarios: Gruy Federal, Inc., Lynn McCoy, Project Engineer.

Subsidence Estimates: ESA, Richard L. Meehan, Principal Engineer and Linda Lee.

In addition, preliminary results were reviewed and many useful suggestions were made by a review board which included:

Anna Bachman,	Louisiana State University Energy Programs Office
Zaki Bassiouni,	Louisiana State University Department of Petroleum Engineering
Ken Gray,	University of Texas Department of Petroleum Engineering
Ray Gregory,	University of Texas Bureau of Economic Geology

Tom Gustavson,	University of Texas Bureau of Economic Geology
Wayne Kraus,	Amoco Production Company Tulsa, Oklahoma
Eugene Turner,	Louisiana State University Center for Wetland Resources
Virginia Van Sickle,	Louisiana Geological Survey Baton Rouge, Louisiana
Ray Wallace,	U. S. Geological Survey NSTL Station, Missippi
Keith Westhusing,	Department of Energy Houston, Texas

This research was a part of the ongoing Geothermal Subsidence Research Program being conducted by Lawrence Berkeley Laboratory of the University of California, under the auspices of the Division of Geothermal Energy of the U. S. Department of Energy. The contract was administered under the technical direction of N. Goldstein, J. E. Noble, J. Philips, W. Schwarz, and R. Sterrett. The contract officer was H. A. Todd.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

5. ESTIMATION OF SUBSIDENCE (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1. INTRODUCTION

1.1 BACKGROUND

Subsidence of the land surface is certainly one of the most potentially significant environmental impacts associated with projected development of Gulf Coast geopressured geothermal resources. In fact, Hartley (1980, p. 5) of the Environmental Protection Agency has stated that subsidence may be "the number one environmental problem" associated with development of this resource. Any subsidence-related impacts would be especially severe in the Gulf Coast region because many of the geopressured fairways[1] are located along or near the coast, where relatively small amounts of subsidence could result in potentially large economic losses due to inundation. However, if the location and amount of possible subsidence could be reliably estimated prior to resource development, appropriate mitigation or preventive measures might be taken.

Recognizing the importance of this potential problem, the Lawrence Berkeley Laboratory (LBL) of the University of California, under direction from the U.S. Department of Energy-Division of Geothermal Energy, contracted EDAW-ESA to take an overall view of the potential development-caused subsidence problem and to suggest a research program that would assure all significant uncertainties, problems, and impacts would be considered and adequately evaluated. This present report constitutes the basis for the recommended research program; it is an analysis of subsidence potential and associated environmental and socioeconomic impacts at representative Gulf Coast sites. Out of this analysis emerged the problems and uncertainties that are the current limiting factors to an accurate estimate of potential subsidence and impacts caused by resource development. These problems and uncertainties are addressed in an unpublished EDAW-ESA research program plan.

---

[1] A fairway is the area of ground surface directly above major sand bodies within which promising geopressured geothermal reservoirs might exist.

1.2 SCOPE

This investigation began with inventorying the environmental and socioeconomic settings of four environmentally representative Gulf Coast geopressured geothermal fairways. Concurrently, subsidence predictions, prepared using feasible development scenarios for the four representative subsidence sites, were made. Based on the results of the subsidence estimates, an assessment of the associated potential environmental and socioeconomic impacts was prepared. An inventory of mitigation measures was also compiled.

These studies are brought together in this final report. Results of the subsidence estimates and impact assessments are presented, as well as our conclusions as to what are the major uncertainties, problems, and issues concerning the future study of geopressured geothermal subsidence.

1.3 SITE SELECTION

Four representative prospects[2] were selected for subsidence analysis, and four were selected for impact assessment. The process used to select these sites is summarized in Appendix A.

The four prospects selected for subsidence analysis are:

- Southeast Pecan Island Prospect (Southeast Pecan Island Fairway), Louisiana
- Austin Bayou Prospect (Brazoria Fairway), Texas
- Gladys McCall Prospect (Gladys McCall Fairway), Louisiana
- Cuero Prospect (Dewitt Fairway), Texas

The principal factors favoring selection of these four sites was the availability of detailed subsurface data, DOE development priorities, and the objective of obtaining a cross section of possible reservoir types.

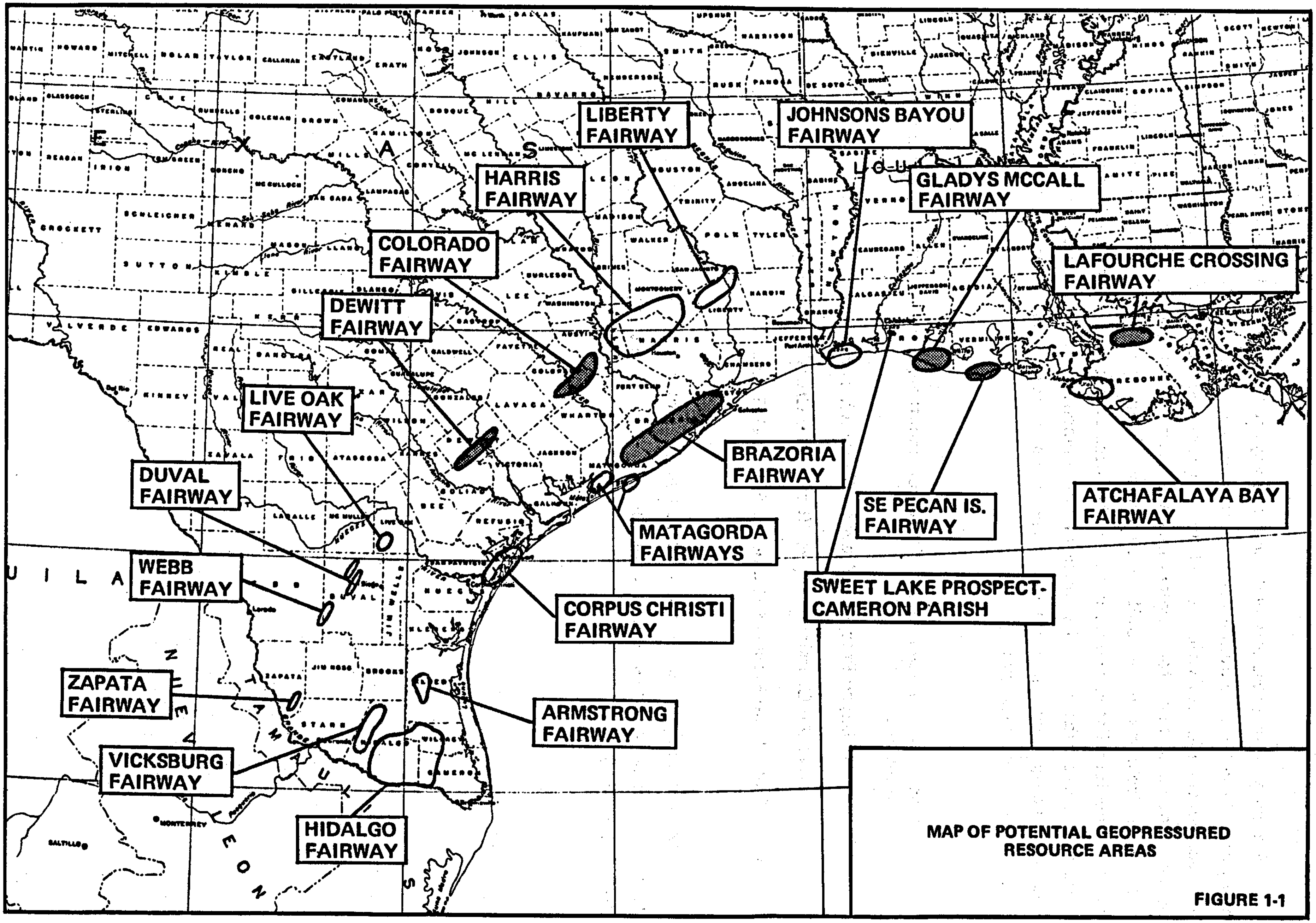
---

[2] A prospect is the area of ground surface directly above a promising geopressured geothermal reservoir.

Similarly, four prospects and their fairways were selected for environmental analysis. These sites contain a cross section of the types of natural environments and socioeconomic activities found in geopressured geothermal fairways and, hence, provide a basis for a generalized assessment of the scope of potential subsidence problems in the Gulf Coast region. Only two of these sites were the same as the four listed above, because the sites selected for subsidence analysis were not representative of the range of environmental settings present within the geopressured geothermal fairways. The sites selected for environmental and socioeconomic analysis are:

- Southeast Pecan Island Prospect (Southeast Pecan Island Fairway), Louisiana
- Austin Bayou Prospect (Brazoria Fairway), Texas
- Lafourche Crossing Prospect (Lafourche Crossing Fairway), Louisiana
- Eagle Lake Prospect (Colorado Fairway), Texas

The locations of all sites considered in the selection process are shown in Figure 1-1. The fairways selected for further study in this report are stippled on the location map.



MAP OF POTENTIAL GEOPRESSURED RESOURCE AREAS

FIGURE 1-1

2. SUMMARY OF RESULTS

The major results of this report are subsidence estimates and related calculations (such as area affected by significant subsidence, rate of subsidence, tilt, and horizontal movement), and the potential environmental and socioeconomic impacts associated with these calculated values. These data are presented in Tables 2-1 and 2-2. The subsidence estimates are based on certain assumptions, known cumulatively as development scenarios, used to model reservoir development. Some of the assumptions common to all prospects are:

- each prospect is developed with one well.
- no reinjection takes place at any depth.
- there is no surface distortion due to movement of growth faults.

The development scenario assumptions particular to each of the four subsidence analysis sites are summarized in Table 2-3.

Table 2-1 shows what we believe to be the most realistic subsidence estimates based on recent laboratory data. These laboratory data suggest that sandstone and shale compressibilities may be quite low. However, the data on shale compressibilities are not sufficient to provide a high level of confidence. Therefore, "more conservative" estimates have been calculated based on a higher, but still credible, shale compressibility and are presented in Table 2-2. Even these estimates are lower by far than some earlier subsidence estimates (Kreitler and Gustavson, 1976; Papadopulos and others, 1975).

Tables 2-1 and 2-2 also show, for each prospect, 1) the surface area estimated to be affected by 0.5 ft or more of subsidence, 2) the subsidence rate, i.e., how much the ground surface is predicted to subside per year, 3) the maximum expected tilt of the ground surface, and 4) the maximum expected horizontal movement. The range of elevation and general topography are given for each prospect, also, to give the reader an idea of the geography of each prospect. Possible environmental and socioeconomic impacts of potential subsidence are identified on the basis of the subsidence and related estimates and the physical, hydrologic, biologic, and socioeconomic characteristics of each representative environmental site.

TABLE 2-1

ESTIMATED POTENTIAL SUBSIDENCE AND ASSOCIATED IMPACTS

Based on Shale Compressibility of $3x10^{-6}$ psi^{-1}*

	SUBSIDENCE							POTENTIAL IMPACTS			
PROSPECT	Vertical Subsidence (ft)	Area of Subsidence > 0.5 ft (sq mi)	Subsidence Rate (ft/yr)	Maximum Tilt (ft/ft)	Maximum Horizontal Movement (ft)	Range of Elevations	Topography	Physical	Hydrologic	Biologic	Socioeconomic
S.E. PECAN ISLAND	0.8	20	0.05 - 1st year 0.03 - 20th year	0.00004	0.5	Sea Level to 20 ft	Flat	◒	◒	◒	⊖
AUSTIN BAYOU	0.05	0	0.02 - 1st year 0.0005 - 5th year	0.000002	0.02	Sea Level to 40 ft	Flat to Hilly	○	○	○	○
GLADYS McCALL	0.4	0	0.02 - 1st year 0.01 - 20th year	0.00002	0.3	Sea Level to 20 ft	Flat (except levees)	⊖	⊖	⊖	⊖
CUERO	0.3	0	0.05 - 1st year 0.001 - 20th year	0.00001	0.1	150 ft to 400 ft	Hilly	⊖	⊖	○	⊖

Magnitude of Impacts: None ○ Slight ⊖ Moderate ◒ Greatest ●

Note: Magnitude of impact ratings are judgements based on comparative evaluation of estimated subsidence impacts in four site-specific areas of the fairways under consideration. Ratings for other prospects or fairways would differ.

*This appears to be a probable value of shale compressibility.

TABLE 2-2

ESTIMATED POTENTIAL SUBSIDENCE AND ASSOCIATED IMPACTS

Based on a Shale Compressibility of 3×10^{-5} psi^{-1} *

	SUBSIDENCE							POTENTIAL IMPACTS			
PROSPECT	Vertical Subsidence (ft)	Area of Subsidence > 0.5 ft (sq mi)	Subsidence Rate (ft/yr)	Maximum Tilt (ft/ft)	Maximum Horizontal Movement (ft)	Range of Elevations	Topography	Physical	Hydrologic	Biologic	Socioeconomic
S.E. PECAN ISLAND	4	100	0.3 - 1st year 0.2 - 20th year	0.0002	2	Sea Level to 20 ft	Flat	●	●	●	●
AUSTIN BAYOU	0.3	0	0.2 - 1st year 0.003 - 5th year	0.00002	0.1	Sea Level to 40 ft	Flat to Hilly	⊖	◒	⊖	⊖
GLADYS McCALL	2	20 (within faults) 60 (total bowl)	0.09 - 1st year 0.05 - 20th year	0.00007	0.7	Sea Level to 20 ft	Flat (except levees)	●	⊖	◒	●
CUERO	2	20 (within faults) 60 (total bowl)	0.3 - 1st year 0.007 - 20th year	0.0001	0.6	150 ft to 400 ft	Hilly	◒	⊖	◒	◒

Magnitude of Impacts: None ○ Slight ⊖ Moderate ◒ Greatest ●

Note: Magnitude of impact ratings are judgements based on comparative evaluation of estimated subsidence impacts in four site-specific areas of the fairways under consideration. Ratings for other prospects or fairways would differ.

*This appears to be a more conservative value of shale compressibility.

Table 2-3

SUMMARY OF DEVELOPMENT SCENARIOS

Prospect	Area (sq mi)	Reservoir Thickness Perforated (ft)	Depth to Reservoir (ft)	Production Life (years)	Initial Reservoir Pressure (psi)	Final Average Reservoir Pressure (psi)	Pressure Depletion, Δp, During Lifetime (psi)	Fluid Produced During Lifetime (bbl)
S.E. Pecan Island	20	500	14,000	20	13,000	9,390	3,610	247,422,000
Austin Bayou	18	60	14,800	5-1/2	11,045	8,277	2,768	16,921,000
Gladys McCall	16	500	15,000	20	14,200	9,619	4,581	251,174,000
Cuero	11	200	12,625	20	10,500	6,734	3,766	40,930,000

3. CONCLUSIONS

3.1 DISCUSSION OF RESULTS

Calculations based on the most up-to-date data available yield relatively small subsidence values at the geopressured geothermal prospects considered in this study. The associated environmental and socioeconomic impacts are likewise relatively small. Results of our study indicate that impacts will be nearly insignificant at the inland sites of Eagle Lake and Lafourche Crossing where natural ground elevations are well above sea level. Impacts at the coastal site of Southeast Pecan Island are potentially greater, because even small levels of subsidence, if unmitigated by human or natural means, could submerge coastal marshlands. However, mitigation measures now employed to control natural and man-made subsidence in the Gulf Coast region could be effective in controlling development-induced subsidence of the magnitude estimated. Projected subsidence caused by resource development at Austin Bayou is so small that, in our opinion, the associated impacts would be insignificant. These preliminary estimates and conclusions indicate that the subsidence impact hazards of geopressured geothermal resource development in the Gulf Coast are acceptably small.

3.2 SUBSIDENCE-RELATED PROBLEMS

A principal purpose of the study was to evaluate uncertainties in the subsidence estimates and to suggest research aimed at reducing these uncertainties. The uncertainties encountered are of several types, including limited knowledge of the influence of shale dewatering on reservoir compaction, limited field and laboratory data on sandstone and, especially, shale compressibilities in the geopressured zones, and imperfect knowledge of overburden characteristics, reservoir boundaries, and the influences on subsidence of natural surface geological processes, brine reinjection, and fault response to production and injection. These uncertainties are discussed briefly as follows:

1. Whether compaction of shale beds within and surrounding the reservoirs would actually occur within a time span of any practical significance is a matter of some controversy. Because shale is much more impervious

to the flow of water than sandstone, there is no doubt that shale will compact more slowly than the sand. One line of argument says that the shale compacts so slowly, in terms of any production time scale, that its contribution to subsidence would be unimportant; hence the shale component of compaction can be neglected. Another opposing view holds that the shale beds could be partially dewatered during the time of production, and that the compressibility of shale is so high that even partial dewatering (or depressurizing) would contribute substantially to subsidence (and fluid production).

In this study, partial shale dewatering was modeled using Terzaghi's theory of consolidation. However, it is not clear if Terzaghi's theory, which was developed for use at shallow depths and normal pressures, applies under geopressured geothermal conditions at great depth.

Compaction of compressible shale interbeds or confining beds, should it occur, could produce more fluid than compaction of the sandstone alone. Therefore, the role of shale dewatering needs to be clarified in order to model accurately reservoir compaction in the future.

2. Much of the current uncertainty (and controversy) over geopressured geothermal resource production and subsidence estimates is attributable to the paucity of data on compressibility of sedimentary rocks in the geopressured zone. Data on shale properties, in particular, are scarce. Some field and laboratory data suggest that the sediments are very rigid, to the extent that production would cause relatively rapid pressure decline and little compaction and subsidence. Much of the most recent data (e.g., Gray's tests on sandstones at the University of Texas, Austin) support this view. However, several investigators have considered that compressibilities and dewatering rates of the sediments, particularly the shales, could be much higher than the limited lab data would suggest, an assumption that leads to much larger production and compaction/subsidence estimates.

Our analyses were based on current lab data that indicate reservoir materials are relatively rigid. This leads to the conclusions that compaction and subsidence will be relatively small. Best estimates of subsidence rates are typically on the order of 0.05 in. or so per year. This has important implications for the feasibility of geopressured geothermal resource development. However, the conclusions are based on very few laboratory tests. Confirmation of these preliminary results is needed.

It must also be remembered that compressibility changes with changes in pressure. Assuming there will be no reinjection into the producing zone, the pressure within the reservoir will decrease during production, and the rock will be subject to a pressure change. A single value for compressibility may, therefore, not be a valid representation of a rock's compressibility during depressurization. To model accurately reservoir compaction, this factor needs to be taken into consideration.

3. Overburden material properties are needed to model realistically the transformation of reservoir compaction to surface subsidence. Although much rock property data exist for both shallow and very deep rocks in the Gulf Coast, due to extensive oil and gas exploration in those zones, the intermediate zone (the major part of the reservoir overburden) has not been as well studied. Thus, necessary rock property data for the bulk of the overburden are lacking and this contributes additional inaccuracies to predicting surface subsidence.

4. The dimensions, or volume, of the prospects are important in both reservoir flow modeling (which is the first step in reservoir compaction calculations) and the transformation of reservoir compaction to surface subsidence. At present, these volumes are not known to an acceptable level of confidence.

It is generally agreed that the size of the geopressured reservoirs is limited by faults or facies changes. The role played by faults is discussed by EPRI (1980):

> The fault system in the Gulf Coast is dominated by the large growth faults which parallel the coast. However, the resulting major fault blocks are cut by innumerable smaller faults, both parallel and transverse. In general, faulting increases in complexity with depth. In the

> geopressured zone major fault blocks are cut by small "splinter faults," which can be expected to isolate segments of existing reservoirs to an unknown degree. Communication between reservoir segments cut by such faults is an unknown quantity.

Whether this "communication" exists between reservoir segments determines, in part, the size of the reservoir.

Reservoirs composed of channel sands (as opposed to blanket sands) may also be limited in their production, as changes in crossbedding can inhibit flow. The presence or absence of channel sands and of communication across designated boundary faults will make a significant difference in how productive the prospect will be, and in the amount of subsidence that might follow development.

5. Subsidence-caused impacts depend not only on the total vertical and horizontal surface displacements but perhaps to a greater degree on the rate of deformation. Subsidence impact is sometimes discussed as if maximum subsidence occurs virtually instantaneously. Impacts estimated on this basis could be highly misleading, however, for it is in large degree the rate of subsidence that creates significant disturbance to natural, geomorphic, biological, and man-made systems. Sudden development of a 2-foot deep, 5-mile diameter subsidence bowl on the Gulf Coast would have a significantly different impact than the more probable development of the same subsidence bowl at the rate of an inch per year; in the latter case, various natural processes--littoral drift, river scour, peat accumulation, fish habitat adjustment--might significantly mitigate adverse impacts. The existing environment is not static, and in the Gulf Coast area subsidence is presently occurring as a result of tectonic downwarping as well as natural compaction of deep and shallow sediments, and man's activities. There is, therefore, some uncertainty in estimating the true impact of a total of a foot or two of subsidence, where the subsidence rate may be only an inch or less per year, possibly on the same order of magnitude as the recovery rate of natural systems and the rate of natural subsidence.

6. The question remains to be answered as to whether reinjection of brine produced from geopressured geothermal wells back into the producing zone should be included in production scenarios. The inclusion of deep reinjection in production scenarios (sometimes suggested as a mitigation measure) would improve recovery efficiency (W. Kraus, personal communication, 1980) and decrease subsidence potential. However, EPRI (1980) indicates that deep reinjection appears prohibitive, both in cost and in energy requirements. There is a conflict between the "must reinject" view and the "cannot reinject" view that needs to be resolved.

7. Movement of the ground along existing faults (or creation of new faults) as a result of subsidence may cause the distribution and amount of subsidence to differ from that caused only by direct transformation of reservoir compaction to the ground surface. There is at present no widely accepted theory for forecasting activation of growth faults due to resource development. Use of a predictive theory for ground movement along faults in a subsiding area (i.e., differentiating between cases where ground deformation does and does not include faulting) would further change the estimate and distributions of subsidence as calculated in this study.

After (and to a preliminary extent, while) these technological uncertainties are resolved and reliable estimates of potential subsidence can be made, the socioeconomic issues of development-induced subsidence must be addressed. In particular, 1) the economic costs of identified environmental and socioeconomic impacts and mitigation measures need to be estimated, and 2) an integrated institutional program for mitigation of environmental and socioeconomic impacts of subsidence needs to be recommended.

This cost estimate and mitigation program recommendation will be of utmost interest to both prospective developers and to the Department of Energy. The dollars per standard cubic feet of recovered methane (or barrels of recovered hot brine, or other applicable unit) that will be required to mitigate or prevent potential subsidence could be estimated and a decision could be made as to whether development is economically feasible at this cost. An integrated institutional regulatory program could minimize regulatory costs and agency jurisdiction confusion or overlap, while maximizing effectiveness of mitigation and/or prevention measures.

In summary, subsidence estimates calculated for this study indicate that subsidence and its associated impacts may be minimal in the Gulf Coast region. However, it is evident from the foregoing inventory of uncertainties that reliable resource assessment and subsidence prediction will require further research. When potential subsidence can be estimated reliably, and socioeconomic issues have been addressed, a recommendation can be made by, or to, the Department of Energy on the feasibility of successfully dealing with development-caused subsidence; this recommendation could be used as input to the ultimate decision on the extent to which Gulf Coast geopressured geothermal resources will be developed.

4. INVENTORY OF ENVIRONMENTAL AND SOCIOECONOMIC FEATURES

The Southeast Pecan Island, Brazoria, Colorado, and Lafourche Crossing Fairways contain many features important to an analysis of potential subsidence impacts. Physical, hydrologic, biological, and socioeconomic conditions in each fairway are briefly described in this section. All of the fairways are more fully described in the references noted within the text. Only features likely to be affected by subsidence have been emphasized. General conditions in the Texas-Louisiana Gulf Coast region are also noted, but are described more fully elsewhere. Important commercial species are described under the fairway in which they are most common, but these species may also be found in other fairways and locations along the Gulf Coast.

4.1 SOUTHEAST PECAN ISLAND FAIRWAY

The Southeast Pecan Island Fairway is located on the Gulf Coast of Louisiana in the coastal marsh of south-central Vermilion Parish (see Figure 4-1). Most of the fairway is contained within the Vermilion Basin at the eastern extreme of the Chenier Plain physiographic unit. Numerous small lakes and natural or man-made canals are found within the Fairway. White Lake is northwest of the Fairway. The Paul Rainey Wildlife Sanctuary comprises the easternmost part of the Fairway. Vermilion Bay is outside the Fairway, farther to the east. The Cheniere Au Tigre, a continuous ridge of beach material built upon marsh deposits, is near the coast. The Fairway includes most marsh types typical of the Gulf Coast region and illustrates both the existing conditions and the potential impacts characteristic of wetland areas.

4.1.1 Physical and Hydrologic Features

The Vermilion Basin is subject to changes in sea level, plus transport and deposition of sediments which are moved along the coast from discharge points within the Mississippi Delta physiographic unit. Some sediment is derived from the discharge of rivers that cross the Chenier Plain; sediment is also discharged by the Atchafalaya River, causing expansion of mudflats in Vermilion Bay. Coastal beach ridges and cheniers protect the inland areas from direct Gulf influence.

LOCATION OF REPRESENTATIVE FAIRWAYS

IN LOUISIANA

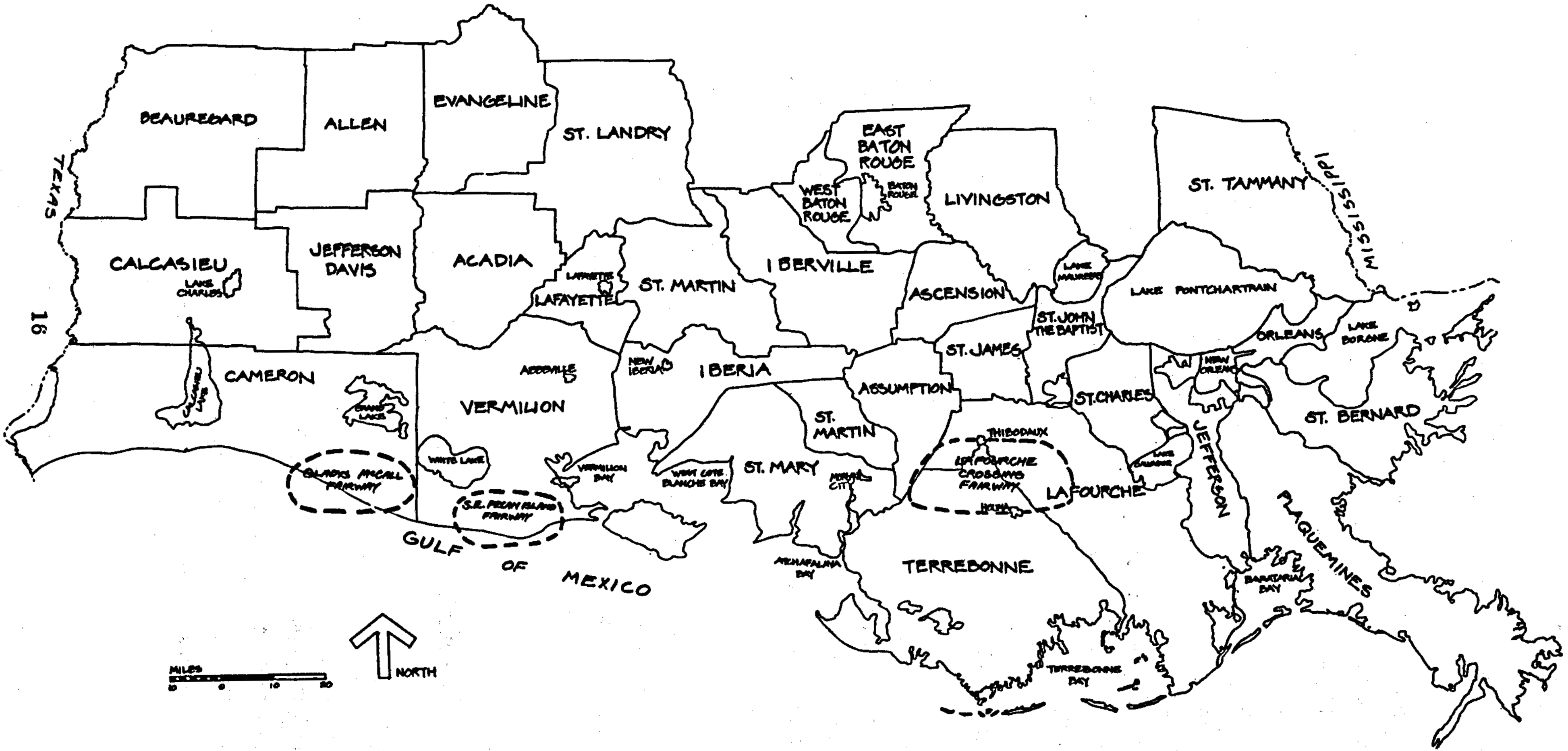


FIGURE 4-1

The flat topography of the Fairway results in dissipated tidal energy and inundation, with minimal sea level rise.

Other existing physical characteristics of the Southeast Pecan Island Fairway are subsidence and shoreline erosion which reduce marsh land and increase salinity over the long term. Natural subsidence due to compaction of sediments and coastal downwarping, combined with man-induced subsidence resulting from the creation and maintenance of canals and channels, has allowed saltwater intrusion. Subsidence in the Chenier Plain is now occurring at an approximate rate of 0.67 in/yr (0.5 ft per decade). Unless affected wetlands are elevated by sediment deposition to compensate for the net subsidence rate, these areas may become covered by water. Between 1952 and 1974, 1,359 acres of wetland area (1.3% of the total wetlands area in 1952) was lost to canals through dredging in the Vermilion Basin (Gosselink, 1979). Other land uses, including wetlands and water systems for the entire Vermilion Parish area, in 1972 are discussed in Section 4.1.3.

Shoreline erosion (see Figure 4-2) allows tidal currents and storm waters to reach farther inland; subsidence greatly accelerates this process. Varying rates of shoreline erosion are found along the Fairway coast, from 4 m/yr west of Freshwater Bayou and 5 to 7.5 m/yr east of the Bayou (Adams and others, 1978). Accretion, caused in part by displacement of the sediments discharged by the Atchafalaya River, counteracts the land lost from shoreline erosion; however, the accretion rate is not great enough to balance the erosion rate, resulting in a net shoreline loss of 494 acres in the 1952-1974 period (Gosselink, 1979).

Hydrologic factors that determine habitat type in the Fairway and surrounding area include water level, flows, salinity, and gradients. Shallow groundwater is important for maintenance of freshwater marshes; little fresh surface water is provided by either rain or runoff from upstream, as this water is largely absorbed by the highly productive vegetation or lost through evaporation. Because river influx is secondary to tidal effects, this area is characterized by flushing -- net freshwater discharge toward the Gulf -- and the subsequent potential for saltwater intrusion. Mixing of tidal and estuarine waters is increased by high water levels, turbulence, and currents. While the cheniers generally impede intrusion by

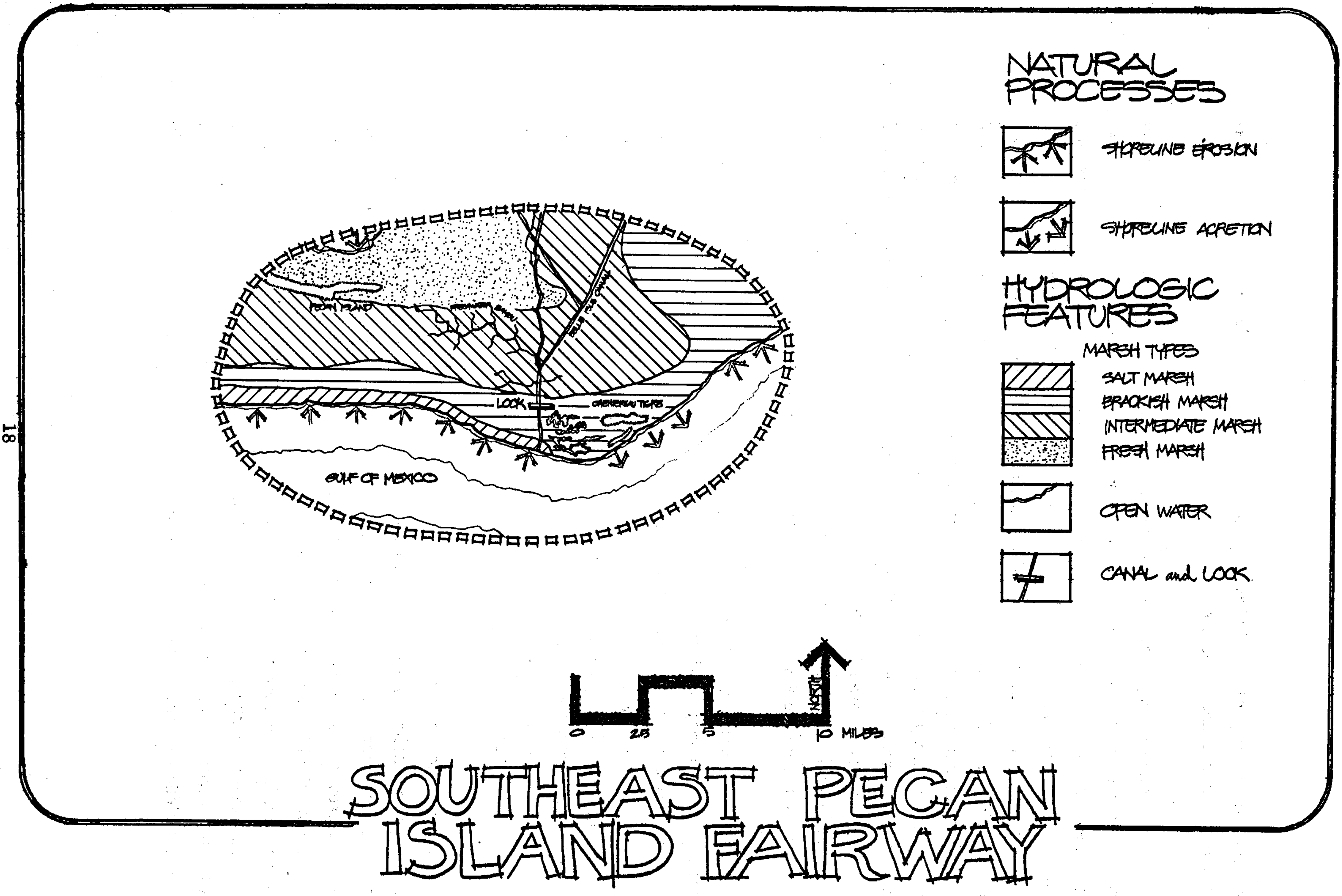

NATURAL PROCESSES
SHORELINE EROSION
SHORELINE ACRETION
HYDROLOGIC FEATURES
MARSH TYPES
SALT MARSH
BRACKISH MARSH
INTERMEDIATE MARSH
FRESH MARSH
OPEN WATER
CANAL and LOCK
PECAN ISLAND
FRESHWATER BAYOU
BELLE ISLE CANAL
LOCK
CHENIERE AU TIGRE
GULF OF MEXICO
NORTH
0
2.5
5
10 MILES
SOUTHEAST PECAN ISLAND FAIRWAY

FIGURE 4-2

controlling the water flow, they are easily breached during high water. The entire area would be inundated by a 100-year[3] or standard project[4] flood.

4.1.2 Biological Features

Most of the Southeast Pecan Island Fairway consists of wetlands. The remainder comprises open water, agricultural, and ridge and upland forest areas. Wetlands contain saline, brackish, intermediate, and fresh marshland. The approximate salinity level ranges from 0.20 parts-per-thousand (ppt) in fresh marsh to 19.46 ppt in saline marsh, as shown below.

Water Salinity (ppt)

Marsh Type	Mean	Range
Saline	10.63	1.80-19.46
Brackish	4.48	0.42-15.72
Intermediate	2.07	0.35- 5.99
Fresh	2.20	0.20- 5.77

Source: Craig and others, 1977.

An average of 475 acres/year of marshland was converted to open water in the Vermilion Basin during the 1890-1960 period, as follows:

---

[3] A 100-year flood is the term applied to the extreme flood condition which occurs, on the average, once every hundred years.

[4] A standard project flood is a hypothetical condition determined by the U.S. Army Corps of Engineers to describe a flood resulting if the most severe storm of record in the region were to occur over the basin under consideration when hydrologic conditions were favorable for flood runoff. It is more extreme than the 100-year flood.

Average Land Loss--Wetlands to Open Waters*
Vermilion Basin

Marsh Type	Acres Per Year
Saline	13
Brackish	398
Intermediate	37
Fresh	27

*Average calculated over period 1890-1960.

Source: Chabreck, 1972.

Brackish marsh (north of Cheniere Au Tigre and immediately east of Freshwater Bayou canal) has experienced a greater than average rate of land loss, primarily due to water impoundment by levees and canal spoil banks (Adams and others, 1978).

Marsh types grade inland according to salinity from salt (with a relatively low salinity of 12%), to brackish, to intermediate, to fresh (see Figure 4-2). Salinity levels and, consequently, wetland habitat undergo large fluctuations — both daily and seasonally. Most of the central part of the Fairway is intermediate marsh, but because of natural subsidence, the marsh habitat boundaries are moving slowly inland.

The highly productive marshlands of the Fairway support a rich diversity of wildlife. The freshwater marshes of the Vermilion Basin are major migratory fowl habitats for the Gulf Coast. Cheniers provide landfall for migratory birds. Estuarine areas are important nurseries for commercial fish and shellfish species (see Section 4.1.3 for further description of commercial fish and wildlife). The biological diversity and productivity are dependent on predictable physical events and the interchange between ecosystems such as tides, water level, temperature, and salinity. Freshwater flushing which occurs during heavy rainfall increases the organic production of the brackish and intermediate marshes of the Fairway.

The animals populating the Fairway have different habitat preferences. Nutria and raccoon are particularly dependent on a freshwater marsh habitat, while otter and mink do not exhibit much preference. Nutria prefer fresh and intermediate marsh, but will also inhabit brackish and, to a lesser degree, saltwater marsh. Muskrat prefer brackish marsh and will not tolerate excessive flooding or drying of the marsh. Mink populations are concentrated in the cypress-tupelo swamplands and fresh, intermediate, and brackish marshes of the Louisiana coast. A fairly wide-ranging species, mink exhibit little preference between marsh types (Palmaisano, 1972), although they concentrate in brackish marsh during periods of peak muskrat density in fresh marsh (Bahr and Hebrard, 1976). Freshwater marsh is also a preferred habitat for wintering puddle ducks. Of the approximately two million wintering ducks, 80% appear in fresh marsh in the winter and 50% during summer (Palmaisano, 1972).

4.1.3 Socioeconomic Features

Southeast Pecan Island is a rural and agrarian area with low population density due to the unsuitability of wetlands for development. No land use data are readily available for the Fairway. But almost all of the Southeast Pecan Island prospect area (which is somewhat smaller than the Fairway) is composed of non-forested wetlands. Agricultural land accounts for only about 1% of the area (Louisiana Department of Transportation and Development, 1977). This is in sharp contrast with the remainder of Vermilion Parish. Land use in 1972 at the Parish level was as follows:

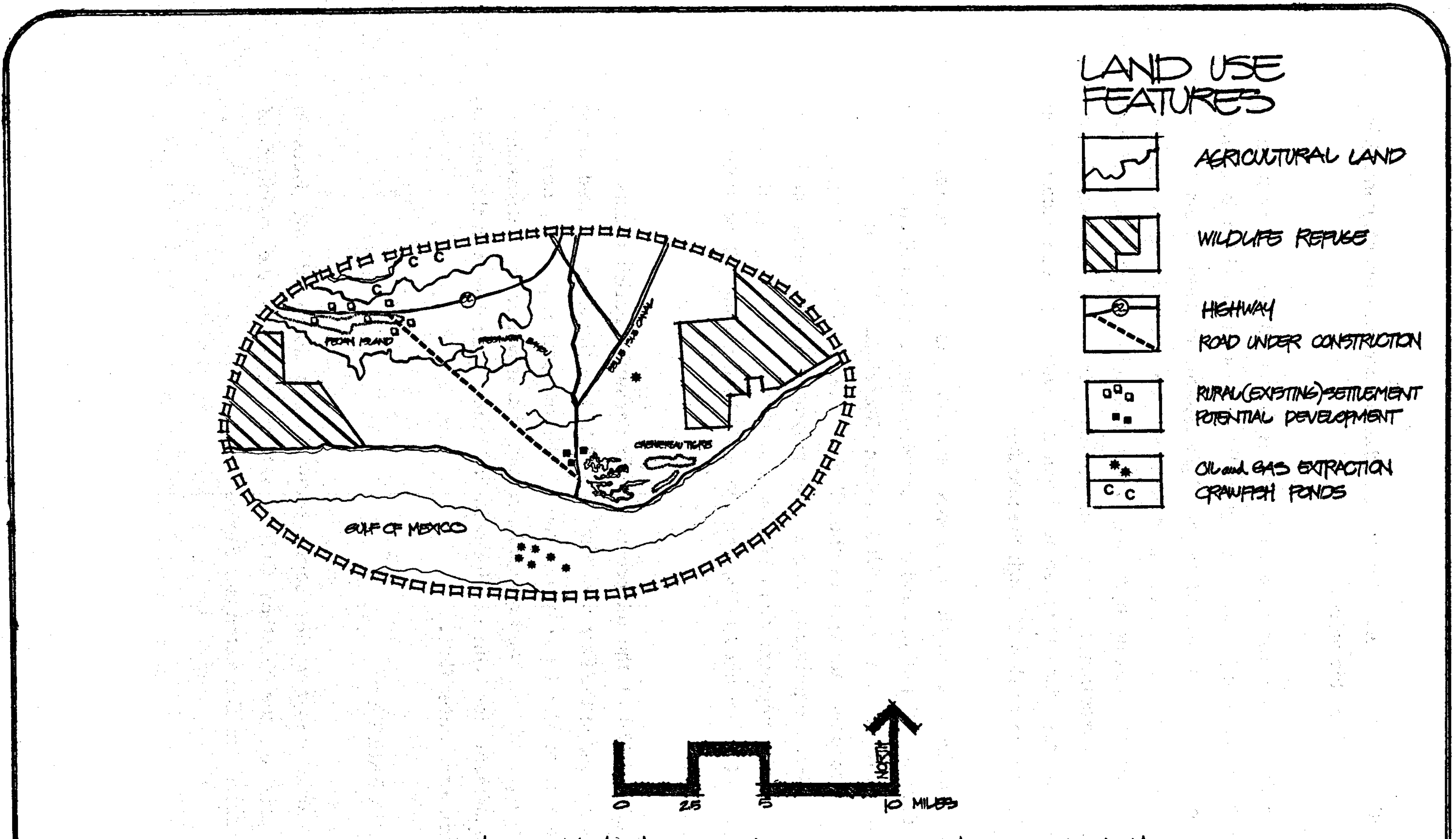
Land Use, Vermilion Parish, 1972

Type	Acres	%
Streams & Waterways	5,434	0.4
Lakes	156,598	11.4
Bays & Estuaries	78,793	5.7
Other Water (marsh)	391,989	28.4
Forested Wetland	28,405	2.1
Non-Forested Wetland	268,242	19.5
Subtotal, Wetlands & Water Systems	929,461	67.5
Urban & Built-up Land	6,916	0.5
Cropland & Pasture	429,039	31.1
Forest Land	7,410	0.5
Extractive Use and Barren Land	5,434	0.4
Subtotal, Developed Lands	448,799	32.5
TOTAL ACREAGE	1,378,260	100.0

Source: Louisiana Department of Transportation and Development, 1977.

The principal socioeconomic processes in the Fairway are fish and wildlife harvesting (both commercial and sport), agriculture, and mineral fuel extraction (petroleum and natural gas) (see Figure 4-3). Estuarine-dependent fish and shellfish in the Vermilion Basin are menhaden, shrimp, blue crab, oyster, croaker, sea trout, spot, and red drum. For the Chenier Plain as a whole, menhaden is approximately 96% of catch volume and 49% of value; shrimp is 3% of volume and 44% of value, followed by oyster and blue crab. Freshwater fish are catfish and bullhead, crayfish, buffalo, gar, and carp (Gosselink, 1979).

Commercial wildlife species in the Fairway are furbearers (primarily muskrat and nutria), fish, and alligators. Recreational hunting is for small game (squirrels, rabbits, quail, and dove), big game (deer and turkey), and water fowl (duck, geese, marsh birds). Total recreational use (including both fishing and hunting) in Vermilion Parish is estimated at 2,200 person days, with a reported value of



SOUTHEAST PECAN ISLAND FAIRWAY

FIGURE 4-3

$11,700 (Gosselink, 1979). Waterfowl hunting is the largest component, comprising 36% of the use and 61% of the value.

The major agricultural use in the Fairway is cattle raising. Other parts of the Vermilion Basin have high value agricultural land, much of which is drained wetlands, upland forest, and natural ridge. Agricultural drainage canals tend to alter water flow and accelerate runoff, increasing erosion and leaching in the area. Other modifications to existing hydrology which accelerate degradation of the wetlands include construction of canals and control structures. Impoundments created by spoils dredged for canals, some of which provide improved access to oil fields, have affected water flow through the marshes.

In 1974, Chenier Plain agriculture was valued at $28 million, recreational hunting and fishing at $21 million, and commercial fishing at $12 million. Oil and gas production, however, was worth $360 million (Gosselink, 1979) making it the most important economic activity in the Chenier Plain. Fuel production and related jobs are also a significant source of employment in the Vermilion Parish. Almost 16% of Parish employment in 1978 was in the mining category, the third highest category after services (31%) and trade (21%) (Louisiana Department of Labor, 1979).

Nearly all (98.7%) of the oil production in Vermilion Parish occurs in the marsh area around and in the Fairway. Similarly, 92.3% of the gas extracted in the Parish is taken from the Fairway environs. The extraction process, however, results in discharges of brine and oil spills, requiring freshwater for mitigation of impact. Impoundments for brine confinement and dredging of canals in the mining process, in turn, alter water flow.

4.2 BRAZORIA FAIRWAY

The Brazoria Fairway lies some twenty miles south of the Houston metropolitan area on the western Gulf Coast of Texas in the counties of Matagorda, Brazoria and Galveston (see Figure 4-4).

LOCATION OF REPRESENTATIVE FAIRWAYS IN TEXAS

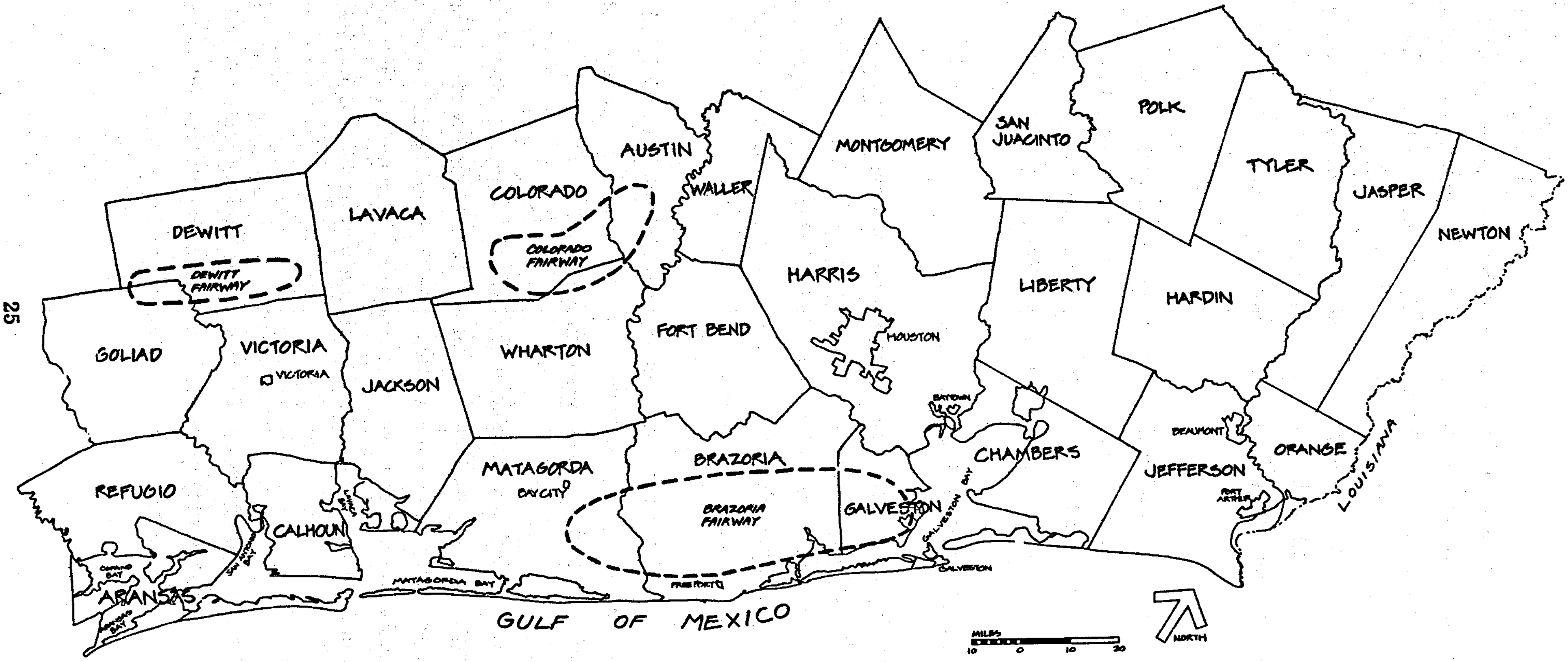


FIGURE 4-4

The Fairway borders on Galveston Bay, West Bay, and (in the Brazos River Delta - Cedar Lakes area) the Gulf itself. Its western end is some four miles inland from the eastern extremity of Matagorda Bay. Major cities in the Fairway are Texas City and Freeport, with Galveston and Bay City lying outside at its eastern and western ends. The Fairway is drained by numerous rivers and streams, the more important being Chocolate Bayou, Austin Bayou, Oyster Creek, Brazos River, San Bernard River and Caney Creek. The Bay City area is drained by the Colorado River.

The Brazoria Fairway includes a range of socioeconomic activities and natural systems. Lying on or close to the Coast, the area exhibits climatic and hydrologic features, flood hazards, land use patterns, and economic activities common to coastal and near-coastal fairways in Texas.

4.2.1 Physical and Hydrologic Features

The following discussion is based largely on the Environmental Geologic Atlas of the Texas Coastal Zone - Bay City-Freeport Area (Fisher and others, 1972) and Galveston-Houston Area (McGowan and others, 1976) and on Natural Hazards of the Texas Coastal Zone (Brown and others, 1974). These volumes should be consulted for more detailed discussions.

The West Gulf Coast Plain is inclined gently inland at 2 to 5 ft/mi from coast marshes across a flat young coastal plain to a mature coastal plain where elevations reach about 40 ft above mean sea level (MSL).

Despite its limited topographic variation, the region is characterized by a diversity of features resulting from several active geologic processes superimposed on Pleistocene and Holocene sediments deposited and worked by fluvial and coastal processes. The Fairway is affected by compaction of sediments, faulting, and rapid accretion and erosion resulting in both gain and loss of land along the coast (see Figure 4-5).

The majority of the Fairway is composed of muddy sediments and associated clay soils with belts of clayey sands and silts along rivers and throughout the margin of the older coastal plain. The lower coastal plain is composed of tidal

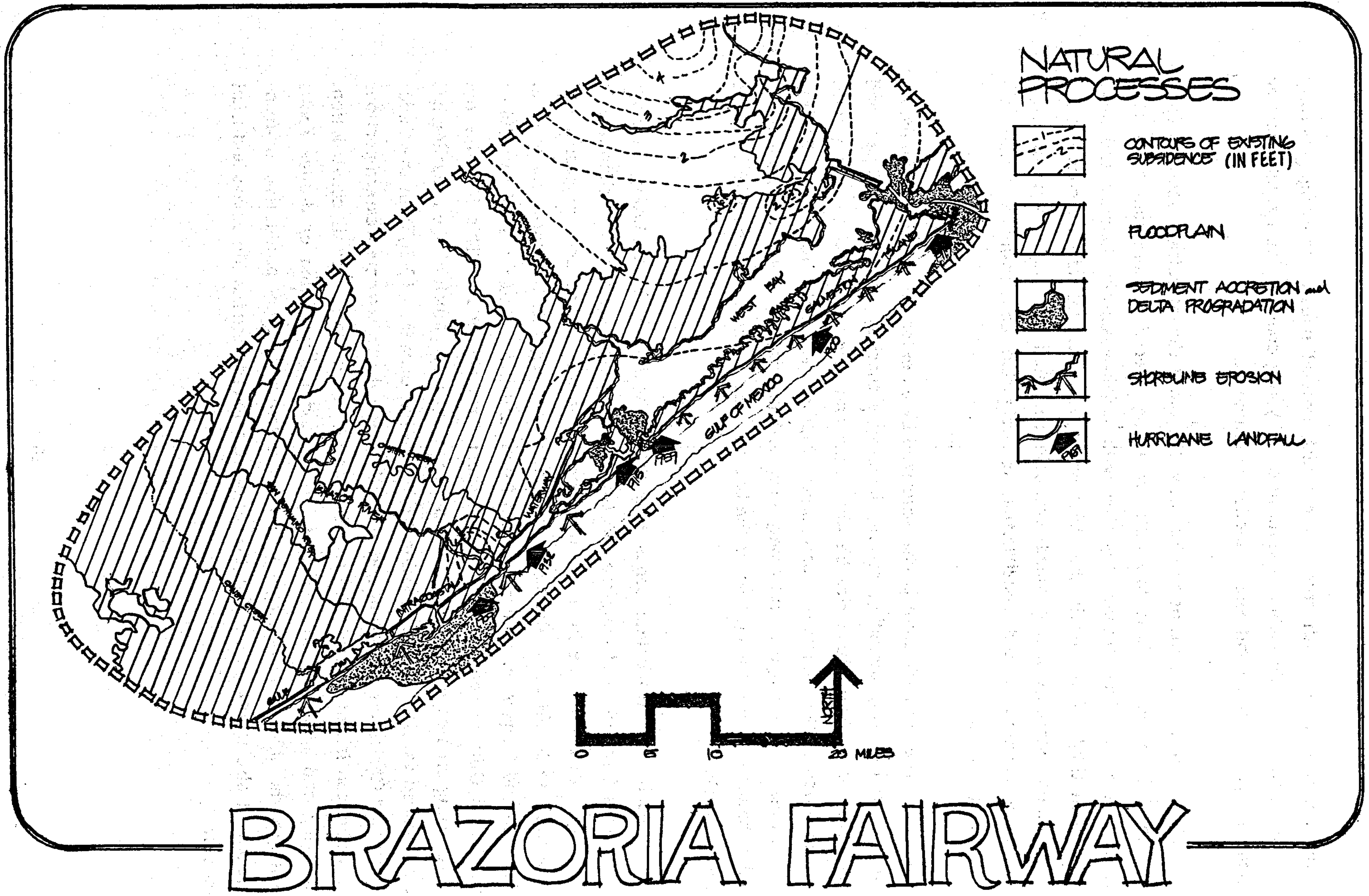

NATURAL PROCESSES
CONTOURS OF EXISTING SUBSIDENCE (IN FEET)
FLOODPLAIN
SEDIMENT ACCRETION and DELTA PROGRADATION
SHORELINE EROSION
HURRICANE LANDFALL
1
2
3
4
WEST BAY
GALVESTON ISLAND
GULF OF MEXICO
1900
1915
1932
WATERWAY
INTRACOASTAL
BRAZOS RIVER
SAN BERNARD RIVER
OYSTER CREEK
CANEY CREEK
NORTH
0
5
10
20 MILES
BRAZORIA FAIRWAY

FIGURE 4-5

flats and salt marsh with fresh to brackish coastal marsh occurring generally farther inland. Soils throughout the mature and young coastal plains exhibit low or moderate permeability and poor or moderate drainage.

In the inland portions of the Fairway, the older fluvial-deltaic deposits form the coastal uplands. These low hills are being altered by numerous headward-eroding streams. The streams, together with storm-washover channels and wave erosion in tidal inlets, supply the coast with sediment. Inland dam construction along major streams has reduced available sediment for deposition, although increased cultivation and construction of irrigation and drainage canals are offsetting factors.

The lower coastal plain is characterized by an extensive system of interconnecting waterways, including rivers, bayous, estuaries, ponds, and open and enclosed bays. The boundaries between high and low salinity waters vary with precipitation, tides, currents, and other factors and help to define habitat boundaries. Tidal range is extremely low, but high energy environments exist in tidal channels, where currents scour the bottom, and at the upper shoreface, where waves break.

Beach and strandplain sands line the coast in the East Matagorda Bay-Christmas Bay area and compose the Galveston Island barrier. The shoreline is actively affected by the intricate interactions of the volume and composition of deposited sediments, stabilizing marsh and dune vegetation, storm magnitude, duration and frequency, tidal range and fetch, and littoral currents. Only 13% of the Texas Gulf shoreline is undergoing short-term accretion. This includes the delta being created by the Brazos River in the Fairway. Much of the coastline has experienced varying rates of erosion. The rate has exceeded 10 ft/yr in the Cedar Lakes and Christmas Bay area, and along the central and extreme western portions of Galveston Island. Efforts to stabilize the coast include seawall construction, dredging and spoil disposal. The reworking and redistribution of dredge spoils blankets the shallow bay-margin grassflats destroying highly productive environments. It also results in modification of circulation patterns in some bays and tidal passes.

Despite their susceptibility to erosion, the barrier islands offer the first natural defense against hurricane surge. Hurricanes and tropical storms occur on average every 1.5 years. The landfall locations of major historic hurricanes are shown in Figure 4-5. The open and enclosed bays inland from the barrier islands contain scattered oyster reefs. These and the extensive marshes and shallow grassflats further dampen the erosive power and wave energy generated by tropical storms.

Low-lying marshes, delta plains, and river floodplains are commonly flooded by storm surge. Floodplains may pond for many months. Runoff from severe storms and hurricane-aftermath rain collects in upper river floodplains, natural depressions, and behind man-made structures, temporarily freshening salt and brackish marshes. Hurricanes also serve to flush bays of pollutants and to accelerate coastal erosion and deposition.

Subsidence and faulting in the Texas Coastal Zone are greatest in the Galveston-Houston area, due to extensive groundwater withdrawal. Similar geologic conditions elsewhere in the region suggest that the potential for significant subsidence may be widespread in the Fairway. At present, subsidence affects parts of Brazoria and Fort Bend Counties, most of mainland Galveston County and the eastern half of Harris County. Groundwater pumping and withdrawal, the principal cause of subsidence, began early in this century. Other causes were oil production which removed large quantities of water along with oil and gas, and solution mining of sulfur and salt. Groundwater withdrawal results in decline in artesian pressure and piezometric surface; water-saturated clay beds are compacted due to the change in effective stress, resulting in volume reduction and subsidence of overlying land. Measurable subsidence, defined by Brown and others (1974) as 0.2 ft or greater, had occurred throughout the Fairway by 1974.

Surface faulting is associated with land subsidence in the study area. There are more than 50 known active faults in the Houston area, as well as numerous potentially active faults in the Houston and Bay City-Freeport areas. These faults are products of natural geologic processes, but man's activities have reactivated or increased movements on certain faults.

4.2.2 Biological Features

The following discussion is based largely on the Environmental Analysis of Geopressured-Geothermal Prospect Areas, Brazoria and Kenedy Counties, Texas (White and others, 1978).

In the eastern half of the upland portion of the Brazoria Fairway, the vegetation is tall grass prairie. Much of the region has been converted to agriculture (rice and grain cultivation and cattle grazing). Several scarce and endangered plant species have been identified in the prairies, including common adder's-tongue, prairie bobwort, and Louisiana palm (Blevins and Novak, 1975 in White and others, 1978). Willow, cattail, and fresh water reeds and rushes occur around frequently flooded small streams, irrigation and drainage ways, and numerous fresh water ponds that dot the area, especially near rice fields.

Fluvial woodland occurs along the freshwater flood plains of major streams that cross the prairie: Dickinson, Hall's, Pleasant, Chocolate, and Austin Bayous. Fluvial woodland also covers most of the western half of the upland portion of the Fairway. The assemblage is characterized by water-tolerant hardwoods, including several species of oak, pecan, elm, ash and hackbery. The boundary between prairie and forest is indirectly related to soil moisture and directly related to clearance of woodland for urban and agricultural activities (White and others, 1978).

Inland marsh vegetation ranging from salt-tolerant species to fresh marsh species occupies the lowlands along the banks of Chocolate Bayou and sloughs to the west of Chocolate Bay where storm tidal inundation mixed with fresh-water floods and runoff causes variable salinities. This is one of the most fragile environments, extremely susceptible to changes in water availability and salinity.

Along the coast, freshwater to brackish coastal marsh and saltwater marsh are bordered by subaerial and subaqueous spoil and vegetated barrier flats. The sword bog-mat, an acutely endangered, very rare species of duckweed occurs in the freshwater to brackish marsh of the Brazoria National Wildlife Refuge along Christmas Bay, just outside the Fairway.

The Fairway is located at the southern terminus of the Central Flyway. Thousands of ducks and geese winter in the region which provides abundant aquatic habitats of high quality. Fluvial woodlands offer perching and nesting habitat for southern bald eagles. Eastern fox squirrels, eastern gray squirrels and other rodents, quail and other fowl, and snakes are also found in the fluvial woodlands. The prairies provide habitat for rodents, quail, and prairie chickens, as well as waterfowl.

The American alligator, classified as threatened in this region, is increasing in number in the coastal marshes and along inland stream corridors, the upper reaches of Chocolate and Austin Bayous offering prime habitat. Habitat of the endangered red wolf in lower coastal prairie and marsh areas has been severely reduced by urban and industrial development.

Aquatic fauna are abundant throughout the marsh estuarine and freshwater habitats in the Fairway. The Chocolate Bayou estuarine system is a major nursery and habitat for commercial (penaeid) shrimps, blue crabs, estuarine game fish, Gulf menhaden, and other fish (Moffet, 1975).

Coastal and salt marshes and bayous offer protection and nutrients to estuarine and non-estuarine fauna, benefitting the nursery system by removal of pollutants (White and others, 1978). The most important commercial species are brown and white shrimp and oysters.

Post-larval brown shrimp enter shallow estuaries generally between February and May, carried by wind-driven currents to the marsh water interface where they adapt to a benthic existence, growing to sub-adults (Gosselink, 1979). White shrimp follow a similar pattern, migrating to marshes between June and September. Moffet (1975) found an abundance of brown shrimp in Chocolate Bay during spring, while white shrimp were prevalent during summer and fall.

Studies of brown shrimp populations in Galveston Bay have found the shrimp to be limited by low salinity levels (less than 9.7 ppt) and water temperatures below 68°F, and have found shrimp in Christmas, Drum, and Bastrup Bays to thrive in high salinity waters (19.9-20.4 ppt) (McEachron and others, 1977; Perret and others, 1971).

White shrimp are dependent on estuarine areas of lower salinities (between 0.5 and 10 ppt) for their development. Although also affected by a complex of factors, including temperature, predation, and nutrient supply, salinity levels can be major factors in white shrimp production; a five-year drought in the Mississippi River Drainage (1962-1967) which increased salinities in the normally low-salinity estuaries has been associated with a sharp decline in white shrimp production (Barrett and Gillespie, 1973).

There are two major oyster reefs in West Bay, and many others in Chocolate Bayou estuary and Christmas and Bastrup Bays (Hofstetter, 1977; Moffet, 1975; McEachron and others, 1977). Oyster production occurs on reefs on stable, firm bottoms, generally on the periphery of bay bottoms (Van Sickle and others, 1976), with tidal current adequate to carry metabolic wastes from the beds and bring in oxygen and food. Oyster reefs may take several years to develop to commercially productive levels, although once established they become an important component of an estuarine ecosystem.

4.2.3 Socioeconomic Features

Socioeconomic and land use data specific to the Fairway are very limited, despite the fact that the Fairway is more intensively developed than the others addressed in this study.

Current land use patterns in Brazoria County and western Galveston County are dominated by agriculture. Rice is the dominant crop in the area followed by upland cotton, grain, corn and sorghum, oats, soy beans, and truck crops. An extensive network of reservoirs plus irrigation and drainage canals (see Figure 4-6) has been constructed throughout the eastern coastal uplands. Groundwater withdrawal for irrigation has contributed to land surface subsidence in some areas.

Range-pasture and grassland for cattle raising and dairy production are also extensive, the distribution varying from year to year depending on acreage in crop production.

The Brazoria Fairway's extensive natural resources include oil, natural gas, and natural gas liquids. Chemical raw materials, including sulfur, salt, shell for

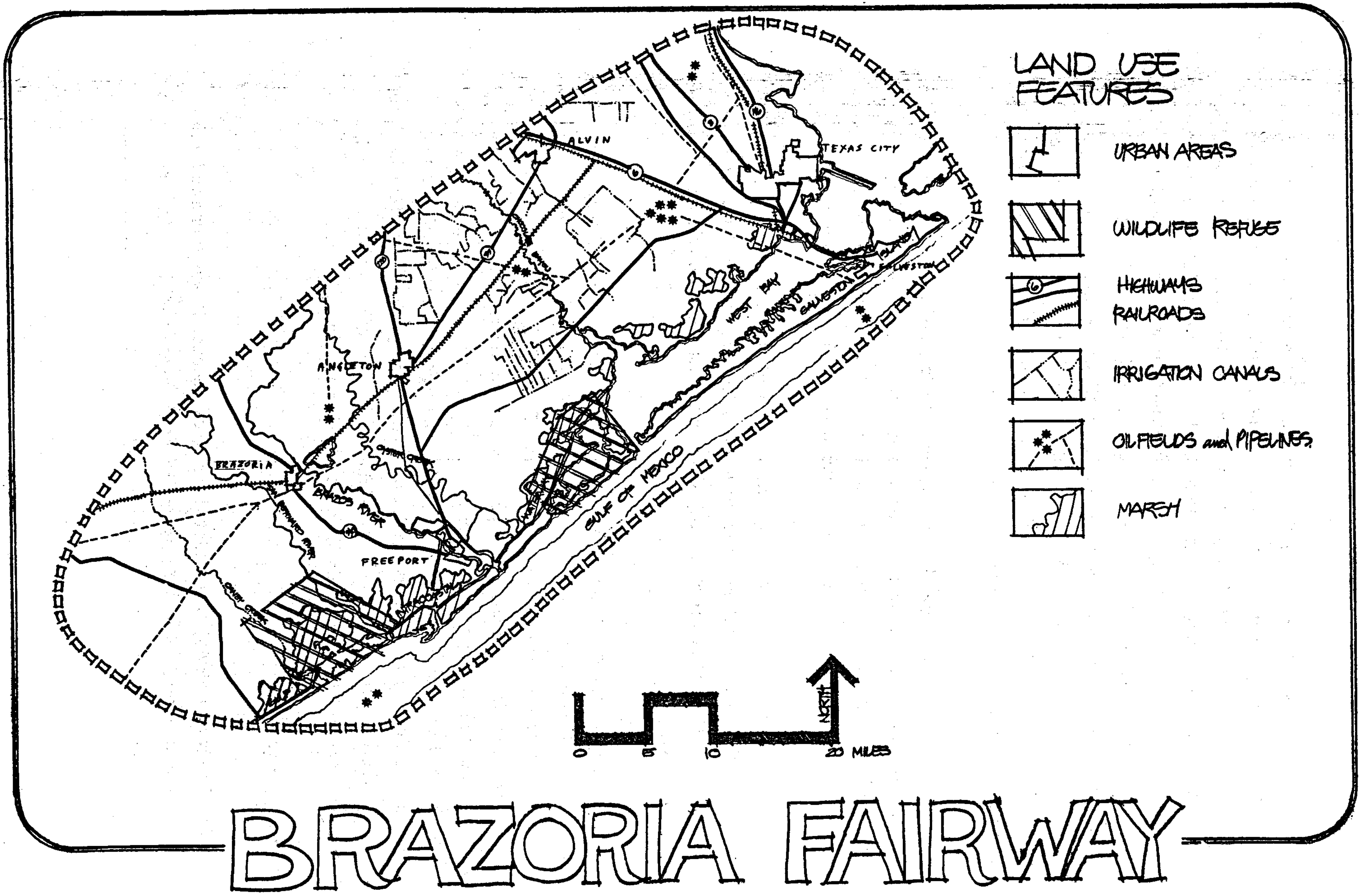

LAND USE FEATURES
URBAN AREAS
WILDLIFE REFUGE
HIGHWAYS
RAILROADS
IRRIGATION CANALS
OILFIELDS and PIPELINES
MARSH
ALVIN
TEXAS CITY
ANGLETON
BRAZORIA
BRAZOS RIVER
FREEPORT
OYSTER CREEK
SAN BERNARD RIVER
CANEY CREEK
WEST BAY
GALVESTON ISLAND
GALVESTON
GULF OF MEXICO
NORTH
0
5
10
20 MILES
BRAZORIA FAIRWAY

FIGURE 4-6

lime, clay, and gravel are also major resources. These resources, combined with suitable port locations, have resulted in one of the world's largest concentrations of petrochemical, refining, and heavy industry within the Houston-Baytown-Texas City industrial triangle along dredged ship canals. The entire Galveston Bay region is experiencing rapid population growth, and already respresents one-third of the population, as well as one-third of the industrial production, of Texas. Texas City, the largest city in the Fairway, is the second largest port on Galveston Bay and had an estimated population in 1975 of 41,000. The estimated population of the Brazoria Fairway in 1975 was 185,000, split almost evenly between Galveston and Brazoria Counties.

Oil fields occur throughout the Fairway, the largest being located east and west of Liverpool, in the upper Austin and Chocolate Bayou areas, east of Chocolate Bay, and between Dickinson and Texas City. Petrochemical plants have also been constructed in the Chocolate Bayou area at Peterson Landing.

The infrastructure (railroads, highways, dredged channels, including the Gulf Intracoastal Waterway, pipelines, and powerlines) serving Texas City, Galveston, Freeport, and the smaller cities of Bay City, Angleton, Austin, and Dickinson, is highly developed.

The concentration of industry and population in the Fairway, and the expanding permanent and second home communities along the coast and the bayous, represent serious conflicts with natural features and processes. All of the lower coastal lands are now subject to flood and hurricane hazards, and to structural damage or inundation due to subsidence resulting from groundwater withdrawal and oil and gas extraction. Efforts to provide protection from flood and storm hazards, as mentioned previously, significantly alter important habitats and natural processes upon which non-industrial economic activities, including hunting, recreation, and sport and commercial fisheries, depend.

4.3 COLORADO FAIRWAY

The Colorado Fairway was selected for study because it was found to be more representative of inland coastal Texas and its hydrologic conditions, transportation systems, and economic activities than other fairways in the inland Texas region.

The Fairway is located in the Texas Coastal Plains about 40 miles west of the city of Houston (see Figure 4-4). The Fairway covers parts of Wharton and Austin Counties, but is mainly located in Colorado County. It surrounds Eagle Lake, a shallow lake seldom more than eight feet deep which covers approximately two square miles. The Fairway is generally flat with a slight coastward tilt. Surface water is a prominent feature of the region. In addition to Eagle Lake, the Fairway contains numerous small ponds. It is drained by the San Bernard River and its tributaries, and by the Colorado River (see Figure 4-7).

The Fairway is an agricultural area. It contains two small urban areas, Sealy and Eagle Lake, and smaller rural settlements. Much of the following discussion is summarized from the draft Environmental Analysis of Geopressured Geothermal Prospect Areas in Colorado and DeWitt Counties, Texas (Texas Bureau of Economic Geology, 1980).

4.3.1 Physical and Hydrologic Features

The Colorado Fairway is underlain by Pleistocene and Recent sediments. Fluvial deposits of the Lissie Formation, consisting of fine and clayey sands, cover most of the area. The Fairway tilts slightly coastward and is cut by the Colorado and San Bernard River systems. Pleistocene and more recent fluvial terrace deposits, ranging from muds to economically important sand and gravel, are present along the river bottomlands.

Broad, flat divides occur between many of the streams. A common feature of the Lissie Formation in the region is the presence of small, shallow depressions which are often water-filled. Poor internal drainage of clay layers, where combined with level topography, makes the area suitable for rice production.

Elevations in the southeasterly half of the Fairway range from 120 to 130 ft above MSL along streambeds to about 150 ft on the divides. In the northwesterly half of the Fairway, streambed elevations range from 140 to 160 ft (and 170 ft along Coushatta Creek and the upper San Bernard River). Divides reach 170 to 200 ft.

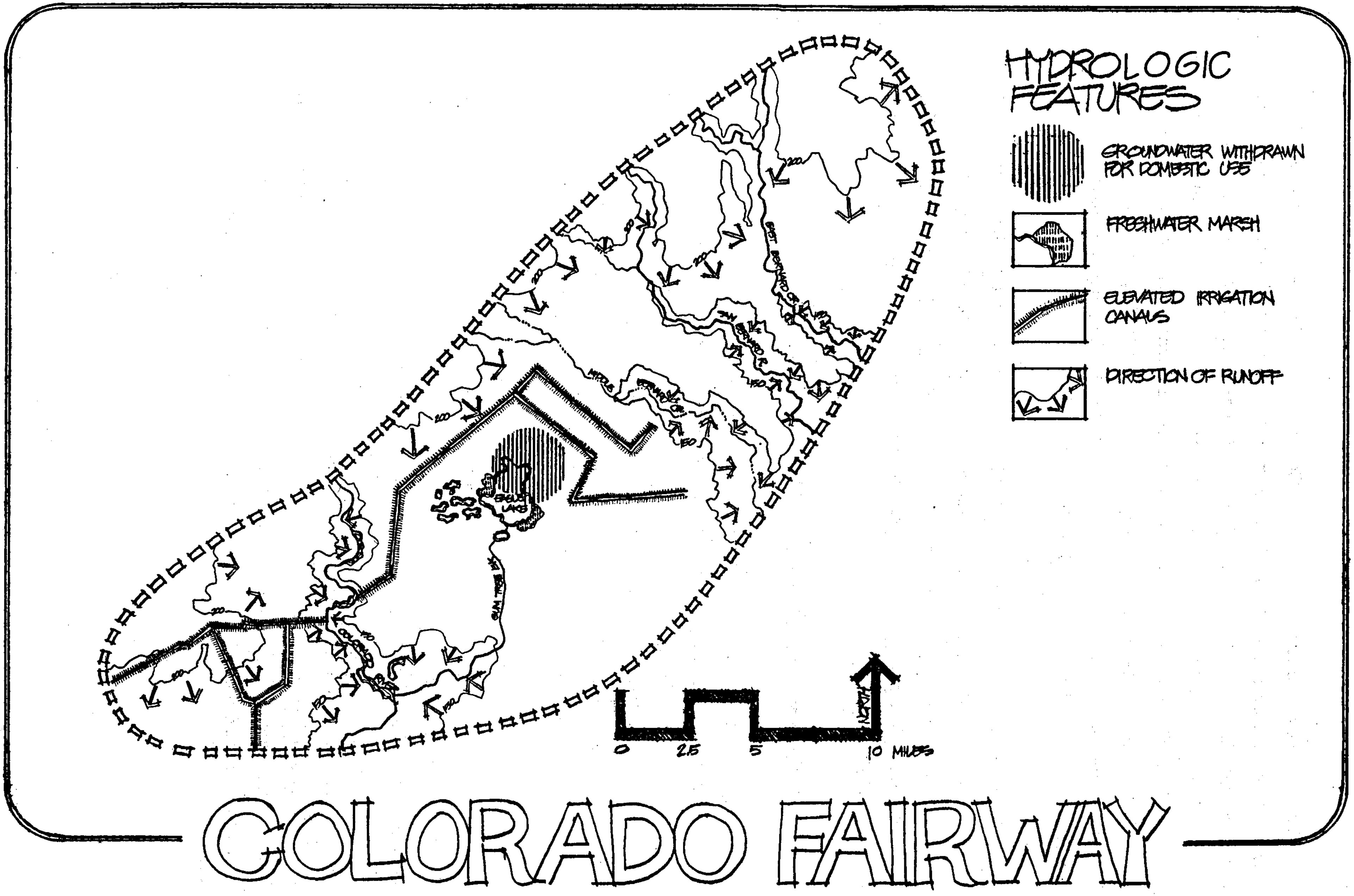

HYDROLOGIC FEATURES
GROUNDWATER WITHDRAWN FOR DOMESTIC USE
FRESHWATER MARSH
ELEVATED IRRIGATION CANALS
DIRECTION OF RUNOFF
EAST BERNARD CR.
SAN BERNARD R.
MIDDLE BERNARD CR.
EAGLE LAKE
GUM TREE BR.
COLORADO R.
200
150
100
0
2.5
5
10 MILES
NORTH
COLORADO FAIRWAY

FIGURE 4-7

Surface runoff from the Colorado Fairway drains into the two major river systems, the Colorado and the San Bernard (see Figure 4-7). Much of the central portion of the Fairway drains first into Eagle Lake and thence to the Colorado River. Natural drainage patterns have been altered by ditches and levees in connection with railroad and highway construction, and with rice farming.

The terrace and alluvial deposits along the Colorado River around Eagle Lake and between the lake and the Colorado River, are almost entirely within the 100-year floodplain. Flood waters would cover land up to the 185-foot level west of Eagle Lake and up to the 165-foot level along the steep eastern bank of Eagle Lake and its outflow, and would be up to 35 ft deep (Texas Bureau of Economic Geology, 1980) (see Figure 4-8). Other streams in the Fairway have smaller drainage basins and the 100-year flood would cover a relatively small strip along these streams. Flood levels would reach 10 ft above the streambed for West Bernard and Middle Bernard Creeks, and 15 ft for the San Bernard River.

The Colorado Fairway's two main aquifers, recharged by rainfall in the aquifers' outcrop areas, supply water for municipal and domestic use (see Figure 4-7). (Irrigation water is drawn primarily from the Colorado River.) Groundwater withdrawal exceeds the annual recharge rate. Water levels in wells are declining and some land subsidence, estimated at between one and two feet as of 1973, has probably occurred as a result (Texas Bureau of Economic Geology, 1980).

There is evidence of several near-surface faults in the Eagle Lake area (see Figure 4-8). The presence of near-surface faults, possibly extensions of deep faults, may increase the likelihood that subsidence would be accompanied by fault activation.

4.3.2 Biological Features

Eagle Lake, the rice fields, and the Attwater Prairie Chicken National Wildlife Refuge along Coushatta Creek, a tributary of the San Bernard River, provide habitats suited to a wide variety of bird species. The following summary is based mainly on the environmental analysis of prospects in Colorado and DeWitt Counties cited at the beginning of this section.

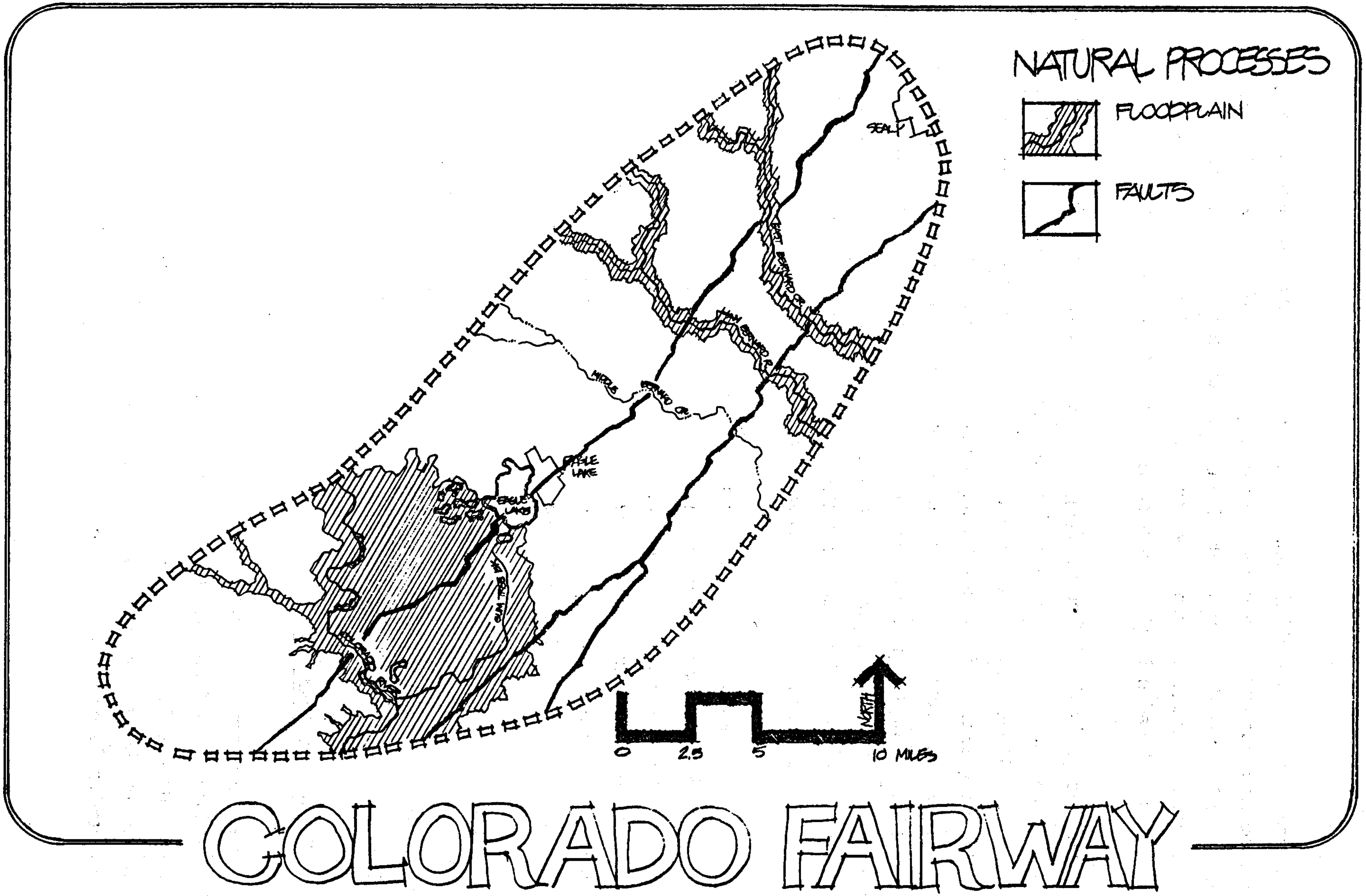

NATURAL PROCESSES
FLOODPLAIN
FAULTS
SEALY
EAST BERNARD CR.
SAN BERNARD R.
MIDDLE BERNARD CR.
EAGLE LAKE
EAGLE LAKE
GUM TREE BR.
COLORADO RIVER
NORTH
0
2.5
5
10 MILES
COLORADO FAIRWAY

FIGURE 4-8

Birds are especially abundant in winter when this section of the Central Flyway supports one of the largest concentration of wintering geese in the United States. Eagle Lake and its environs provide the most extensive waterfowl habitat in the United States, but natural rain ponds and large ponds maintained in rice growing areas are also important.

The population of the endangered Attwater prairie chicken has expanded since acquisition of this refuge began in the mid-1960s. The National Wildlife Refuge was formally established in 1972 to preserve and restore the native grasses and forbs of the prairies which constitute the only habitat capable of satisfying the bird's mating, or "booming", and nesting requirements. The range of the birds extends outside the present refuge (which is to be expanded) into surrounding rice fields and grazing land.

The region provides suitable habitat for other endangered species. The bald eagle is sighted periodically in the woodlands along the San Bernard River. The bald eagle also uses the Prairie Chicken Refuge and the peregrine falcon is expected to do so in the future. The whooping crane has been sighted in the wetlands of Colorado County. The river systems also offer habitats preferred by the interior least tern and the Eskimo curlew, although sightings have not been verified.

The Refuge supports a wide variety of common birds, including bobwhite quail and mourning doves, and less common birds, including the roseate spoonbill, whitefaced ibis, Sennet's white-tailed hawk, Audubon's caracara and prairie falcon.

Numerous common species of mammal inhabit the Refuge and other parts of Colorado County. The waterways in the Fairway and elsewhere in the County support a growing population of the endangered American alligator. Over 300 were present in the County in 1975, making it the sixth largest concentration in Texas. One hundred live in and around Eagle Lake. Other protected reptiles in the area include the Texas tortoise, Texas horned lizard, and Louisiana milk snake.

The Houston toad, although not sighted recently, is believed to be present in Colorado County. Its habitat (loose, sandy, and normally well-drained soils with temporary rain ponds) has been altered in many areas, resulting in its endangered status. The Eagle Lake area appears to offer areas of potentially suitable habitat.

Vegetative types within the Fairway are also varied. In the bottomlands of the Colorado River, range and unimproved pastureland include Dallas grass, Bermuda grass, and moisture-tolerant grasses, such as smut grass and carpet grass. Pecans and cottonwoods are common along the river. Dense growths of willow, some with Chinese tallow, are common in abandoned gravel pit areas. Marshlike vegetation consisting of cattails, sedges, and rushes are present in low-lying areas, including some of the abandoned gravel pits of the bottomlands. The largest area of marsh occurs directly south of Eagle Lake. Intermittent clumps of trees, including small Chinese tallow, willow, chinabery, and hackberry trees, grow above a thick cover of Macartney rose along the banks of rivers, streams, and drainage ditches.

4.3.3 Socioeconomic Features

Agriculture is the primary land use in the Colorado Fairway. Much of the region is covered by rice fields. Soybeans and corn are also important crops. Livestock, including beef, dairy cattle, and hogs, accounts for a significant share of agricultural production. Abandoned gravel pits are often used for cattle grazing.

The other principal basic industries in the Fairway, in addition to agriculture, are oil and gas production, and sand and gravel extraction. Natural gas fields are scattered throughout the area; there is one particularly large field southeast of Eagle Lake. Vigorous construction activity in Houston has led to renewed exploitation of gravel deposits. Several large gravel pits are centrally located, between Eagle Lake and the Colorado River. Abandoned gravel pits are often water-filled and are used for commercial bass fishing, as well as by wildlife. Hunting rights provide an additional revenue source for many landowners.

Residential and other built-up areas are few. The two sizable towns in the Fairway are Eagle Lake (1975 population: 3,515) at the center of the Fairway, and Sealy (1975 population: 3,211). The Fairway is crossed by two railroads (Santa Fe and Southern Pacific), Interstate Highway 10, secondary highways, gas and water transmission pipelines, and numerous irrigation canals.

4.4 LAFOURCHE CROSSING FAIRWAY

The Lafourche Crossing Fairway is located in the Mississippi Delta physiographic unit of Louisiana (see Figure 4-1). The area includes prehistoric distributary delta systems of the Mississippi, plus back-bay freshwater marshes and swamps in the lower areas between the distributary channels. Many of the distributaries are today roughly north-south trending bayous. At least two east-west trending faults run through the Fairway. The Fairway contains scattered but mostly linear urban settlements, agricultural lands, and wetlands, including cypress/tupelo swamp, as well as the marsh types common to other fairways (see Figure 4-9).

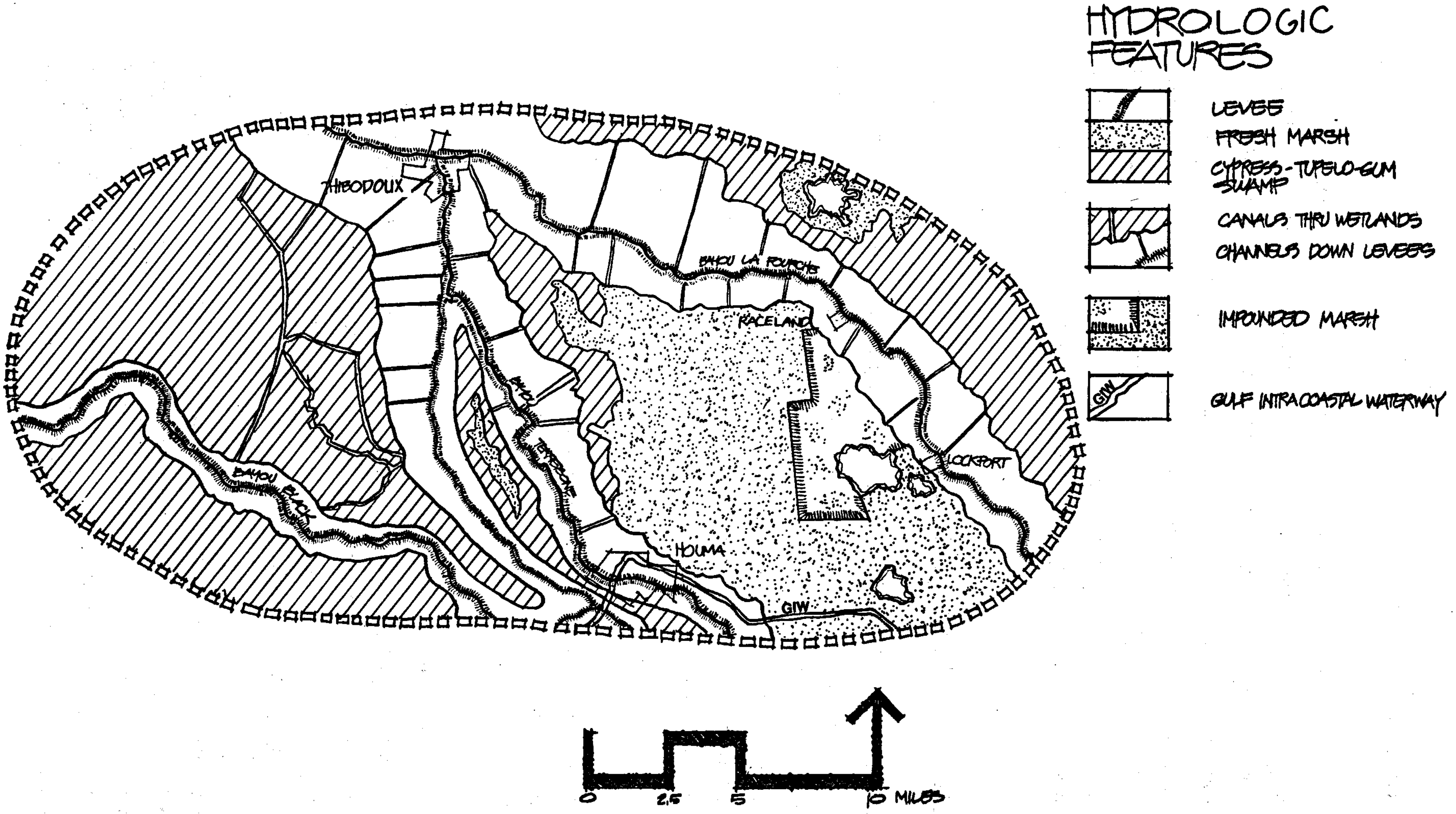
4.4.1 Physical and Hydrologic Features

Until recently, the Mississippi Delta physiographic unit, including the Lafourche Crossing Fairway, received continuous and large-scale sediment deposition. The region has also been subject to the greatest natural subsidence on the Gulf Coast because of compaction and dewatering of the sediments. Man-made alterations have limited further sedimentation to a few areas in the region. This has created a severe imbalance, since subsidence continues without the counteracting sedimentation, resulting in land loss and marsh alteration.

The quality of local groundwater is generally poor, so water taken from Bayou Lafourche for domestic use must be treated. Water wells still in use are primarily used for livestock watering.

The flanks of the natural levees along bayous contain the only arable land in the Fairway. Elevations range from 1 to 18 ft, making the levees the highest features in the area. Drainage on the levees is excellent. East of Bayou Lafourche, drainage is into Barataria Estuary. West of the Bayou, drainage is south into the Gulf Intracoastal Waterway and the coastal marshes of Terrebonne Parish.

The Fairway has a high natural subsidence rate and wetland loss is an ongoing event. Swamp forests in the Lafourche Crossing Fairway have been experiencing land loss at an estimated annual rate of 167 acres/year from 1890 to 1960 (Craig and others, 1977). This has been attributed to the long-term process of change in the deltaic physiographic system (Morgan, 1972) as well as to impoundments of



LA FOURCHE FAIRWAY

FIGURE 4-9

swampland for crawfish cultivation, canal dredging, the creation of spoil banks, settlement, and erosion (Craig and others, 1977).

4.4.2 Biological Features

The Lafourche Crossing Fairway includes bottomland forest, freshwater marsh, ridge, and open freshwater (see Figure 4-9). The dominant wetland type in the western portion of the Fairway is bottomland forest, a freshwater swamp system containing stands of cypress, tupelo gum, and other tree types. Swamps in the Fairway region were diminished at a rate of 167 acres/year between 1890 and 1960 (Craig and others, 1977). This loss is attributable to several factors, including logging activities, impoundment and clearing of swamps for crawfish cultivation, canal dredging and spoil bank creation, salinity increases, subsidence, and natural alterations in a subdeltaic region (Morgan, 1972; Craig and others, 1977).

Freshwater marsh is the dominant wetland type in the eastern portion of the Fairway. Bulltongue, spikerush, and maidencane account for nearly 70% of freshwater marsh vegetation in the Fairway region. Due to processes similar to those in swamp land, fresh marshes in the Fairway have lost about 411 acres/year between 1890 and 1960 (Craig and others, 1977). Extensive freshwater marsh areas surrounding bayou levees are largely forested. These marsh systems are adapted to annual or infrequent watering and dewatering.

Wetland areas in the Fairway serve as habitat for numerous species, including crawfish, deer, raccoon, and squirrel. Crawfish are especially important as a source of local income. Crawfish consume decaying plant material, organisms associated with plant decomposition, and growing aquatic plants (Lovell, 1979). Adult crawfish typically burrow and spawn while the pond is drained during summer months, reemerging and releasing juveniles when rains flood the ponds again during the fall (Gary, 1974; Huner, 1979). Once stocked, crawfish ponds tend to be self-perpetuating (Huner, 1979). Crawfish require fairly shallow ponds, 15 inches being ideal (Gary, 1974), and particular flooding cycles which, if altered, could be financially devastating to crawfish farmers (Sklar and Conner, 1979).

Salinity increases would affect the general level of marshland productivity by altering the vegetation and aquatic life in the marsh. The water salinity in the freshwater marsh in the Fairway is within the range of 0.09 to 4.54 ppt (parts per thousand) (Chabreck, 1972). Alteration of that range would tend to eliminate flora and fauna less tolerant to saline water. This has a particular effect on crawfish, a commercial species that does not tolerate salinities above 6-8 ppt (Huner, 1979).

4.4.3 Socioeconomic Features

The Lafourche Crossing Fairway is located within Lafourche and Terrebonne Parishes (see Figure 4-1) near the communities of Houma, Thibodaux, Raceland, Bayou Cane, and Larose (see Figure 4-10). Human settlement and agricultural development occur in narrow strips that extend across the levees from the bayou into the backswamp areas. Along Bayou Lafourche, this settlement pattern extends for at least 60 miles from the Assumption Parish border to Leeville.

Population density in the Fairway is lower than that in Louisiana as a whole, but settlements are compact. Houma, located on the Gulf Intercoastal Waterway, is a major center for commercial and service activities. Urban settlement covers 13,783 acres in Houma, with 9,050 acres occurring in strip settlements. The area's population is expected to increase 21% by 1990. (Louisiana Department of Transportation and Development, 1977.) Settlements will continue to locate along waterways, creating a continuous linear development. As land bordering waterways and highways becomes completely developed, expansion will move onto agricultural lands. This is already occurring in Thibodaux, Houma, and along Bayou Lafourche (Louisiana Department of Transportation and Development, 1977).

Generalized land use within the Lafourche Crossing Prospect area (which is smaller than the Fairway) is shown below. A much higher percentage of agricultural land exists within the Prospect than at the parish level; the parish level contains high percentages of non-forested wetland and open water.

	Square Miles	%
Cropland and Pasture	18.8	53.0
Forested Wetlands (backswamp)	11.0	31.2
Residential	3.4	9.7
Transportation	1.7	4.7
Commercial and Service	0.4	1.1
	0.1	0.3
	35.4	100.0

Source: Louisiana Department of Transportation and Development, 1977.

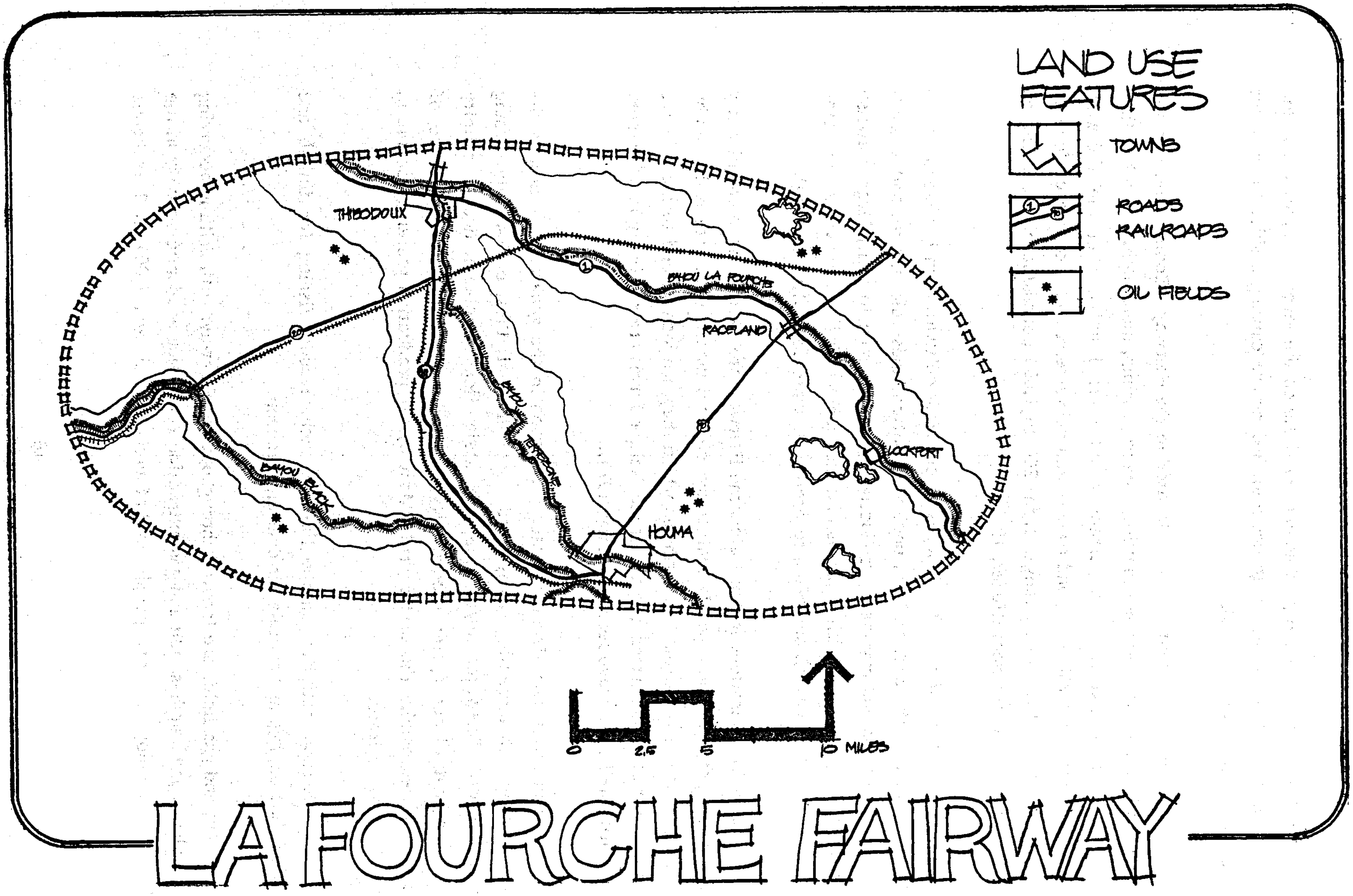

LAND USE FEATURES
TOWNS
ROADS
RAILROADS
OIL FIELDS
THIBODOUX
BAYOU LA FOURCHE
RACELAND
BAYOU TERREBONNE
LOCKPORT
HOUMA
BAYOU BLACK
1
20
0
2.5
5
10 MILES
LA FOURCHE FAIRWAY

FIGURE 4-10

Agriculture is still the predominant land use on the levees. Sugarcane is the major agricultural crop, although declining values are causing a shift to soybeans (Newchurch and others, 1978).

Fish processing plants are also located in the Fairway. Commercial fish and shellfish in the region include crawfish, oysters, shrimp, menhaden, and other fish. Crawfish cultivation is an important marsh-related activity in the Fairway, providing economic value to pond owners and harvesters, and a source of food to local residents. Production ranges from 200 to 1,000 pounds/acre, depending on pond type and management (Huner, 1979).

In 1974, 44% of the 43,470 acres of crawfish cultivation in Louisiana was in large swamp/marsh ponds built on uncleared bottomlands adjacent to, and extending into, swamps and marshes. Productive limits common to many large crawfish ponds include well-established predacious fish populations, lower water temperatures (due to tree cover), and often severe flooding problems (Huner, 1979).

Crawfish operations in the Lafourche Fairway are carried on predominantly in smaller ponds on more poorly drained agricultural lands. Pond size is limited by the small size of the sugarcane farms on which they are located and to the relative newness of crawfish farming in the area. Larger farms are not likely to be started up until small ones prove feasible (Gary, 1974).

Urbanization has affected oyster production in the general area around the Fairway through increasing sewage and waste disposal, thus, periodically closing oyster beds. Saltwater intrusion is also a significant problem, due to salinity changes that affect oyster productivity, as well as the increased presence of predators, especially the oyster drill. Most oyster production presently occurs in neighboring parishes.

Recreation activities in the Fairway include sport fishing for finfish and shellfish, trapping, and hunting for deer and raccoon.

Oil and gas fields are located throughout the Fairway, with drilling occurring on uplands and marshes. Oil and gas extraction is a major economic activity in the Fairway, employing 1,351 people in Lafourche Parish and 7,005 in Terrebonne

Parish in 1978, and creating related employment in equipment manufacture and supply. Houma has become a center for oil production activity in the area, with transportation and service activities serving the on- and offshore oil fields.

Water transportation is another significant use of the area and includes bayous, the Intracoastal Waterway, and an extensive network of canals. Dredging has converted significant amounts of wetland to waterways. In Terrebonne Parish, 1,711 acres of land were converted to canals in 1974, up from 44 acres in 1970. Lafourche Parish had 144 acres converted in 1974, up from six acres in 1970 (Louisiana Department of Transportation and Development, 1977).

4.5 INVENTORY OF INSTITUTIONAL SYSTEMS

In addition to physical, biological, and socioeconomic features, there are numerous local, state, and federal agencies, plus private institutions, in the fairways and the Gulf Coast region which may be affected by, or have certain responsibilities for mitigating, subsidence. A survey of representative institutions is presented below, grouped according to general area of responsibility.

4.5.1 Roads and Highways

Federal Highway Administration (FHA). The FHA distributes funds to states for routine road maintenance, as well as administering emergency funds for natural disasters. Agency funds have been used in the Gulf Coast for subsidence-related road repairs.

Louisiana Department of Transportation and Development (LDOTD). LDOTD maintains all state and federal roads in Louisiana. Cracking and buckling are treated as routine maintenance problems and are not generally identified as the result of subsidence. The Department has had difficulties in constructing a road between Pecan Island and Freshwater Bayou in the Southeast Pecan Island Fairway due to roadway settlement which may have resulted from subsidence.

Texas Department of Highways. An awareness of subsidence is quite high in the Department; all design is currently conducted to accommodate anticipated future subsidence. Examples of existing subsidence-related problems include:

- NASA Road 1, which was built at an elevation of 10 ft above sea level, but which subsided up to 3.7 ft in places. To repair the road and restore it to an elevation of 10 ft is estimated to cost $10 million.

- An existing 400 ft span bridge needs to be replaced. To do so now will necessitate a 1700 ft span to cross subsidence-created wetlands. Additional cost is $6 million.

- On State Highway 146, a drawbridge that once was easily passable by sailboats and other boats has experienced subsidence to the point where the drawbridge must be opened almost constantly, creating traffic backups.

- A bridge across the Houston Ship Channel, designed for one elevation, must be raised two feet to account for anticipated subsidence--at a cost of $1 million extra for each foot raised.

The Department is particularly concerned about the destruction, or blocking, of hurricane escape routes due to subsidence in some areas, and has proposed a program to raise all major coastal roads as evacuation routes. Routine maintenance of subsidence-related road damage occurs within existing budgets.

4.5.2 Agriculture

Soil Conservation Service (SCS). The SCS, a federal agency, is an advisory body charged with providing soil maps, surveys, technical information on land development, drainage, and other aspects of land use and farming to farmers and the public. With regard to subsidence, the SCS provides information on alternative farming methods or types of crops better suited to subsiding lands. The SCS also provides information on building and waste disposal practices suitable to subsiding land.

Farmers Home Administration (FmHA). The federal FmHA offers loans to farmers and ranchers who have suffered losses due to natural disasters. Losses related to subsidence in the Galveston Bay Area are generally the result of flooding. Loan requests thus far have not distinguished between subsidence-induced crop losses and other causes, but the FmHA district office in the Houston-Galveston area expects requests specifying subsidence losses will be submitted in the future.

Agricultural Extension, Lafourche Parish. This local, federally funded agency is responsible for various forms of assistance to local farmers, including sediment retention and erosion control, restoration of native plant cover, and administration of FmHA loans. In terms of subsidence, the Agricultural Extension may conduct assessments of flood damage, administer low-cost loans to farms flooded by storms, and provide some preventive maintenance. However, the agency is no longer able to provide funds for drainage improvements on farmland due to changes in congressional appropriations for the agency. This limits the agency's ability to respond in cases where farm drainage is affected by subsidence.

4.5.3 Fish and Wildlife

Texas Parks and Wildlife (TPW). The TPW is responsible for management of wildlife habitats, including regulation of hunting on public and private lands through licensing and limits, and the maintenance of habitat on public lands through reforestation and restocking. Declines in, or relocation of, fish and wildlife populations, or changes in habitat due to existing subsidence, have not been identified as significant problems.

Louisiana Wildlife and Fisheries Commission. The Commission deals with the effects of subsidence on wildlife and fish populations on an ongoing basis. Areas of concern include loss of marsh habitat, particularly for hunting and trapping species, through submergence of wetlands and saltwater intrusion, and loss of habitat for fish and shellfish species due to saltwater intrusion and increased salinities. While the Commission is able to give advice and provide information regarding the effects of subsidence, the projects needed to mitigate subsidence are beyond its range of responsibility and capability.

4.5.4 Flooding

U.S. Army Corps of Engineers. The Corps is charged with maintaining navigable waterways, and with providing flood protection to floodplains through the design, planning, and construction of flood control structures. Certain costs, including land purchase, easement, operating, and maintenance costs, are shared with local agencies, and the federal government is held immune from damages due to the construction works. The response of the Corps to subsidence would generally be in terms of flood control, although subsidence-induced impediments to navigation, such as lowered bridge elevations or canal locks, would also be addressed by the Corps. The Corps also map flood-prone areas for the National Flood Insurance Program and other programs.

National Flood Insurance Program. The Program is administered by Electronic Data Systems (EDS), a private insurance firm contracted by the federal government. Following a flood, EDS receives claims from various insurance agencies and acts as a claims adjuster. Insurance rates are of two kinds:

- Emergency (subsidized)--a low rate of insurance for those areas not surveyed by the Corps to determine flood elevations. These areas exhibit coverage of $35,000 for structure and $10,000 for contents for single family homes; and, $100,000 for structure and $100,000 for contents for commercial uses. The respective annual premium rates are: $0.25/$100-structure, $0.30/$100/contents (single family) and $0.40/$100-structure, $0.70/$100 contents (commercial).

- Regular (actuarial) rates--these rates are consistently higher and are based on propensity to flooding. The basis for these rates (which vary and cannot be averaged like the subsidized rates) is a series of floodplain maps produced by the Corps of Engineers. These maps identify FIRM zones, which are areas prone to flooding. Levels of flooding are letter coded with zone A being within a 100-year floodplain and zones B, C, D, and V being progressively less flood-prone. An example of a rate for this system would be a single family home in zone C which would have a rate of $0.01/$100; in zone A the rate could be 10 times higher. In zone A, rates vary within the zone by the elevation below the 100 year floodplain; i.e., as elevation decreases, rate increases.

It is important to note that these rates and, hence, coverage are entirely dependent on the Corps' maps. The rates are updated periodically, but the maps must also be updated frequently in active areas for coverage to be adequate and equitable.

4.5.5 Other Institutions

Texas Disaster Emergency Services (TDES). Essentially a coordinating agency, TDES provides information on emergency procedures to other agencies and the public, and facilitates evacuation, law enforcement, and provision of shelter and medical aid during and after an emergency.

Houston-Galveston Subsidence District (HGSD). The effects of subsidence due to groundwater withdrawal in Harris and Galveston Counties are widespread and include structural damage, stream course changes, and increased salinity of groundwater. The Houston Galveston Subsidence District (HGSD) was chartered by the state in 1975, as a separate agency answerable only to its two county jurisdiction, to regulate groundwater extraction. Regulation entails monitoring of subsidence and soil compaction and the granting of water well drilling permits. These permits cost $3.15 per million gallons of use for private users, or $4.50 per million gallons for municipal users, who account for the majority of permits.

When a permit is applied for, the HGSD initially will investigate the location and land use to determine the impact of the groundwater extraction. They will encourage or mandate the use of surface water before resorting to groundwater--even if it costs the user more. If surface water is not immediately available, but feasible in the future, then a time period commitment (say 5 years) is written into the permit to convert to surface water use. If surface water sources are not available, then groundwater extraction is restricted and a permit is issued which defines that limit. HGSD has no police power to penalize excessive groundwater extraction, but works closely with the State Attorney General's Office, which is an enforcing agency. Fines of up to $5,000/day are possible, but most cases are settled out of court.

The degree of success by HGSD is evidenced by no subsidence or a reduced rate of subsidence in the two counties monitored.

HGSD funding is derived from permit fees which average $900,000 to $1,000,000 annually. The staff of 19 consists of professionals, scientists, and administrators. A 15-member board of directors is chosen from public and private sectors by governmental, corporate, and institutional leaders, thus no one body or agency has complete control of HGSD. The HGSD may also commission special studies. One current study by an engineering firm is expected to predict, through the use of computer models, inches of subsidence per gallons of groundwater extraction for given sites.

Louisiana Department of Natural Resources (DNR). The Louisiana Department of Natural Resources (DNR) regulates geopressured-geothermal activities and requires levelling data and logging data to determine if subsidence is occurring. DNR is empowered to shut down an operation in order to mitigate or stop subsidence.

5. ESTIMATION OF SUBSIDENCE AND RELATED GROUND MOVEMENTS

5.1 INTRODUCTION

5.1.1 Scope

Subsidence calculations based on geopressured geothermal fluid production scenarios and up-to-date, but limited, rock compressibility data are reported in this chapter. Methods used to obtain associated calculations (such as estimated area of significant subsidence and rate of subsidence) and estimates of subsidence-related ground movements (such as tilting and horizontal movement) are also discussed. These estimates, and the impact assessments based on them, were made primarily to identify the problems currently faced in estimating potential subsidence.

5.1.2 Subsidence-Related Ground Movements

Viets and others (1979, pp. II-1, II-3) gives the following overview of subsidence-related ground movements:

> Removal of geofluids such as water, gas or oil or mining of solids from below the ground surface can result in the formation of a "subsidence bowl" where the ground surface has settled in response to the subsurface removal. Figure II-1 [EDAW-ESA Figure 5-1] shows an idealized profile across a subsidence bowl. Actual subsidence bowl profiles depend on local geology and the depth and areal extent of the fluid removal but, in general, conform to the profile shown. As a subsidence bowl develops, a number of different types of ground surface movements, herein called subsidence phenomena, occur. First, vertical settlement [or subsidence] of the ground surface occurs. The size of the area in which settlement occurs depends on nature and depth of the subsurface materials being removed. As the subsidence deepens, tilting of the ground surface occurs. All areas within the subsidence bowl usually tilt toward the center of the bowl. All points on the ground surface within the subsidence bowl also are displaced horizontally toward the center of the bowl. Curvature of the bowl introduces horizontal strains in the ground surface. In the outer part of the bowl, the surface is

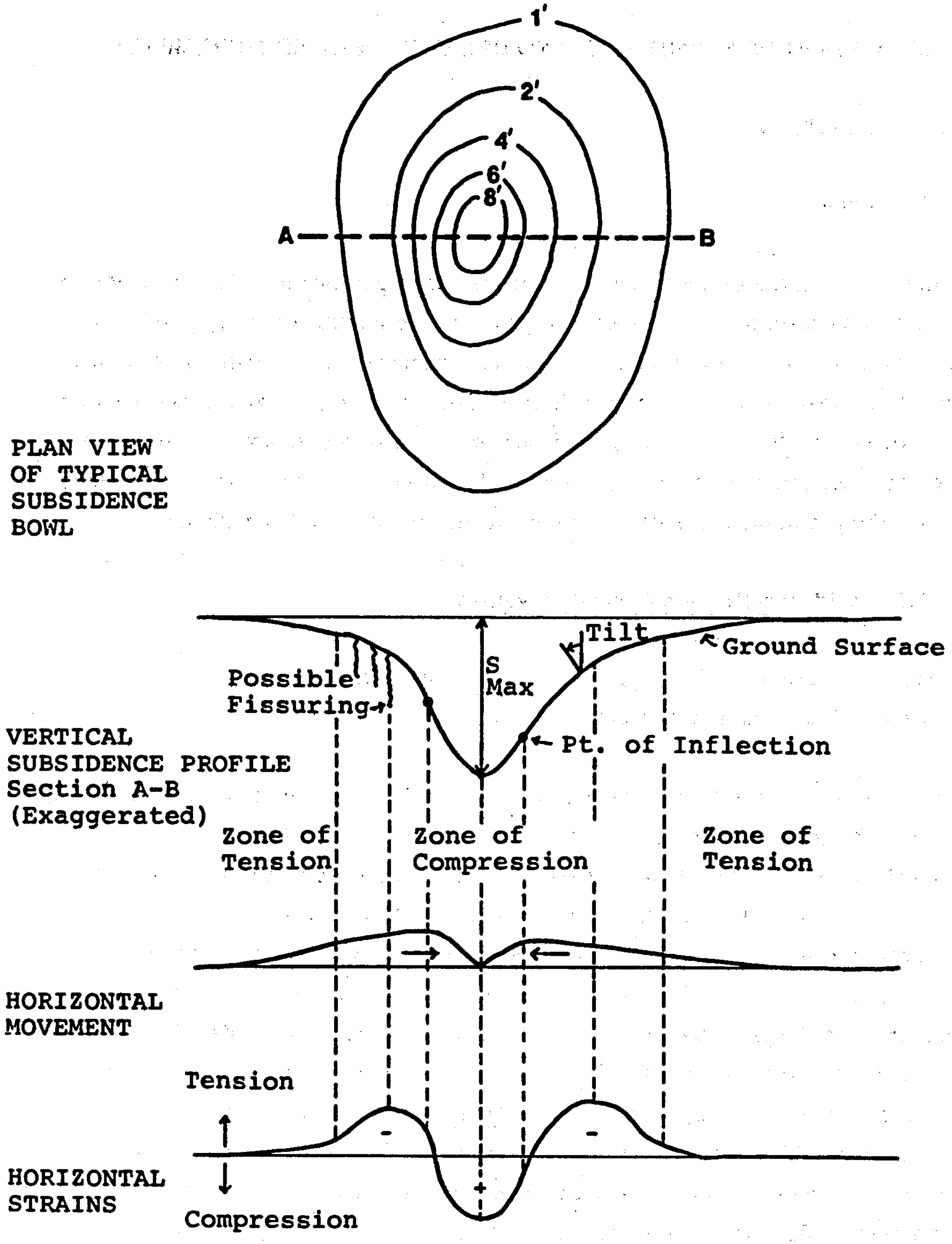


FIGURE 5-1. RELATIONSHIP OF TYPICAL SUBSIDENCE RELATED GROUND MOVEMENTS (from Viets and others, 1979)

in tension and in the middle of the bowl, the surface is in compression. At the points of inflection in the subsidence bowl profile where the slope is a maximum, the horizontal strains are zero. If the tensional strains in the outer portion of the bowl become large enough, tension cracks or fissures in the ground surface may result. Cracking may also occur within the bowl at locations, such as existing faults, where the vertical subsidence is concentrated due to some subsurface discontinuities. The damage causing potential of these subsidence phenomena vary considerably, as discussed in the following sections, depending on the nature and magnitude of the phenomena and on the types of natural features, structures, or land uses present in the area.

It must be kept in mind that this discussion of subsidence phenomena is an oversimplification of the problem. In actual situations, the phenomena occur simultaneously and change with time as the subsidence bowl develops. There is often a problem with clearly isolating the mechanism causing damage, not only because of the complexity of the subsidence-related processes, but also because there are other physical conditions and processes that may also be contributing to the damage. Several subsidence mechanisms may be at work at the same time. In addition to subsidence due to fluid withdrawal. . ., subsidence may also be occurring at the same location due to compression of clay soils and physical loading by engineering structures (as in Mexico City), oxidation of deep organic soils (as in New Orleans), hydrocompaction of near-surface materials (as in the San Joaquin Valley), or from tectonic deformation. Damage from subsidence can be also disguised and difficult to recognize because it is often not dramatic, takes place over a prolonged period, and may be easily mistaken for normal deterioration or poor construction techniques and materials.

5.2 SUBSIDENCE ESTIMATION

Total vertical settlement is the most frequently used parameter to describe subsidence and is often simply called "subsidence". Subsidence is measured vertically from the original ground surface to the deformed surface (Viets and others, 1979).

5.2.1 Overview of Estimation Method

A current, generally accepted method of predicting subsidence is shown diagrammatically in Figure 5-2. The process begins with development of production scenarios and estimates of 1) pressure changes which are expected in the reservoir and 2) volumes of fluid produced during production as a result of resource development. Gruy Federal, petroleum engineering consultants to this project, developed a "Bottomhole Pressure Model" (McCoy and others, 1980; also see Appendix B) to derive production scenarios from which these pressure and fluid volume changes can be calculated. Based on estimates of either pressure or fluid volume changes, along with knowledge of reservoir properties, compaction in the production zone is estimated. Where pressure changes are localized and deep, subsurface strains caused by compaction may not be fully transmitted to the surface, but rather "absorbed" by the surrounding material. Hence, the last step consists of translating the compaction estimate into a prediction of subsidence. This is usually done by means of a mathematical model that takes into account the amount of estimated reservoir compaction, as well as properties of the reservoir and overburden materials.

The most sophisticated methods of analysis attempt to incorporate all of the above steps in one large scale model which recognizes the interdependence of all steps. (For example, production is actually dependent on formation compaction and stress distribution.) Such models may, in principle, track flow, temperature, and pressure changes throughout complex three-dimensional geologic structure and lithology. If production is to be only roughly estimated, and there are few site-specific geologic data, the use of much simpler analytical schemes and models is reasonable. As indicated by Miller and others (1980c) calculation of compaction and subsidence of geothermal prospects by simple hand calculation techniques is straightforward and the resulting answers compare well to those found by using computer programs. Hand calculation models are usually justified except where highly accurate field data are available. We have employed a hand calculation technique, since highly accurate field data are not currently available in the geopressured geothermal areas of the Gulf Coast. Compaction of sandstone is calculated using the method based on reservoir pressure drop as described by Miller and others (1980c, p. 14). Shale compaction estimates are approached in the same way but also utilize Terzaghi's (1943) theory of consolidation. Propagation of

SUBSIDENCE ESTIMATE STEPS

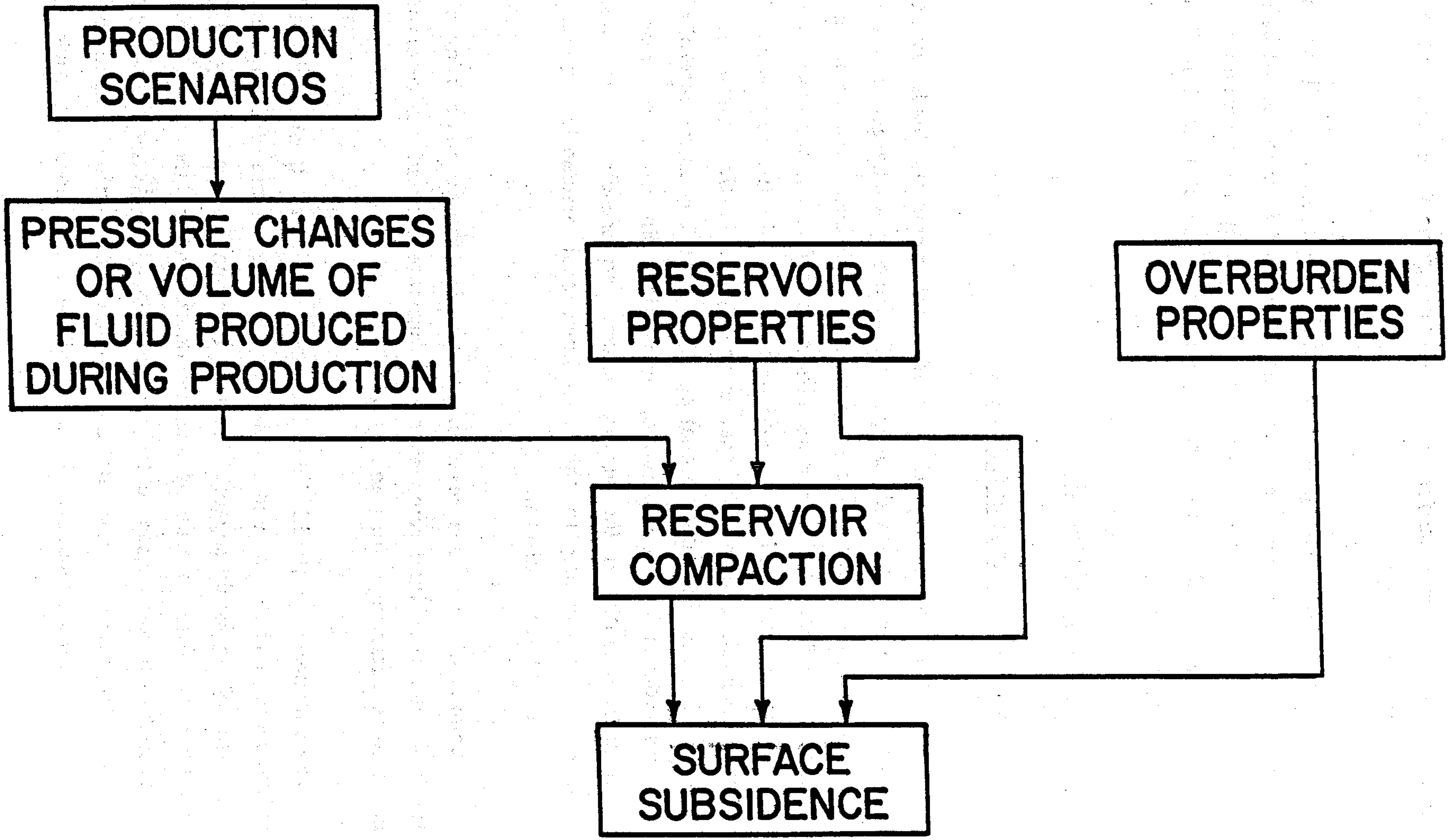


FIGURE 5-2

compaction to the ground surface is modeled using the Geertsma (1973) thin-disk nucleus-of-strain concept.

The above steps leading to subsidence estimates, as well as associated subsidence calculations and phenomena, are described in more detail below. The following discussion will then serve as a starting point for approximations of the amount of subsidence that might be expected at each of four Gulf Coast areas selected for study.

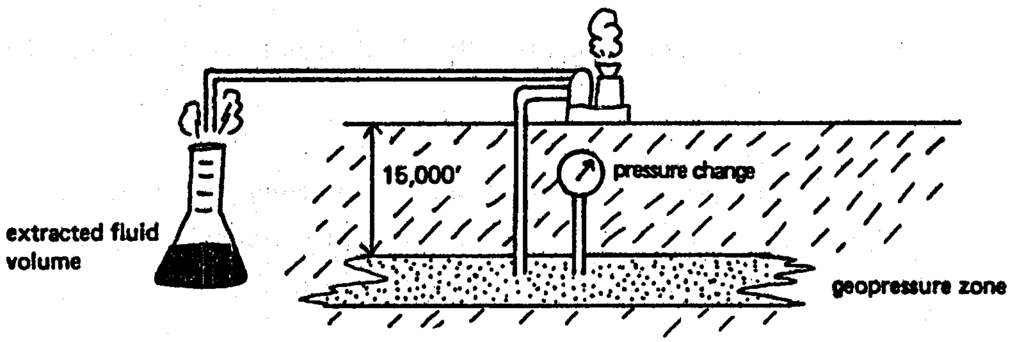
5.2.2 Compaction Estimation

5.2.2.1 Method of Calculation

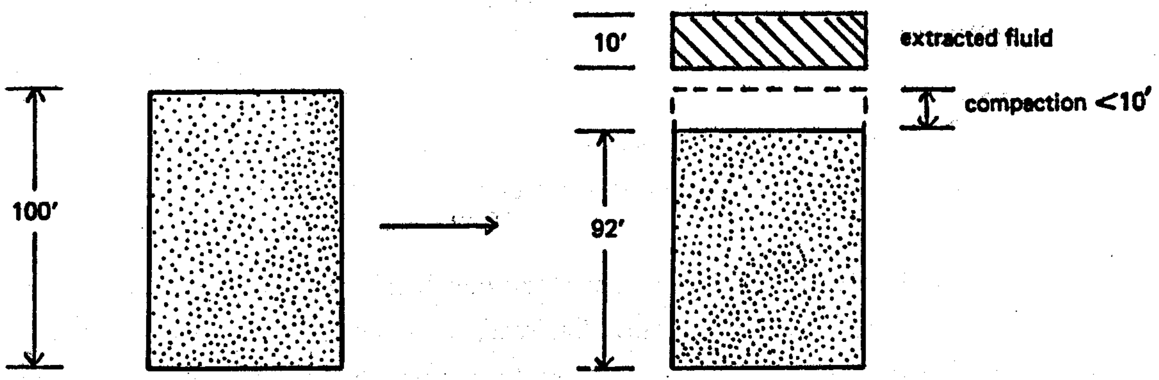
Development of geopressured geothermal resources leads eventually to reduction of both pressure and volume of hot, methane-charged water stored in sandstones and shales within the geopressured zone under two or more miles of constant overburden. This pressure reduction causes an increase in effective stress, which is expressed as a vertical strain within the reservoir. We have computed reservoir compaction, that is to say the vertical strain of the geopressured zone, using one-dimensional equations. As long as the lateral dimension of the reservoir is large compared to its vertical dimension, the reservoir will deform predominantly in the vertical plane, and one-dimensional modeling is adequate. Corresponding to this one-dimensional assumption, compaction is assumed to be laterally uniform.

Estimates of sandstone reservoir compaction can be made using either the estimated volume of fluid removed or the pressure drop in the reservoir during production as a starting point (see Figure 5-3A).

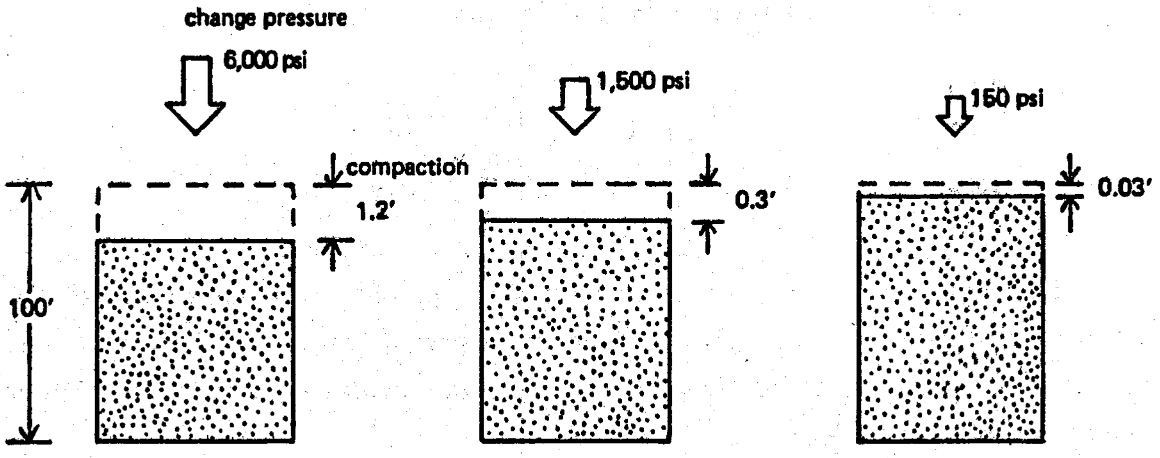
The volumetric method is illustrated in Figure 5-3B. If we begin with a 100-foot thickness of reservoir, and extract from that a volume of fluid equivalent to 10 ft, then reason would suggest a resulting compaction of roughly 10 ft. This would be very close to true at shallow depths, where the fluid is practically incompressible in comparison to the rock matrix. However, at great depths and where the rock matrix is very stiff, the volume of compaction tends to be less than the volume of fluid produced. In the limiting case where the rock matrix is



A. Hypothetical Case



B. Effect of Fluid Volume Removal



C. Effect of Pressure Change

EFFECT OF PRODUCTION VOLUME
AND PRESSURE CHANGE
ON COMPACTION

FIGURE 6-3

perfectly rigid and the fluid compressible, fluid could be produced with no compaction.

Derivation of a simple formula for the ratio of compaction volume, V_c, to fluid production volume, V_p, is found in Appendix C. The ratio of compaction volume to fluid production volume is:

$$\frac{V_c}{V_p} = \frac{1}{1+\frac{nC_w}{C_m}}$$

where, n = porosity
C_w = compressibility of water
C_m = uniaxial compaction coefficient

This equation is simplified in that it does not consider fluid temperature change and compressibility of the rock matrix. However, the change in temperature within the reservoirs under study is not thought to be significant throughout production time, and the compressibility of the rock matrix is also thought to be insignificant. To calculate, approximately, the potential compaction of a sandstone reservoir ($C_{sandstone}$) the volume of compaction, V_c, is divided by the area of the reservoir, A. The resulting compaction equation is as follows:

$$C_{sandstone} = \frac{V_p}{A\,(1+\frac{nC_w}{C_m})}$$

If, on the other hand, we begin with some prediction or knowledge of the subsurface pressure change over the production period, rather than fluid volume production, sandstone compaction, $C_{sandstone}$, can be calculated as follows (Miller and others, 1980c, p. 14):

$$C_{sandstone} = HC_m\ \Delta p$$

where, H = thickness of reservoir
C_m = uniaxial compaction coefficient
Δp = pressure drop vertically averaged

This equation also assumes that the reservoir behaves isothermally. It is necessary to find Δp from reservoir-flow modeling (production scenarios) which, for this study, was supplied by Gruy Federal's "Bottomhole Pressure Model," (McCoy and others, 1980; also see Appendix B).

Due to the simplicity of its equation, we have chosen to use the pressure drop method in this study. Compaction estimates made using the fluid volume change method are within 25% of the estimates made using the pressure change method.

Four separate factors contribute to reservoir compaction as calculated by the pressure drop method :

1. The change in reservoir pressure.
2. The vertical dimension of the zone in which pore-pressure reduction takes place.
3. The compressibility of the reservoir rock.
4. The rate of shale compaction.

These influences are briefly discussed below.

5.2.2.2 Effect of Reservoir Pressure Changes

The effects of various hypothetical pressure changes on a typical 100-foot thickness of geopressured sands are shown in Figure 5-3C. Substantial depressurization of the reservoir (caused by a reduction of pressure of about 6000 psi, for example) produces about 1.2 ft of compaction. Lesser pressure reductions would cause proportionally less compaction as shown. A sandstone compressibility, C_m, of $2 \times 10^{-6} \text{psi}^{-1}$ has been assumed in these examples.

5.2.2.3 Effect of Reservoir Thickness

Compaction of the reservoir shown in part C of Figure 5-3 would also be proportional to reservoir thickness; for example, compaction due to a 6000 psi pressure drop in a 1,000-ft thick (instead of 100-ft thick) reservoir would be 12 ft, using the same compressibility value.

5.2.2.4 Effect Of Rock Compressibility

Another very significant physical factor which influences reservoir compaction is the compressibility of the sandstones and shales within, or adjacent to, the geopressured zone. The compressibility of natural porous rock materials may vary by a factor of 100 or more, depending on, among other factors, the rock type, degree of cementation, and past pressure history. In connection with compaction of reservoirs at a depth of 10,000 or more feet, a brief literature search (see Table 5-1) yields values of uniaxial compaction coefficient, C_m, varying from about 9×10^{-8} psi^{-1} for well consolidated reservoir rocks to 5×10^{-6} psi^{-1} for less well consolidated sandstones or shales. As shown in Figure 5-4, reservoir compaction for a given pressure drop and aquifer thickness could vary from less than half a foot to around 15 ft for this range of rock compressibility. This is a very large range.

Another way to look at the effect of differing rock compressibility values on compaction estimates is to examine the effect C_m has on the ratio of the volume of compaction to the volume of fluid produced in a reservoir, Vc/Vp, as discussed above. Taking n = 0.2 and $C_w = 3 \times 10^{-6}$ psi^{-1}, the effect of C_m on Vc/Vp can be seen as follows:

C_m, psi^{-1}	Vc/Vp
6×10^{-5}	.99
6×10^{-6}	.91
6×10^{-7}	.50

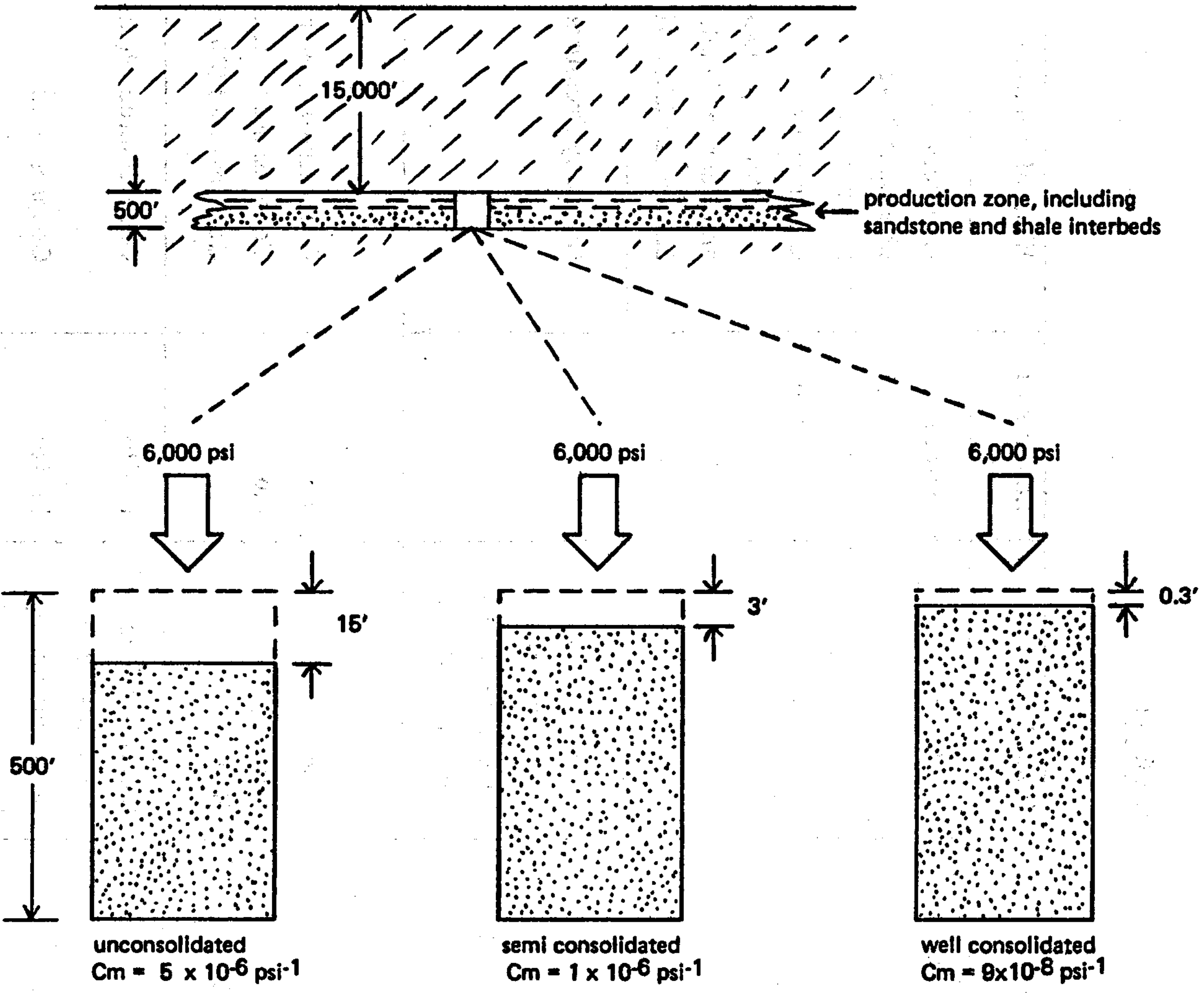
Soft uncemented sandstones and shales have uniaxial compressibilities, Cm, greater than 6×10^{-6} psi^{-1}. Hence, the volume of compaction corresponding to this value of Cm is nearly equal to the volume of production. However, as discussed above, limited test data available for geopressured sandstones indicate a compressibility of 6×10^{-7} psi^{-1}, with a corresponding Vc/Vp of about 0.5. Hence, compaction is about half of the production volume per unit area of reservoir.

Most recent investigators (see Table 5-1) consider values on the order of $C_m = 10^{-6}$psi^{-1} reasonable for deep Gulf Coast sandstones. These estimates are based principally on laboratory tests, but they are also in agreement with some

C_m Values for Gulf Coast Geopressured Geothermal Reservoir Rocks

TABLE 5-1

Source	$C_m\left(\frac{1}{psi}\right)$	Rock Type	Lab/In situ	Well Information
Dorfman, 1980	2×10^{-7} to 3.5×10^{-7}	Sandstone	lab/In situ	Geopressured (Pleasant Bayou)
Dropek and Abousayed, 1978, cited in EPRI, 1980; Swanson, 1978, cited in EPRI, 1980	2×10^{-7} to 5×10^{-6} (average = 10^{-6})	Sandstone	lab/In situ	Geopressured (Pleistocene, Miocene and Younger (Shell Oil Co.)) S.E. Pecan Island (Exxon Corp.)
Geertsma, 1973	2.8×10^{-7} to 12.0×10^{-7}	Sandstone (well-consolidated)		Normally Pressured
	7.1×10^{-7} to 23.3×10^{-7}	Sandstone semi-consolidated		
Gray and others, 1980	(average values)			
	3.6×10^{-7}	Sandstone	lab	Geopressured (Pleas. Bayou #1)
	3.5×10^{-7}	Sandstone	lab	Geopressured (Pleas. Bayou #2)
	6.5×10^{-7}	Shale	lab	Geopressured (Pleas. Bayou #2)
Gregory, 1980; Gregory and Backus, 1980, Table 5	9.83×10^{-8}	Sandstone (well-consolidated)	in situ	Geopressured (Pleas. Bayou #2)
	8.63×10^{-8}	Shale and Shaley Sandstone	in situ	Geopressured



EFFECT OF ROCK COMPRESSIBILITY ON COMPACTION

FIGURE 5-4

field production data. We have chosen to use 6×10^{-7} psi^{-1} as the C_m value for sandstone in our subsidence calculations. This particular value was chosen as a result of conversations with petroleum engineering consultants who have extensive geologic experience in the Gulf Coast.

Few laboratory tests have been run on the shales which are interbedded with, or surround, the geopressured geothermal sandstone reservoirs. Values for the more compressible shales are, therefore, only educated guesses. After discussions with petroleum engineering consultants, we have chosen to use 3×10^{-6} psi^{-1} as the C_m value for shale. To investigate the possibile situation in which the shales are actually even more compressive than this, we have also made compaction and subsidence calculations using the higher C_m value of 3×10^{-5} psi^{-1}.

Obviously, definitive, and perhaps site specific, values of C_m will be necessary for accurate predictions of compaction and subsidence.

5.2.2.5 Effect of Rate Of Shale Compaction

Whether compaction of shale beds within and surrounding geopressured reservoirs would actually occur within a time span of any practical significance is a matter of some controversy. Compaction of the shale requires that water be squeezed from it. Because shale is much more impervious to the flow of water than sandstone, there is no doubt that shale will compact more slowly than the sand. One line of argument says that the shale compacts so slowly, in terms of any production time scale, that its contribution to subsidence would be unimportant; hence the shale component of compaction can be neglected. Another opposing view holds that shale beds could be partially dewatered during the time of production, and that the compressibility of the shale is so high that even partial dewatering (or depressurizing) would contribute substantially to subsidence (and fluid production).

Permeability and thickness of shale beds affect the dewatering rate. Unfortunately, only a few data are available on the permeability of shales in geopressured zones. Representative studies of consolidation of a hypothetical shale bed (70 ft thick, permeability of 0.003 millidarcies (md)) by Miller and others (1980c) suggests that substantial compaction would occur in only a few years (50% in about three years). However, shale beds of lower permeability or greater thickness would be proportionately less affected. For example, a shale bed with permeability of 0.0003 md and thickness of 700 ft would require 3,000 years for 50% compaction. A 1970 review of fluid pressures in the Chocolate Bayou Field, Texas, by Fowler, suggests that shale permeabilities (across bedding) are probably on the order of 10^{-6} md, or perhaps 1000 times smaller than the 0.003 md assumed by Miller and others (1980c). Substantial compaction of a 70-ft thick shale bed would take several thousand years for this lower permeability.

For this study we assume that only partial dewatering of the shales will occur during the period of production; we have modeled this phenomenon using Terzaghi's (1943) theory of consolidation. We also assume that continuing compaction of the shale will not occur after wells are shut in, because water draining from the shale would restore pressure in the depressurized sandstone, thereby considerably slowing or stopping the dewatering process.

Use of Terzaghi's (1943) consolidation theory is straightforward. Shale compaction, C_{shale}, is calculated as:

$$C_{shale} = H \Delta p C_m U\%$$

where, U% = degree of consolidation.

U% depends on a time factor, T:

$$T = \frac{C_v t}{H^2}$$

where,

C_v = consolidation coefficient

t = time (in seconds if C_v includes seconds as its time dimension)

H = vertical distance to an impervious boundary. This is one-half the shale bed thickness if the shale is interbedded in the reservoir sandstone. H is the total shale bed thickness if the shale bounds the geopressured zone above or below.

An example of a shale compaction calculation follows. If a 20 ft thick shale interbed, with a C_v of 2×10^{-8} ft^2/sec and a C_m of 3×10^{-6} psi^{-1} is subjected to depressurization of 4000 psi, 0.1 ft of compaction can be expected in 20 years, as shown by the following calculation steps:

Step 1 - Calculate T

$$T = \frac{(2.0 \times 10^{-8}\ \text{ft}^2/\text{sec})\ (6.3 \times 10^{8}\ \text{sec})}{(10\ \text{ft})^2}$$

$$= .13$$

Step 2- Determine U%

Graphs exist to find U% directly as a function of T, or a simple equation may be solved to find U% (see Appendix D). If $T = .13$, $U\% = 42\%$.

Step 3 - Calculate shale compaction

$$C_{shale} = HC_m \Delta p\ U\%$$

$$= (20\ \text{ft})\ (3 \times 10^{-6}\ \text{psi}^{-1})\ (4000\ \text{psi})\ (42\%)$$

$$= 10\ \text{ft}$$

Another interesting point arising from a discussion of the rate of shale compaction is discussed here. Assuming that $C_v = 3.8 \times 10^{-8}$ ft^2/sec for shale, it may be shown that the time required for significant (10%) compaction of shale beds will be given by the following approximate equation:

$$t = \frac{.008\ H^2}{C_v},$$

where, H = one-half the shale bed thickness.

If we take t = 20 years (the expected production life) and solve for H, we find that only those shale beds with $H < 55$ ft compact significantly in this time period. Hence, in the foregoing problem the shale would probably contribute to compaction if individual shale beds were no more than 110 ft thick. If, however, the shale were massively bedded — having a thickness of hundreds of feet or more — then the shale compaction during a 20 year operational life would be limited to several feet of shale immediately adjacent to depressurized sands; the compaction would be consequently small, relative to the total shale thickness, during the period of depressurization.

Compaction of compressible shale interbeds or confining beds, if it should occur, would produce more fluid than compaction of the sandstone alone, so fluid production estimates based on sandstone compressibility alone could be misleadingly low. If an overall value of system compressibility, which includes consideration of any shale beds present (both their thickness and the degree of compaction expected during the limited life of the development) as well as sandstone compressibility, is used in the production analysis, then fluid production and compaction prediction should be correspondingly correct. Hence, estimates of system compressibility, where based on laboratory tests (for example) should consider results of compressibility tests on all materials present in the production zone, including shales and siltstones. In connection with the finer grained materials, permeability (or coefficient of consolidation, C_v) must also be known to determine the amount of potential compaction that could be realized during the time of production, because the degree of compaction in the finer grained rocks is clearly time-dependent.

5.2.3 Subsidence Estimation

5.2.3.1 Method of Calculation

Transformation of a compaction prediction into a subsidence prediction is of particular importance in estimating subsidence in geopressured zones because of their great depth, the effect of which being that the compaction of zones of small areal extent may be "absorbed" by the overlying material so that the surface ground subsidence may be much less than the compaction at depth. Various "modeling" techniques of various degrees of sophistication may be employed to analyze this element of the problem. The recent LBL-funded research by Golder Associates, Inc. (Pinder, 1979; Miller and others, 1980a; 1980b, 1980c; 1980d) gives full treatment of this problem.

To transform reservoir compaction into surface subsidence, the interaction between the shrinking reservoir and the surrounding rock must be determined. Geertsma (1973) has used the theory of poroelasticity, with the help of the nucleus-of-strain concept, to calculate this interaction. He uses an idealized disc-shaped reservoir of thickness H and radius R at depth D for a uniform reservoir pressure reduction, Δp, throughout the reservoir. To use Geertsma's simple formulation, one must assume that both the reservoir and its surrounding rock are homogeneous with regard to their deformational properties (C_m and ν, Poisson's ratio, for example). Subsidence above a disc-shaped reservoir can be found by calculating the percentage of compaction transmitted to the surface as subsidence at different distances from the center of the disc. Geertsma does this using the following equation:

$$\frac{\text{Subsidence}}{\text{Compaction}} = -2(1-\nu)\ A$$

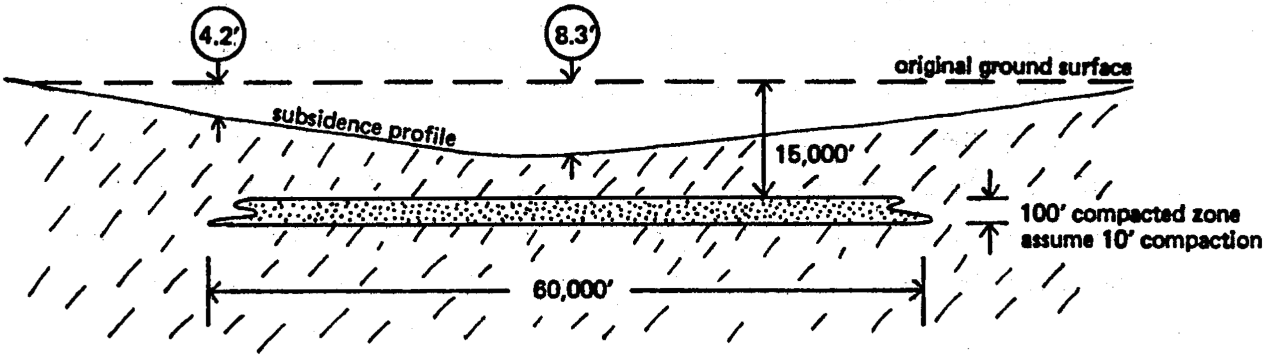
where, ν = Poisson's ratio
A = a Hankel Lipschitz integral

Poisson's ratio was found for the overburden by Gruy Federal's elastic properties model (McCoy and others, 1980). This model uses log responses to approximate the elastic properties of a reservoir and its overburden. "A" is a "Hankel-Lipschitz integral", the value of which can be looked up in a table (see Appendix E, Table E-1). From this table, it can be seen that the ratio between maximum subsidence and reservoir compaction is largely determined by the depth of burial and the lateral extent of the reservoir.

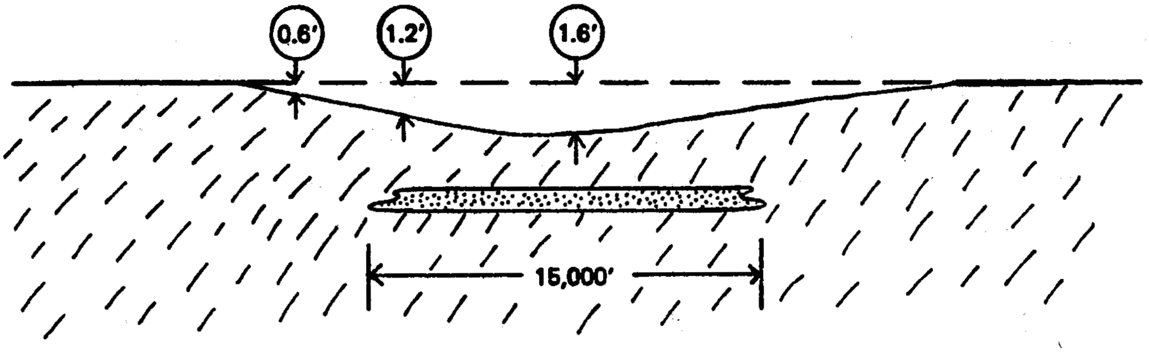
Reservoirs which are not even close to disc-shaped in reality, are modeled using superposition of smaller discs.

5.2.3.2 Effect of Reservoir Dimensions

The effect of varying the principal dimensions of a typical geopressured zone on subsidence is illustrated on Figure 5-5. The upper part of the figure depicts a situation in which an extensive disc-shaped geopressured zone compacts a total of



A. Extensive Zone



B. Local Zone

EFFECT OF COMPACTED ZONE
DIMENSIONS ON SUBSIDENCE

FIGURE 6-5

10 ft. This case has been analyzed using the well known Geertsma model, with the result that subsidence at the center of the affected area is 8.3 ft or 83% of the compaction, and about half that value at the edge of the field. Note that lesser, but nonetheless significant, subsidence is indicated as occurring outside the limits of the compacted zone. Figure 5-5B illustrates the case of a more restricted compacted zone, a disc with diameter equal to 15,000 ft, which also compacts a total of 10 ft. In this case only 1.6 ft of subsidence is seen over the center of the zone, tapering to 1.2 ft over the edge of the zone and 0.6 ft a mile outside the edge of the zone. In general, the smaller the dimensions of the compacted area, the less subsidence of the ground surface. Although these predictions were made using the relatively simple Geertsma model, comparative calculations with other more elaborate models should give very similar results.

5.2.3.3 Effect Of Brine Reinjection

The development of geopressured geothermal resources will require the production and subsequent disposal of large volumes of brine. For example, the scenario presented in this report for the Southeast Pecan Island prospect calls for an initial brine production rate of 40,000 bbl/day. A viable alternative for disposal of the brine is subsurface disposal, either injection into large, shallow aquifers or reinjection into the producing formation. The probable effects on subsidence and the feasibility of each strategy are briefly evaluated below.

Shallow injection of brine would appear to have no effect on resource development-related subsidence, as the shallow aquifers allow wide lateral transmission of the fluid, causing injection pressure dissipation and hence preventing rebound. Miller and others (1980a, p. 139) state that ". . . the same net subsidence occurs as would have occurred without [shallow] reinjection ".

Although shallow injection would appear not to mitigate subsidence, it does appear feasible. Oil and gas operators in southern Louisiana and Texas have disposed of produced brines in the shallow aquifers of the Gulf Coast for more than 30 years. It is estimated that nearly three million barrels of brine are being injected daily into aquifers without serious injectivity impairment or environmental damage (McCoy and others, 1980). These shallow aquifers, which are blanket sands extending over large areas, are characterized by thicknesses in excess of 100 ft, porosities greater than 30%, and permeabilities of one darcy or more.

However, 86% of these wells have injection rates of less than 3000-5000 bbl/day (EPRI, 1980) "with the maximum rate being 34,000 bbl/day for a well in Stratton Ridge Field in Brazoria County" (Knutson and Boardman, 1978, in EPRI, 1980, p. 41). Still, "although there is little [local] experience for injection in the 30,000 to 50,000 bbl/day range, the potential disposal zones appear large enough and thick enough to take these quantities of fluid" (EPRI, 1980, p. 48).

To avoid hydrofracturing, a rule of thumb of allowable injection pressures of 0.5 lb/ft of depth has been designated by the Texas Railroad Commission (Bachman, 1979). However, higher injection pressures would be required if pore plugging resulted from clay hydration or the precipitation of minerals in the formation (Bachman, 1979).

Deep reinjection of waste brine into the producing formation has been proposed as a resource development-related subsidence alleviation measure (Garg, 1979, EPRI, 1980; Miller and others, 1980a). If the original high pressures experienced in the formation before fluid production began could be permanently maintained through reinjection of spent brine, theoretically a rebound nearly equal to the total subsidence would be produced. Similar reinjection into producing formations at some normally pressured oil and gas fields has in fact caused reduction or even reversal of fluid withdrawal-related subsidence (Viets and others, 1979).

The benefits associated with reinjection into the producing zone include increased methane recovery, a factor viewed as essential to the success of this resource development by some in industry.

However, the high pressures required for deep reinjection would demand nearly as much energy as would be produced from the methane in the fluid (EPRI, 1980). Although another study concludes that the geothermal energy produced from the well could power the injection pumps instead of the methane-produced energy, the net economics of such a reinjection operation is still open to question (Garg, 1979). Accordingly, the effects of brine reinjection on resource development-related subsidence were not considered in the calculations made in this report.

5.2.3.4 Effect of Fault Activation

Compaction of reservoirs at depth is one of the mechanisms which contributes to surface subsidence. Subsidence can also occur as a result of slippage along faults due to fluid production or reinjection. A hand calculation technique for subsidence that considers fault slippage does not exist at this time, so this possible influence on subsidence was not addressed in this study. However, reservoir boundary faults are shown on the potential subsidence maps which follow. The potential subsidence contours calculated using Geertsma's nucleus-of-strain theory are depicted as solid lines within the fault boundaries. The contours are dashed beyond the fault boundaries to bring attention to the presence of the faults and the uncertainty of the effect of the faults on subsidence calculations.

5.2.3.5 Estimate of Area Significantly Affected by Subsidence

The area within which less than a certain amount of subsidence is expected to occur is the area significantly affected by subsidence. We chose 0.5 ft of total potential subsidence as being significant, compared to the amount of natural or man-made subsidence that would be occurring simultaneously. This area was measured for each subsidence study site from the maps of potential subsidence in Figures 5-7 through 5-10.

5.2.3.6 Estimate of Subsidence Rate

Examination of the production scenario computer printouts show that the rate of subsidence at each site is not expected to be linear. That is, the amount of subsidence expected each year would not be constant, but would decrease year after year.

The amount of subsidence expected each year (i.e., a yearly subsidence rate) was calculated from the production scenario printouts. Because the rate decreased, only the rates for the first and last years of production are given in Tables 2-1 and 2-2.

5.2.4 Estimation of Subsidence-Related Ground Movements

5.2.4.1 Tilt

Viets and others (1979, p. II-7) describe tilting as follows:

> Tilting of the ground surface toward the center of the subsidence bowl occurs in most parts of the bowl except at the edge of the bowl and in the center where the surface remains in its original orientation. In cases where fluids are withdrawn at a relatively uniform rate over a wide area. . . the degree of tilt may be relatively minor or negligible. In other areas with considerable subsidence over a small area, the tilt may be considerable. . . The points of maximum tilt are at the points of inflection in the subsidence profiles.

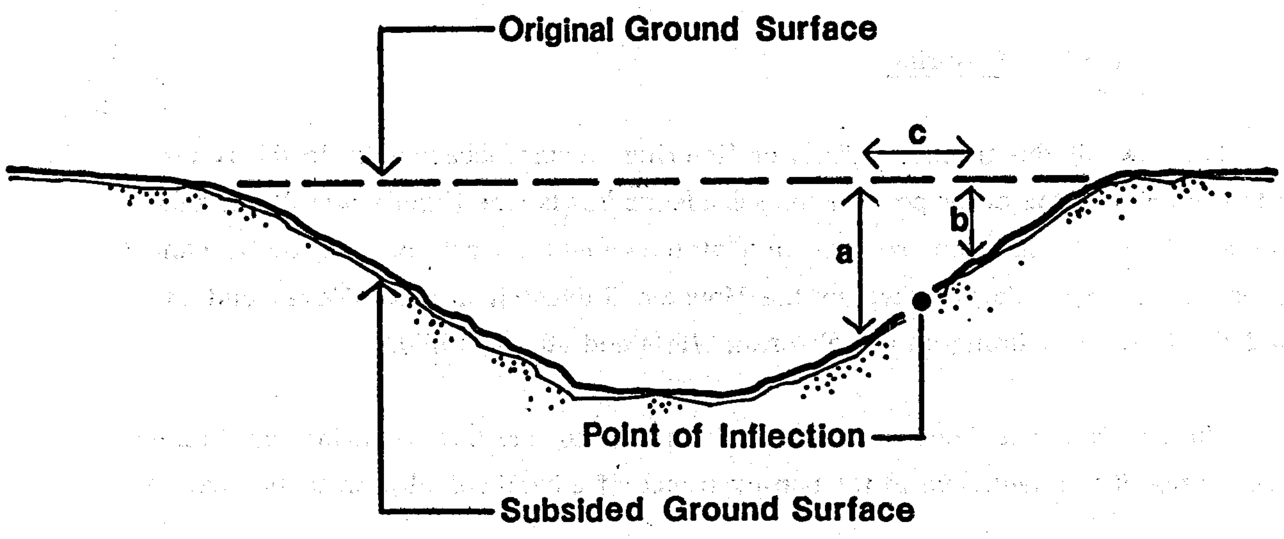
Maximum potential tilt was calculated at the point of inflection of subsidence profiles made for each study site as illustrated in Figure 5-6.

5.2.4.2 Horizontal Movement

Viets and others (1979, p. II-10) describe horizontal movement as follows:

> When a subsidence bowl develops, not only do points on the ground surface move vertically downward, but they also move laterally toward the center of the bowl. Both tensile and compressive strains are produced in the ground surface, as shown on Figure II-1 EDAW-ESA Figure 5-1 . It has been observed that there is usually no horizontal movement at the point of maximum subsidence in the center of the bowl. The point of maximum horizontal movement occurs at the point of inflection, the steepest slope of the vertical subsidence profile. Theoretically, horizontal strain at this point is zero. Compressive strains develop over the central area, and tensile strains develop in the outer portion of the subsidence bowl.

Geertsma (1973) has used the theory of poroelasticity and the nucleus-of-strain concept to calculate horizontal ground movements above a compacting reservoir. To use Geertsma's formulation, one must assume that both the reservoir and its surrounding rock are homogeneous with regard to their deformational properties (C_m and ν, Poisson's ratio, for example). Using the following equation, maximum horizontal ground movement above a disc-shaped reservoir can be found at the distance from the center of the disc that corresponds to the point of inflection of the subsidence profile:



$$* \text{Tilt} = \frac{a-b}{c}$$

FIGURE 5-6. METHOD USED TO ESTIMATE TILT
(from Viets and others, 1979)

$$\frac{\text{Horizontal surface movement}}{\text{Reservoir compaction}} = 2(1 - \nu)B$$

where, ν = Poisson's ratio

B = a Hankel Lipschitz integral, the value of which can be looked up in a table (see Appendix E, Table E-2).

5.2.4.3 Fissuring

Cracking of the ground surface, or fissuring, occurs occasionally in the zones of tension within the outer portions of subsidence bowls (see Figure 5-1) (Viets and others, 1979). In addition, reactivation of movement on pre-existing faults can occur, as has been documented in the Houston-Galveston area of Texas and at Baldwin Hills and Wilmington in California (Viets and others, 1979).

No attempt has been made in this study to predict fissuring or fault reactivation movements due to the non-existence of a hand calculation technique.

5.2.4.4 Subsurface Deformation

Viets and others (1979, pp. II-16, II-18) describe possible subsurface deformations as follows:

> Both vertical and horizontal deformations of the subsurface materials occur between the zone of fluid withdrawal and the ground surface. Vertical subsurface deformations occur within the zones of fluid withdrawal due to vertical compaction of the geologic formations and within the overlying materials as they subside because of the loss of support. Horizontal movements and strains develop below the surface just as they do at the surface. These vertical and horizontal deformations may be relatively uniform or concentrated along geologic discontinuities and pre-existing faults.

Vertical deformations are dealt with in this report to the extent of calculating reservoir compaction. Maximum potential vertical deformation would therefore be the maximum reservoir compaction calculated for each site. Horizontal deformations at depth were not calculated.

5.3 ESTIMATED SUBSIDENCE FOR SELECTED PROSPECTS

5.3.1 Introduction

Four prospects were selected for subsidence analysis: Southeast Pecan Island (Louisiana), Austin Bayou (Texas), Gladys McCall (Louisiana), and Cuero (Texas). The geology of each prospect, its production scenario, and potential compaction and subsidence estimates are given for each site. Table 5-2 contains the well deliverability parameters used in the production scenarios for each prospect.

5.3.2 Southeast Pecan Island Prospect

5.3.2.1 Geology

The Southeast Pecan Island prospect is located in southern Louisiana, in the coastal marshlands of south Vermilion Parish, partially offshore. It is situated near the Pecan Island, Fresh Water Bayou and Vermilion Area Block 16 gas fields. The prospect has a total area of about 20 square miles (sq mi) and is bounded by two major east-west trending growth faults, with throws of several hundred feet.

The prospect is in lower Miocene geopressured reservoir sandstones between about 13,400 and 17,500 ft. Below this depth is additional sandstone, but it produces conventional gas. Top of geopressure is at a depth of 13,400 to 14,500 ft. The sandstone occurs in three stratigraphic intervals. Sandstones have been thought to be up to 600 ft thick, although new data indicate they may be much thinner (D. B. Bebout, personal communication, 1980). Net sandstone thickness ranges from 100 to 1,400 ft, being greatest in the central and western parts of the prospect area. Permeabilities from cores and well logs appear to range from 7 to 278 md with an average porosity of 23%. Dissolved gas is estimated to be 20-40 scf/bbl (standard cubic feet/barrel). Temperatures range from 244° F to 350° F.

5.3.2.2 Production Scenario

A single well in this 20 sq mi prospect is modeled as producing from 500 ft. of sandstone at a depth of 14,000 ft with an initial reservoir pressure of 13,000 psi. The well produces 247,422,000 bbl of fluid over a 20 year production life, with

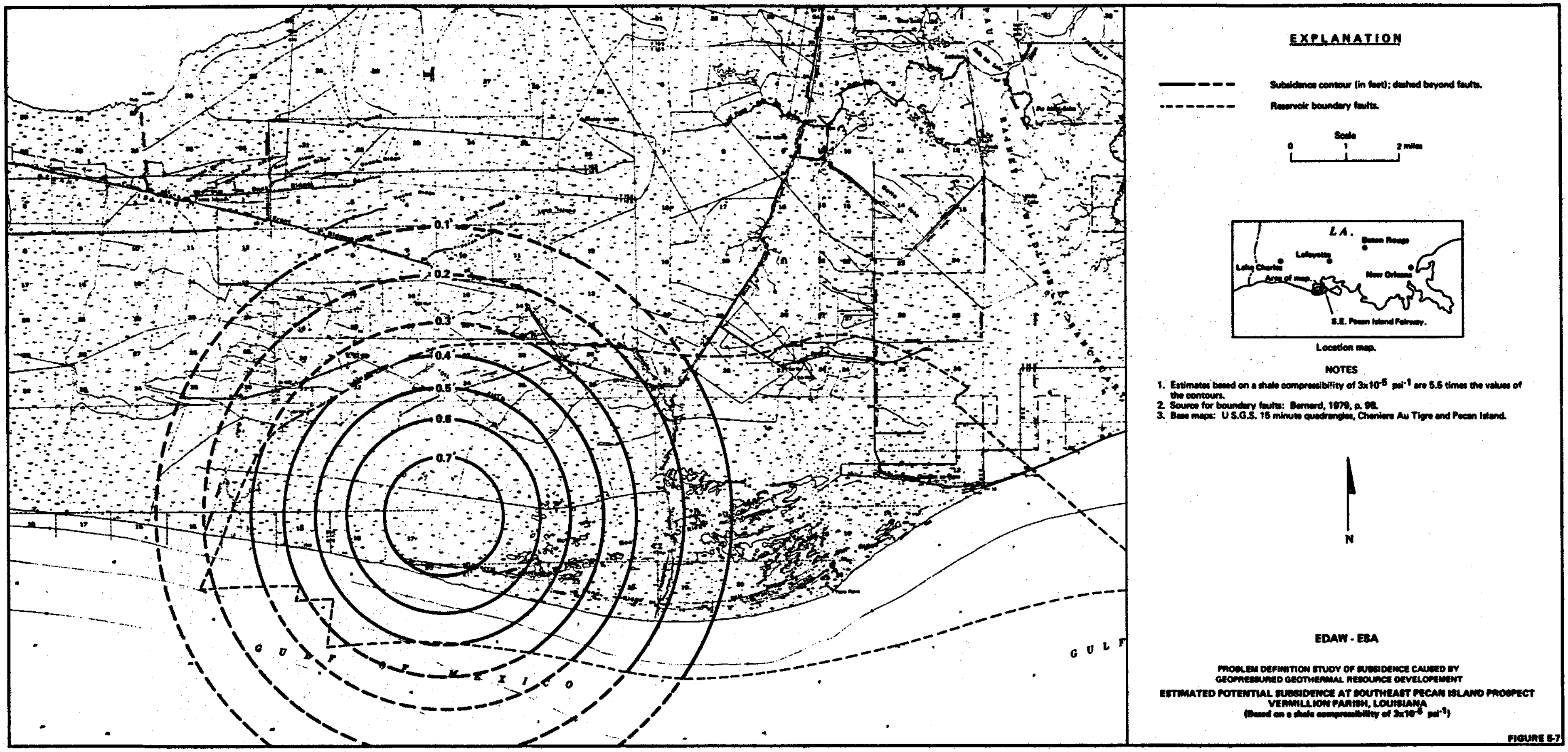
TABLE 5-2

WELL DELIVERABILITY PARAMETERS

Parameter	Gladys McCall	Austin Bayou	Pecan Island	Cuero
Inner diameter of pipe, in. (1)	4.778	4.778	4.778	4.778
Fluid density, lb/gal	8.690(2)	9.450(3)	8.750(4)	8.690(5)
Fluid viscosity, cp	0.300(2)	0.400(3)	0.300(4)	0.300(5)
Surface pressure, psia	1000	1000	1000	1000
Initial reservoir pressure, psia	14,200(6)	11,045(7)	13,000(6)	10,500(8)
Initial desired rate, Mbbl/D	40.000	40.000	40.000	40.000
Aquifer permeability, md	20.9(9)	148.0(7)	20.0(9,12)	15.0(9)
Aquifer thickness, ft	500.0	60.0	500.0	200.0
Aquifer porosity, decimal	0.230(6)	0.190(7)	0.230(6)	0.160(8)
System Compressibility, decimal (9)	5.0E-6	5.0E-6	5.0E-6	5.0E-6
Aquifer depth, ft (10)	15,000(10)	14,800	14,000	12,625(8)
Wellbore radius, ft	0.310	0.310	0.310	0.310
Skin effect, decimal	0.000	0.000	0.000	0.000
Epsilon for friction, decimal	6.5E-4	6.5E-4	6.5E-4	6.5E-4
Computation tolerance, decimal	1.0E-4	1.0E-4	1.0E-4	1.0E-4
Aquifer area, acres	10,240(13)	11,520(8)	12,800(14)	7,296(8)
Shape factor, decimal (11)	10.84	5.380	2.08	5.380
Dim. critical time, decimal (11)	0.15	0.300	0.50	0.300

Notes:

1. All production strings assumed to be 5-1/2 in., 20 lb/ft casing.
2. Calculated for salinity of 56,000 ppm (Bernard, 1979).
3. Calculated for salinity of 175,000 ppm (actual produced sample).
4. Calculated for salinity of 70,000 ppm (Bernard, 1979).
5. Calculated for salinity of 60,000 ppm (Bebout and others, 1979).
6. (Bernard, 1979).
7. Actual test data.
8. (Bebout and others, 1979) gradient 0.83 psi/ft.
9. Based on information obtained by Gruy Federal in similar depositional environments.
10. Based on actual log evaluations.
11. Based on available geological data.
12. Exxon Production Research.
13. Gruy Federal unsolicited proposal.
14. Approximate area of fault block as depicted per (Bernard, 1979).



EXPLANATION

Subsidence contour (in feet); dashed beyond faults.

Reservoir boundary faults.

Location map.

NOTES

1. Estimates based on a shale compressibility of $3x10^{-5}$ psi^{-1} are 5.5 times the values of the contours.
2. Source for boundary faults: Bernard, 1979, p. 98.
3. Base maps: U S.G.S. 15 minute quadrangles, Cheniere Au Tigre and Pecan Island.

EDAW - ESA

PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY
GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPEMENT

ESTIMATED POTENTIAL SUBSIDENCE AT SOUTHEAST PECAN ISLAND PROSPECT
VERMILLION PARISH, LOUISIANA
(Based on a shale compressibility of $3x10^{-6}$ psi^{-1})

FIGURE 5-7

final average pressure of 9390 psi (a pressure drop of 3610 psi). A copy of the production scenario computer printout is shown in Appendix F.

5.3.2.3 Subsidence and Related Estimates

Maximum reservoir compaction and associated surface subsidence have been estimated at 3 ft and 1 ft, respectively, for the Southeast Pecan Island prospect. Using a higher value of C_m for shale (3×10^{-5} psi^{-1}), compaction and subsidence were estimated at 12 ft and 4 ft, respectively. Compaction and subsidence calculations are shown in Appendix G, Tables G-1 and G-2. Estimated potential subsidence based on what appears to be the most realistic data available is shown in Figure 5-7.

The other subsidence-related calculations and estimates of related ground movements are summarized in Tables 2-1 and 2-2.

5.3.3 Austin Bayou Prospect

5.3.3.1 Geology

The Austin Bayou prospect is located in Brazoria County, within the Brazoria Fairway, and has a total area of about 18 sq mi. DOE has drilled two test wells in the area, DOE/General Crude #1 and #2 Pleasant Bayou, from which considerable geologic and reservoir data have been collected. Testing of the #2 Pleasant Bayou well is currently underway. The prospect is in the Frio trend with reservoir sandstone at a depth of 13,500 ft (D.B. Bebout, personal communicaton, 1980) to 17,000 ft, and is in a structural low between Danbury Salt dome and the faulted anticline at Chocolate Bayou field. Top of the geopressured zone is at a depth of 16,000 ft (D.B. Bebout, personal communication, 1980). Sandstone thickness in the prospect area is believed to be up to 800 ft, occurring in individual beds a few feet to 70 ft thick.

Permeabilities are variable, ranging from 20 to about 175 md above the 300° F. isotherm, with average porosities of 18%. The 300°F isotherm is at an approximate depth of 15,000 ft. Below this level, permeabilities are very low in the thin sandstones and very high (8 to 1,041 md) in the thicker sandstones. Average porosities in this zone are about 16%. Dissolved gas is estimated at 20-25 scf/bbl.

5.3.3.2 Production Scenario

A single well in this 18 sq mi prospect is modeled as producing from 45 ft of sandstone within a 60 ft perforation, at a depth of 14,800 ft and an initial reservoir pressure of 11,045 psi. The well produces 16,921,000 bbl of fluid over a period of 5½ years, at which time the reservoir pressure drops too low for continued production. Final average pressure is 8,277 psi (a pressure drop of 2,768 psi). A copy of the production scenario computer printout is shown in Appendix F.

5.3.3.3 Subsidence and Related Estimates

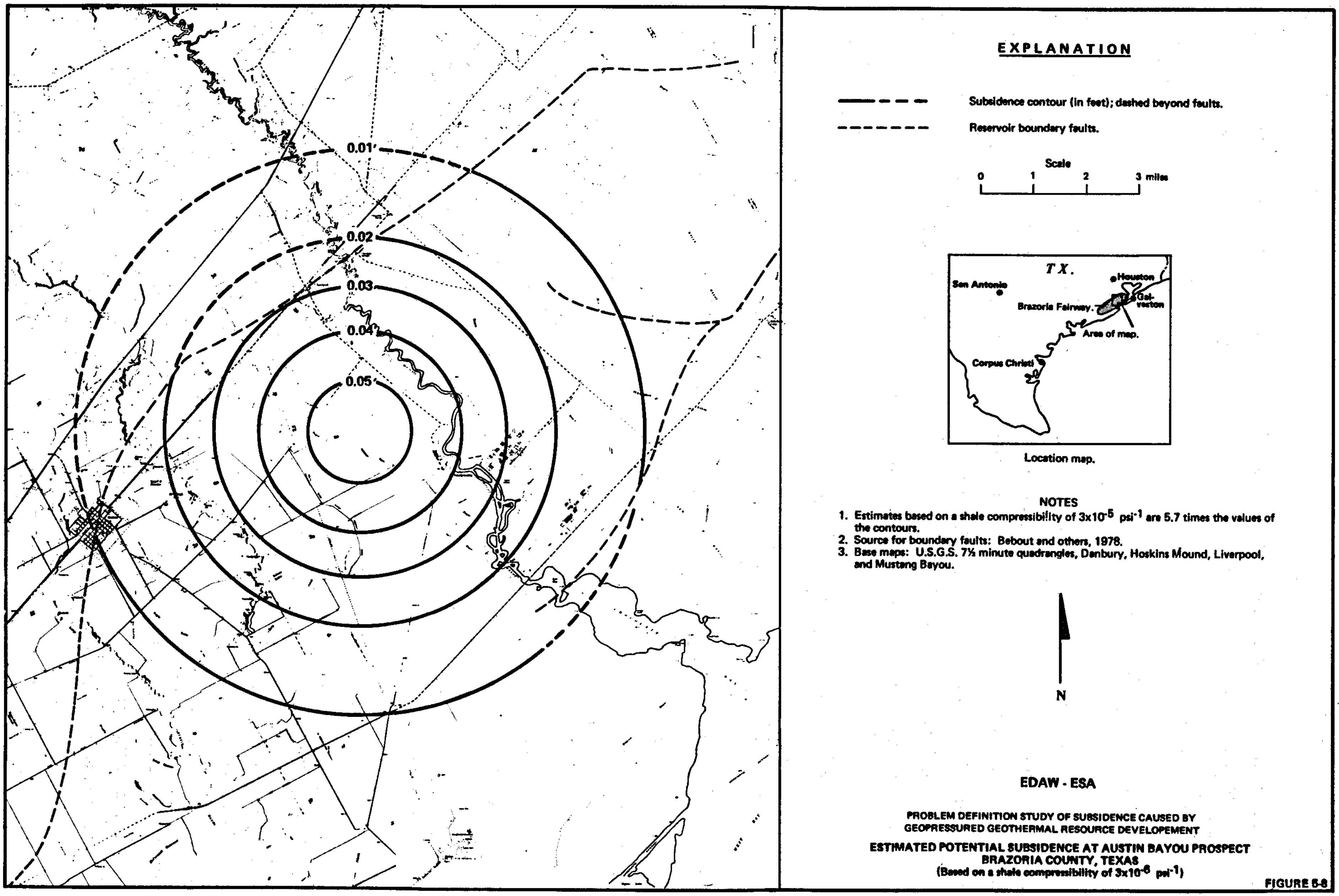
Maximum reservoir compaction and associated surface subsidence have been estimated as 0.2 ft and 0.05 ft, respectively. Using a higher value for C_m for shale (3×10^{-5} psi^{-1}), compaction and subsidence were estimated at 1 ft and 0.3 ft, respectively. Compaction and subsidence calculations are shown in Appendix G Tables G-3 and G-4. Estimated potential subsidence, based on what appears to be the most realistic data available, is shown in Figure 5-8.

The other subsidence-related calculations and estimates of related ground movements are summarized in Tables 2-1 and 2-2.

5.3.4 Gladys McCall Prospect

5.3.4.1 Geology

The Gladys McCall prospect is located in southeastern Cameron Parish and encompasses an area of about 16 sq mi. The prospect is in the Lower and Middle Miocene trend of southeastern Louisiana, and potential reservoir sandstones are at depths of 14,500 to more than 17,000 ft. The area is bounded by a series of east-west trending faults. There are four producing oil and gas fields in the area, all of which produce from normally pressured Upper Miocene sands. In the geopressured section, net sandstone thickness is expected to be 750-1,500 ft.



NOTES

1. Estimates based on a shale compressibility of $3x10^{-5}$ psi^{-1} are 5.7 times the values of the contours.
2. Source for boundary faults: Bebout and others, 1978.
3. Base maps: U.S.G.S. 7½ minute quadrangles, Danbury, Hoskins Mound, Liverpool, and Mustang Bayou.

EDAW - ESA

PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY
GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPEMENT

ESTIMATED POTENTIAL SUBSIDENCE AT AUSTIN BAYOU PROSPECT
BRAZORIA COUNTY, TEXAS
(Based on a shale compressibility of $3x10^{-6}$ psi^{-1})

FIGURE 5-8

XBL 812-8101

Permeabilities from well log analysis are in the range of 5-47 md with average porosity of 19%. Dissolved gas is estimated at 20-25 scf/bbl. A temperature of 324° F has been measured in the reservoir.

5.3.4.2 Production Scenario

A single well in this 16 sq mi prospect is modeled as producing from 500 ft of sandstone at a depth of 15,000 ft with an initial reservoir pressure of 14,200 psi. The well produces 251,174,000 bbl of fluid over a 20 year production life, with final average pressure of 9,619 psi (a pressure drop of 4,581 psi). A copy of the production scenario computer printout is shown in Appendix F.

5.3.4.3 Subsidence and Related Estimates

Maximum reservoir compaction and associated surface subsidence have been estimated as 3 ft and 0.07 ft, respectively. Using a higher value of C_m for shale (3 x 10^{-5} psi^{-1}), compaction and subsidence were estimated as 6 ft and 2 ft, respectively. Compaction and subsidence calculations are shown in Appendix G, Tables G-5 and G-6. Estimated potential subsidence, based on what appears to be the most realistic data available, is shown in Figure 5-9.

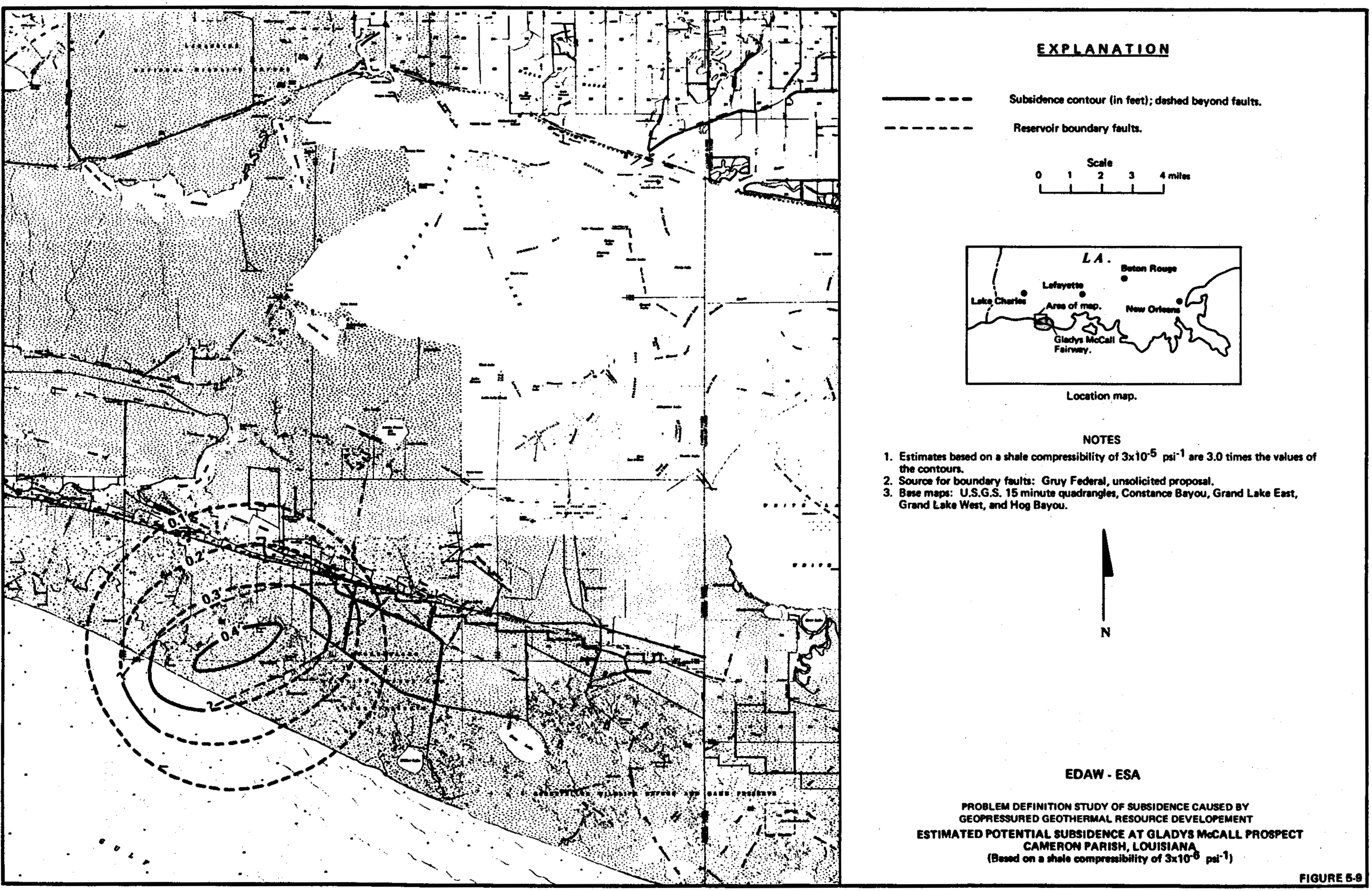
The other subsidence-related calculations and estimates of related ground movements are summarized in Tables 2-1 and 2-2.

5.3.5 Cuero Prospect

5.3.5.1 Geology

The Cuero prospect is located in DeWitt County, in the southwest end of an elongated fault block. The prospect has an area of roughly 11 sq mi, with dimensions of about 1.7 mi in a northwest direction by about 7.7 mi in a northeast direction.

The Cuero prospect is in the Eocene Wilcox trend with potential reservoir sandstone occurring from about 10,500 to 12,850 ft. The top of the geopressured zone is at about 10,000 ft. Data from the Atlantic #1 Schorre and wells outside



NOTES

1. Estimates based on a shale compressibility of 3×10^{-5} psi^{-1} are 3.0 times the values of the contours.
2. Source for boundary faults: Gruy Federal, unsolicited proposal.
3. Base maps: U.S.G.S. 15 minute quadrangles, Constance Bayou, Grand Lake East, Grand Lake West, and Hog Bayou.

EDAW - ESA

PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY
GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPEMENT

ESTIMATED POTENTIAL SUBSIDENCE AT GLADYS McCALL PROSPECT
CAMERON PARISH, LOUISIANA
(Based on a shale compressibility of 3×10^{-6} psi^{-1})

FIGURE 5-9

XBL 812-8102

the prospect area indicate that sandstone beds are on the order of 5 to 40 ft thick, with more than 550 ft net sandstone thickness in the reservoir section.

Data on porosity and permeability are limited, but tests on the Schorre well show a range in porosity from 6-25% and permeabilities from less than 1 to 242 md. Fluid temperatures of 300° F have been measured within the reservoir.

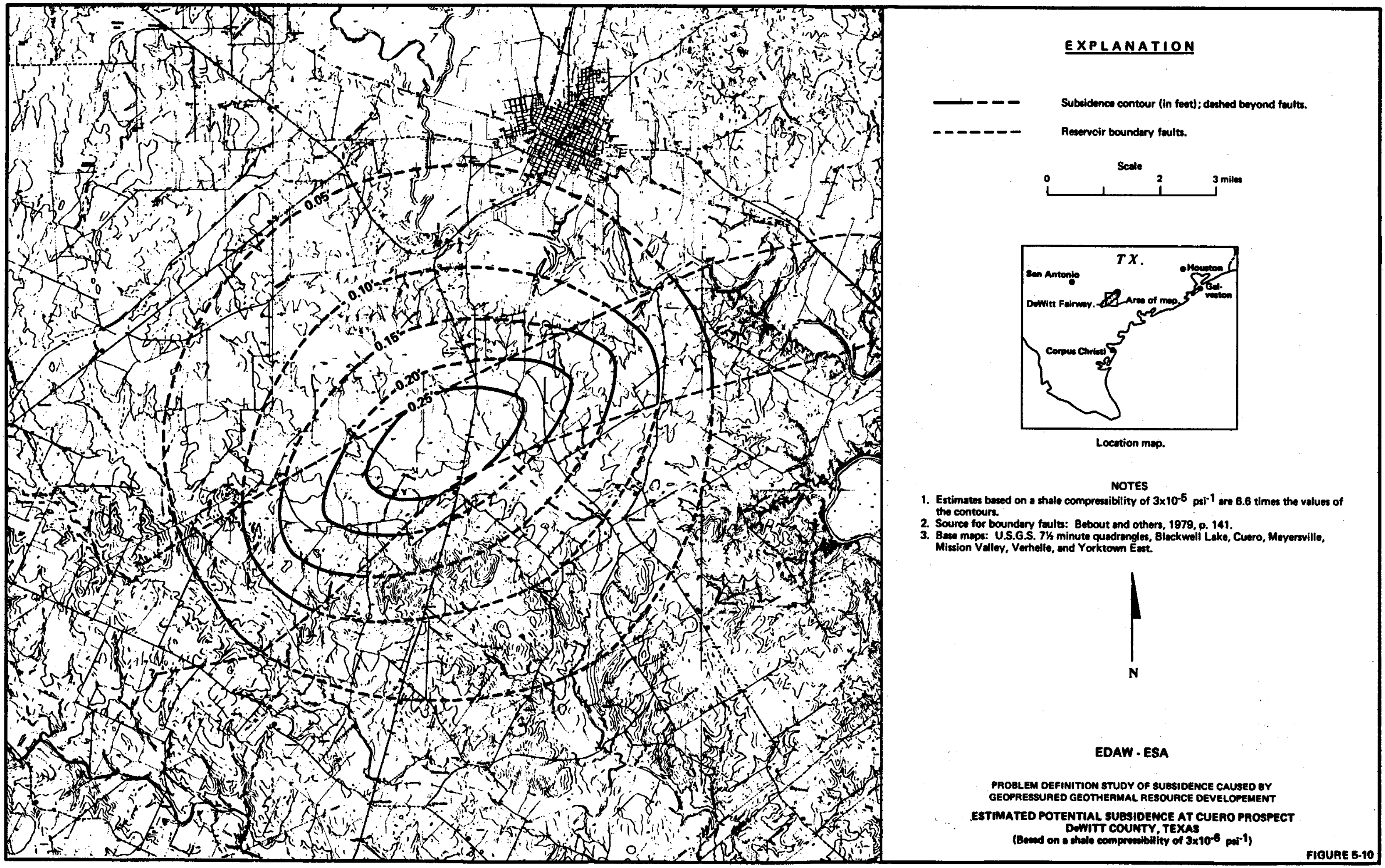
5.3.5.2 Production Scenario

A single well in this aproximately 11 sq mi prospect is modeled as producing from 200 ft of sandstone at a depth of 12,625 ft with an initial reservoir pressure of 10,500 psi. The well produces 40,930,000 bbl of fluid over a 20 year production life, with final average pressure of 6,734 psi (a pressure drop of 3766 psi). A copy of the production scenario computer printout is shown in Appendix F.

5.3.5.3 Subsidence and Related Estimates

Maximum reservoir compaction and associated surface subsidence have been estimated as 1 ft and 0.3 ft, respectively. Using a higher value of C_m for shale (3×10^{-5} psi^{-1}), compaction and subsidence were estimated as 8 ft and 2 ft, respectively. Compaction and subsidence calculations are shown in Appendix G, Tables G-7 and G-8. Estimated potential subsidence, based on what appears to be the most realistic data available, is shown in Figure 5-10.

The other subsidence-related calculations and estimates of related ground movements are summarized in Tables 2-1 and 2-2.



NOTES

1. Estimates based on a shale compressibility of 3×10^{-5} psi^{-1} are 6.6 times the values of the contours.
2. Source for boundary faults: Bebout and others, 1979, p. 141.
3. Base maps: U.S.G.S. 7½ minute quadrangles, Blackwell Lake, Cuero, Meyersville, Mission Valley, Verhelle, and Yorktown East.

EDAW - ESA

PROBLEM DEFINITION STUDY OF SUBSIDENCE CAUSED BY
GEOPRESSURED GEOTHERMAL RESOURCE DEVELOPEMENT

ESTIMATED POTENTIAL SUBSIDENCE AT CUERO PROSPECT
DeWITT COUNTY, TEXAS
(Based on a shale compressibility of 3×10^{-6} psi^{-1})

FIGURE 5-10

XBL 812-8103

6. SCOPE OF POTENTIAL SUBSIDENCE IMPACTS AND ISSUES

6.1 INTRODUCTION

The following impact evaluations contain information general to the Gulf Coast area and items specific to individual fairways. Potential impacts that might apply to the Gulf Coast area in general are discussed in Section 6.2; impacts are analyzed under the headings "Physical and Hydrologic Impacts", "Biological Impacts", and "Socioeconomic Impacts". Sections 6.3 through 6.6 focus on the site-specific impacts likely to occur in connection with withdrawal of geopressured fluids at single wells within each representative fairway, based on the subsidence estimates presented in Chapter 5. In reading the latter sections it should be recognized that, were additional wells to be developed, overlapping subsidence bowls could be created. Effects described could then become more widespread and locally severe. Where possible, impacts are discussed under the most appropriate fairway. It is important to remember, however, that impacts may occur in varying degrees at any of the fairways and are generally applicable to the Gulf Coast region.

Viets and others, in their report Environmental and Economic Effects of Subsidence (1979), summarize the impacts that could occur in response to subsidence and related ground movements. Although their discussion is not restricted to subsidence caused by the extraction of geothermal fluids, it still serves as excellent background material for this chapter. Therefore, pertinent parts of the Viets report (pp. II-4 through II-18) have been included as Appendix H.

6.2 GULF COAST IMPACTS

6.2.1 Physical and Hydrologic Impacts

Deformation of the ground surface through subsidence, tilt, and fault activation could have a significant effect on hydrologic systems, which include bays, estuaries, marshes, rivers, impounded water, and groundwater. Physical and hydrologic concerns include altering existing patterns of streamflow, drainage, tidal flow, erosion, and sedimentation, as well as of saltwater intrusion and fault activation. Based on a study of subsidence in recent subdeltaic areas of the Mississippi River, Morgan (1972) describes the impacts of physical changes caused by subsidence as follows:

> As subsidence continues, lakes, ponds, and levee flank depressions within the topographically lower interdistributary basins gradually enlarge and become interconnected. Bank erosion is accelerated as a result of increased wave fetch across the enlarging water bodies. Tidal ebb and flow through the interconnected lakes and bays allow progressively more saline waters to intrude into the formerly fresh or brackish marshes forcing vegetation types to change in response to salinity increases. Broad expanses of marsh land change character, become dissected and are eventually destroyed. Fauna within the enlarging estuaries reflect the increasing salinity.

Hydrologic impacts may also depend on the type of subsidence taking place. If subsidence results in a bowl-shaped depression, existing drainage is diverted to the bowl's center, resulting in increased ponding and flooding, as well as changes in sediment transport patterns. On the other hand, fault activation caused by subsidence could produce a subsidence block resulting in stream diversion or other hydrologic changes.

While many hydrologic effects may have complex ecologic and economic effects, the exposure of land to temporary or permanent flooding is particularly significant. Existing freshwater floodplains are likely to become enlarged in areas of vertical settlement. As the floodwater capacity of the stream is reduced or streamside gradients are altered, more areas are exposed to freshwater flooding. Fault movement due to subsidence may weaken or breach retaining structures, such as levees and dams. Within the fairways, water systems which may be susceptible to tilt, gradient alteration, and fault movements include irrigation canals, reservoirs, and bayou and agricultural levees.

Decline in ground surface elevation will also expose greater areas to hurricane flooding from rainfall and tidal surge. Brown and others (1974) have noted that if a hurricane hit upper Galveston Bay with storm tides of the same height as those of Hurricane Carla in 1961, an additional 70 sq mi would have been exposed to flooding due to increased subsidence since 1961.

Subsidence on or near the shoreline of the coastal fairways allows for tidal encroachment and wetland loss. These effects would be particularly significant on barrier islands, coastal marshland and other natural storm buffers, as their ability to limit the impact of storms would be greatly reduced. Subsidence beneath barrier islands would widen inlets and tidal passes between islands, allowing greater tidal access during storms, in addition to reducing the land surface of the islands. Subsidence of coastal marsh would submerge marsh vegetation and reduce the ability of the marshland to absorb the force of storm tides. Coastal areas lacking the protection of marsh and islands, or those in which such natural buffers have been filled in or bulkheaded for development, would be especially susceptible to damage (Craig and others, 1979). Lowering the ground surface of a wetland region may also cause ponding, salinity changes, and alteration of circulatory patterns and sediment transport, and increase the potential for flooding and eutrophication.

6.2.2 Biological Impacts

Physical and hydrologic changes due to subsidence result in impacts on biological systems of both upland and coastal areas. With the exception of wildlife habitat alteration by permanent inundation or drainage, biologic impacts are generally less severe in upland or inland area. On the other hand, biologic changes due to subsidence are likely to be particularly extensive and complex in wetlands.

The conversion of marshland to open water through natural processes and human activities is an ongoing process in the Gulf Coast region. Geopressured resource development-caused subsidence might contribute to this process, resulting in alteration of flora and fauna habitats in response to salinity changes, deterioration of vegetation and substrate soils, change or loss of wildlife habitat, loss of storm buffer, and loss of waste absorption capacity. Loss or alteration of vegetation due to subsidence may occur through submergence or salinity changes. The potential for subsidence-induced salinity alteration will vary by location, being less significant in an inland site such as the Lafourche Crossing or the Colorado Fairways, and more significant in Southeast Pecan and Brazoria Fairways. Hydrologic changes can also affect the process of detritus and nutrient production which support biologic activity in estuaries, nearshore, and Gulf waters. Salinity increases in a swamp forest may adversely affect cypress and other tree types.

Conversion of land surface and vegetative cover in wetlands by subsidence may change habitat for mammalian and aquatic wetland-dependent species. Many fish and shellfish species are dependent on bays, estuaries, and marsh for part or all of their life cycles. Gulf menhaden, for example, spawn offshore and move into estuarine waters for up to a year after hatching; blue crab move into brackish water to mate, then into high salinity waters to spawn. Species may require a relatively narrow salinity range or tolerate a wide range of salinities or different salinity levels during different life stages. Other estuarine characteristics which are significant to aquatic species include detritus production and export, freshwater inflow, bottom character, water depth, temperature, and circulatory patterns. Resource development-caused subsidence, in altering the physiographic characteristics of bays and estuaries, can potentially alter these important estuarine characteristics.

Oyster reefs, located in bays and inlets throughout the Gulf Coast, are also commercially important and vulnerable to several phenomena associated with subsidence. The productivity of oyster beds is determined by water temperature, salinity, turbidity, and circulation, bottom character, food supplies, pollution, disease, and competition and predation (Van Sickle and others, 1976). Salinity levels control oyster growth rates and limit the presence of a major oyster predator, the southern oyster drill (Thais Haemastoma). Salinity levels in oyster grounds are determined by freshwater inflow, seasonal rainfall, stream diversion, and tidal patterns. Subsidence which influences freshwater inflow and saltwater intrusion rates may, in altering the salinity balances in oyster cultivation waters, allow intrusion and predation by the oyster drill.

Pollution from domestic sewage and agricultural runoff also affects oyster productivity by increasing the biological oxygen demands of affected waters, thereby reducing the amount of dissolved oxygen available to oysters. Additionally, oysters may absorb toxic wastes in runoff and sewage outfall, with deleterious effects on the organism itself and its predators, including humans. Subsidence of marshland would submerge vegetation and substrate, reducing the ability of the marsh to act as a waste buffer. Loss of this natural buffer might increase the flow of nutrients and waste to oyster beds and cause their closure.

6.2.3 Socioeconomic Impacts

Socioeconomic impacts could occur as a result of subsidence-induced changes in physical, hydrologic, and biologic systems. Among other effects, subsidence may alter or disrupt certain types of land use, cause physical damage to structures, or increase the danger of flooding. The degree to which an impact is felt is determined by the amount and location of subsidence, the effectiveness of mitigation measures, and the economic or cultural ability of affected areas to respond to or recover from the subsidence-induced change.

Resource development-related subsidence occurring in relatively developed Fairways might result in some damage to structures. Although of less significance, ground surface tilt may affect vertical structures in the Fairways as well. Although a study of subsidence effects on homes in New Orleans (Earle, 1975) found structural tilting to be "one of the most serious and expensive subsidence problems", the probable subsidence over relatively long distances due to geothermal fluid withdrawal is not likely to significantly affect houses and other small structures in the Fairways examined, due to the low tilt values found for the prospects under study.

Any costs associated with subsidence-induced structural damage would likely include increased maintenance costs to the government for road repairs, as well as private costs for repairs to large buildings and pipelines. In terms of cost, however, structural damage caused by differential settlement should be less significant than structural damages caused by flooding. For example, a 1975 study of the economic effects of subsidence in an urban area (Galveston Bay) found that flood-related costs (including repairs, mitigation measures, and loss of property value) accounted for 87% of all subsidence-related costs, but structural damage accounted for only 13% (Jones and Larson, 1975).

Saltwater inundation due to hurricanes, tropical storms, or tidal encroachment is a major problem in highly developed portions of some Fairways. Subsidence in low-lying residential and industrial areas would subject these areas to greater hurricane inundation and related damage and mitigation costs. The degree of increased damage and costs cannot be reasonably estimated on a fairway-wide basis, but rather on a more local basis. The primary factors affecting the degree of damage include the size of the hurricane or storm, the design and location of flood protection facilities, and the value and design of residential, commercial, and industrial structures in the affected area. It is probable that subsidence related to resource development would make, relative to the above factors, a smaller contribution to the overall impacts.

Futher subsidence near the harbor area of Texas City and Freeport, for example, could subject piers, wharves, warehouses, and other port facilities to periodic, or permanent, tidal inundation. The costs associated with this occurrence may include water damage to property, the cost of raising structures above the water level, and possibly, loss of business (due to damaged property) to the port.

Structural damage or inundation of highways would impair access and could have impacts on public safety. For example, Galveston Island depends on Route 45 through Texas City as an evacuation route in event of a hurricane. Interstate 45 is already prone to hurricane flooding because of natural subsidence and subsidence due to groundwater withdrawal; further subsidence would increase the potential for flooding along this route, leaving Galveston residents with restricted avenues of evacuation in the event of a hurricane. Subsidence could also have serious consequences during a hurricane if it caused hospitals and emergency facilities to become inaccessible or flooded.

Overbank flooding of freshwater streams is common in many parts of the Gulf Coast. For example, the western half of the Brazoria Fairway is vulnerable to potential flooding from rivers during tropical storms or in the aftermaths of hurricanes. The city of Freeport, built on islands at the mouth of the Brazos and surrounded by levees, is particularly vulnerable to overbank flooding (Brown and others, 1974). Subsidence in or near such flood-prone areas would extend the floodplain, exposing a wider area to potential freshwater flooding.

The costs and damages associated with expanded fairway floodplains due to subsidence are difficult to determine. Without subsidence, the costs of flooding are already quite high, and may include loss of life in addition to loss and damage to property. With subsidence, areas which were high enough to escape flood damage in previous hurricanes may be vulnerable to flooding, and flood damage may increase for smaller storms. In addition, property owners whose land and buildings are increasingly vulnerable to flooding may find themselves no longer able to get flood insurance. A recent proposal by the Department of the Interior to reduce funding of programs which encourage development in areas prone to hurricane flooding and to reduce post-catastrophe rehabilitation aid for such areas indicates a desire to put constraints on federal assistance to high flood-prone areas. Declines in federal assistance and denial of insurance to those in high-risk flood areas may result in a greater amount of subsidence-related flooding costs being borne by private home owners and local and state government.

Subsidence in irrigated agricultural land in the Fairway may adversely affect irrigation and drainage patterns. Ground surface tilting will alter the gradients of the elevated irrigation canals and drainage ditches, and may require relevelling of irrigated fields and canals and increased pumping capacity and associated expenditures.

Increased subsidence might alter salinity regimes, thermal gradients, and circulatory patterns in the bays and estuaries in and adjacent to the Fairways. The potentially deleterious effects on oyster beds and spawning grounds of the shrimp and menhaden caught offshore would result in local declines in income and employment. Declining oyster production could also result in a loss of state revenues from the leasing of bay bottoms for oyster cultivation.

Boundaries between public and private ownership are often defined by land-water boundaries. If subsidence should raise the water line on floodplains or coastlines significantly, conflicts over use of submerged private lands may arise. In Louisiana, submerged land reverts to the state; therefore, extension of permanently inundated areas would impact land ownership as well as tax revenues.

6.3 SOUTHEAST PECAN ISLAND FAIRWAY IMPACTS

As discussed in Chapter 4, Southeast Pecan Island Fairway includes many marsh types and provides a good example of wetland degradation caused by subsidence. Topography in the Fairway is flat with the exception of chenier ridges which form a barrier to storm flooding and saltwater intrusion. Existing subsidence roughly equals accretion, but the coastal location and low elevation of chenier ridges make the Fairway particularly vulnerable to flooding if subsidence rates increase.

Total vertical subsidence over a 20-year period in the Southeast Pecan Island Fairway as a result of resource development could be as high as 4 ft under conservative assumptions, but a more realistic estimate is less than 10 in. (0.8 ft).

A conservative subsidence rate is estimated to be less than 0.3 ft in the first year of production declining to less than 0.2 ft by the 20th year. A more realistic rate is less than 0.04 ft (0.5 in.) per year on the average. (It declines from 0.05 ft in the first year to 0.03 ft by the 20th year). These rates are in addition to the present natural subsidence rate of 2/3 in. per year. Thus, even under the realistic estimate, the natural rate would be almost doubled. The area of significant subsidence under conservative assumptions is 100 sq mi, whereas the more realistic estimate is 20 sq mi.

Keeping the above potential amounts, rates, and areas of subsidence in mind, we can now look specifically at the sort of impacts that might be caused by resource development in the Southeast Pecan Island Fairway. The potential impacts specific to the Southeast Pecan Island Fairway are summarized in Figures 6-1 and 6-2.

6.3.1 Physical and Hydrologic Impacts

Among the fairways examined, alteration of hydrologic systems by subsidence due to geopressured geothermal resource development is likely to be most significant in the Southeast Pecan Island Fairway, particularly with respect to salinity levels.

Construction of spoil banks and levees and channelization of rivers have reduced the amount of sheetflow from overbank flooding in the Southeast Pecan Island Fairway. As a result, rainfall is the primary source of freshwater input to wetlands. The total freshwater input to the Vermilion Basin, east of the Fairway, has been calculated at 11×10^8 m^3/yr, with a renewal time of 61 days (Gosselink and others, 1979). With increased subsidence, considerable salinity increases are likely to occur in all of the marsh types of the Fairway, primarily because of the area's low gradient. This will occur through inland movement of the shoreline itself, exposing previously protected areas to Gulf waters, as well as through greater saline water access through deepened and widened tidal inlets and canals.

POTENTIAL SUBSIDENCE IMPACTS
Based on Subsidence Estimates Calculated with a Shale Compressibility of $3x10^{-6}$ psi^{-1}

FIGURE 6-1

Physical	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Coastline subsidence	◒	○	○	○
2. Inland subsidence and ground surface deformation	◒	⊖/○	⊖	⊖
3. Alteration in sediment deposition	⊖	○	○	⊖
4. Alteration in coastal or fluvial erosion	◒	○	⊖	○
5. Fault activation	○	○	○/⊖	○

Hydrologic -- Changes In	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Drainage patterns	○	○	○	○
2. Streamflow and rate	○	○	○	⊖
3. Tidal flow and reach	◒	○	○	⊖
4. Expansion of salt or freshwater floodplain	◒	○	○	⊖
5. Groundwater salinity	◒	○	○	⊖
6. Surface of lakes, ponds and inundated areas	◒	○	○	⊖

Biological -- Loss of or changes in	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Woodland, woodland or prairie habitat	○	○	○	○
2. Freshwater marsh	⊖	○	○	○
3. Saline or brackish marsh	◒	○	○	⊖
4. Estuarine or coastal aquatic habitat	○	○	○	○
5. Endangered or important commercial species	⊖	○	○	⊖

Socioeconomic	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Impairment or disruption of economic activity				
a. Recreation	⊖	○	○	○
b. Agriculture	⊖	○	◒	◒
c. Fishery	○	○	○	⊖
2. Damage to structures by surface deformation	◒	○	○	○
3. Increased susceptibility to storm hazards	◒	○	○	⊖
4. Reduction in waste assimilation capacity	⊖	○	○	○
5. Increased maintenance	◒	○	⊖	⊖
6. Costs of all impacts, including mitigation and repairs	◒	○	⊖	⊖

MAGNITUDE OF IMPACTS

None	○
Slight	⊖
Moderate	◒
Severe	●

Note: Magnitude of impact ratings are judgements based on comparative evaluation of estimated subsidence impacts in four site-specific areas of the fairways under consideration. Ratings for other prospects or fairways would differ.

POTENTIAL SUBSIDENCE IMPACTS

Based on Subsidence Estimates Calculated with a Shale Compressibility of $3x10^{-5}$ psi^{-1}

FIGURE 6-2

Physical	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Coastline subsidence	●	○	○	○
2. Inland subsidence and ground surface deformation	●	◒/⊖	◒	◒
3. Alteration in sediment deposition	◒	⊖	⊖	◒
4. Alteration in coastal or fluvial erosion	●	○	◒/⊖	⊖
5. Fault activation	○	○	◒/⊖	○

Hydrologic -- Changes In	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Drainage patterns	⊖	○	⊖	○
2. Streamflow and rate	⊖	⊖	⊖	◒
3. Tidal flow and reach	●	○	○	◒
4. Expansion of salt or freshwater floodplain	●	⊖	⊖	◒
5. Groundwater salinity	●	⊖	⊖/○	◒
6. Surface of lakes, ponds and inundated areas	●	○	◒	◒

Biological -- Loss of or changes in	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Woodland, woodland or prairie habitat	○	⊖	◒/⊖	○
2. Freshwater marsh	●	⊖	●/◒	◒
3. Saline or brackish marsh	●	○	○	◒
4. Estuarine or coastal aquatic habitat	⊖	○	○	⊖
5. Endangered or important commercial species	○	⊖	●/◒	◒

Socioeconomic	S.E. PECAN	BRAZORIA	COLORADO	LAFOURCHE
1. Impairment or disruption of economic activity				
a. Recreation	◒	○	⊖	⊖
b. Agriculture	◒	○	●	●
c. Fishery	○	○	○	◒
2. Damage to structures by surface deformation	●	○	○	⊖
3. Increased susceptibility to storm hazards	●	⊖	⊖	◒
4. Reduction in waste assimilation capacity	◒	○	○	⊖
5. Increased maintenance	●	⊖	◒	◒
6. Costs of all impacts, including mitigation and repairs	●	⊖	◒	◒

MAGNITUDE OF IMPACTS

None	○
Slight	⊖
Moderate	◒
Severe	●

Note: Magnitude of impact ratings are judgements based on comparative evaluation of estimated subsidence impacts in four site-specific areas of the fairways under consideration. Ratings for other prospects or fairways would differ.

Benchmark elevations around the Cheniere Au Tigre vary from 3 to 12 ft with most above 5 ft. The canals in the Fairway vary in elevation from 2 to 5 ft above sea level. Inundation could occur under conservative assumptions unless protective measures are taken. Little impact is expected under the more realistic assumptions.

Sand Ridge and Bill Ridge near the shoreline have elevations ranging from 2 to 8 ft, but mostly 3 to 4 ft, so these would be largely inundated under conservative assumptions, but less affected under realistic estimates. Nearby Mulberry Island varies from 4 to 9 ft and will be less affected under either estimate. Maximum subsidence plus storm action would allow Gulf waters to extend inland over the natural barriers formed by the chenier ridges. This may result in formation of a new inland shoreline and an inland extension of the hydrologic influence of the Gulf waters. However, loss of shoreline may be balanced by sediment accretion from the Atchafalaya River.

The many small water bodies between the shoreline ridges and State Route 82 would be expanded and coalesced under both the conservative and realistic estimates.

State Route 82, located in the northwest part of the Fairway, would continue to act as a partial barrier to hydrologic effects, but with increased susceptibility to storm damage. State Route 82 has already had settlement problems because of subsidence (Louisiana Department of Transportation and Development, 1977).

With the exception of the Atchafalaya and Mississippi Deltas, most of the Gulf Coast Region is presently sediment deficient due to dam, canal and flood-control construction, pumping of surface water for irrigation which decreases downstream movement, and impoundment of wetlands, in addition to natural shifts in the rivers themselves (Adams and others, 1978). Poor sediment distribution, which occurs in continuous flow conditions or during floods, limits the ability of the marsh to rebuild itself naturally.

6.3.2 Biological Impacts

The Southeast Pecan Island Fairway well illustrates the potential impacts of subsidence on wetland biological systems. Habitat changes caused by subsidence may be significant problems.

Resource development-induced subsidence in the wetlands of Southeast Pecan Island, or similar areas, would tend to submerge vegetation, thus reducing the amount used as wildlife habitat and food source over the long term. It will also increase (as plants die) then decrease (as no new vegetation appears) the amount of detritus available to lower-trophic level organisms (Odum and others, 1972). There is a tendency in fresh and intermediate marsh, and to a lesser extent in brackish marsh, for the root masses of some plant types to disassociate themselves from the substrate as it subsides (Blackmon, 1979). The resulting floating marsh, or flotant, is then anchored in a relatively thin layer of decomposing vegetable debris, either floating on water or supported by a highly aqueous organic ooze (Davis and Detro, 1975).

In addition to causing a loss of vegetation and land within the subsidence bowl itself, subsidence will accelerate the erosion of surrounding wetlands, as an open water body allows greater wind and tidal forces to act on adjacent shorelines. The potential for deterioration of wetland is also related to its soil type. Brackish marsh has been shown to have the greatest rate of loss of all wetlands in the Louisiana Coastal Region (Gagliano and Van Beek, 1970; Craig and others, 1977; Adams and others, 1978; Blackmon, 1979). Organic soils, such as muck (20-50% organic content) and peat (50% or greater organic content), tend to be more unstable than other soil types and thus more susceptible to natural and human forces (Craig and others, 1977). Swamp forests are the wetland vegetative types most capable of slowing erosion (Adams and others, 1978).

The deterioration of marshland through subsidence represents an absolute loss of wildlife habitat and biologic productivity. Estimates of the annual above-ground net production of marsh plants range from 500 to 2,800 dry grams of organic matter per square meter per year (Odum and others, 1972). In addition, studies have found the highest production for a given species to be associated with the smallest fluctuation in salinity, while the lowest production is associated with the largest fluctuation in salinity (Odum and others, 1972). Marsh vegetation is made available to estuarine, near-shore, and offshore species as nutrients through a process of decomposition, detritus production, and detritus export. A loss of vegetation or a shift from a dominant plant species of high productivity to one of lower productivity would decrease the food supply of estuarine-dependent species.

In the Southeast Pecan Island Fairway, these habitat changes may affect both fish and shellfish species (discussed in Section 6.2) and wildlife species such as nutria, muskrat, otter, mink, deer, and raccoon. These species have considerable commercial and recreational importance in the Fairway. Subsidence of the land and vegetation would tend to reduce ground cover and vegetation available for these animals' habitats, leading to a decline in wildlife populations. Saltwater intrusion into fresh and intermediate marsh may force the animals to adapt to a more saline habitat or to find a less saline one (perhaps in a new freshwater wetland which might form within the Fairway area).

6.3.3 Socioeconomic Impacts

The slightly elevated cheniers of Pecan Island and Cheniere Au Tigre may become wholly or partially submerged through subsidence, as discussed above. The reduction of existing land in the Fairway reduces its ability to buffer potentially developable inland areas from storms, with subsequent losses in potential land values.

Existing pastoral land on and around the cheniers may become permanently inundated, or be subject to increased periodic flooding due to lowered elevation and loss of surrounding marsh. Cattle grazing profitability would, therefore, be lessened.

Subsidence may also lessen the suitability of affected cheniers as sites for residential development. Construction of levees or other means of flood control may be necessary to prevent increased storm flooding of these upland areas.

Canal and road transportation systems may be affected by subsidence. Lowering of the ground surface will lower the effective height of locks in the canal; although this may affect navigation, the depth and width of the canal will increase, expanding the canal's capacity. Roads built on pilings and fill across wetlands will be more vulnerable to periodic flooding and, if located in the center of the subsidence bowl, subject to permanent inundation. As already noted, State Route 82 has been subject to considerable settlement; any additional subsidence and cracking from differential settlement would increase the costs of road maintenance.

Submergence of marsh through subsidence would decrease the amount of marshland wildlife habitats, and consequently, hunting and trapping activities in affected areas. Since much of the marsh in the Fairway is owned by land companies and leased to hunting and trapping clubs and individuals, a loss of marsh may result in a financial loss to land owners and a loss of recreational opportunity to users of the land. Similarly, a loss of game species may result in a loss of income to commercial hunters and trappers, and may require local families dependent on subsistence hunting and trapping to purchase substitute food, or to travel out of the area to hunt and trap.

Construction of a support facility for offshore oil development, planned for marshland at Freshwater Bayou and serviced by a road from Pecan Island, may be hampered by increased subsidence. Ongoing subsidence itself may require structures to be built at greater heights above the water, and periodic adjustment of docks and piers, with subsequent economic costs.

6.4 BRAZORIA FAIRWAY IMPACTS

The Austin Bayou Prospect, for which subsidence estimates have been made, lies in the center of the upland prairie portion of the Brazoria Fairway. Development of the prospect is expected to result most probably in subsidence of approximately 0.05 ft (0.5 in.) over the 5.5 year life of the prospect. A negligible land area would be significantly affected. Under the more conservative assumption, almost 0.3 ft of subsidence could potentially occur.

The subsidence bowl expected to be affected under the conservative estimate is centered just south of Liverpool on Chocolate Bayou. It would include the Peterson Landing petrochemical plants, the town of Liverpool, and portions of Austin, Pleasant, and Chocolate Bayous. The area northeast of Liverpool had already experienced subsidence of at least one foot by 1974 (Brown and others, 1974). The area to the southwest had subsided by between 0.2 and 2.0 ft. (Contours of existing subsidence are shown in Figure 4-3.)

The potential impacts specific to the Brazoria Fairway are summarized in Figures 6-1 and 6-2.

6.4.1 Physical and Hydrologic Impacts

The most significant subsidence resulting from geothermal fluid withdrawal (0.2 ft) is estimated to occur in the first year of operation. Thus, the amount of subsidence that has occurred in response to groundwater withdrawal in parts of the area over perhaps twenty years (see Figure 4-5) would be doubled in a single year. However, in the portion of the bowl where larger amounts of subsidence have already occurred, the addition of under three inches may represent a relatively small increment. Subsidence due to groundwater withdrawal is expected to continue throughout the area, at least for the near future. All impacts attributable to the resource development-related subsidence must, therefore, be seen in relation to ongoing subsidence from other causes.

A decline in streambed elevation in the upper reaches of streams and bayous within the bowl will slightly enlarge existing freshwater floodplains because of the extremely slight relief between the bayous. Slight additional sediment deposition would also likely occur within the bowl.

No significant amounts of Gulf or bay shoreline areas lie within the conservatively estimated bowl of subsidence. Therefore, no extension of the zone of saltwater flooding should occur along the shoreline, although the upper end of the saltwater floodplain along Chocolate Bayou may be slightly enlarged.

6.4.2 Biological Impacts

Little or no impact from increased freshwater flood levels is expected on flood-tolerant fluvial woodland species. Some slight improvement in habitat may occur due to enlargement of ephemeral ponds. Extension of the zone of saltwater flooding along Chocolate Bayou will impair a small area of fluvial habitat.

Because the estimated extent of subsidence will not reach the Gulf shoreline, no changes in salinities, which would impact aquatic fauna, are anticipated.

6.4.3 Socioeconomic Impacts

Under the conservative estimate, maximum horizontal movement is expected to be 0.1 ft with a maximum tilt of 0.00002. Neither movement is expected to have any significant structural effect on canals, levees, highways, railroads, or pipelines. The threshold for architectural damage (0.001) and for damage to the most sensitively leveled canals (0.00004) are far above what is anticipated in this area (see Figure H-1).

Slightly increased flood levels are not expected to affect any but isolated residential structures. The system of levees and drainage ditches, and road and highway elevations, appear to provide adequate protection. It must also be noted that the need for periodic structural improvements already exists, due to the increasing amount and area of subsidence resulting from groundwater withdrawal and oil and gas extraction.

6.5 COLORADO FAIRWAY IMPACTS

The potential impacts of resource development in the Colorado Fairway must be estimated on the basis of subsidence estimates made for the Cuero Prospect, for reasons discussed in Section 1.3 and Appendix A. The Draft Environmental Analysis of Geopressured Geothermal Prospect Areas in Colorado and DeWitt Counties, Texas (Texas Bureau of Economic Geology, 1980) indicates that many of the characteristics of the Cuero geothermal reservoir are similar to those of the Eagle Lake Prospect in the Colorado Fairway. Cementation of sands, plus overburden thickness in the Eagle Lake area, are such that subsidence effects are likely to be less severe than at Cuero. However, environmentally and economically, the Eagle Lake Prospect and other parts of the Colorado Fairway are diverse and appear to be more susceptible to impacts than the Cuero area.

The Colorado Fairway has an area of about 360 sq mi. The centrally located Eagle Lake Prospect occupies about 18 sq mi. Under the most realistic assumption, 0.3 ft of subsidence can be expected to occur during a 20-year period. A negligible land area would be significantly affected. Under the conservative estimate, up to 2 ft of subsidence would likely occur in a subsidence bowl 60 sq mi in area, or in a 20 sq mi fault-bounded block. A 20 sq mi area would include the town of Eagle Lake, the Chesterfield Oil Field, West Bernard Creek, and a branch of the Southern Pacific Railroad. A 60 sq mi area would involve Eagle Lake and the town of Eagle Lake, the extensive gravel pits west of the lake, and portions of the radial road and rail network centering in the town.

In examining potential impacts, it will be assumed that development occurs in the center of the Eagle Lake Prospect. The Eagle Lake Prospect, according to the Texas Bureau of Economic Geology (1980), runs northeasterly from the northwestern extension of Eagle Lake to a point a short distance north of Middle Bernard Creek. The upper and lower bounds of the Cuero subsidence estimates will be used: up to 0.3 ft over a negligible area and up to 2 ft over a 60 sq mi area.

The potential impacts specific to the Colorado Fairway are summarized in Figures 6-1 and 6-2.

6.5.1 Physical and Hydrologic Impacts

Subsidence of up to 0.3 ft is not expected to expand the 100-year floodplain significantly. Subsidence of up to 2 ft would extend the floodplain to include one to two additional blocks on the southwestern side of the town of Eagle Lake. Other significant features, including roads and railroads, appear to be high enough above the Colorado River, Eagle Lake, and San Bernard Creek floodplains to prevent inundation if 2 ft of subsidence were to occur.

The normal elevation of Eagle Lake is 151 ft above MSL. Marshes on the flatter western side extend to the 155-foot contour. Two feet of subsidence could result in loss of half of the marsh on that side of the lake. The loss on the steep eastern side would be insignificant.

Subsidence of up to 2 ft over 20 years will have a severe impact on the rice fields that presently occupy much of the Prospect area. The slope and irrigation water flow in fields throughout the subsidence bowl could be reversed, causing formation of ponds at new low points and the reduction of water available to rice fields at higher elevations.

Subsidence under maximum estimates is likely to result in significant enlarging and deepening of the numerous ponds that exist throughout the potential subsidence area and elsewhere in the Fairway.

Ground surface tilt is estimated to reach 0.07 ft/mi approximately 2 mi from the well, or, under the conservative estimate, 0.5 ft/mi approximately 6 mi from the well. Slight tilting of the perimeter of Eagle Lake towards the center of the subsidence bowl could expose land between the normal lake surface and up to 6 in. below the current water level, were it not for an existing levee. A corresponding increase in water depth could occur at the northern end of the lake. Because of the steepness of the lakeshore at the northern end, the effect would be insignificant.

Up to 0.3 ft (4 in.) of subsidence could occur at the center of the bowl over 20 years under the realistic assumption. Some rice fields would be impacted, since the rice fields are often separated by levees with as little as a 3 in. drop between levees, making them vulnerable to small gradient changes. Ground surface tilt, even under the maximum estimate (0.00001 or 0.5 ft/mi), is less than the amount likely to affect the most sensitive drainage canals (Viets and others, 1979).

The Texas Bureau of Economic Geology (1980) notes that fault movement across the San Bernard River due to subsidence may cause the stream to divert along the fault traces. In addition, the formation of a scarp along a fault trace would cause ponding or would create a nick-point in the stream profile. Similar effects could occur on other streams and rivers crossed by the fault.

Under the conservative estimate, subsidence, plus the very slight tilt and horizontal movement anticipated, and any stream diversion resulting from fault activation, are all likely to induce changes in natural drainage systems. These include expansion of floodplains and changes in flow rates and patterns of erosion and sediment transport. The most likely short-term effects would be

- increased sediment deposition
- lower flow rates
- lowered flood-carrying capacity of the streams
- expansion of existing floodplains and creation of new floodplains along stream diversions.

Longer-term effects would be increased headward erosion and increased downstream scour by flood waters from the subsidence bowl.

Altered discharge rates to downstream water bodies could have secondary impacts on freshwater inflow to coastal marshes and sediment available for deposition and transport along the coast.

6.5.2 Biological Impacts

Loss of perhaps 100 acres of marsh around Eagle Lake could result from subsidence under the conservative estimate. This would, at least temporarily, impair the value of the lake and its environs for wintering waterfowl, although the increased water surface could have an offsetting positive effect. Higher water levels would also reduce the habitat of the American alligator, both in the Eagle Lake marshes and along stream corridors.

Serious impacts on the vegetation and water quality of Eagle Lake would also likely occur as a result of subsidence. The fresh water inflow into the lake could be reduced or reversed, resulting in increased salinity. Marsh salinity over 10% is a limiting factor in the distribution of the American alligator. However, additional study of the potential effects of subsidence on inland freshwater bodies is required for a better understanding of impacts on vegetation and wildlife.

No significant impacts on prairie lands and the species using the Attwater Prairie Chicken Refuge are expected. Increase in surface area of small ponds and possible creation of new ponds would have a positive impact on waterfowl.

6.5.3 Socioeconomic Impacts

Probably the most significant impact of subsidence, even using the realistic estimates, would be on the rice fields and irrigation canals. Releveling of fields for rice production has been estimated to cost approximately $50/acre. Although releveling is often undertaken as part of the annual routine of rice planting, adjustment to subsidence of approximately 0.5 in./year in the first four years would probably make annual releveling a necessity. Under the conservative estimate, subsidence of as much as 4 in. in the first year, and close to that amount in the following 3 years, would require a major adjustment. Such amounts of subsidence might also require repair or reinstallation of irrigation equipment and reconstruction of dikes, ditches, and furrows. If the cost of reconstruction exceeded the future earnings potential, owners could be expected to convert to lower cost and lower value row crops or pasture. In extreme cases, farm closures could occur with impacts on farm and secondary employment.

A slight to moderate impact on the town of Eagle Lake, and on isolated residential structures, could result from floodplain expansion using the conservative estimate of subsidence. Fault movement triggered by subsidence could also impact structures in the town of Eagle Lake which lies astride one of the apparent surface faults.

6.6 LAFOURCHE CROSSING FAIRWAY IMPACTS

Calculations of potential subsidence resulting from resource development in the Lafourche Crossing Fairway were not made because the Lafourche Crossing Prospect was not chosen as a representative site for subsidence analysis. (See Section 1.3 and Appendix A for the reasoning behind this decision.) Therefore, for purposes of estimating potential impacts, the range of vertical subsidence calculations made for the Louisiana sites (Gladys McCall and Southeast Pecan Island) have been applied to Lafourche Crossing. No attempt was made to apply values of significant area, rate of subsidence, tilt, or horizontal movement to the Lafourche site. Accordingly, the higher value of vertical subsidence applied to the Lafourche Crossing area is 4 ft, and the lower amount is less than 5 in. This application could, admittedly, be misleading, but should still prove useful in informing the reader of the range of impacts to which the Lafourche Crossing site could possibly be subject.

The Lafourche Crossing Fairway is an inland site which includes agricultural and urban areas, freshwater marsh, bottomland forest, and cypress swamp. The Lafourche Crossing prospect is more than 35 sq mi in area (Louisiana Department of Transportation and Development, 1977) and the Fairway area is about twice the prospect area, or 70 sq mi.

6.6.1 Physical and Hydrologic Impacts

Potential impacts in the Lafourche Crossing Fairway should in some cases be similar to the wetlands impacts in Southeast Pecan Fairway. The Lafourche Crossing Fairway, however, contains cypress/tupelo gum swamp. Although the Fairway is farther inland and not as susceptible to saltwater intrusion as other fairways, salinity increases could alter vegetation and habitat of these freshwater wetlands.

Subsidence of the bayous of Lafourche Crossing Fairway (under the higher assumption of 4 ft of subsidence) may also cause overbank flooding along low points of the bayou during peak flows if the gradients of the bayous change. The formation of a subsidence bowl beneath a streambed may act as a catch basin, collecting water at a low point on the stream profile. Overbank flooding could result if the capacity of the stream channel were exceeded, inundating surrounding lands and creating a new or extended floodplain. Ponding of water at one point along the stream would increase the rate of sediment deposition in that portion of the stream, reducing the amount of sediment discharged downstream and contributing to the streambed at the point of deposition. Subsidence beneath the lakes or other standing water bodies in the area would increase the depth and extent of the water body. A lesser amount of subsidence would increase the extent of the lakes, but probably would not produce severe overflowing.

Overbank flooding due to altered surface gradient is especially a problem during storm runoff. In general, however, the higher relief of levees and the inland location of Lafourche Crossing Fairway make it less vulnerable to storm flooding, although subsidence would increase the potential flood level on the levees.

6.6.2 Biologic Impacts

The biological systems in the Lafourche Crossing Fairway are largely dependent on freshwater marsh and forested swamp areas. These wetlands support a variety of vegetation and aquatic life, provide habitat for economically important fish and wildlife, serve as a storm buffer for urban areas and agricultural land, and filter wastes. These areas are susceptible to subsidence-induced impacts, such as rising water levels, salinity level variations, and changes in circulation patterns.

Salinity increases in a swamp forest may adversely affect cypress and other tree types. Salinity increases in the Houma Navigation Canal have been suspected of causing dieback of cypress trees along the levee banks (St. Amant and others, 1973). Similarly, oak trees along tidal channels, levees, and ridges of the Mississippi River Gulf outlet have also died back because of higher salinities in the channels (Gosselink, 1979). The formation of a bowl of subsidence within a swamp forest may hold storm waters without draining, causing permanent inundation and, if storm waters were saline, salinity changes. Under the smaller amounts of potential subsidence, the marshes and swamps will not be significantly affected. Several feet of added subsidence could, however, add to the inundation and salinity problems now being faced.

Inundation of marsh vegetation, due to several feet of subsidence, would also reduce the ability of the marsh to absorb waste from urban and agricultural sewage and runoff (Craig and others, 1977). This may be particularly significant around Houma, as much of that city's sewage enters the marsh untreated at a daily rate (in 1969) of 5.2 million gallons/day (Perret and others, 1971). While the marsh has been able to absorb much of that nutrient load, its capacity is often exceeded, causing serious problems for shellfish in the marshes below (Craig and others, 1977).

If subsidence were to induce saltwater intrusion into freshwater marsh, crawfish productivity would begin to be affected at a level around 8 ppt. In lowering the land surface and levee height, subsidence would also tend to deepen crawfish ponds and alter the flooding regime in the ponds, again affecting the crawfish habitat.

6.6.3 Socioeconomic Impacts

The urban areas and developed lands concentrated along levee crests and in "strip-settlements" down levee banks may be subject to increased risk of flooding under the larger amounts of potential subsidence. This would be particularly true during storm runoff, because subsidence changes the orientation of the water channels. The lesser amounts of potential subsidence would not significantly increase the risk of flooding.

Submergence and loss of marsh and swamp vegetation may also increase the risk of tidal flooding along lower levee elevations, as the effectiveness of marsh as a storm buffer is eliminated and tidal and storm surges are allowed greater reach through wetlands.

An increase in the water level in wetlands surrounding the bayous would inundate low-lying land along the levees and effectively increase the height of flood waters. This would eliminate a certain amount of land at the bottom of each strip of property from productive use as agricultural or residential land. If significant, loss of levee land and increased areas exposed to flooding would affect property value along the levees and could raise local costs of flood insurance. Extension of permanently inundated areas would also impact land ownership and tax revenues more directly since, under Louisiana law, ownership of submerged lands reverts to the state.

Local losses of wetland-dependent fish and wildlife, due to inundation of marsh from the higher estimates of potential subsidence, would cause a decline in recreational hunting and fishing, with declines in associated expenditures in local communities. As in the Southeast Pecan Island Fairway, wetlands are frequently leased by land development companies to hunters and trappers during seasons. Submergence of marsh would represent a loss of income from leases, in addition to a property loss. Houses scattered through the marsh to accommodate hunters and trappers may be made vulnerable to flooding. In addition to impacts on recreational hunting and trapping, loss of fish and wildlife habitat due to subsidence would have an impact on local families who depend on hunting and trapping as a food source and a source of income.

Crawfish cultivation in ponds near levees may be adversely affected by subsidence due to alteration in pond depth, gradient, flushing, drainage, and circulatory patterns. The cost of adjustments to gradient, levee height, or pond depth, if judged greater than potential returns on future crawfish sales, would result in reduced local availability of crawfish, and a loss of income to pond owners. As crawfish cultivation in the Lafourche Crossing area is conducted largely by, and for, French Louisianians, subsidence-induced declines in cultivation would have a cultural, as well as an economic impact.

Transportation systems throughout the wetlands may become increasingly vulnerable to flooding as a result of higher amounts (4 ft) of subsidence, and could become impassable during storms. This higher subsidence value would locally submerge small portions of roads. In addition to lowering road surfaces, subsidence could cause cracking and buckling of roads and pipelines due to differential settlement and faulting.

7. MITIGATION MEASURES

A range of measures exists to mitigate the various deleterious effects of subsidence. These include fluid production adjustments, structural flood control features, direct repair to damaged structures, land use and zoning regulation, and other measures directed at specific problem areas. These mitigation measures are inventoried below with respect to the success with which they were used in other subsidence situations, their costs, and institutional factors. The review of each measure is followed by a short discussion of that measure's usefulness relative to the geopressured geothermal resource development-related subsidence calculated in the present report.

7.1 Reservoir Management

Reservoir management, as it relates to subsidence mitigation, includes brine reinjection, pumping limitations by regulatory agencies, and, as a last resort, field abandonment.

Brine reinjection was successfully used to reduce subsidence at the Wilmington oil field in California (Viets and others, 1979). Its successfulness as a mitigation measure for resource development-induced subsidence is debatable, as discussed in Section 5.2.3.3. Even if reinjection to the producing reservoir were to prove successful in reducing subsidence, monetary and energy costs would be great. Therefore, despite the anticipated ability to enhance geothermal fluid production, the high costs and, as yet, questionable successfulness make it an unlikely candidate to mitigate resource development-related subsidence.

Pumping regulation by a public agency is being used in the Houston-Galveston area to mitigate local ground water-related subsidence (Viets and others, 1979). However, this measure is probably not a viable alternative for geopressured resource development in the Gulf Coast. Any limitation of fluid production sizable enough to mitigate subsidence would also be likely to make the venture economically unsound.

Well relocation and field abandonment would be necessary in the Gulf Coast only if actual subsidence were to exceed greatly the values predicted in this report. In this case, relocation of resource development to areas with lower rock compressibilities would be a possible mitigation measure, but would probably be prohibitively expensive. Louisiana, and probably Texas, do have the regulatory authority to stop geopressured resource development operations should subsidence be unexpectedly severe (Ann Bachman, personal communication, 1980).

All of the above reservoir management techniques are considered too drastic and expensive to be warranted by the relatively minor subsidence values calculated in the present report.

7.2 Structural Flood Control Features

Structures which prevent or reduce overbank flooding of streams, rivers, canals, bayous, and other waterways include levees and dikes along stream diversion channels, and dredging. Such structures have been used to mitigate the deleterious effects of subsidence in the Houston-Galveston area and at the Wilmington oil field in California (Viets and others, 1979), and are expected to contribute successfully towards mitigation of any Gulf Coast geopressured geothermal-associated subsidence.

Structural flood control features, once constructed, incur very low monetary costs, although their secondary impacts may include environmental costs, such as those caused by disposal of dredging spoil in environmentally sensitive wetlands. (Dredging may be necessitated in subsidence bowls if stream gradients are reversed as a result of the subsidence.)

The U.S. Army Corps of Engineers is primarily responsible for construction of public structures for flood control. Corps projects require congressional authorization and appropriation of federal funds; federal funds may be provided for up to 80% of the cost of the project. However, local interests are required to provide real estate, alterations to existing structures, operation and maintenance costs and, often, to institute floodplain management plans.

In addition to overbank flood protection, hurricane and tidal flood protection in subsiding areas may be provided by shoreline levees and seawalls, also largely the responsibility of the Corps. Many coastal cities in the Gulf Coast region, such as Galveston and Freeport, have such protective structures.

Private structural flood control has been practiced in a residential subdivision near Clear Lake, Texas, south of Houston, where property owners were forced to install pumps and to construct levees to mitigate groundwater-related subsidence.

Farmers also bear much of the financial burden for subsidence-induced flood damage to their land. Although some low cost loans are available to ease the financial burden of these farmers, the Congressional Appropriations Bill now prohibits the Agricultural Extension's former practice of providing preventive maintenance (such as drainage improvements) to individual farmers (Richard Folse, personal communication, 1980).

The amounts and rates of resource development-related subsidence estimated for the Gulf Coast, although low, will cause additional coastline areas to be flooded unless both public and private flood control structures are constructed.

7.3 Repair of Damaged Structures

Structures that would require repair from geopressured geothermal-associated subsidence damage include housing, landscaping elements, utilities, roads, irrigation systems, and geothermal power plants themselves. The major types of damage directly associated with subsidence (cracking, buckling, and differential settlement) are often treated as routine maintenance and are not necessarily attributed to subsidence. Structural damage caused by flooding, however, may be more severe and more closely identified with subsidence.

Repair of damaged structures is really only a palliative measure; hence, the need for repair would recur as long as subsidence continued, and the long-term costs of this approach would be high. Nevertheless, repair of structural damage is the principal form of mitigation in many areas now experiencing subsidence (Viets and others, 1979).

A recent study of structural damage to houses in New Orleans (Earle, 1975) reports the extent of damages and costs that have occurred as a result of localized consolidation settlements in an urban Gulf Coast area. Although consolidation settlement differs considerably from subsidence caused by fluid withdrawal, their effects on structures are similar. The study recorded damages to structures, landscape elements, and utility systems resulting from settlement rates ranging from 0.01 ft/year to 2.5 ft/month (an extreme case). Damage to the structures themselves were among the most expensive repairs, although damage to landscape elements (average cost per property unit: $200-$500) occurred more frequently. Damage to utility systems occurred less frequently and tended to have lower average repair costs (less than $200). The costs of repairs were generally borne by home owners; the most expensive repair was foundation work made necessary by tilting and differential settlement of houses (average cost: $1900).

A second study of the costs of subsidence-related repairs done in 1975 for the Houston-Galveston area, which experienced over 8 ft of subsidence between 1943 and 1973 (Viets and others, 1979), emphasized structural damages and loss of property value due to increased flooding (Jones and Larson, 1975). Estimated annual average costs incurred by public and private agencies and property owners are shown below.

Estimated Annual Average Costs and Losses of Property Value
Due to Subsidence, Houston-Galveston Area

Type of Cost	Cost of Damages	Property Losses	Total
Private (Residential and Commercial)	$15,319,111	$15,811,143	31,130,254
Public	537,600	–	537,600
Total	$15,856,711	$15,811,143	$31,667,854

Source: Jones and Larson, 1975.

The cost of repairs to irrigation systems affected by subsidence may be prohibitive. Similarly, the cost of repairs to houses and structures that become increasingly prone to flooding as the land beneath them subsides may make repair impractical, particularly if the value of the property declines as well.

In addition to repair of homes and inundated areas, subsidence may require repairs to geothermal power plants, including gravity flow systems, pipelines, and structures at the site of the geopressured well. For example, subsidence at the Wairakei, New Zealand geothermal field has created compressive strains in a concrete drainage channel, causing cracks through which hot water has escaped and eroded the underlying soil. Strains in steam mains at the site require the periodic addition or removal of sections of pipe as the length of the pipe changes. Resultant costs include $250,000 for repair to the channel and replacement of soils, and $10,000 annually for repair and maintenance of the steam mains.

Despite the costly repairs mentioned in this section, which were primarily necessitated by ongoing settlements and subsidence in the Gulf Coast area, very little additional cost is expected from resource development-induced subsidence damage in the prospect areas investigated in the present report. In fact, even the maximum estimated subsidence figures would generate tilts that are well below 0.001 ft/ft, the "threshold of architectural damage" (Cording and O'Rourke, in Viets and others, 1979, p. II-12). Hence, virtually no additional repair of damaged structures from geopressured geothermal resource development is expected based on the subsidence calculated in the present report, except for the repair of houses, roads, or other features that would be flooded as a result of the increased subsidence.

7.4 Land Use and Zoning Regulations

Local and state agencies have flood protection-related zoning ordinances which vary among localities in both intent and effectiveness. Although these ordinances were generally not created to deal with subsidence, they may be effective mechanisms to mitigate subsidence-induced flood problems, such as preventing construction in increasingly flood-prone areas. For example, Baytown, Texas, in the subsiding Houston-Galveston area, has adopted land use controls as a requisite for National Flood Insurance coverage (Viets and other, 1979).

The National Flood Insurance Program requires both that construction standards be met for new subdivisions and that substantial improvements be made to existing structures in order for all structures within a mapped floodplain area to become eligible for the program. In reclaimed wetlands, house-raising may be required in order to meet flood insurance eligibility standards. The average 1975 cost of raising the foundation of a conventional slab house with fill was estimated at between $400 for a one foot rise and $3,000 for an eight foot rise above base elevation (Earle, 1975).

In addition, the U.S. Army Corps of Engineers issues permits for all small and large scale developments occurring in navigable waters and unprotected flood areas, based in part on development guidelines for minimization of flood damage.

Institutional controls are therefore currently available to implement land use or zoning restrictions in flood-prone areas. However, subsiding areas that are not susceptible to flooding are not covered under these programs and would require more extensive institutional changes in order to be regulated. Since the only major impact of resource development-related subsidence requiring mitigation in the prospects under study is expected to be flood damage, zoning changes to accommodate subsidence should be relatively easy to implement.

7.5 Other Mitigation Measures

Some additional mitigation measures that may be required are discussed below.

First, if research or experience indicates that reactivation of growth faults will be a contributing factor to resource development-related subsidence, a combination of repair or reinforcement of affected structures and land use controls would be necessary in fault zones.

Second, resource development-related subsidence in wetlands may be mitigated by stricter control on other human activities that also produce subsidence and marsh deterioration. For example, the levees that are built alongside new canals cut off the circulation of water in adjacent marshes, eventually causing ponding, water evaporation, and drying of the marsh sediments. This drying leads to compaction and lowering of the ground surface. Limitations on new canal construction may consequently be required in areas that might subside because of geopressured geothermal resource development. Also, saltwater intrusion may be mitigated by increasing freshwater flow into the headwaters of wetlands, as implemented, for example, in the Barataria Basin with the Bonnet Carre Spillway. Simultaneously increasing the volume of sediment flowing into the wetlands would rebuild the marshland submerging by subsidence.

Third, housing relocations may be indicated should buildings be damaged beyond repair, or should access roads be flooded.

Fourth, subsidence can be taken into consideration in the design of structures to be located within the subsiding area. The Texas Department of Highways, for example, plans for potential subsidence in the design of all new roads in currently subsiding areas (James Barr, personal communication, 1980).

7.6 Conclusion

Although a variety of subsidence mitigation measures are currently available, the low subsidence estimates reported in the present study indicate that few of these measures will be necessary. The only anticipated mitigation measures necessary to alleviate geopressured geothermal resource development-related subsidence are structural flood control features, repair of flood-damaged structures, and the institutional adjustments necessary to implement these measures. By and large, the costs of these mitigation measures should not be prohibitive, and the institutional channels exist through which they could be implemented.

TEXT REFERENCES

Adams, R. O., Banas, P. J., Bauman, R. H., Blackmon, J. H., and McIntire, W. G., 1978, Shoreline erosion in coastal Louisiana: Inventory and assessment: Coastal Resources Program, Louisiana Department of Transportation and Development.

Bachman, A. L., ed., 1979, Workshop on subsurface disposal of geopressured fluids, Gulf Coast-Proceedings: Baton Rouge, Louisiana State University, 186 p.

Bahr, L. M. and Hebrard, J. J., 1976, Barataria Basin: Biological characterization: Baton Rouge, Center for Wetland Resources, Louisiana State University.

Barrett, Barney and Gillespie, Marilyn, 1973, Primary factors which influence commercial shrimp production in coastal Louisiana: Technical Bulletin, Louisiana Wildlife and Fisheries Commission, New Orleans, no. 9.

Bebout, D. B., Loucks, R. G. and Gregory, A. R., 1978, Frio sandstone reservoirs in the deep subsurface along the Texas Gulf Coast--Their potential for the production of geopressured geothermal energy (in Bebout, D. B., Loucks, R. G., and Gregory A. R., 1980, United States Gulf Coast Geopressured-Geothermal Energy Conference, 4th, Austin, October 29-31, 1979, Proceedings: Austin, Center for Energy Studies, The University of Texas at Austin, v. 1, p. 11-45): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 76-3, 1976.

Bebout, D. B., Weise, B. R., Gregory, A. R., and Edwards, M. B., 1979, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast, their potential for production of geopressured goethermal energy: The University of Texas at Austin.

Bernard, W. J., 1979, Evaluation of five potential geopressure geothermal test sites in southern Louisiana: Baton Rouge, Petroleum Engineering Department, Louisiana State University, 121 p.

Blackmon J. H., 1979, A detailed analysis of marsh deterioration for selected sites in the Barataria Basin, Louisiana, in Day, J. W., and others, eds., Coastal Marsh and Estuary Management Symposium, 3rd, Proceedings: Baton Rouge, Louisiana State University.

Brown, L. F., Morton, R. A., McGowen, J. H., Kreitler, C. W., and Fisher, W. L., 1974, Natural hazards of the Texas coastal zone: Bureau of Economic Geology, The University of Texas at Austin.

Chabreck, Robert, 1972, Vegetation, water and soil characteristics of the Louisiana coastal region: Agricultural Experiment Station, Louisiana State University.

Craig, N. J., Day, J. W., Jr., Kemp P., Seaton, A., Smith, W. G., and Turner, R. E., 1977, Cumulative impact studies in the Louisiana coastal zone: Eutrophication and land loss: Baton Rouge Center for Wetland Resources, Louisiana State University.

Craig, N. J., Turner R. E., and Day J. W., 1979, Land loss in coastal Louisiana, in Coastal Marsh and Estuary Management Symposium, 3rd, 1979, Proceedings: Baton Rouge, Center for Wetland Resources, Louisiana State University.

Davis, Donald and Detro, R. A., 1975, Louisiana's marsh as a recreational resource, in Walker, H. J., ed., Coastal Resources, v. 12 of Geoscience and Man: Baton Rouge, Louisiana State University.

Dorfman, M. H., 1979, Status report to geothermal board of advisers: The University of Texas at Austin.

Dropek, A. K. and Abou-Sayed, A. S., 1978, Exxon total reservoir compressibility study: Exxon Co., U.S.A., TR 78-27, cited in EPRI, 1980.

Earle, D. W., 1975, Land subsidence problems and maintenance costs to home owners in east New Orleans, Louisiana: Louisiana State University and Agriculture and Mechanical College, dissertation.

Electric Power Research Institute (EPRI), 1980, Geopressured energy availability: Palo Alto, California, Geothermal Program, Advanced Power Systems Division, EPRI AP-1457, Research project 1272-1, 82 p.

Fisher, W. L., McGowen, J. H., Brown, L. F., Jr., and Grout, C. G., 1972, Environmental geologic atlas of the Texas coastal zone, Galveston-Houston area: Bureau of Economic Geology, The University of Texas at Austin.

Fowler, W. A., 1970, Pressures, hydrocarbon accumulation, and salinities-Chocolate Bayou Field, Brazoria County, Texas: Journal of Pet. Tech., April, p. 411-423.

Gagliano, S. M. and Van Beek, J. L., 1970, Geologic and geomorphic aspects of deltaic processes, Mississippi delta system: Hydrologic and geologic studies of coastal Louisiana, Baton Rouge, Louisiana State University, Report No. 1.

Gaidry, Wilson and White, Charles, 1973, Investigations of commercially important penaeid shrimp in Louisiana estuaries: Technical Bulletin, New Orleans, Louisiana Wildlife and Fisheries Commission, no. 8.

Garg, S. K., 1980, Reinjection of fluids into a producing geopressured reservoir, in Dorfman, M. H., and Fisher, W. L., eds., United States Gulf Coast Geopressured Geothermal Energy Conference: Research and Development, 4th, Austin, October 29-31, 1979, Proceedings: Center for Energy Studies: The University of Texas at Austin, v. 2, p. 1000-1030.

Gary, D. L., 1974, The commercial crawfish industry of south Louisiana: Baton Rouge, Center for Wetland Resources, Louisiana State University.

Gary, D. L. and Davis, D. W., 1979, Recreational dwellings in the Louisiana coastal marsh: Baton Rouge Center for Wetland Resources, Louisiana State University.

Geertsma, J., 1973, Land subsidence above compacting oil and gas reservoirs: Jour. Pet. Tech., v. 25, p. 734-744.

Gosselink, James, 1979, An ecological characterization study of the Chenier Plain coastal ecosystem of Louisiana and Texas: Baton Rouge, Center for Wetland Resources, Louisiana State University.

Gray, K. E., Jogi, P. N., Morita, Nobuo, and Thompson, T. W., 1980, The deformation behavior of rocks from the Pleasant Bayou wells, in Dorfman, M. H. and Fisher, W. L., eds., United States Gulf Coast Geopressured Geothermal Energy Conference: Research and Development, 4th, Austin, October 29-31, 1979, Proceedings: Center for Energy Studies, The University of Texas at Austin, v. 2, p. 1031-1059.

Gregory, A. R., 1980, Study effects of geopressured-geothermal subsurface environment on elastic properties of Texas Gulf Coast sandstones and shales using well logs, core data, and velocity surveys: unpublished, 184 p.

Gregory, A. R., and Backus, M. M., 1980, Geopressured formation parameters, geothermal well, Brazoria County, Texas, in Dorfman, M. H. and Fisher, W. L., eds., United States Gulf Coast Geopressured Geothermal Energy Conference: Research and Development, 4th, Austin, October 29-31, 1979, Proceedings: Center for Energy Studies, The University of Texas at Austin, v. 1, p. 235-311.

Hartley, Robert, 1980, Review of geopressured geothermal environmental research program in DOE/Industry Geopressured Geothermal Resource Development Program Working Group Meetings, Houston, May 28-29, 1980, Minutes from, Part 3. Minutes of the Informal Meeting of the Environmental/Laboratory Research Subgroup Meeting. Houston, Texas - May 29, 1980: C. K. GeoEnergy Corporation, Las Vegas, p. 4-6.

Hofstetter, R. P., 1977, Trends in population levels of the American oyster on public reefs in Galveston Bay, Texas: Technical Series, Texas Parks and Wildlife Department, no. 24.

Huner, J. V., 1979, Aquaculture in Louisiana's coastal zone, in Day, J. W., and others, eds., Coastal Marsh and Estuary Management Symposium, 3rd, Proceedings: Baton Rouge, Louisiana State University.

Jones, Lonnie and Larson, James, 1975, Economic effects of land subsidence due to excessive groundwater withdrawal in the Texas Gulf Coast area, Texas Water Resources Institute, Texas A&M University.

Kreitler, C. W., and Gustavson, T. C., 1976, Geothermal resources of the Texas Gulf Coast, in Vanston, J. H., and others, eds., Geopressured Geothermal Energy Conference, 2nd, Austin, February 23-25, 1976, Proceedings: Center for Energy Studies, The University of Texas at Austin, v. 5, part 3, 55 p.

Lovell, Richard, 1979, Fish Culture in the United States: Science, v. 206.

Louisiana Department of Labor, 1979, Employment and wages, 1978: Baton Rouge.

Louisiana Department of Transportation and Development, 1977, Projected parish land needs: Coastal Resources Program.

McCoy, R. L., Swift, T. E., and Hartsock, J. H., 1980, Land subsidence overview: Gruy Federal, Inc., Houston, 40 p.

McEachron, L. W., Shaw, C. R., and Moffet, A. W., 1977, A fishery survey of Christmas Drum and Bastrop bays, Brazoria County, Texas: Technical Series, Texas Parks and Wildlife Department, no. 20.

McGowen, J. H., Brown, L. F., Jr., Evans T. J., Fisher, W. L., and Groat, C. G., 1976, Environmental geologic atlas of the Texas coastal zone, Bay City-Freeport Area: Austin, Bureau of Economic Geology, The University of Texas at Austin.

Miller, I., Dershowitz, W., Jones, K., Myer, L., Ramon, K., and Schauer, M., 1980a, Simulation of geothermal subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-6, LBL-10794, 160 p.

_______________, 1980b, Physical processes of compaction-Companion report 1 to simulation of geothermal subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-7, LBL-10838, 39 p.

_______________, 1980c, Detailed report on tested models-Companion report 2 to simulation of geothermal subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-8, LBL-10837, 142 p.

_______________, 1980d, Case study data base-Companion report 3 to simulation of geothermal subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-9, LBL-10839, 66 p.

Moffet, A. W., 1975, The hydrology and macro-biota of the Chocolate Bayou estuary, Brazoria County Texas (1969-1971): Technical Series, Texas Parks and Wildlife Department, no. 14.

Morgan, James, 1972, Impact of subsidence and erosion on Louisiana coastal marshes and estuaries, in Chabreck, R., ed., Coastal Marsh and Estuary Management Symposium, Proceedings: Baton Rouge, Louisiana State University.

Mumphrey, A., Brooks, J., and Miller, J. C., 1976, Urban development in the Louisiana coastal zone: Problems and guidelines: Urban Studies Institute, University of New Orleans.

Newchurch, E. J., Bachman, A. L., Bryan, C. F., Harrison, D. P., Muller, R. A., Newman, J. P., Jr., Smith C. G., Jr., Bailey, J. I., Jr., Kelly, G. G., and Reibert, K. C., 1978, A preliminary environmental assessment of selected geopressured-geothermal prospect areas: Louisiana Gulf Coast region: Baton Rouge, Institute for Environmental Studies, Louisiana State University, 2 vols.

Palmaisano, A. W., 1972, Habitat preference of water-fowl and fur animals in the northern Gulf Coast marshes, in Chabreck, R., ed., Coastal Marsh and Estuary Management Symposium, Proceedings: Baton Rouge, Louisiana State University.

Papadopulos, S. S., Wallace, R. H., Jr., Wesselman, J. B., and Taylor, R. E., 1975, Assessment of onshore geopressured-geothermal resources in the northern Gulf of Mexico basin: U.S. Geological Survey Circular 726, p. 125-146.

Perret, W. S., Barrett, B. B., Latapie, W. R., Pollard, J. F., Mock, W. R., Adkins, G. B., Gaidry, W. J. and White, C. J., 1971, Cooperative Gulf of Mexico estuarine inventory and study, Louisiana: Phase 1, area description: New Orleans Louisiana Wildlife and Fisheries Commission.

Pinder, G. F., 1979, State-of-the-art review of geothermal reservoir modeling: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-5, LBL-9093, 144 p.

Odum, William, Zieman, Joseph, and Heald, Eric, 1972, The importance of vacular plant detritus to estuaries, in Chabreck, ed., Coastal Marsh and Estuary Management Symposium, Proceedings: Baton Rouge, Louisiana State University.

Sklar, F. H., and Conner, W. H., 1979, Effects of altered hydrology on primary production and aquatic animal populations in a Louisiana swamp forest, in Day, J. W., and others, ed., Coastal Marsh and Estuary Management Symposium, 3rd, Proceedings, Baton Rouge, Louisiana State University.

St. Amant, Lyle, Benson, L. K., Bradburn, D. M., Harris, A. H., Janvier, C., Laborde, D. P., Salinovich, O. G., Saltzman, M., VanLopik, J. R., Ward, M. F., Herschman, M. J., Templet, P. H., Smith, J. A., Holmes, B. H., Laverdet, N., Bohner, E., and Miller, M., 1973, Louisiana wetlands prospectus: Louisiana Advisory Commission on Coastal and Marine Resources, Conclusions, recommendations and proposals.

Swanson, B. F., 1978, Compressibility of geopressured reservoirs: Houston, Shell Development Co., cited in EPRI, 1980.

Terzaghi, Karl, 1943, Theoretical soil mechanics: New York, John Wiley & Sons 510 p.

Texas Bureau of Economic Geology, 1980, Environmental analysis of geopressured-geothermal prospect areas in Colorado and DeWitt counties, draft: Austin, The University of Texas at Austin.

Texas Department of Water Resources, 1979, A study of the influence of fresh-water inflows: Trinity-San Jacinto Estuary. Draft.

University of New Orleans, 1977, Statistical abstract of Louisiana.

Van Sickle, Virginia, Barrett, B. B., Ford, T. B., and Gulick, L. J., 1976, Barataria Basin: Salinity changes and oyster distribution: Baton Rouge Center for Wetland Resources, Louisiana State University.

Viets, V. F., Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

White, William, McGraw, Maryann, and Gustavson, Thomas, 1978, Environmental analysis of geopressured-geothermal prospect areas, Brazoria and Kenedy Counties, Texas: Austin, The University of Texas at Austin.

APPENDIX A

SELECTION OF REPRESENTATIVE PROSPECTS

The process used by the study team to select sites for further analysis is summarized in Figure A-1 and described below.

In order to choose study sites which were representative of the range of surface and subsurface environments present within the known geopressured geothermal fairways, characteristics of each fairway were examined, and the availability of data was evaluated. Environmental information and data on reservoir geology and geometry were considered separately. South Texas fairways were not included in this data review because no viable prospects had been identified at that time.

After compilation of general information on each fairway, an advisory group was formed to assist in selecting the study sites and to provide access to unpublished or in-progress work. The advisory group consisted of individuals actively involved in either environmental or geologic and engineering research relating to development of geopressured resources. DOE representatives were also included, because of their knowledge of current research in the Gulf Coast region. Advisory group members for the site selection task were as follows:

Ann Bachman,	Louisiana State University Energy Programs Office
Zaki Bassiouni,	Louisiana State University Department of Petroleum Engineering
Don Bebout,	Louisiana Geological Survey Department of Natural Resources
Ray Gregory,	University of Texas Bureau of Economic Geology
Tom Gustavson,	University of Texas Bureau of Economic Geology
Ron Stearns,	Department of Energy Las Vegas, Nevada
Ray Wallace,	U.S. Geological Survey NSTL Station, Mississippi
Keith Westhusing,	Department of Energy Houston, Texas

STUDY SITES SELECTION PROCESS

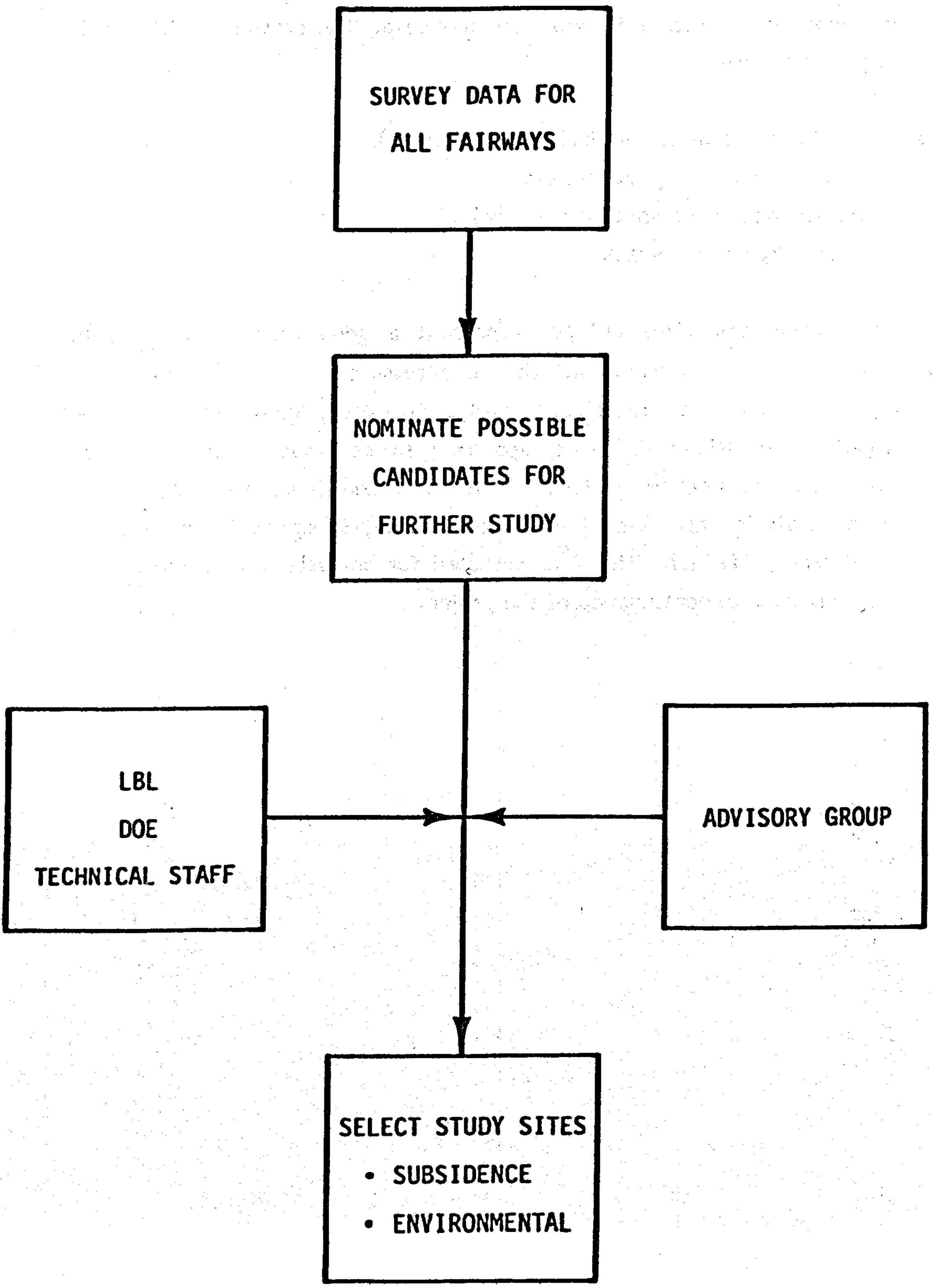


FIGURE A-1

Based on discussions with advisory group members (a formal meeting was held during the Fourth Geopressured Geothermal Energy Conference in Austin), it was concluded that the choice of sites for subsidence analysis was limited to a few areas where geologic and reservoir data were adequate. The prospects selected for subsidence analysis were:

- Southeast Pecan Island Prospect (Louisiana),
- Austin Bayou Prospect (Texas),
- Gladys McCall Prospect (Louisiana),
- Cuero Prospect (Texas).

Because these few sites did not represent a good cross section of the environmental features present in the geopressured fairways, areas for environmental analysis were selected separately. Two sites, Austin Bayou Prospect and Southeast Pecan Island Prospect, appeared to be good choices for both environmental and subsidence analyses. The two additional sites chosen for environmental analysis only were Lafourche Crossing Prospect (Louisiana) and Eagle Lake Prospect (Texas). The sites selected for analysis were reviewed and approved by LBL prior to continuance of the project.

APPENDIX B

FLOWING BOTTOMHOLE PRESSURE MODEL

A flowing bottomhole pressure (BHP) model was used to derive a production scenario for each site analyzed for subsidence. This model was developed to determine the pressure and flow rate history, given specified reservoir geometry and operating restrictions and using basic energy and material balances. The model assumes that a single-phase, slightly compressible fluid is flowing in a homogeneous, isotropic, porous medium. It uses either an infinite-aquifer drawdown equation or a bounded-reservoir flow equation. The BHP model uses input data supplied by the user and the infinite-aquifer solution to determine the time required to reach pseudo-steady-state; thereafter, the bounded-reservoir solution is used. The model accounts for friction losses and skin effect and treats the variable-rate case by the superposition theorem. Ideal reservoir performance can be obtained through a fully open flow system; however, for a more operational approach the BHP model allows the user to specify a choke size. Because of the sensitivity of the time step size, it is recommended that different time steps be used to assure that the solution is accurate. A complete documentation of the BHP model and the equations required is presented below.

B.1 The Model

The energy balance (Eq. 1B), pressure drawdown equation (Eq. 2B) and friction factor relations (Eq. 3B, Eq. 4B) are given below.

$$p_w = p_s + (.052)\ \rho\ L + (5.5026 \times 10^{-6})\ (L\ \rho\ /D^5)\ fq^2 \qquad (1B)$$

where

p_w = Bottomhole pressure (psia)
p_s = Surface pressure (psia)
ρ = Fluid density (lb/gal)
L = Depth (ft)

D = Inner diameter of production string (in.)
f = Friction factor
q = Flow rate (bbl/day)

For an infinite aquifer:

$$p_w = p_i - \left(\frac{162.6\mu q}{kh}\right)\left[\log\left\{\frac{.1929\,kt}{\phi\mu C_e r_w^2}\right\} + .351 + .87s\right] \qquad (2B)$$

where

P_i = Initial reservoir pressure (psia)
μ = Viscosity (cp)
k = Permeability (md)
h = Thickness (ft)
t = Time (months)
ϕ = Porosity (decimal)
C_e = Compressibility (1/psi)
r_w = Wellbore radius (ft)
s = Skin effect

<u>Turbulent flow:</u> ($N_R > 2000$)

$$\frac{1}{\sqrt{f}} = -4\log\left\{\frac{e}{3.72\,D} + \frac{1.255}{N_R\sqrt{f}}\right\} \qquad (3B)$$

where

e = Relative roughness of tubing
N_R = Reynold's Number

(Note: $N_R = 11.057\rho q/(D\mu)$

<u>Laminar flow:</u> ($N_R \leqslant 2000$)

$$f = 16/N_R \qquad (4B)$$

The preceding equations involve three unknowns: q, p_w, and f. All remaining parameters are assumed to be known. For turbulent flow, a Jacobian solution method is applied. A direct analytical solution is used for laminar flow, and both solution methods are presented in Sections B.2.1 and B.2.2. The pressure drawdown equation (Eq. 2B) applies for an infinite-acting reservoir. A real system can be approximated by Eq. 2B from $t = 0$ until the pseudo-steady-state time (t_{pss}) is reached. This method is subject to error during the late transient period. However, relative to the life of a given well, this error is minimal. Once the production enters the pseudosteady-state flow regime, the BHP model switches over to a bounded-reservoir pressure drawdown equation. The accuracy of a given solution is highly dependent on the size of the time step. As the time step is decreased, the solution method becomes more exact. The user must be aware of this inherent mathematical constraint and decrease the time step until the desired accuracy is obtained. If the flow rates vary significantly, superposition techniques must be applied. The superposition equations are presented in Section B. 2. 5

For a bounded-reservoir case, Eq. 2B can be replaced by Eq. 5B. This equation is exact provided the time step is large enough (i.e., the late transient period has ended). Additional data are required for the bounded case (i.e., Ca, TDIM, AREA).

$$p_w = p_i - \left(\frac{162.6 \mu q}{kh}\right) \log \left(\frac{2.2458A}{Ca\, r_w^2}\right) + .87s - \left(\frac{170.78\, qB}{\phi C_e h A}\right) t \qquad (5B)$$

where

A = Area (ft^2)
h = Thickness (ft)
Ca = Shape factor for a given aquifer geometry.

The bounded-reservoir equation (Eq. 5B) is applied when the time is greater than the pseudosteady-state time. Earlougher (1977) has presented shape factors and dimensionless pseudosteady-state time for various reservoir geometries. These values are shown in Table B-1. The bottomhole pressure model uses the infinite reservoir solution for times less than the pseudosteady-state time. The pseudosteady-state time is determined by Eq. 6B:

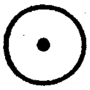
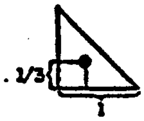
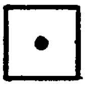
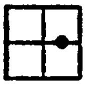
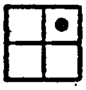
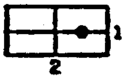
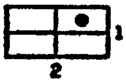
$$t_{pss} = 225816.5 * t_D\, \phi\, \mu\, C_e\, A/k \qquad (6B)$$

where

t_{pss} = Pseudosteady-state time (months)
t_D = Dimensionless time for pseudosteady-state
A = Area (acres)

TABLE B-1

SHAPE FACTORS FOR VARIOUS CLOSED SINGLE-WELL DRAINAGE AREAS

IN BOUNDED RESERVOIRS	C_A	$\ln C_A$	$1/2 \ln\left(\frac{2.2458}{C_A}\right)$	EXACT FOR $t_{DA} >$	LESS THAN 1% ERROR FOR $t_{DA} >$	USE INFINITE SYSTEM SOLUTION WITH LESS THAN 1% ERROR FOR $t_{DA} <$
	31.62	3.4538	−1.3224	0.1	0.06	0.10
	31.6	3.4532	−1.3220	0.1	0.06	0.10
	27.6	3.3178	−1.2544	0.2	0.07	0.09
	27.1	3.2995	−1.2452	0.2	0.07	0.09
	21.9	3.0865	−1.1387	0.4	0.12	0.08
	0.098	−2.3227	+1.5659	0.9	0.60	0.015
	30.8828	3.4302	−1.3106	0.1	0.05	0.09
	12.9851	2.5638	−0.8774	0.7	0.25	0.03
	4.5132	1.5070	−0.3490	0.6	0.30	0.025
	3.3351	1.2045	−0.1977	0.7	0.25	0.01
	21.8369	3.0836	−1.1373	0.3	0.15	0.025
	10.8374	2.3830	−0.7870	0.4	0.15	0.025
	4.5141	1.5072	−0.3491	1.5	0.50	0.06
	2.0769	0.7309	+0.0391	1.7	0.50	0.02
	3.1573	1.1497	−0.1703	0.4	0.15	0.005

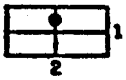
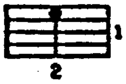
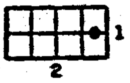
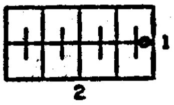
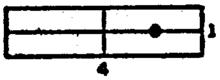
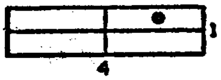
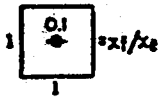
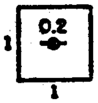
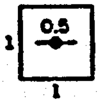
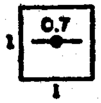
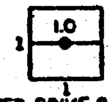



TABLE B-1 CONT'D.

	C_A	$\ln C_A$	$\frac{1}{2}\ln\left(\frac{2.2458}{C_A}\right)$	EXACT FOR $t_{DA}>$	LESS THAN 1% ERROR FOR $t_{DA}>$	USE INFINITE SYSTEM SOLUTION WITH LESS THAN 1% ERROR FOR $t_{DA}<$
	0.5813	-0.5425	+0.6758	2.0	0.60	0.02
	0.1109	-2.1991	+1.5041	3.0	0.60	0.005
	5.3790	1.6825	-0.4367	0.6	0.30	0.01
	2.6896	0.9894	-0.0902	0.8	0.30	0.01
	0.2318	-1.4619	+1.1355	4.0	2.00	0.03
	0.1155	-2.1585	+1.4838	4.0	2.00	0.01
	2.3606	0.8589	-0.0249	1.0	0.40	0.025
IN VERTICALLY-FRACTURED RESERVOIRS	USE $(x_e/x_f)^2$ IN PLACE OF A/r_w^2 FOR FRACTURED SYSTEMS					
	2.6541	0.9761	-0.0835	0.175	0.08	CANNOT USE
	2.0348	0.7104	+0.0493	0.175	0.09	CANNOT USE
	1.9986	0.6924	+0.0583	0.175	0.09	CANNOT USE
	1.6620	0.5080	+0.1505	0.175	0.09	CANNOT USE
	1.3127	0.2721	+0.2685	0.175	0.09	CANNOT USE
	0.7887	-0.2374	+0.5232	0.175	0.09	CANNOT USE
IN WATER-DRIVE RESERVOIRS						
	19.1	2.95	-1.07	—	—	—
IN RESERVOIRS OF UNKNOWN PRODUCTION CHARACTER						
	25.0	3.22	-1.20	—	—	—

The solution methods for the bounded case and the infinite case are identical. However, the determination of one reservoir flow constant is different. The determination of this constant is presented in Section B.2.

Earlougher (1977) states, "If pressure data are available during both the infinite-acting and the pseudo-steady-state period, it is possible to estimate the drainage shape for the test well. The semilog plot is used to determine m and P_{1hr}; the Cartesian plot is used to get m* and P_{int}." Equation 7B shows how the shape factors are estimated.

$$C_A = 5.456\left(\frac{m}{m*}\right) \exp\left\{2.303\ (P_{1hr} - P_{int})/m\right\} \tag{7B}$$

If the shape factor is known, the geometry can be approximated by Table B-1.

The bottomhole pressure (BHP) model has been developed to operate with a choke in the system. The general liquid flow choke equation is given below.

$$q = C'\sqrt{h_w} \tag{8B}$$

where

q = Liquid flow rate (gallons/hour)

C' = Choke constant

h_w = Differential pressure (inches of water)

If oilfield units are used, Eq 8B becomes

$$q = C'\,(9.21)\sqrt{(p_s - p_b)}$$

where

q = Liquid flow rate (Bbbls/day)

p_s = Wellhead pressure (psia)

p_b = Line or backpressure (psia)

The introduction of the choke equation changes Eq. 1B to

$$p_w = p_b + (CF*q)^2 + (5.5026 \times 10^{-6})\,(L\rho/D^5)\,fq^2 + .052\rho L$$

where

$$CF = 1/C'$$

By letting CF = 1/C', the unrestricted (no choke) solution can be obtained if $p_b = p_s$ and CF = 0.0. Therefore, the Jacobian solution presented in the BHP model uses the more general equations.

B.2. BOTTOMHOLE PRESSURE MODEL DERIVATIONS

B.2.1 Turbulent Flow Solution: ($Y = p_w$ $Z = q$ $X = 1/\sqrt{f}$)

Equations 1B, 2B, and 3B can be rearranged to yield

$$Y = AO + A1(Z/X)^2 \tag{9B}$$

where

$$AO = p_s + .052\,\rho L$$
$$A1 = (5.5026 \times 10^{-6})\,L\rho/D^5$$

$$Y = CO - C1\,Z \tag{10B}$$

where

$$CO = p_i$$
$$C1 = (162.6\,\mu/kh)\left[\log\left\{\frac{.1929\,kt}{\phi\mu C_e r_w^{\,2}}\right\} + .351 + .87\,s\right]$$

$$X = -4 \log \; BO + B1\,(X/Z) \tag{11B}$$

and where

$$BO = e/3.72D$$
$$B1 = .1135\,\mu D/\rho$$

Y can be eliminated from Eq. 9B using Eq. 10B. The system is then reduced to two equations in two unknowns.

$$F_1\,(X, Z) = (CO - AO) - C1Z - A1(Z/X)^2 = 0$$

$$F_2\,(X, Z) = X + 4 \log\left[BO + B1(X/Z)\right] = 0$$

These two nonlinear equations can be solved using an iterative technique based on Newton's method and the Jacobian matrix. To construct the Jacobian matrix, the partial derivatives of F_1 and F_2 must be taken as shown below:

$$\frac{\partial F_1}{\partial X} = 2A1Z^2/X^3$$

$$\frac{\partial F_1}{\partial Z} = -(C1 + 2A1Z/X^2)$$

$$\frac{\partial F_2}{\partial X} = 1 + \frac{1.73716\ B1}{(B0Z + B1X)}$$

$$\frac{\partial F_2}{\partial Z} = \frac{-1.73716\ B1X}{(B0Z^2 + B1XZ)}$$

The determinate of the Jacobian matrix must be taken to determine the (k+1) iteration values.

$$DET_k = \left(\frac{\partial F_1}{\partial X}\right)\left(\frac{\partial F_2}{\partial Z}\right) - \left(\frac{\partial F_1}{\partial Z}\right)\left(\frac{\partial F_2}{\partial X}\right)$$

$$X_k+1 = X_k - \left[F_1(X, Z)\left(\frac{\partial F_2}{\partial Z}\right) - F_2(X, Z)\left(\frac{\partial F_1}{\partial Z}\right)\right]_k / DET_k$$

Addition of choke equation:

$$Q = \left(\frac{1}{CF}\right)\sqrt{(p_s - p_b)} \qquad p_s = p_b + (CF*Q)^2$$

where

CF = Choke factor

p_s = Wellhead surface pressure (psia)

p_b = Backpressure or line pressure (psia)

Eq. 1B then becomes

$$Y = p_b + (CF*Q)^2 + A1(Z/X)^2 + .052\rho L$$

Y is then eliminated from Eq. 1B using Eq. 2B. The system is then reduced to two equations in two unknowns:

$$F_1\,(X, Z) = (C0 - A0) - C1Z - (CFZ)^2 - A1(Z/X)^2 = 0$$

$$F_2\,(X, Z) = X + 4 \log \left[BO + B1(X,/Z)\right] = 0$$

where

$$A0 \quad = P_B + .052\rho L$$

(Note that if the choke factor is set equal to zero, the system reduces to the original unrestricted drawdown system.)

$$\frac{\partial F_1}{\partial X} = \text{Unchanged}$$

$$\frac{\partial F_1}{\partial Z} = -C1 - 2(CF)^2 Z - 2(\frac{A1}{X^2})\,Z$$

B.2.2. Laminar Flow Solution

For laminar flow ($N_R \leqslant 2000$) with no choke,

$$Y = AO + A1(Z/X)^2 \qquad \text{and} \qquad (12B)$$

$$Y = CO - C1*Z \qquad (13B)$$

The friction factor becomes

$$f = 16/N_R \qquad (14B)$$

where

$$N_R = 11.057\rho\,q/D\mu$$

Recalling that $f = 1/X^2$, yields

$$Z = EX^2 \qquad (15B)$$

where

$$E = 1.447\ D/\rho$$

Substitution of Eq. 15B into Eq. 13B yields

$$Y = CO - C1\ E\ X^2$$

Elimination of Y and rearrangement gives

$$X = (\ CO - AO\ /\ [A1E + C1]\ E)^{1/2}$$

B.2.3. Infinite Flow

$$P_{wf} = P_i - (\frac{162.6\ qB\mu}{kh})\left[\log t + \log\ (\frac{k}{\phi\mu CE\ r_w^2}) - 3.2275 + .86859s\right]$$

Let B = 1 and change time units from hours to months.

Then,

$$P_{wf} = P_i - (\frac{162.6\ q\mu}{kh})\left[\log\ (24*30.4*t) + \log\ (\frac{k}{\phi\mu CE\ r_w^2}) - 3.2275 + .86859s\right]$$

Consider

$$\log\ (24*30.4*t) = \log 729.6 + \log t$$

and

$$-3.2275 = -\log 1688.49$$

Combining logarithms yields

$$P_{wf} = P_i - \frac{162.6\ q\mu}{kh}\left[\log\ (\frac{729.6\ kt}{1688.49\ \phi\ \mu\ CE\ r_w^2}) + .87\ s\right]$$

or

$$P_{wf} = P_i - \frac{162.6\ q\mu}{kh}\left[\log\ (\frac{.4321\ kt}{\phi\mu CE\ r_w^2}) + .87\ s\right]$$

Finally,

$$\log(.4321) = \log(.1924) + \log(2.24585)$$

or

$$\log(.4321) = \log(.1924) + .35138$$

Once again, combining logarithms yields

$$p_{wf} = p_i - \frac{162.6\, Q\mu}{kh} \left[\log\left(\frac{.1924\, kt}{\phi \mu CE\, r_w^2}\right) + .351 + .87s\right]$$

B.2.4. Bounded Flow

$$p_{wf} = m^* t + p_{int}$$

where

$$m^* = \frac{.23395\, qB}{\phi\, CE\, h\, A}$$

$$p_{int} = p_i - \left(\frac{70.6\, qB\mu}{kh}\right) \left[\ln\left(\frac{A}{r_w^2}\right) + \ln\left(\frac{2.2458}{Ca}\right) + 2s\right]$$

Changing time from hours to months and area from ft^2 to acres gives

$$p_{wf} = \frac{-.003919\, qBt}{\phi\, CE\, h\, A} + p_i - \frac{162.6\, qB\mu}{kh} \left[\log\left(\frac{97827A}{Ca\, r_w^2}\right) + .87s\right]$$

Rearranging yields and setting $B = 1.0$

$$p_{wf} = p_i - \left(\frac{162.6\, q\mu}{kh}\right) \left[\log\left(\frac{97827A}{Ca\, r_w^2}\right) + .87s\right] - \frac{.003919\, Qt}{\phi\, CE\, h\, A}$$

Note: The preceding derivations have been designed for computer applications. The separation of constants from logarithms and the conversion of units facilitates the computer programming.

B.2.5 Superposition

If the flow rate of a given well varies substantially over the life of the well, then the principle of superposition must be applied. The size of the time step (i.e., hours, days, months, or years) can become a critical BHP input parameter. For a well with a flow rate of 20,000 BWPD (± 10%) over a 20 year period, the time step can be made yearly. However, for a well with a flow rate of 20,000 BWPD (± 50%) over a 10 year period, the time step should be made monthly. Due to the solution method, the solution converges as the time step is decreased. The superposition relation (Eq.16 B) is given below.

$$pw_n = p_i - F\,(t_n)\,q_1 - \sum_{j=2}^{n} F\,(t_n - t_{j-1})\,(q_j - q_{j-1}) \qquad (16B)$$

where

F(t) = time flow function (i.e.....infinite or bounded)

Fortunately the Jacobian solution can still be used with only slight modification of the $C\phi$ and C1 terms.

$$C\phi = p_i - F(t_n)q_1 + \sum_{j=2}^{n-1} F(t_n - t_{j-1})\,(q_j - q_{j-1}) - F\,(\Delta t)q_{n-1}$$

$$C1 = F(\Delta t)$$

B.3 Operating Details

To operate the BHP model, the user must input five data cards of information. Certain parameters are given default values. Table B-2 illustrates the data entry procedure for a bounded reservoir. The user must select the time unit of interest (i.e., hours, days, months, or years). This is accomplished by input of a time alpha sequence (ITIM) and a time constant (TC). The program defaults to months (i.e., TC = 1). The user must also specify the life of the well or the maximum time desired (i.e., TMAX). The maximum time must always be input as months. Several examples are presented below to illustrate the time parameter input.

DATA INPUT FOR BHP MODEL

TABLE B-2

CARD	COLUMNS	FORMAT	VARIABLE	DESCRIPTION	EXAMPLES
1	1-80	20A4	ITLE	Title or Well Name	GENERAL WELL
2	1-10	F10.0	D	Inner tubing diameter (in.)	4.7780
2	11-20	F10.0	RHO	Density of fluid (lb/gal)	8.9200
2	21-30	F10.0	U	Viscosity of fluid (cp.)	.3000
2	31-40	F10.0	PI	Static bottomhole pressure (psia)	13015.0000
2	41-50	F10.0	QI	Initial rate estimate (BWPD)	30000.0000
2	51-60	F10.0	XK	Permeability (md)	20.0000
2	61-70	F10.0	H	Thickness (ft)	200.0000
2	71-80	F10.0	TMAX	Maximum time (months)	240.0000
3	1-10	F10.0	POR	Porosity (decimal)	.2350
3	11-20	F10.0	S	Skin effect	0.0000
3	21-30	F10.0	RW	Wellbore radius (ft)	.3200
3	31-40	F10.0	CE	Compressibility (psi^{-1})	.000006
3	41-50	F10.0	RELTOL	Relative tolerance	.0001
3	51-60	F10.0	DEPTH	Depth (ft)	14000.0000

TABLE B-2 (CONT.)

CARD	COLUMNS	FORMAT	VARIABLE	DESCRIPTION	EXAMPLES
3	61-70	F10.0	PS	Surface pressure (psia)	500.0000
3	71-80	F10.0	EPS	Relative roughness	.00065
4	1-10	A10	IWRD	Finite key control	FINITE
4	11-20	A10	IGEO	Geometry descriptor	TRIANGLE
4	21-30	A10	ITIM	Time unit descriptor	YEARS
4	31-40	F10.0	TC	Time constant	12.0000
4	41-50	F10.0	A	Area of reservoir (acres)	10000.0000
4	51-60	F10.0	CA	Geometry shape factor	27.6000
4	61-70	F10.0	TCDIM	Dimensionless time	.07
4	71-80	F10.0	CHOKE	Constant for choke $\left(\frac{\text{Day - psi}^{.5}}{\text{bbl}}\right)$	.005
5	1-10	F10.0	RATIO	Gas to water ratio (Mcf/bbl)	24.0000

Case A: Output desired for 240 months

ITIM = Months
TC = 1.0
TMAX = 240.(months)

Case B: Output desired for 12 days

ITIM = Days
TC = 1.0/30.4 = .032895
TMAX = 12.0/30.4 = .39474 (months)

Case C: Output desired for 20 years

ITIM = Years
TC = 1.0 x 12. = 12.0
TMAX = 12. x 20. = 240.(months)

Case D: Output desired for 100 hours

ITIM = Hours
TC = (1/30.4) (1/24) = .001371
TMAX = (100/30.4)/24 = .1371 (months)

The five data cards may be repeated, changing only specified parameters, as often as required. For example, if the pipe size is to be varied 5 times, then the program will require 25 data cards. The inner tubing diameter would be different on the second card of each five-card set. Any other input variable can be studied similarly.

A simplified flow diagram of the BHP model is shown in Figure B-1. Initially, the required variables are dimensioned and the default values are set:

IMAX = 10
RELTOL = .0001
TMAX = 36.0
EPS = .00065
RHO = 8.92
ITIM = MONTHS
TC = 1.0

The time parameters are then initialized and the input data are echo checked. The constants which are not dependent on time are computed. The program then branches to either the restricted flow (i.e., choke) or unrestricted flow (i.e., no choke) solution scheme. The unrestricted case represents the "ideal" deliverability, whereas the restricted case represents an operational approach.

The computation of the choke constant must be made prior to data entry. Standard industry tables can be used to determine the constant on the basis of choke size and the flow conditions. However, actual test data should be used if available. For example, the following data were obtained from a geopressured geothermal test well.

Positive choke = 18/64"
Adjustable choke = 23/64"

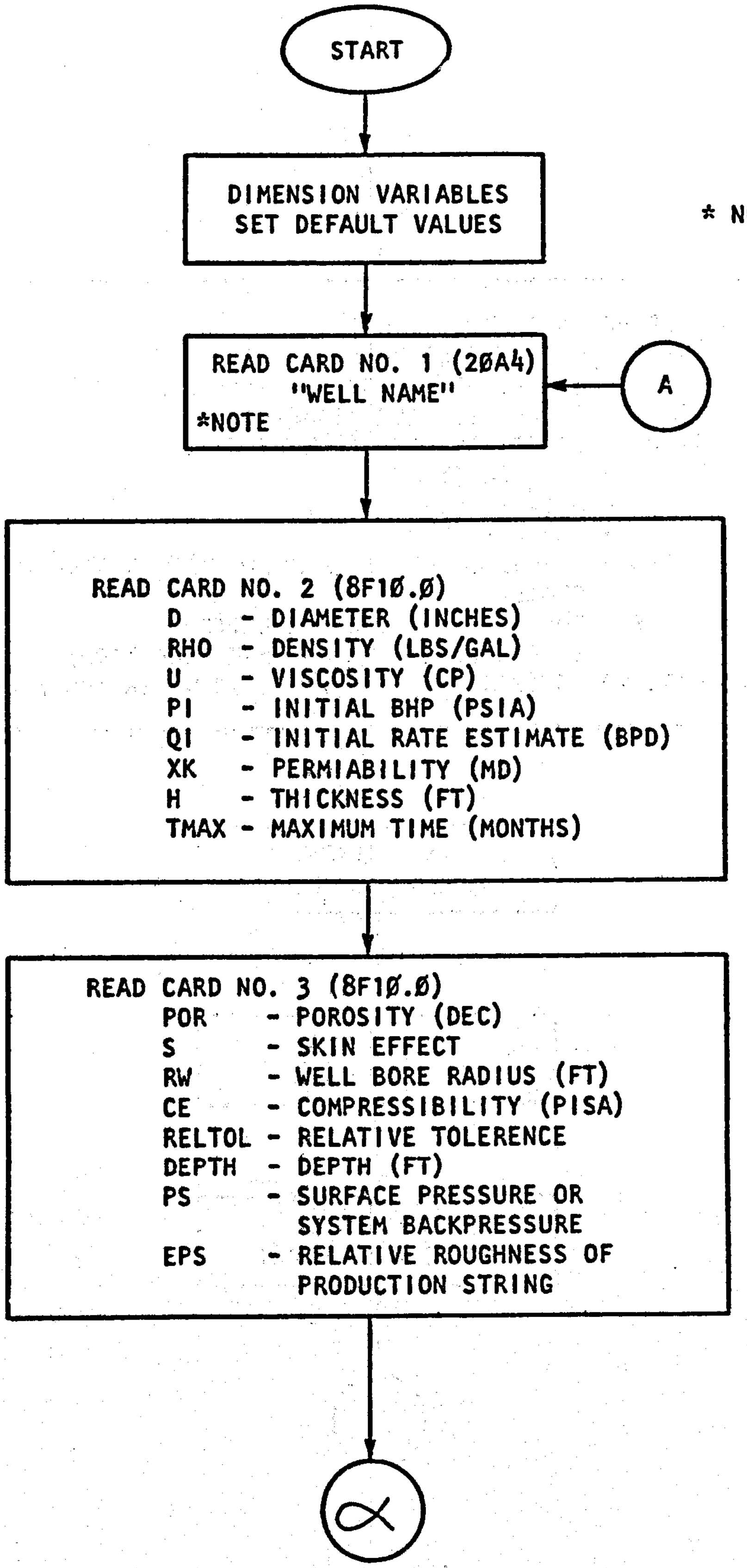
Separator pressure = 500 psia
Wellhead pressure = 3225 psia

Measured flow rate = 10776 bbl/day
Fluid temperature = 256°F
Fluid specific gravity = 1.1

$$CF = (3225 - 500)^{1/2}/10776$$

$$CF = .00484 \text{ (Day - psi}^{.5}\text{/bbl)}$$

If standard industry tables are used, the effective choke size must be determined. For the test well, the effective choke size was approximately 29/64-inch. The choke constant can be approximated using Eq. 17B.



* NOTE: IF END OF FILE
STOP PROGRAM

FIGURE B-1

BHP FLOW DIAGRAM

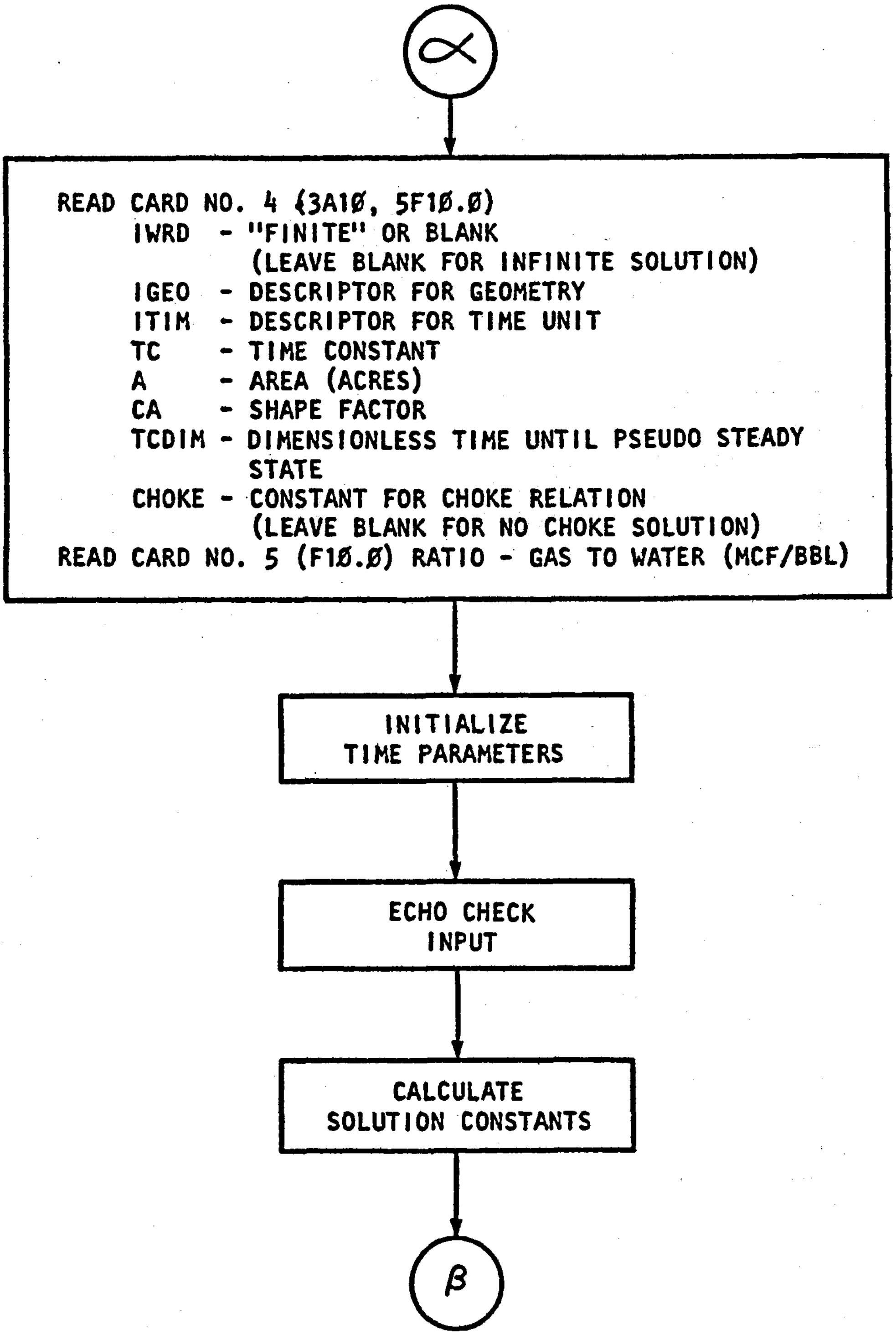


FIGURE B-1 (Continued)
BHP FLOW DIAGRAM

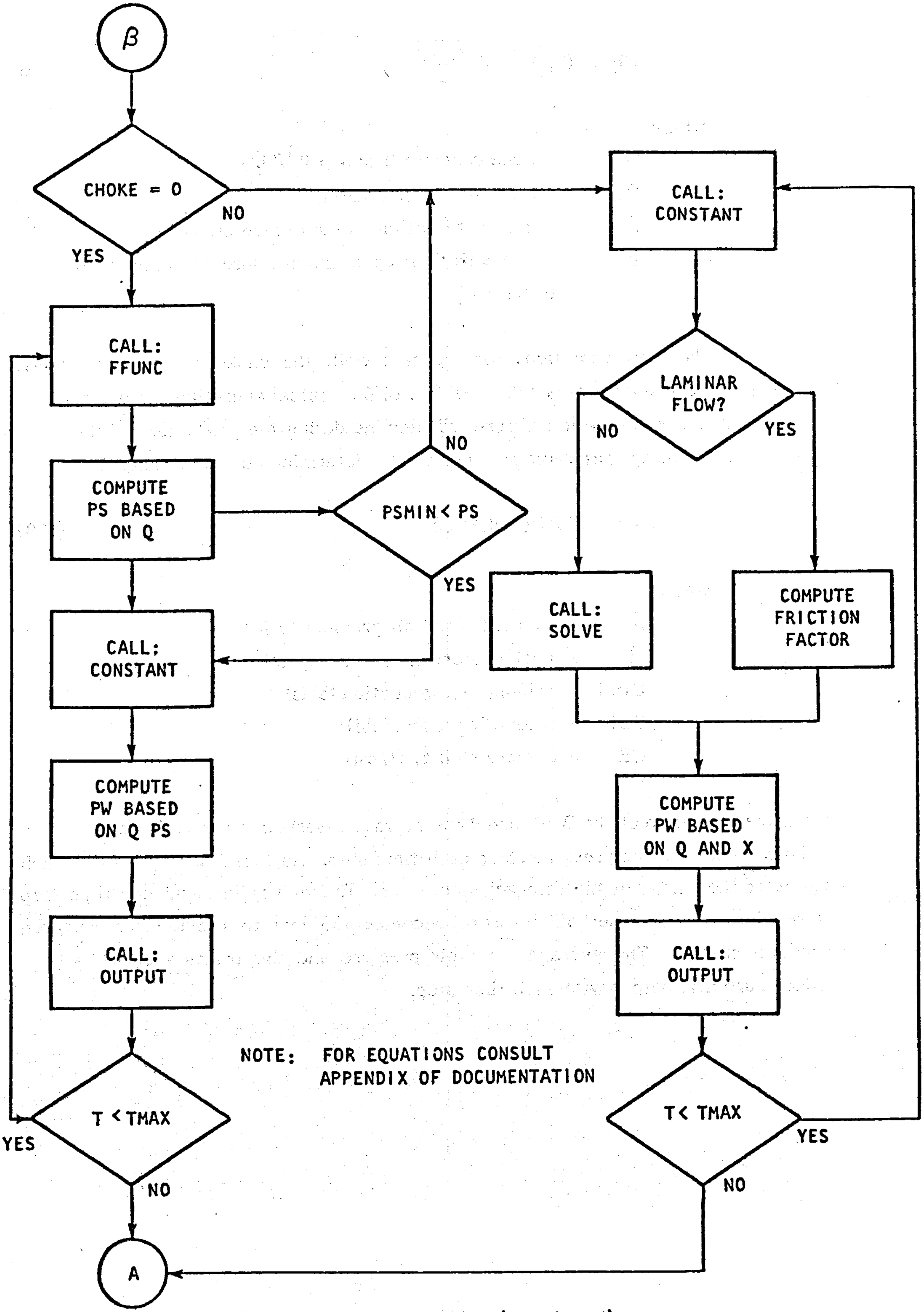


FIGURE B-1 (Continued)
BHP FLOW DIAGRAM

$$CF = \left(\frac{.00847}{D_t^2}\right)\sqrt{\frac{1-\beta}{\rho}} \qquad (17B)$$

where

CF = Choke constant (Day - $psi^{.5}$/bbl)

D_t = Throat diameter (inches)

β = Ratio of throat diameter to pipe diameter

ρ = Fluid density at upstream pressure and temperature (lb/ft^3)

Using the flow conditions for the test well, the choke constant is .00491. Generally, the choke constants will be within 10% of actual operating conditions.

The average reservoir pressure will decline during the production of the reservoir. The average reservoir pressure can be determined using equation 18B.

$$\bar{p} = pi - CUM/(VOL*CE) \qquad (18B)$$

where

$\bar{p}$ = average reservoir pressure (psia)

pi = initial reservoir pressure (psia)

CUM = cumulative production (bbls)

VOL = reservoir volume (bbl)

CE = compressibility (1/psi)

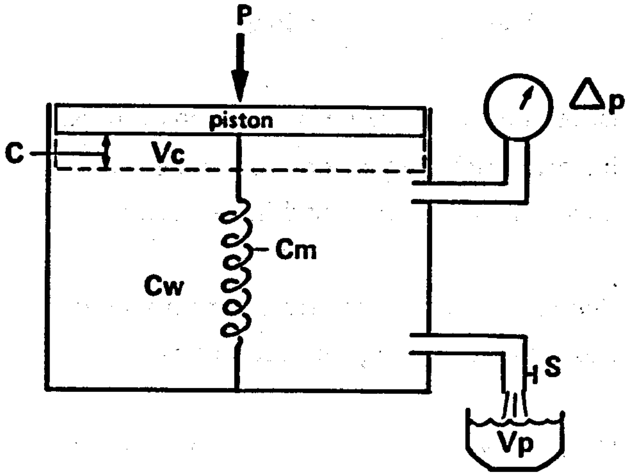
During the execution of the BHP model the average reservoir pressure is compared to the bottomhole flowing pressure after each time step. As these two values approach each other the energy of the reservoir decreases. The well is "shut-in" one time step before the average reservoir pressure becomes too low to provide the required drawdown energy. The average reservoir pressure and the fraction of fluid produced are also output with each time step.

Subroutines for BHP

FFUNC -	Uses iterative solution to obtain friction factor given flow rate. 1. Solves Eq. 3B if turbulent. 2. Solves Eq. 4B if laminar.
CONSTANT -	Determines the value of the constant "C1". Standard package uses infinite flow equation for times less than t_{pss}. The actual equations used are found in Section B.2.3 and program listing. The user can incorporate alternate solutions (i.e., single or multiple faults) by changing this subroutine.
SOLVE -	Uses Newton's method to solve two equations in two unknowns. The solution scheme is shown in Section B.2 A relative tolerance criterion is used to determine convergence. Depending on the size of the time steps and the initial guess for q, this routine generally converges in two to four iterations.
OUTPUT -	Presents the final results of a solved time step; i.e., the time, bottomhole pressure, surface wellhead pressure, liquid flow rate, cumulative liquid production and cumulative gas production. The pressures correspond to the end of the time step. The rate is the average or mid-time step rate. The cumulative production is based on the average rate and is through the entire time step. The average reservoir pressure and the fraction of fluid recovered is also printed. See Appendix F for the outputs for the four subsidence analysis sites.

APPENDIX C

VOLUME METHOD EQUATION DERIVIATION



A unit volume, V, of geopressured sandstone is represented by a fluid-filled, spring-loaded piston which is loaded by a constant overburden pressure, p. The compressibility of the rock matrix, C_m, under uniaxial load is represented by a spring. The compressibility of the fluid is C_w and the volume of the fluid is n, porosity of the formation $\left(\text{i.e. } n = \frac{V_{voids}}{V_{total}} = V_{fluid}\right)$ Opening of the valve S allows some of the fluid to escape, causing a pressure drop, Δp. Movement of the piston, C, results in a volume of compaction, V_c.

If the piston were locked (or the spring were perfectly rigid) when the pressure dropped, then the volume of fluid production, V_p, would be equal to $nC_w\Delta p$, i.e., the net expansion of n volume of fluid as a result of pressure decrease, p. If the piston moves, an additional volume of fluid, V_c, is produced. Therefore:

$$V_p = V_c + nC_w\Delta p \qquad \text{(C1)}$$

V_c is related to the spring compressibility and pressure change as follows:

$$V_c = C_m \Delta p \tag{C2}$$

Substituting (C2) into (C1):

$$V_p = C_m \Delta p + nC_w \Delta p$$

$$= (C_m + nC_w)\Delta p \tag{C3}$$

Dividing both sides by $n\Delta p$, gives:

$$\frac{V_p}{n\Delta p} = \frac{C_m}{n} + C_w \tag{C4}$$

$V_p/n \Delta p$ is the fluid production, as a fraction of fluid volume in place, per unit pressure drop. C_m/n is sometimes defined as the pore compressibility, C_p, and $C_p + C_w$ is the system compressibility, C_e.

The ratio V_c/V_p is obtained by dividing Eq. (C2) by Eq. (C3):

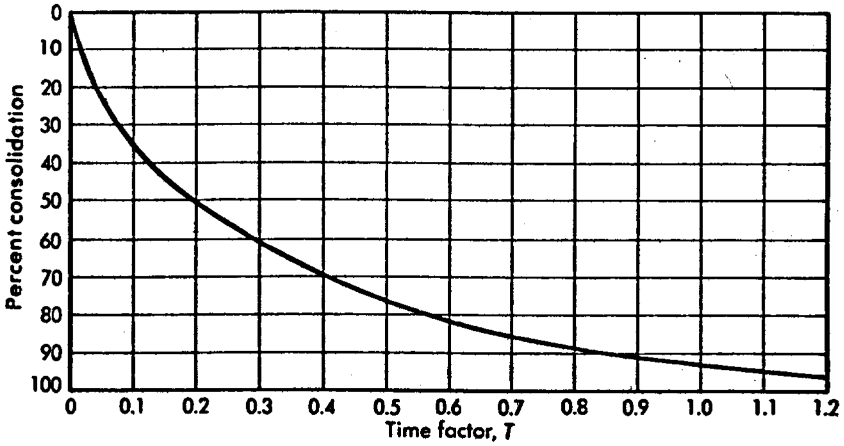
$$\frac{V_c}{V_p} = \frac{C_m \Delta p}{C_m \Delta p + nC_w \Delta p} = \frac{1}{1 + \frac{nC_w}{C_m}}$$

The foregoing derivation is simplified in that it ignores certain second order effects such as fluid temperature change and compressibility of the rock matrix material. However, full consideration of these will not change compaction estimates by more than a percent or two.

APPENDIX D

U% CALCULATIONS

U% Graph:



Time of rate of consolidation for a stratum drained on both surfaces or for a stratum drained on one surface. (from Sowers, 1979)

Equations:

for U% = 0 to 52.6%,

$$U\% = 100\sqrt{\frac{4T}{\pi}}$$

for U%>52.6%,

$$U\% = 100-10^{\left(\frac{1.781-T}{0.9033}\right)}$$

(from Terzaghi, 1943).

APPENDIX E

HANKEL-LIPSCHITZ INTEGRAL TABLES

TABLE E-1

VALUES OF $A = R \int_0^\infty J_1(\alpha R)\, J_0(\alpha r)\, e^{-D\alpha}\, d\alpha$ FOR RANGES OF VALUES OF $\rho = r/R$ AND $\eta = D/R$

	η											
ρ	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	3.0
0.0	1.0000	0.8039	0.6286	0.4855	0.3753	0.2929	0.2318	0.1863	0.1520	0.1258	0.1056	0.0513
0.2	1.0000	0.7983	0.6201	0.4771	0.3683	0.2876	0.2279	0.1835	0.1500	0.1244	0.1045	0.0510
0.4	1.0000	0.7789	0.5924	0.4508	0.3473	0.2720	0.2167	0.1754	0.1442	0.1202	1.1014	0.0502
0.6	1.0000	0.7349	0.5377	0.4043	0.3124	0.2470	0.1989	0.1628	0.1351	0.1135	0.0965	0.0488
0.8	1.0000	0.6301	0.4433	0.3368	0.2658	0.2147	0.1762	0.1465	0.1234	0.1049	0.0901	0.0470
1.0	0.5000	0.3828	0.3105	0.2559	0.2130	0.1787	0.1510	0.1286	0.1102	0.0951	0.0827	0.0449
1.2	0.0000	0.1544	0.1871	0.1795	0.1621	0.1433	0.1257	0.1103	0.0965	0.0848	0.0748	0.0424
1.4	0.0000	0.0717	0.1101	0.1216	0.1197	0.1120	0.1024	0.0925	0.0831	0.0744	0.0667	0.0398
1.6	0.0000	0.0400	0.0682	0.0829	0.0876	0.0865	0.0824	0.0768	0.0707	0.0646	0.0589	0.0370
1.8	0.0000	0.0249	0.0449	0.0580	0.0647	0.0668	0.0659	0.0633	0.0597	0.0557	0.0516	0.0343
2.0	0.0000	0.0168	0.0312	0.0418	0.0485	0.0519	0.0528	0.0520	0.0502	0.0477	0.0450	0.0315
3.0	0.0000	0.0042	0.0082	0.0118	0.0149	0.0174	0.0193	0.0207	0.0216	0.0221	0.0222	0.0198

TABLE E-2

VALUES OF $B = R \int_0^\infty J_1(\alpha R)\, J_1(\alpha r)\, e^{-D\alpha}\, d\alpha$ FOR RANGES OF VALUES OF $\rho = r/R$ AND $\eta = D/R$

	η											
ρ	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	3.0
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.2	0.1015	0.0954	0.0804	0.0628	0.0472	0.0350	0.0259	0.0194	0.0147	0.0113	0.0089	0.0032
0.4	0.2134	0.1979	0.1622	0.1238	0.0917	0.0675	0.0500	0.0375	0.0285	0.0220	0.0173	0.0062
0.6	0.3530	0.3163	0.2443	0.1789	0.1298	0.0949	0.0703	0.0529	0.0405	0.0314	0.0248	0.0090
0.8	0.5721	0.4573	0.3151	0.2197	0.1570	0.1147	0.0854	0.0648	0.0500	0.0391	0.0311	0.0117
1.0	∞	0.5456	0.3422	0.2355	0.1693	0.1252	0.0945	0.0726	0.0567	0.0448	0.0359	0.0139
1.2	0.5235	0.4278	0.3072	0.2237	0.1666	0.1265	0.0976	0.0764	0.0605	0.0485	0.0393	0.0158
1.4	0.3293	0.3026	0.2482	0.1958	0.1535	0.1208	0.0958	0.0766	0.0619	0.0504	0.0414	0.0174
1.6	0.2338	0.2228	0.1962	0.1650	0.1358	0.1110	0.0907	0.0743	0.0611	0.0506	0.0422	0.0185
1.8	0.1767	0.1711	0.1566	0.1377	0.1180	0.0997	0.0838	0.0703	0.0590	0.0496	0.0420	0.0194
2.0	0.1390	0.1358	0.1272	0.1152	0.1018	0.0885	0.0762	0.0653	0.0559	0.0478	0.0410	0.0199
3.0	0.0580	0.0576	0.0562	0.0541	0.0514	0.0483	0.0449	0.0414	0.0380	0.0346	0.0314	0.0190

(from Geertsma, 1973)

Note: r = distance from center of reservoir
R = radius of reservoir
D = depth of reservoir

APPENDIX F

PRODUCTION SCENARIO
COMPUTER PRINTOUTS

SOUTHEAST PECAN ISLAND PROSPECT

```
   D    =     4.276  (INCHES)      INNER DIAMETER
   RHO  =     8.750  (LB/GAL)      FLUID DENSITY
   MU   =      .300  (CP)          VISCOSITY

   PS   =     1000.  (PSIA)        SURFACE PRESSURE
   PI   =    13000.  (PSIA)        INITIAL RESERVOIR PRESSURE
   Q    =    40.000  (MBBLS/DAY) RATE ESTIMATF

   K    =      20.0  (MD)          PERMEABILITY
   H    =     500.0  (FEET)        THICKNESS
   POR  =      .230  (DECIMAL)     POROSITY

   CE   =   .000006  (DECIMAL)     COMPRESSIBILITY
  DEPTH=     14000.  (FEET)        DEPTH
   RW   =      .310  (FEET)        WELLBORE RADIUS

   S    =      0.00  (DECIMAL)     SKIN EFFECT
   EPS  =    .00065  (DECIMAL)     EPSILON FOR F
 RELTOL=  .00010000  (DECIMAL)     RELATIVE TOLERANCE

   A    =    12800.  (ACRES)       AREA
   CA   =      2.08  (DECIMAL)
   TC   =       .50  (DECIMAL)     T CRITICAL
   TC   =     29.92  (MONTHS)      T CRITICAL

   FINITE RESERVOIR


   TIME CONSTANT =    12.000000     TMAX =   240.000000  (MONTHS)     RATIO =       .02400  (MCF/BBL)

   CHOKE=0.00000000  (DAY-PSI**.5 / BBL.)
```

```
TIME     BOTTOM HOLE      WELL HEAD       RATE       CUM LIQUIDS       CUM GAS       AVERAGE       FRACTION
YEARS     PRESSURE        PRESSURE        BWPD          MBBLS            MMCF        PRESSURE      RECOVERED

  0.         13000.0          6630.0         0.000          0.000          0.000
  1.         11162.8          2264.2     40000.000      14592.000        350.208       12787.1         .00128
  2.         11104.1          2205.4     40000.000      29184.000        700.416       12574.1         .00256
  3.         10449.2          1550.6     40000.000      43776.000       1050.624       12361.2         .00383
  4.         10236.1          1337.5     40000.000      58368.000       1400.832       12148.3         .00511
  5.         10023.1          1124.4     40000.000      72960.000       1751.040       11935.3         .00639
  6.          9834.0          1000.0     39738.754      87456.698       2098.961       11723.8         .00766


  7.          9680.1          1000.0     38841.634     101626.126       2439.027       11517.0         .00890
  8.          9534.5          1000.0     37584.479     115336.944       2768.087       11317.0         .01010
  9.          9400.9          1000.0     36374.556     128606.382       3086.553       11123.3         .01124
 10.          9273.0          1000.0     35203.629     141448.666       3394.768       10935.9         .01238
 11.          9150.1          1000.0     34043.644     153867.787       3692.827       10754.7         .01347
 12.          9032.7          1000.0     32894.921     165867.854       3980.828       10579.6         .01452


 13.          8920.7          1000.0     31759.985     177453.897       4258.894       10410.5         .01554
 14.          8813.9          1000.0     30639.370     188631.139       4527.147       10247.4         .01652
 15.          8712.3          1000.0     29533.404     199404.924       4785.718       10090.2         .01746
 16.          8615.7          1000.0     28442.575     209780.776       5034.739        9938.8         .01837
 17.          8524.0          1000.0     27367.407     219764.406       5274.346        9793.1         .01921
 18.          8437.2          1000.0     26308.428     229361.720       5504.681        9653.1         .02008


 19.          8355.0          1000.0     25266.172     238578.820       5725.892        9518.6         .0 089
 20.          8277.5          1000.0     24241.190     247422.006       5938.128        9389.5         .02166
```

AUSTIN BAYOU PROSPECT

```
  D    =     4.276  (INCHES)     INNER DIAMETER
  RHO  =     9.450  (LB/GAL)     FLUID DENSITY
  MU   =      .400  (CP)         VISCOSITY

  PS   =     1000.  (PSIA)       SURFACE PRESSURE
  PI   =    11045.  (PSIA)       INITIAL RESERVOIR PRESSURE
  Q    =    40.000  (MBBLS/DAY)  RATE ESTIMATE

  K    =     148.0  (MD)         PERMEABILITY
  H    =      60.0  (FEET)       THICKNESS
  POR  =      .190  (DECIMAL)    POROSITY

  CE   =   .000006  (DECIMAL)    COMPRESSIBILITY
 DEPTH=     14800.  (FEET)       DEPTH
  RW   =      .310  (FEET)       WELLBORE RADIUS

  S    =      0.00  (DECIMAL)    SKIN EFFECT
  EPS  =    .00065  (DECIMAL)    EPSILON FOR F
RELTOL=  .00010000  (DECIMAL)    RELATIVE TOLERANCE

  A    =    11520.  (ACRES)      AREA
  CA   =      5.38  (DECIMAL)
  TC   =       .30  (DECIMAL)    T CRITICAL
  TC   =      2.40  (MONTHS)     T CRITICAL

  FINITE RESERVOIR


  TIME CONSTANT =     1.000000     TMAX =   240.000000  (MONTHS)     RATIO =       .02400  (MCF/BBL)

  CHOKE=0.00000000  (DAY-PSI**.5 / BBL.)
```

```
TIMF     BOTTOM HOLE     WELL HEAD      RATE       CUM LIQUIDS      CUM GAS      AVERAGF     FRACTION
MONTHS    PRESSURE       PRESSURE       BWPD          MBBLS           MMCF       PRESSURE    RECOVEPED

  0.       11045.0        3772.3        0.000         0.000           0.000
  1.        9394.5        1000.0    24590.858       747.562          17.941       10922.7       .00073
  2.        9363.7        1000.0    24416.411      1489.821          35.756       10801.3       .00146
  3.        9173.1        1000.0    23102.949      2192.151          52.612       10686.5       .00215
  4.        9112.5        1000.0    21577.433      2848.105          68.355       10579.2       .00279
  5.        9066.3        1000.0    20886.778      3483.063          83.594       10475.3       .00342
  6.        9015.5        1000.0    20237.683      4098.288          98.359       10374.7       .00402


  7.        8966.4        1000.0    19547.996      4692.547         112.621       10277.5       .00461
  8.        8920.2        1000.0    18867.789      5266.128         126.387       10183.7       .00517
  9.        8876.4        1000.0    18203.697      5819.520         139.668       10093.2       .00571
 10.        8835.0        1000.0    17552.680      6353.122         152.475       10005.9       .00623
 11.        8795.8        1000.0    16914.403      6867.320         164.816        9921.8       .00674
 12.        8758.8        1000.0    16289.245      7362.513         176.700        9840.8       .00723


 13.        8723.9        1000.0    15677.403      7839.106         188.139        9762.8       .00769
 14.        8691.0        1000.0    15079.010      8297.508         199.140        9687.9       .00814
 15.        8660.1        1000.0    14494.197      8738.131         209.715        9615.8       .00858
 16.        8631.0        1000.0    13923.089      9161.393         219.873        9546.6       .00899
 17.        8603.7        1000.0    13365.797      9567.713         229.625        9480.1       .00939
 18.        8578.2        1000.0    12822.418      9957.515         238.980        9416.4       .00977


 19.        8554.3        1000.0    12293.033     10331.223         247.949        9355.2       .01014
 20.        8531.9        1000.0    11777.708     10689.265         256.542        9296.7       .01049
 21.        8511.0        1000.0    11276.493     11032.071         264.770        9240.6       .01083
 22.        8491.6        1000.0    10789.420     11360.069         272.642        9187.0       .01115
 23.        8473.5        1000.0    10316.503     11673.691         280.169        9135.7       .01146
 24.        8456.7        1000.0     9857.738     11973.366         287.361        9086.6       .01175


 25.        8441.1        1000.0     9413.100     12259.524         294.229        9039.8       .01203
 26.        8426.6        1000.0     8982.546     12532.594         300.782        8995.2       .01230
 27.        8413.3        1000.0     8566.012     12793.001         307.032        8952.6       .01255
 28.        8400.9        1000.0     8163.415     13041.168         312.988        8912.0       .01280
 29.        8389.5        1000.0     7774.652     13277.518         318.660        8873.3       .01303
 30.        8379.0        1000.0     7399.597     13502.466         324.059        8836.6       .01325


 31.        8369.3        1000.0     7038.109     13716.424         329.194        8801.6       .01346
 32.        8360.5        1000.0     6690.024     13919.801         334.075        8768.3       .01366
 33.        8352.3        1000.0     6355.161     14112.998         338.712        8736.7       .01385
 34.        8344.8        1000.0     6033.319     14296.411         343.114        8706.7       .01403
 35.        8338.0        1000.0     5724.282     14470.429         347.290        8678.2       .01420
 36.        8331.8        1000.0     5427.816     14635.434         351.250        8651.2       .01436

 37.        8326.1        1000.0     5143.672     14791.802         355.003        8625.7       .01452
 38.        8320.9        1000.0     4871.586     14939.898         358.558        8601.4       .01466
 39.        8316.2        1000.0     4611.282     15080.081         361.922        8578.5       .01480
 40.        8311.9        1000.0     4362.472     15212.700         365.105        8556.8       .01493
 41.        8308.0        1000.0     4124.857     15338.096         368.114        8536.3       .01505
```

```
   42.        8304.4       1000.0    3898.129    15456.599     370.958      8516.9      .01517

   43.        8301.2       1000.0    3681.973    15568.531     373.645      8498.6      .01528
   44.        8298.3       1000.0    3476.067    15674.204     376.181      8481.3      .01538
   45.        8295.7       1000.0    3280.085    15773.918     378.574      8465.0      .01548
   46.        8293.3       1000.0    3093.697    15867.966     380.831      8449.7      .01557
   47.        8291.2       1000.0    2916.569    15956.630     382.959      8435.1      .01566
   48.        8289.3       1000.0    2748.370    16040.181     384.964      8421.5      .01574

   49.        8287.5       1000.0    2588.765    16118.879     386.853      8408.6      .01582
   50.        8286.0       1000.0    2437.425    16192.977     388.631      8396.5      .01589
   51.        8284.6       1000.0    2294.019    16262.715     390.305      8385.1      .01596
   52.        8283.3       1000.0    2158.223    16328.325     391.880      8374.4      .01602
   53.        8282.2       1000.0    2029.716    16390.028     393.361      8364.3      .01608
   54.        8281.2       1000.0    1908.184    16448.037     394.753      8354.8      .01614

   55.        8280.3       1000.0    1793.316    16502.554     396.061      8345.9      .01519
   56.        8279.5       1000.0    1684.811    16553.772     397.291      8337.5      .01625
   57.        8278.7       1000.0    1582.373    16601.876     398.445      8329.6      .01629
   58.        8278.1       1000.0    1485.715    16647.042     399.529      8322.2      .01634
   59.        8277.5       1000.0    1394.558    16689.437     400.546      8315.3      .01638
   60.        8277.0       1000.0    1308.632    16729.219     401.501      8308.8      .01642

   61.        8276.5       1000.0    1227.676    16766.540     402.397      8302.7      .01645
   62.        8276.1       1000.0    1151.436    16801.544     403.237      8297.0      .01649
   63.        8275.7       1000.0    1079.669    16834.366     404.025      8291.6      .01652
   64.        8275.4       1000.0    1012.141    16865.135     404.763      8286.6      .01655
   65.        8275.1       1000.0     948.628    16893.973     405.455      8281.8      .01658
   66.        8274.8       1000.0     888.912    16920.996     406.104      8277.4      .01661

WELL SHUT IN DUE TO FLOW LIMITATIONS
```

GLADYS McCALL PROSPECT

```
  D    =      4.276  (INCHES)     INNER DIAMETER
  RHO  =       8.690  (LB/GAL)    FLUID DENSITY
  MU   =        .300  (CP)        VISCOSITY

  PS   =       1000.  (PSIA)      SURFACE PRESSURE
  PI   =      14200.  (PSIA)      INITIAL RESERVOIR PRESSURE
  Q    =      40.000  (MBBLS/DAY) RATE ESTIMATE

  K    =        20.0  (MD)        PERMEABILITY
  H    =       500.0  (FEET)      THICKNESS
  POR  =        .230  (DECIMAL)   POROSITY

  CE   =    .000006  (DECIMAL)    COMPRESSIBILITY
 DEPTH=       15000.  (FEET)      DEPTH
  RW   =        .310  (FEET)      WELLBORE RADIUS

  S    =        0.00  (DECIMAL)   SKIN EFFECT
  EPS  =     .00065  (DECIMAL)    EPSILON FOR F
RELTOL=  .00010000  (DECIMAL)     RELATIVE TOLERANCE

  A    =     10240.  (ACRES)      AREA
  CA   =       10.84  (DECIMAL)
  TC   =         .15  (DECIMAL)   T CRITICAL
  TC   =        7.18  (MONTHS)    T CRITICAL

  FINITE RESERVOIR


  TIME CONSTANT =     12.000000     TMAX =   240.000000  (MONTHS)     RATIO =       .02400  (MCF/BBL)

  CHOKE=0.00000000  (DAY-PSI**.5 / BBL.)
```

```
 TIME    BOTTOM HOLE     WELL HEAD      RATE      CUM LIQUIDS      CUM GAS      AVERAGE     FRACTION
 YEARS     PRESSURE       PRESSURE      BWPD         MBBLS           MMCF       PRESSURE    RECOVERED

   0.       14200.0        7421.8       0.000         0.000          0.000
   1.       12180.9        2711.5   40000.000     14592.000        350.208      13933.8       .00160
   2.       11914.5        2445.1   40000.000     29184.000        700.416      13667.7       .00319
   3.       11648.2        2178.8   40000.000     43776.000       1050.624      13401.5       .00479
   4.       11381.9        1912.4   40000.000     58368.000       1400.832      13135.3       .00639
   5.       11115.5        1646.1   40000.000     72960.000       1751.040      12869.2       .00798
   6.       10849.2        1379.7   40000.000     87552.000       2101.248      12603.0       .00958

   7.       10582.8        1113.4   40000.000    102144.000       2451.456      12336.9       .01118
   8.       10359.0        1000.0   39579.024    116582.428       2797.978      12073.5       .01276
   9.       10172.2        1000.0   38425.241    130599.956       3134.399      11817.8       .01429
  10.        9994.4        1000.0   36967.716    144085.779       3458.059      11571.8       .01577
  11.        9825.4        1000.0   35526.729    157045.930       3769.102      11335.4       .01719
  12.        9665.0        1000.0   34103.031    169486.715       4067.681      11108.5       .01855

  13.        9513.1        1000.0   32697.406    181414.729       4353.953      10890.9       .01985
  14.        9369.6        1000.0   31310.680    192836.865       4628.085      10682.6       .02110
  15.        9234.2        1000.0   29943.718    203760.333       4890.248      10483.3       .02230
  16.        9106.7        1000.0   28597.425    214192.674       5140.624      10293.0       .02344
  17.        8987.1        1000.0   27272.749    224141.773       5379.403      10111.6       .02453
  18.        8875.0        1000.0   25970.675    233615.875       5606.781       9938.8       .02557

  19.        8770.3        1000.0   24692.231    242623.601       5822.966       9774.5       .02655
  20.        8672.7        1000.0   23438.482    251173.960       6028.175       9618.5       .02749
```

CUERO PROSPECT

```
  D    =     4.276  (INCHES)     INNER DIAMETER
  RHO  =      8.690  (LB/GAL)     FLUID DENSITY
  MU   =       .300  (CP)         VISCOSITY

  PS   =      1000.  (PSIA)       SURFACE PRESSURE
  PI   =     10500.  (PSIA)       INITIAL RESERVOIR PRESSURE
  Q    =     40.000  (MBBLS/DAY)  RATE ESTIMATE

  K    =       15.0  (MD)         PERMEABILITY
  H    =      200.0  (FEET)       THICKNESS
  POR  =       .160  (DECIMAL)    POROSITY

  CE   =    .000006  (DECIMAL)    COMPRESSIBILITY
 DEPTH=      12625.  (FEET)       DEPTH
  RW   =       .310  (FEET)       WELLBORE RADIUS

  S    =       0.00  (DECIMAL)    SKIN EFFECT
  EPS  =     .00065  (DECIMAL)    EPSILON FOR F
RELTOL=   .00010000  (DECIMAL)    RELATIVE TOLERANCE

  A    =     7296.  (ACRES)       AREA
  CA   =       5.38  (DECIMAL)
  TC   =        .30  (DECIMAL)    T CRITICAL
  TC   =       9.49  (MONTHS)     T CRITICAL

  FINITE RESERVOIR


  TIME CONSTANT =     1.000000     TMAX =   240.000000  (MONTHS)     RATIO =      .02400  (MCF/BBL)

  CHOKE=0.00000000  (DAY-PSI**.5 / BBL.)
```

```
 TIME     BOTTOM HOLE      WELL HEAD      RATE     CUM LIQUIDS      CUM GAS       AVERAGE     FRACTION
MONTHS      PRESSURE       PRESSURE       BWPD        MBBLS           MMCF        PRESSURE    RECOVERED

   0.        10500.0        4795.0       0.000         0.000          0.000
   1.         7437.7        1000.0   22503.111       684.095         16.418        10437.1       .00038
   2.         7402.9        1000.0   22226.236      1359.772         32.635        10374.9       .00075
   3.         7383.7        1000.0   21793.279      2022.288         48.535        10313.9       .00112
   4.         7370.5        1000.0   21529.071      2676.772         64.243        10253.7       .00148
   5.         7360.6        1000.0   21338.535      3325.463         79.811        10194.1       .00184
   6.         7352.6        1000.0   21189.722      3969.631         95.271        10134.8       .00219

   7.         7346.0        1000.0   21067.807      4610.092        110.642        10075.9       .00254
   8.         7340.3        1000.0   20964.677      5247.418        125.938        10017.2       .00290
   9.         7335.4        1000.0   20875.399      5882.030        141.169         9958.8       .00325
  10.         7174.1        1000.0   19367.247      6470.795        155.299         9904.7       .00357
  11.         7165.1        1000.0   17811.463      7012.263        168.294         9854.9       .00387
  12.         7153.4        1000.0   17605.621      7547.474        181.139         9805.6       .00417

  13.         7140.9        1000.0   17362.689      8075.300        193.807         9757.1       .00446
  14.         7128.1        1000.0   17105.083      8595.294        206.287         9709.2       .00474
  15.         7115.2        1000.0   16839.823      9107.225        218.573         9662.1       .00503
  16.         7102.3        1000.0   16569.960      9610.952        230.663         9615.8       .00531
  17.         7089.6        1000.0   16297.057     10106.382        242.553         9570.2       .00558
  18.         7076.9        1000.0   16021.997     10593.451        254.243         9525.4       .00585

  19.         7081.7        1000.0   15936.653     11077.925        265.870         9480.8       .00612
  20.         7070.9        1000.0   15869.954     11560.372        277.449         9436.4       .00638
  21.         7060.8        1000.0   15637.761     12035.760        288.858         9392.7       .00664
  22.         7051.1        1000.0   15415.320     12504.385        300.105         9349.6       .00690
  23.         7041.8        1000.0   15198.540     12966.421        311.194         9307.1       .00716
  24.         7032.8        1000.0   14986.224     13422.002        322.128         9265.1       .00741

  25.         7024.0        1000.0   14777.889     13871.250        332.910         9223.8       .00766
  26.         7015.6        1000.0   14573.312     14314.279        343.543         9183.1       .00790
  27.         7007.3        1000.0   14372.384     14751.199        354.029         9142.9       .00814
  28.         6997.2        1000.0   14148.746     15181.321        364.352         9103.3       .00838
  29.         6989.2        1000.0   13924.275     15604.619        374.511         9064.3       .00861
  30.         6981.3        1000.0   13723.798     16021.822        384.524         9026.0       .00884

  31.         6973.6        1000.0   13524.479     16432.967        394.391         8988.1       .00907
  32.         6966.0        1000.0   13326.987     16838.107        404.115         8950.9       .00929
  33.         6958.7        1000.0   13131.488     17237.304        413.695         8914.1       .00952
  34.         6951.5        1000.0   12938.028     17630.620        423.135         8877.9       .00973
  35.         6944.5        1000.0   12746.611     18018.117        432.435         8842.3       .00995
  36.         6937.7        1000.0   12557.225     18399.857        441.597         8807.2       .01016

  37.         6931.3        1000.0   12373.563     18776.013        450.624         8772.6       .01036
  38.         6924.8        1000.0   12192.735     19146.672        459.520         8738.5       .01057
  39.         6918.5        1000.0   12011.286     19511.815        468.284         8704.9       .01077
  40.         6912.5        1000.0   11832.264     19871.516        476.916         8671.8       .01097
  41.         6906.5        1000.0   11655.541     20225.845        485.420         8639.2       .01116
```

```
42.        6900.7       1000.0   11481.075   20574.869    493.797     8607.1     .01136

43.        6895.1       1000.0   11308.842   20918.658    502.048     8575.4     .01155
44.        6889.7       1000.0   11138.826   21257.279    510.175     8544.3     .01173
45.        6884.3       1000.0   10971.013   21590.797    518.179     8513.6     .01192
46.        6879.1       1000.0   10804.850   21919.265    526.062     8483.4     .01210
47.        6874.1       1000.0   10640.709   22242.742    533.826     8453.6     .01228
48.        6869.2       1000.0   10479.060   22561.306    541.471     8424.3     .01245

49.        6864.4       1000.0   10319.462   22875.017    549.000     8395.5     .01263
50.        6859.8       1000.0   10161.917   23183.940    556.415     8367.0     .01280
51.        6855.2       1000.0   10006.411   23488.135    563.715     8339.0     .01297
52.        6850.9       1000.0    9852.927   23787.664    570.904     8311.5     .01313
53.        6846.6       1000.0    9701.447   24082.588    577.982     8284.4     .01329
54.        6842.4       1000.0    9551.953   24372.967    584.951     8257.6     .01345

55.        6838.4       1000.0    9404.507   24658.864    591.813     8231.3     .01361
56.        6834.5       1000.0    9259.036   24940.339    598.568     8205.4     .01377
57.        6830.6       1000.0    9115.454   25217.448    605.219     8179.9     .01392
58.        6826.9       1000.0    8973.801   25490.252    611.766     8154.8     .01407
59.        6823.3       1000.0    8834.058   25758.807    618.211     8130.1     .01422
60.        6819.8       1000.0    8696.206   26023.172    624.556     8105.8     .01437

61.        6816.4       1000.0    8560.228   26283.403    630.802     8081.9     .01451
62.        6813.1       1000.0    8426.104   26539.557    636.949     8058.3     .01465
63.        6809.9       1000.0    8293.819   26791.689    643.001     8035.1     .01479
64.        6806.7       1000.0    8163.342   27039.854    648.957     8012.3     .01493
65.        6803.7       1000.0    8034.663   27284.108    654.819     7989.8     .01506
66.        6800.7       1000.0    7907.773   27524.504    660.588     7967.7     .01519

67.        6797.9       1000.0    7782.648   27761.097    666.266     7945.9     .01532
68.        6795.1       1000.0    7659.269   27993.939    671.855     7924.5     .01545
69.        6792.4       1000.0    7537.618   28223.082    677.354     7903.4     .01558
70.        6789.7       1000.0    7417.678   28448.580    682.766     7882.7     .01570
71.        6787.2       1000.0    7299.430   28670.482    688.092     7862.3     .01583
72.        6784.7       1000.0    7182.857   28888.841    693.332     7842.2     .01595

73.        6782.3       1000.0    7067.943   29103.707    698.489     7822.4     .01607
74.        6779.9       1000.0    6954.668   29315.128    703.563     7803.0     .01618
75.        6777.7       1000.0    6843.014   29523.156    708.556     7783.8     .01630
76.        6775.5       1000.0    6732.964   29727.838    713.468     7765.0     .01641
77.        6773.3       1000.0    6624.500   29929.223    718.301     7746.5     .01652
78.        6771.2       1000.0    6517.605   30127.358    723.057     7728.2     .01663

79.        6769.2       1000.0    6412.261   30322.291    727.735     7710.3     .01674
80.        6767.3       1000.0    6308.451   30514.068    732.338     7692.6     .01684
81.        6765.4       1000.0    6206.156   30702.735    736.866     7675.3     .01695
82.        6763.5       1000.0    6105.360   30888.338    741.320     7658.2     .01705
83.        6761.7       1000.0    6006.046   31070.922    745.702     7641.4     .01715
84.        6760.0       1000.0    5908.196   31250.531    750.013     7624.9     .01725
85.        6758.3       1000.0    5811.792   31427.209    754.253     7608.6     .01735
86.        6756.7       1000.0    5716.819   31601.001    758.424     7592.6     .01744
87.        6755.1       1000.0    5623.258   31771.948    762.527     7576.9     .01754
88.        6753.5       1000.0    5531.093   31940.093    766.562     7561.4     .01763
89.        6752.0       1000.0    5440.307   32105.478    770.531     7546.2     .01772
90.        6750.6       1000.0    5350.884   32268.145    774.435     7531.3     .01781
```

91.	6749.2	1000.0	5262.806	32428.134	778.275	7516.5	.01790
92.	6747.8	1000.0	5176.057	32585.487	782.052	7502.1	.01799
93.	6746.5	1000.0	5090.621	32740.241	785.766	7487.8	.01807
94.	6745.2	1000.0	5006.481	32892.438	789.419	7473.8	.01816
95.	6744.0	1000.0	4923.621	33042.117	793.011	7460.1	.01824
96.	6742.8	1000.0	4842.025	33189.314	796.544	7446.5	.01832
97.	6741.6	1000.0	4761.676	33334.069	800.018	7433.2	.01840
98.	6740.4	1000.0	4682.559	33476.419	803.434	7420.1	.01848
99.	6739.3	1000.0	4604.658	33616.400	806.794	7407.2	.01856
100.	6738.3	1000.0	4527.958	33754.050	810.097	7394.6	.01863
101.	6737.2	1000.0	4452.442	33889.405	813.346	7382.1	.01871
102.	6736.2	1000.0	4378.095	34022.499	816.540	7369.9	.01878
103.	6735.3	1000.0	4304.902	34153.368	819.681	7357.8	.01885
104.	6734.3	1000.0	4232.847	34282.046	822.769	7346.0	.01892
105.	6733.4	1000.0	4161.916	34408.568	825.806	7334.3	.01899
106.	6732.5	1000.0	4092.094	34532.968	828.791	7322.9	.01906
107.	6731.7	1000.0	4023.365	34655.278	831.727	7311.6	.01913
108.	6730.8	1000.0	3955.714	34775.532	834.613	7300.6	.01920
109.	6730.0	1000.0	3889.128	34893.762	837.450	7289.7	.01926
110.	6729.2	1000.0	3823.592	35009.999	840.240	7279.0	.01933
111.	6728.5	1000.0	3759.091	35124.275	842.983	7268.5	.01939
112.	6727.7	1000.0	3695.611	35236.622	845.679	7258.2	.01945
113.	6727.0	1000.0	3633.138	35347.069	848.330	7248.0	.01951
114.	6726.3	1000.0	3571.658	35455.648	850.936	7238.0	.01957
115.	6725.7	1000.0	3511.157	35562.387	853.497	7228.2	.01963
116.	6725.0	1000.0	3451.622	35667.316	856.016	7218.5	.01969
117.	6724.4	1000.0	3393.039	35770.464	858.491	7209.0	.01975
118.	6723.8	1000.0	3335.394	35871.860	860.925	7199.7	.01980
119.	6723.2	1000.0	3278.674	35971.532	863.317	7190.5	.01986
120.	6722.6	1000.0	3222.867	36069.507	865.668	7181.5	.01991
121.	6722.1	1000.0	3167.958	36165.813	867.980	7172.7	.01996
122.	6721.5	1000.0	3113.936	36260.477	870.251	7164.0	.02002
123.	6721.0	1000.0	3060.787	36353.525	872.485	7155.4	.02007
124.	6720.5	1000.0	3008.499	36444.983	874.680	7147.0	.02012
125.	6720.0	1000.0	2957.059	36534.878	876.837	7138.7	.02017
126.	6719.5	1000.0	2906.454	36623.234	878.958	7130.6	.02022
127.	6719.1	1000.0	2856.674	36710.077	881.042	7122.6	.02026
128.	6718.6	1000.0	2807.705	36795.431	883.090	7114.7	.02031
129.	6718.2	1000.0	2759.536	36879.321	885.104	7107.0	.02036
130.	6717.8	1000.0	2712.155	36961.770	887.082	7099.4	.02040
131.	6717.4	1000.0	2665.550	37042.803	889.027	7092.0	.02045
132.	6717.0	1000.0	2619.709	37122.442	890.939	7084.7	.02049
133.	6716.6	1000.0	2574.622	37200.711	892.817	7077.5	.02054
134.	6716.2	1000.0	2530.277	37277.631	894.663	7070.4	.02058
135.	6715.9	1000.0	2486.663	37353.226	896.477	7063.4	.02062
136.	6715.5	1000.0	2443.768	37427.516	898.260	7056.6	.02066
137.	6715.2	1000.0	2401.583	37500.524	900.013	7049.9	.02070
138.	6714.9	1000.0	2360.096	37572.271	901.735	7043.3	.02074
139.	6714.6	1000.0	2319.296	37642.778	903.427	7036.8	.02078

```
140.        6714.3       1000.0   2279.174   37712.065    905.090    7030.4    .02082
141.        6714.0       1000.0   2239.718   37780.152    906.724    7024.2    .02086
142.        6713.7       1000.0   2200.919   37847.060    908.329    7018.0    .02089
143.        6713.4       1000.0   2162.767   37912.808    909.907    7011.9    .02093
144.        6713.1       1000.0   2125.251   37977.416    911.458    7006.0    .02096

145.        6712.9       1000.0   2088.362   38040.902    912.982    7000.2    .02100
146.        6712.6       1000.0   2052.090   38103.286    914.479    6994.4    .02103
147.        6712.4       1000.0   2016.425   38164.585    915.950    6988.8    .02107
148.        6712.1       1000.0   1981.359   38224.818    917.396    6983.2    .02110
149.        6711.9       1000.0   1946.881   38284.004    918.816    6977.8    .02113
150.        6711.7       1000.0   1912.983   38342.158    920.212    6972.4    .02117


151.        6711.5       1000.0   1879.655   38399.300    921.583    6967.2    .02120
152.        6711.3       1000.0   1846.888   38455.445    922.931    6962.0    .02123
153.        6711.1       1000.0   1814.674   38510.611    924.255    6956.9    .02126
154.        6710.9       1000.0   1783.004   38564.815    925.556    6952.0    .02129
155.        6710.7       1000.0   1751.869   38618.071    926.834    6947.1    .02132
156.        6710.5       1000.0   1721.261   38670.398    928.090    6942.2    .02135


157.        6710.3       1000.0   1691.172   38721.809    929.323    6937.5    .02137
158.        6710.2       1000.0   1661.592   38772.322    930.536    6932.9    .02140
159.        6710.0       1000.0   1632.515   38821.950    931.727    6928.3    .02143
160.        6709.8       1000.0   1603.931   38870.710    932.897    6923.8    .02146
161.        6709.7       1000.0   1575.834   38918.615    934.047    6919.4    .02148
162.        6709.5       1000.0   1548.215   38965.681    935.176    6915.1    .02151


163.        6709.4       1000.0   1521.066   39011.921    936.286    6910.8    .02154
164.        6709.3       1000.0   1494.381   39057.350    937.376    6906.6    .02156
165.        6709.1       1000.0   1468.151   39101.982    938.448    6902.5    .02158
166.        6709.0       1000.0   1442.369   39145.830    939.500    6898.5    .02161
167.        6708.9       1000.0   1417.028   39188.908    940.534    6894.5    .02163
168.        6708.7       1000.0   1392.121   39231.228    941.549    6890.7    .02166


169.        6708.6       1000.0   1367.640   39272.804    942.547    6886.8    .02168
170.        6708.5       1000.0   1343.580   39313.649    943.528    6883.1    .02170
171.        6708.4       1000.0   1319.932   39353.775    944.491    6879.4    .02172
172.        6708.3       1000.0   1296.690   39393.195    945.437    6875.7    .02175
173.        6708.2       1000.0   1273.848   39431.920    946.366    6872.2    .02177
174.        6708.1       1000.0   1251.398   39469.962    947.279    6868.7    .02179


175.        6708.0       1000.0   1229.336   39507.334    948.176    6865.2    .02181
176.        6707.9       1000.0   1207.653   39544.047    949.057    6861.9    .02183
177.        6707.8       1000.0   1186.344   39580.111    949.923    6858.6    .02185
178.        6707.7       1000.0   1165.403   39615.540    950.773    6855.3    .02187
179.        6707.6       1000.0   1144.824   39650.342    951.608    6852.1    .02189
180.        6707.5       1000.0   1124.600   39684.530    952.429    6848.9    .02191


181.        6707.4       1000.0   1104.726   39718.114    953.235    6845.9    .02192
182.        6707.4       1000.0   1085.196   39751.104    954.026    6842.8    .02194
183.        6707.3       1000.0   1066.004   39783.510    954.804    6839.8    .02196
184.        6707.2       1000.0   1047.144   39815.343    955.568    6836.9    .02198
185.        6707.1       1000.0   1028.612   39846.613    956.319    6834.0    .02200
186.        6707.1       1000.0   1010.401   39877.329    957.056    6831.2    .02201


187.        6707.0       1000.0    992.507   39907.502    957.780    6828.4    .02203
188.        6706.9       1000.0    974.923   39937.139    958.491    6825.7    .02205
189.        6706.9       1000.0    957.645   39966.252    959.190    6823.0    .02206
```

```
190.     6706.8     1000.0     940.668     39994.848     959.876     6820.4     .02208
191.     6706.8     1000.0     923.986     40022.937     960.550     6817.8     .02209
192.     6706.7     1000.0     907.595     40050.528     961.213     6815.3     .02211

193.     6706.7     1000.0     891.490     40077.629     961.863     6812.8     .02212
194.     6706.6     1000.0     875.665     40104.250     962.502     6810.3     .02214
195.     6706.6     1000.0     860.117     40130.397     963.130     6807.9     .02215
196.     6706.5     1000.0     844.840     40156.080     963.746     6805.6     .02217
197.     6706.5     1000.0     829.830     40181.307     964.351     6803.2     .02218
198.     6706.4     1000.0     815.082     40206.086     964.946     6801.0     .02219

199.     6706.4     1000.0     800.593     40230.424     965.530     6798.7     .02221
200.     6706.3     1000.0     786.356     40254.329     966.104     6796.5     .02222
201.     6706.3     1000.0     772.369     40277.809     966.667     6794.4     .02223
202.     6706.2     1000.0     758.627     40300.871     967.221     6792.2     .02225
203.     6706.2     1000.0     745.126     40323.523     967.765     6790.2     .02226
204.     6706.2     1000.0     731.862     40345.772     968.299     6788.1     .02227

205.     6706.1     1000.0     718.830     40367.624     968.823     6786.1     .02228
206.     6706.1     1000.0     706.027     40389.087     969.338     6784.1     .02230
207.     6706.0     1000.0     693.449     40410.168     969.844     6782.2     .02231
208.     6706.0     1000.0     681.092     40430.873     970.341     6780.3     .02232
209.     6706.0     1000.0     668.952     40451.210     970.829     6778.4     .02233
210.     6705.9     1000.0     657.025     40471.183     971.308     6776.6     .02234

211.     6705.9     1000.0     645.309     40490.800     971.779     6774.8     .02235
212.     6705.9     1000.0     633.798     40510.068     972.242     6773.0     .02236
213.     6705.9     1000.0     622.490     40528.992     972.696     6771.3     .02237
214.     6705.8     1000.0     611.382     40547.578     973.142     6769.5     .02238
215.     6705.8     1000.0     600.469     40565.832     973.580     6767.9     .02239
216.     6705.8     1000.0     589.748     40583.760     974.010     6766.2     .02240

217.     6705.8     1000.0     579.217     40601.368     974.433     6764.6     .02241
218.     6705.7     1000.0     568.871     40618.662     974.848     6763.0     .02242
219.     6705.7     1000.0     558.708     40635.647     975.256     6761.4     .02243
220.     6705.7     1000.0     548.725     40652.328     975.656     6759.9     .02244
221.     6705.7     1000.0     538.918     40668.711     976.049     6758.4     .02245
222.     6705.6     1000.0     529.284     40684.801     976.435     6756.9     .02246

223.     6705.6     1000.0     519.821     40700.604     976.814     6755.5     .02247
224.     6705.6     1000.0     510.524     40716.124     977.187     6754.0     .02248
225.     6705.6     1000.0     501.393     40731.366     977.553     6752.6     .02248
226.     6705.6     1000.0     492.423     40746.336     977.912     6751.3     .02249
227.     6705.5     1000.0     483.611     40761.038     978.265     6749.9     .02250
228.     6705.5     1000.0     474.956     40775.476     978.611     6748.6     .02251

229.     6705.5     1000.0     466.454     40789.657     978.952     6747.3     .02252
230.     6705.5     1000.0     458.103     40803.583     979.286     6746.0     .02252
231.     6705.5     1000.0     449.900     40817.260     979.614     6744.7     .02253
232.     6705.5     1000.0     441.843     40830.692     979.937     6743.5     .02254
233.     6705.4     1000.0     433.928     40843.883     980.253     6742.3     .02255
234.     6705.4     1000.0     426.154     40856.838     980.564     6741.1     .02255

235.     6705.4     1000.0     418.517     40869.561     980.869     6739.9     .02256
236.     6705.4     1000.0     411.017     40882.056     981.169     6738.8     .02257
237.     6705.4     1000.0     403.649     40894.327     981.464     6737.6     .02257
238.     6705.4     1000.0     396.413     40906.378     981.753     6736.5     .02258
239.     6705.4     1000.0     389.305     40918.213     982.037     6735.4     .02259
240.     6705.4     1000.0     382.323     40929.836     982.316     6734.4     .02259
```

APPENDIX G

SITE SPECIFIC
RESERVOIR COMPACTION AND SURFACE SUBSIDENCE CALCULATIONS

TABLE G-1

SOUTHEAST PECAN ISLAND PROSPECT

RESERVOIR COMPACTION CALCULATIONS

Production life = 20 years = 6.307×10^8 seconds

SANDSTONE				SHALE BEDS				
							Compaction (ft)	
H (ft)	Δp (psi)	C_m (psi^{-1})	Compaction (ft)	H (ft)	Δp (psi)	U%	$C_m = 3\times10^{-6}$ psi^{-1}	$C_m = 3\times10^{-5}$ psi^{-1}
500	3610	6×10^{-7}	1.083	10	3610	78.7	0.085	0.852
				10	3610	78.7	0.085	0.852
				5	3610	99.6	0.054	0.539
				10	3610	78.7	0.085	0.852
				10	3610	78.7	0.085	0.852
				20	3610	41.6	0.090	0.901
				10	3610	78.7	0.085	0.852
				160	3610	5.20	0.090	0.901
				5	3610	99.6	0.054	0.539
				10	3610	78.7	0.085	0.852
				10	3610	78.7	0.085	0.852
				10	3610	78.7	0.085	0.852
				150 (boundary bed)	3610	2.77	0.045	0.450
				330 (boundary bed)	3610	1.26	0.045	0.450
							1.058 (Total)	10.596 (Total)

Compaction due to sandstone and less compressible shale:

1.083 ft + 1.058 ft = 2.141 ft.

Compaction due to sandstone and more compressible shale:

1.083 ft + 10.596 ft = 11.679 ft.

TABLE G-2

SOUTHEAST PECAN ISLAND PROSPECT
SURFACE SUBSIDENCE CALCULATIONS

Compaction estimate based on less compressible shale = 2.141 ft.

Compaction estimate based on more compressible shale = 11.679 ft.

Area of reservoir = 12,800 acres = $20\ \text{mi}^2$.

Depth of reservoir = 14,000 ft = 2.65 mi.

Reservoir was modeled as one disc.

Radius of disc = 2.52 mi $\cong$ 2.5 mi = R.

Using Geertsma's model:

$$\frac{\text{Subsidence}}{\text{Compaction}} = {}^{-}2\,(1-v)\,A = {}^{-}1.28A$$

where v = Poisson's ratio = 0.36 (Gruy Federal, personal communication, 1980).

A is found from Geertsma's chart of Hankel-Lipschitz integrals (Appendix E, Table E-1).

$$\eta\,(\text{on the integral chart}) = \frac{\text{depth}}{\text{radius}} = \frac{2.65\ \text{mi}}{2.52\ \text{mi}} = 1.05.$$

TABLE G-2 (Continued)

			SUBSIDENCE	
Distance from center of disc (mi)	$\rho = \frac{r}{R}$	$\frac{\text{Sub.}}{\text{Comp.}}$ (%)	Less compressible shale (ft)	More compressible shale (ft)
Center of disc	0	35.6	0.762	4.16
0.50	0.2	34.9	0.747	4.08
1.0	0.4	33.0	0.707	3.85
1.5	0.6	30.1	0.644	3.52
2.0	0.8	26.2	0.561	3.06
2.5	1.0	22.0	0.471	2.57
3.0	1.2	17.8	0.381	2.08
3.5	1.4	14.1	0.302	1.65
4.0	1.6	11.0	0.236	1.28
4.5	1.8	8.6	0.18	1.0
5.0	2.0	6.7	0.14	0.78
7.6	3.0	2.3	0.049	0.27

Note: r = distance from center of disc.

Maximum surface subsidence is estimated as:

based on less compressible shale, 0.8 ft.

based on more compressible shale, 4 ft.

TABLE G-3

AUSTIN BAYOU PROSPECT

RESERVOIR COMPACTION CALCULATIONS

Production life = 66 months = 5.5 years = 1.734×10^8 seconds

SANDSTONE				SHALE BEDS				
H (ft)	Δp (psi)	C_m (psi^{-1})	Compaction (ft)	H (ft)	Δp (psi)	U%	Compaction (ft) $C_m = 3 \times 10^{-6}$ psi^{-1}	$C_m = 3 \times 10^{-5} psi^{-1}$
45	2768	6×10^{-7}	0.075	10	2768	43.6	0.036	0.362
				5	2768	81.4	0.034	0.338
				90 (boundary bed)	2768	2.42	0.018	0.181
				35 (boundary bed)	2768	6.23	0.018	0.181
							0.106 (Total)	1.062 (Total)

Compaction due to sandstone and less compressible shale:

0.075 ft + 0.106 ft = 0.181 ft.

Compaction due to sandstone and more compressible shale:

0.075 ft + 1.062 ft = 1.137 ft.

TABLE G-4

AUSTIN BAYOU PROSPECT

SURFACE SUBSIDENCE CALCULATIONS

Compaction estimate based on less compressible shale = 0.181 ft.

Compaction estimate based on more compressible shale = 1.137 ft.

Area of reservoir = 11,520 acres = 18 mi ^{2}.

Depth to reservoir = 14,800 ft = 2.80 mi.

Reservoir was modeled as one disc.

Radius = 2.39 mi = R.

Using Geertsma's model:

$$\frac{\text{Subsidence}}{\text{Compaction}} = -2\,(1-v)\,A = -1.28A$$

where v = Poisson's ratio = 0.36 (Gruy Federal, personal communication, 1980).

A is found from Geertsma's chart of Hankel-Lipschitz integrals (Appendix E, Table E-1).

$$\eta \text{ (on the integral chart)} = \frac{\text{depth}}{\text{radius}} = \frac{2.80\text{ mi}}{2.39\text{ mi}} = 1.17 \approx 1.2.$$

TABLE G-4 (Continued)

Distance from center of disc (mi)	$\rho = \frac{r}{R}$	$\frac{\text{Sub.}}{\text{Comp.}}$ (%)	SUBSIDENCE Less compressible shale (ft)	 More compressible shale (ft)
Center of disc	0	29.7	0.054	0.34
0.48	0.2	29.2	0.053	0.33
0.96	0.4	27.8	0.050	0.32
1.4	0.6	25.5	0.046	0.29
1.9	0.8	22.5	0.041	0.26
2.4	1.0	19.3	0.035	0.22
2.9	1.2	16.1	0.029	0.18
3.3	1.4	13.1	0.024	0.15
3.8	1.6	10.5	0.019	0.12
4.3	1.8	8.4	0.015	0.10
4.8	2.0	6.8	0.012	0.077
7.2	3.0	2.4	0.0043	0.027

Note: r = distance from center of disc.

Maximum surface subsidence is estimated as:

based on less compressible shale, 0.05 ft.

based on more compressible shale, 0.3 ft.

TABLE G-5

GLADYS McCALL PROSPECT

RESERVOIR COMPACTION CALCULATIONS

Production life = 20 years = 6.307×10^8 seconds

SANDSTONE				SHALE BEDS				
							Compaction (ft)	
H (ft)	Δp (psi)	C_m (psi^{-1})	Compaction (ft)	H (ft)	Δp (psi)	U%	$C_m=3\times10^{-6}$ psi^{-1}	$C_m=3\times10^{-5} psi^{-1}$
500	4581	6×10^{-7}	1.374	20	4581	41.6	0.114	1.143
				10	4581	78.7	0.108	1.082
				5	4581	99.6	0.068	0.684
				100 (boundary bed)	4581	4.2	0.058	0.577
				100 (boundary bed)	4581	4.2	0.058	0.577
							0.406 (Total)	4.063 (Total)

Compaction due to sandstone and less compressible shale:

1.374 ft + 0.406 ft = 1.780 ft.

Compaction due to sandstone and more compressible shale:

1.374 ft + 4.063 ft = 5.437 ft.

TABLE G-6

GLADYS McCALL PROSPECT

SURFACE SUBSIDENCE CALCULATIONS

Compaction estimate based on less compressible shale = 1.780 ft.

Compaction estimate based on more compressible shale = 5.437 ft.

Area of reservoir = 10,240 acres = 16 mi^2.

Depth to reservoir = 15,000 ft = 2.84 mi.

Reservoir was modeled as two discs.

Radius of each disc = 1.6 mi = R.

Using Geertsma's model:

$$\frac{\text{Subsidence}}{\text{Compaction}} = -2\,(1-v)\,A = -1.28A$$

where v = Poisson's ratio = 0.36 (Gruy Federal, personal communication, 1980).

A is found from Geertsma's chart of Hankel-Lipschitz integrals (Appendix E, Table E-1).

$$\eta \text{ (on the integral chart)} = \frac{\text{depth}}{\text{radius}} = \frac{2.8 \text{ mi}}{1.6 \text{ mi}} = 1.8.$$

TABLE G-6 (Continued)

Distance from center of disc (mi)	$\rho = \frac{r}{R}$	$\frac{\text{Sub.}}{\text{Comp.}}$ (%)	SUBSIDENCE Less compressible shale (ft)	SUBSIDENCE More compressible shale (ft)
Center of disc	0	16.1	0.287	0.875
0.3	0.2	15.9	0.283	0.864
0.6	0.4	15.4	0.274	0.837
1.0	0.6	14.6	0.260	0.794
1.3	0.8	13.4	0.239	0.729
1.6	1.0	12.2	0.217	0.663
1.9	1.2	10.9	0.194	0.593
2.2	1.4	9.5	0.17	0.52
2.6	1.6	8.3	0.15	0.45
2.9	1.8	7.2	0.13	0.39
3.2	2.0	6.1	0.11	0.33
4.8	3.0	2.8	0.050	0.15

Note: r = distance from center of disc.

Using superposition of discs, maximum surface subsidence is estimated as:

based on less compressible shale, 0.4 ft.

based on more compressible shale, 1 ft.

TABLE G-7

CUERO PROSPECT

RESERVOIR COMPACTION CALCULATIONS

Production Life = 20 years = 6.307×10^8 seconds

SANDSTONE				SHALE BEDS				
H (ft)	Δp (psi)	C_m (psi^{-1})	Compaction (ft)	H (ft)	Δp (psi)	U%	Compaction (ft)	
							$C_m=3\times10^{-6}$ psi^{-1}	$C_m=3\times10^{-5}$ psi^{-1}
200	3766	6×10^{-7}	0.452	5	3766	99.6	0.056	0.563
				5	3766	99.6	0.056	0.563
				30	3766	27.7	0.094	0.939
				5	3766	99.6	0.056	0.563
				5	3766	99.6	0.056	0.563
				5	3766	99.6	0.056	0.563
				10	3766	78.8	0.089	0.890
				15	3766	55.3	0.094	0.937
				10	3766	78.8	0.089	0.890
				170 (boundary bed)	3766	2.45	0.047	0.471
				40 (boundary bed)	3766	10.4	0.047	0.471
							0.740 (Total)	7.413 (Total)

Compaction due to sandstone and less compressible shale:

0.452 ft + 0.740 ft = 1.192 ft.

Compaction due to sandstone and more compressible shale:

0.452 ft + 7.413 ft = 7.865 ft.

TABLE G-8

CUERO PROSPECT

SURFACE SUBSIDENCE CALCULATIONS

Compaction estimate based on less compressible shale = 1.192ft.

Compaction estimate based on more compressible shale = 7.865 ft.

Area of reservoir = 7296 acres = 11.4 mi^2.

Depth to reservoir = 12,625 ft = 2.39 mi.

Reservoir was modeled as three discs.

Radius of each disc = 1.10 mi = R.

Using Geertsma's model:

$$\frac{\text{Subsidence}}{\text{Compaction}} = {}^{-}2\,(1-v)\,A = {}^{-}1.30A$$

where v = Poisson's ratio = 0.35 (Gruy Federal, personal communication, 1980).

A is found from Geertsma's chart of Hankel-Lipschitz integrals (Appendix E, Table E-1).

$$\eta \text{ (on the integral chart)} = \frac{\text{depth}}{\text{radius}} = \frac{2.39 \text{ mi}}{1.10 \text{ mi}} \cong 2.2.$$

TABLE G-8 (Continued)

Distance from center of disc (mi)	$\rho = \frac{r}{R}$	$\frac{\text{Sub.}}{\text{Comp.}}$ (%)	SUBSIDENCE Less compressible shale (ft)	SUBSIDENCE More compressible shale (ft)
Center of disc	0	12.4	0.148	0.975
0.2	0.2	12.2	0.145	0.960
0.4	0.4	11.8	0.141	0.928
0.7	0.6	11.3	0.135	0.889
0.9	0.8	10.7	0.128	0.842
1.1	1.0	9.8	0.12	0.77
1.3	1.2	8.8	0.10	0.69
1.5	1.4	7.9	0.094	0.62
1.8	1.6	7.2	0.086	0.57
2.0	1.8	6.2	0.074	0.49
2.2	2.0	5.5	0.066	0.43
3.3	3.0	2.9	0.035	0.23

Note: r = distance from center of disc.

Using superposition of discs, maximum surface subsidence is estimated as:

based on less compressible shale, 0.3 ft.

based on more compressible shale, 2 ft.

APPENDIX H

RANGE OF POSSIBLE SUBSIDENCE IMPACTS

The following, taken directly from Viets and others (1979, pp. II-4 through II-18), is a summary of impacts caused by subsidence and related ground movements. This summary is not restricted to subsidence caused by the extraction of geothermal fluids, and so all impacts discussed will not necessarily be applicable to the Gulf Coast geopressured geothermal study. However, the summary does provide background for Section 6 of this report.

The ground movements discussed are vertical subsidence (called "vertical settlements" by Viets), tilt, horizontal movement and strain, fissuring, and subsurface deformation.

H.1 Vertical Subsidence

Uniform vertical settlements [subsidence] alone are not usually responsible for damage. Structures are generally not subject to damage from the vertical component of subsidence since a structure resting on the land surface subjected to uniform vertical settlement would maintain its locational relationship to the sinking surface.

However, when vertical settlements occur adjacent to a water body such as a river, lake, or the ocean, the increased risk of flooding in the subsidence bowl can be a serious problem. Permanent inundation of some lands and increased exposure to flooding have resulted from subsidence in Houston-Galveston; Long Beach; Santa Clara Valley; Venice, Italy; Lake Maracaibo, Venezuela; and in several Japanese coastal cities. In these areas the problems of land settlement in relationship to the water bodies far exceed in severity the problems related to other subsidence phenomena. Defense against permanent inundation and hazard of recurrent floods has required major capital investments to construct dikes, levees, pumping stations, and other facilities.

In addition to increasing flooding potential, vertical settlement can cause difficulties with hydraulic systems such as canals, sewers, and streams which depend on gravity flow and can cause changes in the groundwater levels relative to the ground surface. Changes in hydraulic systems are discussed in the following section which deals with tilting. In shallow groundwater areas, subsidence of the surface can result in apparent rising groundwater levels which disrupt plant growth, interfere with subsurface drainage, and eventually cause surface ponding and disruptions in land use as illustrated in Figure II-2 [EDAW-ESA Figure H-1]... In some cases, permanent drains and wells with pumping stations may be necessary to avoid adverse effects. In shallow groundwater areas where water tables are perched on subsurface horizontal beds which restrict downward movement of water, a decline in groundwater levels may result if subsidence-induced fissures rupture the water-retarding beds.

H.2 Tilt

Tilting must be considered in two ways when evaluating damage-causing potentials, rigid-body tilting and differential settlement, depending on the type of structures involved.

Rigid-Body Tilting

Tilting of the ground surface may adversely affect tall structures such as tall buildings, silos, smokestacks, and communication towers. The term tilting, as used in this context, refers to uniform or rigid-body tilting without bending deformations within the structure. Adverse effects from rigid-body tilting may include disruption of sensitive machinery, misalignment of elevators in tall buildings, and misalignment of microwave communication beams. Tilts as small as 0.0002 have been reported to affect sensitive machinery but tilts in the range of 0.003-0.005 may be generally acceptable for tall buildings. . .

Tilting over considerable horizontal distances can change surface drainage patterns in relatively flat land and can cause changes in river hydrology through alteration of stream gradients which in turn alter natural erosion-sedimentation processes and flood-carrying capacities. Formation of marshes and ponds may result from disruption of natural surface drainage. Tilting which increases stream gradients will tend to encourage erosion and increase flood-carrying capacities, while tilting which decreases stream gradients will have the opposite effects.

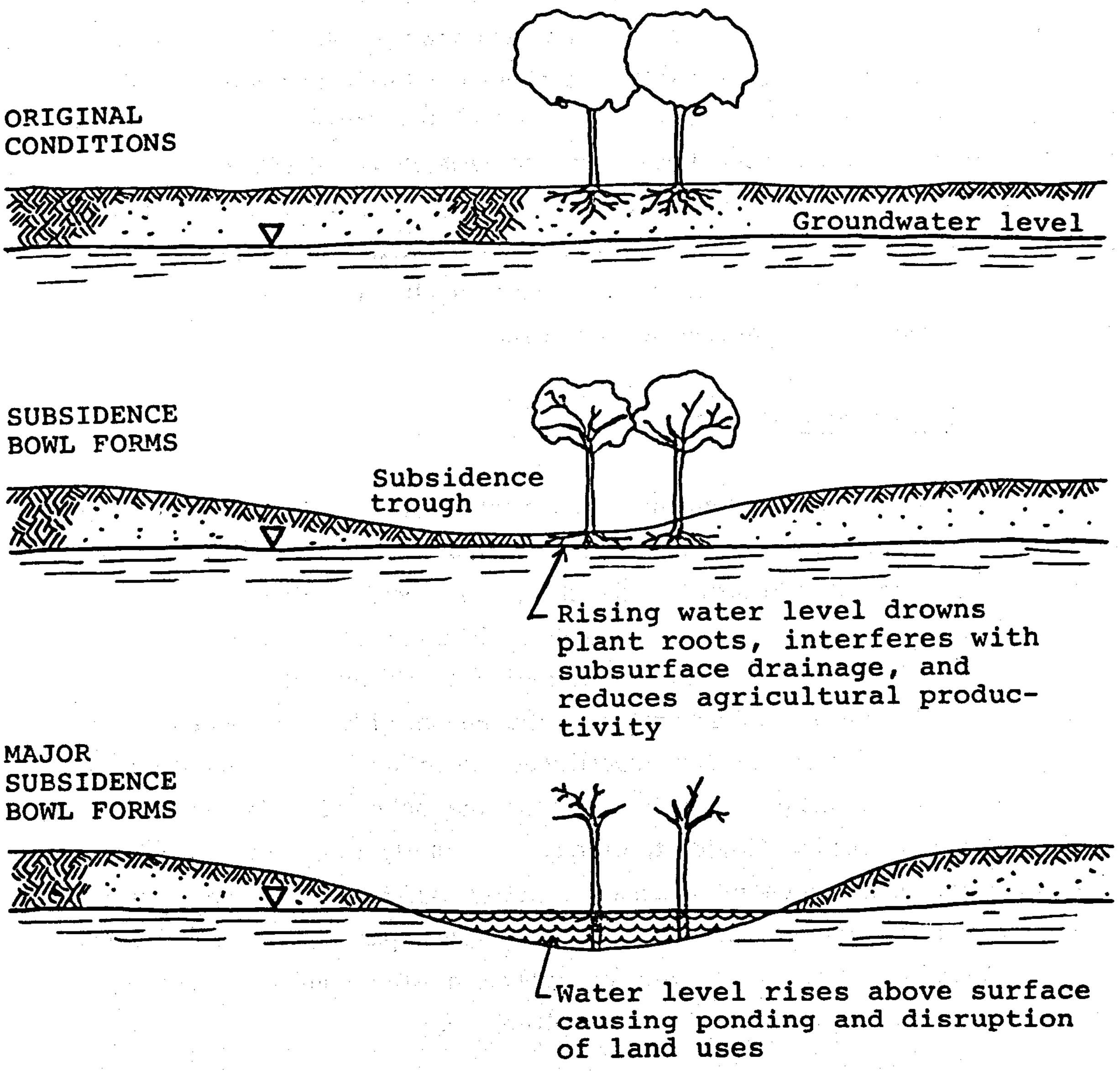


FIGURE H-1. EFFECTS OF SUBSIDENCE IN SHALLOW GROUNDWATER AREAS (from Viets and others, 1979)

Similarly, tilting can increase or decrease capacities of man-made hydraulic structures such as canals, agricultural drains and sewage collection systems and may require releveling of agricultural fields where flood irrigation is used. Tilting may also reduce the effective height of flood control levees and canal banks requiring costly reconstruction. Because of the variability in design factors, it is impossible to accurately generalize as to the amount of slope change that is critical to hydraulic facilities. Canals with slopes of as little as 0.00004 (2.5 inches per mile) have been constructed so even very small amounts of tilting over appreciable distances can have significant effects.

Differential Settlement

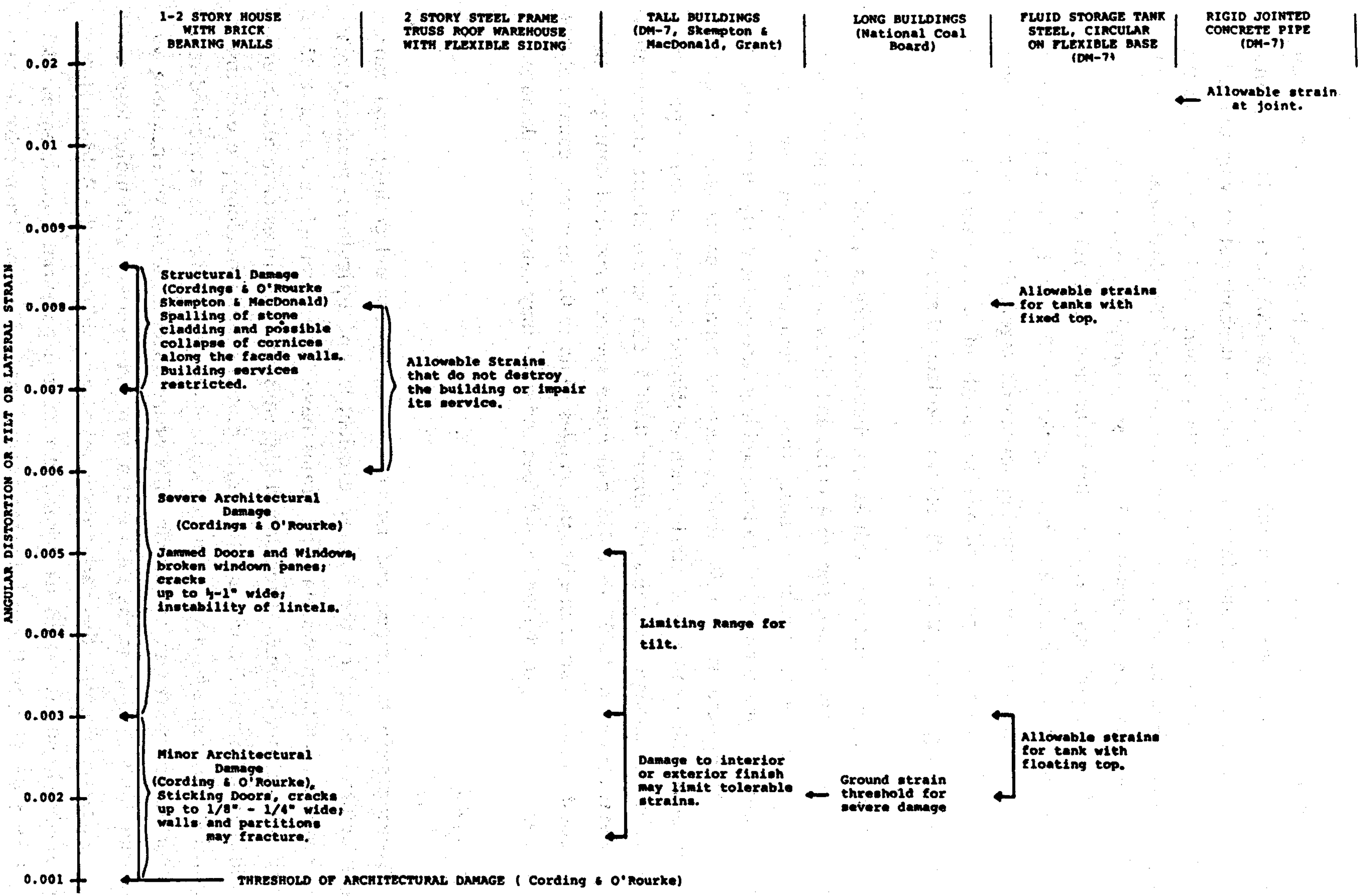
Differential vertical settlement is the most common and one of the most potentially damaging of the subsidence phenomena. Normally, the differential settlement is represented in terms of the change in elevation between two points by the ratio of Δ/L, where Δ is the amount of differential settlement occurring over a distance L. This is the same definition as tilting but, as used here, differential settlement of a building refers to the amount of "angular distortion" or non-rigid-body tilt that the building experiences. In an idealized subsidence bowl, the greatest angular distortion also occurs at the point of inflection of the subsidence bowl's profile. Rigid structures, particularly those which occupy a relatively small surface area will experience mostly rigid-body tilting and little or no differential settlement. More flexible structures, particularly those which occupy a relatively large area, will experience mostly angular distortion or differential settlement and little rigid-body tilting. . .

The results of a literature review to establish the range of angular distortion required to cause various levels of damage to different types of structures are shown on Table II-6 [EDAW-ESA Table H-1].

H.3 Horizontal Movement and Strain

It has been observed that horizontal strains induced in structures are sometimes less than the ground strains. In assessing the damage-causing potential of horizontal strains, it is therefore important to distinguish between ground strain and the strain transmitted to the structure. . .

Table H-1. The Effect of Subsidence Related Ground Surface Strains on Engineering Structures



1-2 STORY HOUSE WITH BRICK BEARING WALLS

Structural Damage (Cordings & O'Rourke Skempton & MacDonald) Spalling of stone cladding and possible collapse of cornices along the facade walls. Building services restricted.

Severe Architectural Damage (Cordings & O'Rourke)

Jammed Doors and Windows, broken windown panes; cracks up to ½-1" wide; instability of lintels.

Minor Architectural Damage (Cording & O'Rourke), Sticking Doors, cracks up to 1/8" - 1/4" wide; walls and partitions may fracture.

THRESHOLD OF ARCHITECTURAL DAMAGE (Cording & O'Rourke)

2 STORY STEEL FRAME TRUSS ROOF WAREHOUSE WITH FLEXIBLE SIDING

Allowable Strains that do not destroy the building or impair its service.

TALL BUILDINGS (DM-7, Skempton & MacDonald, Grant)

Limiting Range for tilt.

Damage to interior or exterior finish may limit tolerable strains.

LONG BUILDINGS (National Coal Board)

Ground strain threshold for severe damage

FLUID STORAGE TANK STEEL, CIRCULAR ON FLEXIBLE BASE (DM-7)

Allowable strains for tanks with fixed top.

Allowable strains for tank with floating top.

RIGID JOINTED CONCRETE PIPE (DM-7)

Allowable strain at joint.

(from Viets and others, 1979)

The results of a literature review to establish the levels of horizontal strain that may cause damage are shown on Table II-6 [EDAW-ESA Table H-1]. The total amount of strain that will accumulate in a structure depends not only on the level of strain in the underlying ground surface and the portion that is transferred to the building, but also depends on the length of the building. For instance, a short 20-foot building may be able to absorb 0.2 feet of movement from a compressional strain of 0.001 by distributing it over the structure. But for a 200-foot long structure subjected to the same strain level, the 0.2 foot shortening might concentrate at some weak point, causing severe damage. For this reason, some investigators feel that the total change in length of a structure is a better indication of damage potential than the level of horizontal strain.

Long, fairly rigid structures such as warehouses, bridges, pipelines, concrete highways, airport runways, and concrete curbs and sidewalks are most sensitive to damage from horizontal strain because they accumulate strains over long distances. Service pipe connections to long buildings are particularly susceptible to damage. Long structures with flexibility, such as asphalt pavements, or with numerous joints which can absorb strain, such as jointed concrete or clay pipe, are less sensitive to damage. Strains of about 0.0005 can cause slight structural damage while strains of 0.003 to 0.006 can cause severe structural damage. In terms of total change in structure length, changes of up to 0.2 feet may cause only slight damage while length changes of 0.4 feet and more may cause severe damage.

H.4 Fissuring

Fissuring disrupts surface and subsurface water flow and drainage and can damage facilities located on the fissure. Erosion, loss of agricultural productivity and damage to irrigation systems and drains have been reported as a result of fissuring in agricultural areas. Cracking of highways and structures have also been reported from both new fissures and from differential movement along pre-existing faults within subsidence bowls. The most serious damage that may be attributed to ground surface cracking was at Baldwin Hills where differential movement along a pre-existing fault resulted in the failure of a dam and reservoir with major loss of life and property. Clearly, this catastrophic event was unique to the Baldwin Hills subsidence bowl, but it serves as a reminder of the potential consequences of unanticipated or uncontrolled subsidence phenomena. Fissuring from subsidence has been suggested as the cause of failure of an embankment of Picacho Reservoir in Arizona. In that case, the desert soils have a very low resistance to piping so water-retaining structures can be easily undermined and eroded if fissuring occurs to initiate piping.

H.5 Subsurface Deformation

The vertical compression and horizontal and vertical shearing of strata at depth can result in serious damage to wells which pass through the zone of deformation. Vertical subsurface deformation can cause wells and well casings to be compressed and rupture or, if there is not much friction between the well casing and the rock material, subsurface deformation can cause wells to protrude from the ground as the ground surface sinks away from the well head. This mechanism is associated principally with groundwater production and has caused damage to wells and well casings in Arizona, the Houston-Galveston region, Las Vegas Valley, Mexico City and in the San Joaquin and Santa Clara Valleys to name some of the most significant experiences. . .

Some damaged wells have been abandoned; others have been repaired at depth; still others that have protruded from the ground have been cut off and the pump replaced at the new ground surface level. New wells in known subsidence areas may be installed with a sleeved casing to compensate for vertical compression along the axis of the casing.

The only notable report of damage from horizontal displacement at depth comes from the Wilmington Oil Field at Long Beach where numerous oil wells were sheared off at depth due to horizontal strains and their relief along pre-existing fault planes.

APPENDICES REFERENCES

Cording, E. J., and O'Rourke, T. D., Excavation, ground movements and their influence on buildings: Urbana, Illinois, Unversity of Illinois, unpublished, in Viets, V. F., Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

Earlougher, R. C., Jr., 1977, Advances in well test analysis: SPE Monograph, vol 5.

Geertsma, J., 1973, Land subsidence above compacting oil and gas reservoirs: Jour. of Pet. Tech., vol. 25, p. 734-744.

Grant, R. J., Christian, T., and Vanmarcke, E. H., 1974, Differential settlement of buildings: Jour. of Geotechnical Division, ASCE, vol. 100, no. GT9, p. 973-991, in Viets, V. F. , Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

National Coal Board Mining Department, 1975, Subsidence engineer's handbook, London, in Viets, V. F., Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

Skempton, A. W., and MacDonald, D. H., 1956, The allowable settlement of buildings: Procedures Institute of Civil Engineers, vol. 5, part 3, p. 727-784, in Viets, V. F., Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

Sowers, G. F., 1979, Soil mechanics and foundations: geotechnical engineering (4th ed.): New York MacMillan Publishing Co., Inc., 621 p.

Terzaghi, Karl, 1943, Theoretical soil mechanics: New York John Wiley and Sons, Inc., 510 p.

U. S. Department of the Navy Bureau of Yards and Docks, 1972, Soil mechanics, foundations and earth structures: NAVDOCKS Design Manual, DM-7, in Viets, V. F., Vaughan, C. K., and Harding, R. C., 1979, Environmental and economic effects of subsidence: Geothermal Subsidence Research Management Program, Berkeley, Lawrence Berkeley Laboratory, Earth Sciences Division, GSRMP-1, LBL-8615, 120 p.

U.S.GPO:1981/789-009/5713