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Final Report
October 10, 1983 to September 31, 1984

Environmental Impact of Geopressure - Geothermal Cogeneration Facility on Wetland Resources and Socioeconomic Characteristics in Louisiana Gulf Coast Region

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DISCLAIMER

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SUMMARY

AUGUST 9, 1984

Environmental Assessment of Geopressured - Geothermal Site Operations in Southwestern Louisiana

The major objective of this research is the establishment of an environmental assessment of the cogeneration facilities installed in the Gladys McCall and Hulan sites located on or near the Southwestern Coast of Louisiana. Our initial intentions included the assessment of air quality changes as a result of gaseous emission and cooling towers' drifts, determination of the effects of disposal of cooling water and brine injection on the quality of both ground and surface waters, changes in the regional lakes' productivities as a result of the waste disposal from the cogeneration facility, assessment of the possible implications of an accidental failure or continuous spill-out, and monitoring the change in the brine composition with time. The operation of a pilot plant for direction filtration of brine is also a long-range goal of this study.

In a preliminary report prepared by the Institute for Environmental Studies of Louisiana State University, assessment of selected geopressured-geothermal prospect areas of the Louisiana Gulf Coast region was made on the basis of the nature and extent of the proposed testing activities and environmental characteristics of each prospect area. Data from existing sources provided information concerning levels of dissolved solids, water salinity, geology and geohydrology. This investigation extends the environmental assessment to such factors as the identification and quantification of

the chemical products of the geopressured-geothermal operation and their impacts on the area environment.

Since initiation of this study during the fall of 1983, the initial baseline data have been studied and summarized, and experiments designed or studied to attain the goals stated in this summary. Besides the previously stated objectives, our planned studies have been extended to include an investigation of the effect of the cogeneration operation on the biota of the area.

The most recent report of results of a ten-month study by the U.S. Army Corps of Engineers indicates the existence of pollution of ground water supplies in the coastal areas of Louisiana due to saltwater intrusion from the Gulf of Mexico. Our future studies of environmental effects of the cogeneration operation must also take this factor into consideration.

Brief summaries of assessments of the areas stated in the initial objectives of this investigation are listed in the following sections.

BASE LINE DATA RELEVANT TO:

DOE GLADYS McCALL NO. I

CAMERON PARISH, LOUISIANA

AIR QUALITY

M. M. Fontenot
January, 1984

Base Line Data Releuant
To Air Quality
Summary

Gladys McCall

The Rockefeller Refuge geothermal prospect area is in the Chenier plain of Southwest Louisiana, a physiographic region characterized by relict beach ridges and low-lying coastal marsh. The DOE Gladys McCall well was drilled near the Western border of Rockefeller Refuge in an area of impounded brackish marsh. The well is located in the East Crab Lake field approximately 2.3 miles south of Grand Chenier Ridge. Figure 1-1. The DOE Gladys McCall well site lie within the southern Louisiana-Southeast Texas Air Quality Control Region, AQCR 106. The region is presently a non-attainment area with respect to ozone. Ambient air quality standards for the other criteria pollutants are achieved (Louisiana Air Control Commission).

The region contains three distinct areas of heavy industrial concentration: Beaumont-Port Arthur in Southeastern Texas, Lake Charles in Southwestern Louisiana and the Mississippi River area between Baton Rouge and New Orleans. Land use in the immediate vicinity of the well site is extractive; surface hydrology of the area has been modified by levees and canals excavated for oil and gas development.

Two reports containing air quality data relevant to the Gladys McCall Geothermal test site were found during this phase I base line data search. The reports were: 1) "A Preliminary Environmental Assessment of Selected Geopressured-Geothermal Prospect Areas" (1978), and 2) "Environmental Assessment-Geothermal Energy Geopressure Subprogram (1981). The reports indicated that no air quality measurements have been collected on the well test site. However, the well test site is located on the same flat coastal plain as the nearby Lake Charles. Therefore, the air quality were approximated from observations made in the Lake Charles area. Except for ozone and nonmethane hydrocarbons, other pollutants as listed and regulated by Federal and state agencies were within the primary standards. The Climatological Dispersion Model-CDM (EPA, 1973) predicted a SO_x concentration of zero everywhere within the Rockefeller Refuge Area. Additional predictions on the air quality due to drilling, maintenance, flow testing, operation, blowouts, etc. are also included in the reports.

A Preliminary Environmental Assessment

of Selected Geopressured-Geothermal Prospect Areas:

Louisiana Gulf Coast Region

Volume II

Environmental Baseline Data

Institute For Environmental Studies

Louisiana State University

Baton Rouge, Louisiana

Prepared for

U. S. Department of Energy

Division of Geothermal Energy

Contact No. ET-78-S-05-5862

October 15, 1978

AIR QUALITY

Measured Ambient Air Quality

The Louisiana Air Control Commission (LACC) sampling station nearest to the Rockefeller Refuge prospect area is located at Lake Charles, approximately 77 km (48mi) northwest of the prospect area. 1976 annual average pollutant concentrations measured at the Lake Charles station are shown in Table 1

Table 1 1976 Ambient air quality data: Lake Charles health unit station. (From LACC, 1976).

	Sulfur Dioxide (μg/m³)	Ozone (μg/m³)	Nitrogen Dioxide (μg/m³)	particulat (μg/m³)
Annual average*	1.5	-	43	55
24 hr. maximum*	13	-	77	154
3 hr. maximum**	181	282	--	--
1 hr. maximum**	223	282	--	--

* Non-continuous monitor: 24 hour sample taken once per week.

** Continuous monitor: operated only approximately 10% of the time during 1976.

In addition to the Lake Charles-LACC station, limited air quality data resulting from special studies by Radian Corporation (1977) and Ashland Chemical Company are available (Minott, personal communication, 1978). The Radian study covered a three month sampling period in 1976. The Ashland study was carried out during 1975 and 1976. Two sampling stations were located in the general vicinity of the Rockefeller Refuge prospect area. Their distance and direction from the center of the prospect area are as follows:

Lafayette (Radian)	96 km-NNE	(60 mi)
New Iberia (Ashland)	98 km-NE	(61 mi)

Average measured concentrations for six pollutants from the Lafayette monitoring station, along with their dates of collection are presented in Table 3-5.

Table 2. Average concentrations of selected pollutants: Lafayette station. (From Radian Corporation, 1977).

Pollutant	Period of Data Collection	Average Concentration ($\mu g/m^3$)
Nitrogen Oxides	July 17 - Sept. 30, 1976	10.1
Nitric Oxide	July 17 - Sept. 30, 1976	3.9
Nitrogen Dioxide	July 17 - Sept. 30, 1976	6.1
Sulfur Dioxide	July 17 - Sept. 30, 1976	1.0
Ozone	July 17 - Oct. 17, 1976	78.0
Particulate	July 17 - Oct. 17, 1976	52.3

The Ashland Chemical Company study reported only 24-hour average SO_2 values. The single highest value of 115 $\mu g/m^3$ was approximately 32 per cent of the primary standard and 45 percent of the secondary. The second highest value was 61 $\mu g/m^3$ while most daily readings were below 20 $\mu g/m^3$.

Measured concentrations of all pollutants except ozone are well below ambient air quality standards (listed in Table 3-6, below). The entire south Louisiana region has been designated a non-attainment area with respect to ozone.

Table 3. Ambient air quality standards; State of Louisiana. (From LACC, 1976).

Pollutant	Standards Primary	Standards Secondary
Sulfur Dioxide		
Annual Arithmetic Mean	80 $\mu g/m^3$**	60 $\mu g/m^3$
24-Hour Maximum	365 $\mu g/m^3$	260 $\mu g/m^3$
3-Hour Maximum	-----	1300 $\mu g/m^3$
Carbon Monoxide		
8-Hour Maximum	10 mg/m^3***	10 mg/m^3
1-Hour Maximum	40 mg/m^3	40 mg/m^3
Ozone (Oxidant)		
Annual Arithmetic Mean	58.8 $\mu g/m^3$	58.8 $\mu g/m^3$
1-Hour Maximum	160 $\mu g/m^3$	160 $\mu g/m^3$
Nitrogen Dioxide		
Annual Arithmetic* Mean	100 $\mu g/m^3$	100 $\mu g/m^3$
Total Suspended Particulate*		
Annual Geometric Mean	75 $\mu g/m^3$	60 $\mu g/m^3$
24-Hour Maximum	260 $\mu g/m^3$	150 $\mu g/m^3$

*Non-continuous monitor.
**$\mu g/m^3$ + micrograms per cubic meter.
***mg/m^3 + milligrams per cubic meter.

Predicted Ambient Air Quality

Due to the absence of sampling stations within the prospect area, the anuual average air quality was predicted using the Climatological Dispersion Model---CDM (U.S. Environmental Protection Agency, 1973). Sulfur oxides were selected as the pollutants for the modelling effect because emissions from a geopressure test well are more likely to contribute to SO_x levels than other pollutants for which standards exist. However, there are no SO_x emission point sources within 35 km (22 mi) of the center of the prospect area that meet the criterion for significant SO_x emitters (≥ 1 ton per yr). As a result, the model predicts an SO_x concentration of zero everywhere within the prospect area.

2.6.3 Air Quality - GENERAL

Since the proposed well site has no air quality measurements and is located on the same flat coastal plain as the nearby Lake Charles, the air quality for the study area may be approximated from observations made at the Lake Charles area. Table 2-11 summarizes the existing air quality in the general area compared to the National Ambient Standards. For comparison purposes, measurements of carbon monoxide at Nederland and West Orange, Texas were also included in the table since these two areas are located in the same Air Quality Control Region, i.e., 106, as Lake Charles and the proposed well site (EPA, 1978a). From Table 2-11 it can be seen that, except for ozone and nonmethane hydrocarbons, other pollutants as listed and regulated by Federal and state agencies were within the primary standards. Since the site is a rural area it is expected that the pollution level is much less than that at Lake Charles.

Due to the absence of sampling stations within the study area, the annual average air quality was predicted using the Climatological Dispersion Model - CDM (EPA, 1973). Sulfur oxides were selected as the pollutants for the modelling effort because emissions from a geopressured test well are more likely to contribute to SO_x levels than other pollutants for which standards exist (DOE, 1978). However, there are no SO_x emitters (≤ 1 ton per year). As a result, the model predicts an SO_x concentration of zero everywhere within the Rockefeller Refuge area (DOE, 1978).

Table 4. Summary of Air Quality Data Observed in the Lake Charles Area as Compared to National Ambient Standards.

Pollutant	Average Time	Primary Standards[a]	Lake Charles Ar
Particulate matter	Annual (Geometic mean)	75	55[c]
	24-hour[b]	260	154[c]
Sulfur oxides	Annual (Arithmetic mean)	80	26[c]
	24-hour[b]	365	108[c]
Carbon Monoxide	1-hour[b]	40	5.7[d], 8.4[e], 7.5[f]
Nitrogen dioxide	Annual (Arithemtic Mean)	100	42[c]
Photochemical Oxidants, O_3	1 hour[b]	160	282[c]
Hydrocarbons (Nonmethane)	3 hour (6 to 9 a.m.)	160	185[g]

a. Units are in $\mu g/m^3$ except for CO which is in mg/m^3.

b. Not to be exceeded more than once per year.

c. For the year of 1976 (data source: EPA, 1978a).

d. Measured by Louisiana Dept. of Highways at Westlake opposite industries about 200m form I-10 on Feb. 10, 1976 during Jan. - Feb. 1976.

e. Nederland, Texas, same as c, for comparison only

f. West Orange, Texas, same as e.

g. Measured by Louisiana Dept. of Highways at Cameron Evacuation Route in Cameron Parish at 11 a.m. on January 20, 1976.

Air Quality - During Drilling And Maintenance

During the exploration phase, air pollutants will be emitted by vehicles, drill rigs, and construction equipment (e.g., tractors, generators, compressors) (DOI, 1978). Exhaust emmissions form drilling and construction machinery will include SO_2, SO_x, CO, hydrocarbons, and particulates. Diesel drives for the drilling rigs typically consume 2,000 l/da (550 gal/da) of fuel, resulting in emissions of approximately 23 Kg/da (51 lbs/da) of CO, 9 Kg/da (20 lbs/da) of exhaust hydrocarbons, 107 Kg/da (236 lbs/da) of NO_x, 7 Kg/da (15 lbs/da) of SO_x, and 7.5 Kg/da (17 lbs/da) of particulates (ERDA, 1976). The emissions associated with the operations of diesel-powered equipment for five days to prepare a well pad would be equivalent to those associated with a single day of drilling. A small amount of polluting emissions will also result from the operation of delivery trucks and private vechicles. These releases are expected to be minor and short-term, and should be readily dispersed because about 62% of the time the atmosphere stability classes are in D and E (see Section 2.6.2). The accumulated level of impacts due to exhaust emission from drilling and construction machinery will be negligible. Because the concentration of total suspended particulates in the air at Lake Charles is within national ambient standards (see Section 2.6.3), the added effect on air quality due to construction will be minimal.

Air Quality - During Testing and Operation

Well-testing will result in the direct release of steam and a variety of gases and particulates. The contaminant of greatest concern is hydrogen sulfide. No data are presently available on the hydrogen sulfide concentration in the Frio Formation in this project area. Hydrogen sulfide concentrations for the Frio along the Gulf coast in Texas range from .32 mg/1 to 1.6 mg/1 (Kharaka et al., 1977). Concentrations from geopressured zones in the Frio in Vermillion Parish near the Gladys McCall well site range from .4 mg/1 to .5 mg/1 (Kharaka et al., 1979). The H_2S concentrations at the project will probably be between those values shown in Table 5. Hydrogen sulfide levels will be monitored in order to determine if a significant impact will occur. No Louisiana or Federal air standards for hydrogen sulfide presently exist. The H_2S odor threshold is .002 mg/1.

Table 5. Hydrogen Sulfide concentrations in the Frio Formation.

Well	Field	Country or Parish	H_2S Concentration mg/1
Kitchen #1	Chocolate Bayou	Brazoria, Tex.	1.6 [a]
Cozby #2	Chocolate Bayou	Brazoria, Tex.	.85[a]
Gardiner #1	Chocolate Bayou	Brazoria, Tex.	.32[a]
Rachel #66	East White Pt.	San Patrizio, Tex.	1.0 [a]
St. Un. A #9	Weeks Island	Vermilion, La.	.4 [b]
Edna Delcambre No. 1	Tigre Lagoon	Vermilion, La.	.5 [b]

Source: [a]Kharaka et al., 1977
[b]Kharaka et al., 1979

Other gases that may be omitted are CO, NO_x, NH_3, CN_4, N_2, and H_2. Based on typical noncondensable gas content for pressure fluids. Particulates released with the geopressured fluids or raised by equipment should not add significantly to the background level of particulates in the proposed well site area. The short duration of these emissions makes it unlikely that the air quality will be significantly affected outside of the immediate area of the well.

The impact of flaring the gases from a single plume is expected to be small, based on the experiences from similar geopressured well tests (ERDA, 1977). This particular project is miniscule when compared to the many flares which exist in major refineries in the Lake Charles area where the air quality is still within national ambient standards (see Seciton 2.6.3) (DOE, 1980).

The impact of the cooling device is expected to be negligible because of the small size required for the single well operation. A possible impact would be the increased occurrence of fog (or the formation of "steam fog" during freezing temperatures in winter; but the frequency of this is small, since the mean number of days with temperature equal or less than $0^{o}C$ ($32^{o}F$) as observed at Lake Charles is approximately 13 days per year).

Noncondensable geopressured gases will be released during drilling (ERDA, 1976). Although the weight of the drilling mud should prevent a large release of gases to the surface during drilling, the mud will carry some gases to the surface. These gases will be released to the atmosphere from the water/steam separator at the well, from the drilling-mud cooling tower, and from the liquid sump. Maintenance of sufficient pressure within the well to protect against blowouts should result in acceptably low levels of gaseous emissions during drilling. Impact on air quality due to blowout will be discussed later.

Air Quality - During Accidents

During site preparation and access construction, the impacts on air quality will result from dust, exhaust emissions from construction machinery and non-condensable gases released from geopressured fluids during pre-construction flow-testing. These releases are expected to be minor and short-term, and should be readily dispersed because about 62% of the time the atmospheric stability classes are in D and E (see Section 2.6.2). However, accidents such as a blowout may occur due to pre-construction flow-testing. For a discussion of blow-out with respect to air qualtiy, see Section 5.2.8.

Air Quality - During Blowout

By standards of normal oil field operation, extraordinary precautions will be taken in the proposed action to prevent blowout of the test well. Yet the possibility of a blowout should be considered in view of the high pressure anticipated in the geopressured zone. Some documentation exists on blowout occurrences at various geothermal fields (ERDA, 1976).

Very little air quality impact data as a result of blowout are available in the literature. Some preliminary information may be inferred from the blowout of Edna Delcambre #4 gas well in the Tigre Lagoon area in Louisiana (ERDA, 1976). The blowout took place on July 13, 1971, and resulted from negligence during workover as rams were changed on the blowout preventers. Depth of the producing interval at the time of the blowout (July 13, 1971) was between 4081 to 4233 (13,380 to 13,880 ft), with three to four thousand pounds flowing pressure.

The well caught fire 10 hours after blowout and the fire lasted for 10 days. Discharge of the highly saline ($\pm$150 ppt) formation fluid continued for approximately three months until the well was made inactive. The well was finally plugged and abondoned on November 4, 1971, by pumping cement through the relief well.

Since the emission rate of H_2S due to possible blowout from the proposed action is not known, one may calculate the impact on air quality as the result of the oxidation from H_2S to SO_2 from the experience gained by Edna Delcambre #4 well (ERDA, 1976).

The Computation of SO_2 is based on the following assumptions:

A. Emission height is assumed to be about 31 m (100 ft). This is based on data that during both the first and second blowout of Edna Delcambre #4 well, saline formation fluid was blown about 31 m (100 ft) vertically into the air.

B. Emission rate of H_2S is assumed to be about 6.8 Kg/hr. This is based on a Union Oil Co. well testing, which produced a total flow of 22,500 Kg/hr., of which 3% was noncondensable gases. Ninety-nine percent of this was CO_2. If the remaining percent is assumed to be entirely H_2S, the total emissions of H_2S would equal 6.8 Kg/hr.

C. Atmospheric stability is assumed to be F, the moderately stable condition commonly used as the air pollution computation for safety analysis.

D. Wind speed during stability F, which occurs about 14% per year in the study area, is 1.7 m/s. This is given in Section 2.6.2.

E. Blowout will result in the burning of the gas, which in turn will result in oxidation of the H_2S to SO_2. Available data showed that 620 grams of H_2S would produce 1136 grams of SO_2.

On the basis of the preceding information, the maximum concentration of SO_2 may be computed from standard EPA techniques to be about 192 $\mu g/m^3$, which is below national ambient air quality standards of maximum 24 hour concentration of 365 $\mu g/m^3$. The distance of this maximum concentration is expected to be about 1.6 km (1 mi) downwind from the blowout well. Although the concentration of SO_2 is below air quality standards, because of the unusual odor of H_2S, the area within a 3.2 km (2 mi) radius of the blowout well (such as campsites, if any) should be advised to evacuate.

In summary, the impacts of the proposed action on air quality are insignificant during construction and operation. However, should blowout occur, important pollutants will be SO_2 and H_2S. The maximum concentration of SO_2 is estimated to be below national ambient air quality standards. At present there is no national ambient standard for H_2S. However, because the "rotten egg" odor of H_2S can be detected at levels of 30 ppb, estimated H_2S concentrations of 80 ppb as a result of a blowout will be a nuisance. The distance of this maximum concentration is expected to be about 1.6 km (1 mi) downwind form the blowout well. No adverse effect on air quality is anticipated even under conservative estimates during stable atmospheric conditions. The effect of inversion layer is also small, because the minimum height of that layer is about 390 m (1280 ft) above ground (Section 2.6.2).

GEOLOGY AND RESOURCE ASSESSMENT

The Sweet Lake and Rockefeller Refuge geopressured-geothermal prospects in southwestern Louisiana are presently being tested as sources of energy for cogeneration. High pressures in these reservoirs act as a driving force to produce high temperature brines. These brines contain methane in various concentrations depending on the relative salinities and porosities of the geopressured aquifers.

All of the parameters which influence the development of these reservoirs are controlled to some extent by the depositional history and structural setting of the Louisiana Gulf Coast.

Geopressured corridors are defined by time stratigraphic units which were deposited during a tertiary and early holocene regression of the sea. During this time the focus of deposition shifted along the shoreline and out toward the axis of the Gulf Coast Basin (4). The time stratigraphic units therefore decrease in age toward the south in Louisiana. The exact cause of this regression is not completely understood. The regression may be a result of continental uplift, sea level fall, or both. Regardless of the cause, the geologic history has produced a sequence of lithologic units which, in general, fine downward and outward toward the axis of the Gulf Coast basin (4). Of particular interest are the Wilcox and Frio formations and the Miocene series of Southwestern Louisiana because of their relatively shallow depth, frequency of anomalously thick geopressured sandstones and growth faulting which effectively seals the sandstones from fluid migration. In general, sandstone units decrease in thickness and effective porosity with depth in these units. Geopressuring increases with depth and toward the axis of the Gulf Coast basin. The upper Wilcox, Frio and lower Miocene are optimum targets for geopressured-geothermal resources from land-based operations in the Southwestern Louisiana Gulf Coast.

DESIGN WELL PROSPECTS IN SOUTHWESTERN LOUISIANA

Sweet Lake

The Sweet Lake Amoco Fee No. 1 well is located 14 miles (23 km) southwest of Lake Charles, Louisiana (Fig. 1). The well is targeted for a depth of between - 15,387 to -15,414 ft (-4,690 to -4,698m) MSL. This producing horizon is in the Frio formation in a structural basin on the north flank of the Hackberry/Big Lake/Sweet Lake salt ridge separated from the top of geopressure by a shale which is approximately 5,000 ft (1,524 m) thick (Fig 2). Above geopressure are the alternating sands and shales of the Miocene. The disposal well is designed to reinject the spent production fluids into the lower Miocene at a depth of -7,015 to -7,320 ft (-2,138 to -2,231 m) MSL. Another stratigraphic section indicates that the sequence of alternating sands and shales continues to the ground surface through Miocene, Pliocene and Pleistocene units (Fig.3). Groundwater quality observation wells produce from Pleistocene sands and gravels at a depth of -280 to -435 ft)-95 to -133 m) MSL. An overlying clay unit separates the sand and gravel unit from thin unevely distributed Holocene sands which lie in proximity to the ground surface.

Surficially, the Sweet Lake test site is situated on the southern edge of the Pleistocene Prairie Terrace which borders the coastal marshlands (Fig. 1). Elevation and relief are low and the hydrologic gradient is to the south through man-made canals and levees built for agricultural irrigation and drainage.

Rockefeller Refuge

The Rockefeller Refuge Gladys McCall No. 2 well is located approximately 7 miles (11 km) southeast of Grand Chenier, Louisiana Fig. 4). This well is producing from a depth of -15,597 to -15,626 ft (-4,754 to -4,763 m) MSL or in the lower Miocene (Fig. 2). Thick sandstone units are located within and above the producing horizon to a depth of about -14,000 ft (-4,268 m) MSL at the top of geopressure. Predominately shale grading to alternating sand and shale units occupy the stratigraphic column upward through the remainder of the section. Sands of the lower Pliocene at the top of this section are the site of spent brine injection at a depth of -3,050 to -3,500 ft (-930 to -1,067 m) MSL (Fig. 2). As at the Sweet Lake site, the sequence of alternating sands and shales continues up through the younger Pliocene and Pleistocene units (Fig. 5). The groundwater quality observation wells at Rockefeller Refuge tap two Pleistocene sands and gravels which are locally hydraulically separate. These units are at depths of -310 and -660 ft (-95 and -201 m) MSL respectively. Locally around the test site, these Pleistocene sands are separated from the ground surface by about 95 ft (29 m) of clay.

The surface geology at the Rockefeller Refuge test site is characterized by relict beach ridges and Holocene coastal marsh (Fig.4). The site is within a region known as the chenier Plain. The relict beach ridges (cheniers) parallel the coastline and are younger toward the south in southwestern Louisiana. Drainage around the site is tidally dominated and is controlled by the postition of these relict ridges and the present beach which is juxtaposed on the present shoreline. In addition, drainage is further altered by man-made canals and levees used for oil-field access.

WATER QUALITY

MONITORING

Sweet Lake

Water quality monitoring at Sweet Lake began in October, 1980. Monthly sampling and analysis of waters from three wells and three surface water stations continued until May, 1982. The operation was scaled down in June, 1982 to continue sampling natural waters on a quarterly basis.

Three observation wells are producing water from the uppermost Pleistocene sand. Two wells are completed at a depth of -280 ft (-85 m) (Fig. 1). Well No. 1 is located 100 ft (30 m) north of the disposal well and well No. 2 is located 150 ft (46 m) north of the production well. Well No. 3 produces from a depth of -435 ft (-133 m) MSL and is located 200 ft (61 m) north of the production well. These wells were positioned to be down the groundwater flow gradient from the production and disposal well sites.

Three surface water sampling stations are located down gradient from the test site (Fig. 1). Station L1 is located at a bridge crossing in a canal which collects all runoff from the test site. Another station, L2, was located to the south where the canal enters an irrigation return reservoir. Station L3 is located still further south in Sweet Lake, a natural marshland lake which is hydraulically connected to the irrigation network.

All water sampling and analyses were conducted using EPA standard methods. The constituents which were characterized are listed in Table 1.

Rockefeller Refuge

Water quality monitoring began at Rockefeller Refuge in May, 1981. Monthly sampling and analysis of surface waters was initiated in May at two stations and in August at a third surface water station. Sampling and analysis commenced at two wells in June, 1981. The contract for monthly sampling and analysis was altered in June, 1983 to be conducted on a quarterly basis.

Two Pleistocene sand units are being monitored by observation wells at Rockefeller Refuge (Fig. 4). The first sand is at a depth of -100 to -310 ft (-30 to -95 m) MSL. Well No. 1 located 2,000 ft (610 m) north-northwest of the test site is screened in the bottom of this sand. A second well, No. 2, is located 200 ft. (61 m) north-northwest of the test site. This well taps a lower sand at -660 ft (201 m) which is separated from the upper sand by a layer of clay approximately 330 ft (101 m) thick.

Three surface water sampling stations were also installed in the vicinity of the Gladys McCall test site (Fig. 4). The first S1, is located in a lake inside the Gladys McCall levee system. This lake probably formed as a result of marsh degradation associated with canal dredging and levee building. A second station is located near a sluice in the southeastern corner of the levee system through which tidal flow is allowed to enter and exist. Adjacent to the sluice is a natural marshland lake which is hydraulically connected to the Gulf of Mexico via a leveed channel known as Hog Bayou. Sample station 83 is located about 1 mile (1.6 km) down this channel.

CHEMICAL ANALYSIS

Water quality in southwestern Louisiana is controlled mainly by the rate and extent of salt-water intrusion. Tidal exchange is responsible for a high variability in the chemical character of surface waters where land surface is at or below sea level and where channels have been cut to below sea level in the Gulf Coastal Plain. Movement of the interface in surface waters is dependent on precipitation and runoff rates and on tidal ranges which are controlled by seasonal forces and long-term sea-level rise.

The position of the subsurface salt-water interface is also controlled by seasonal and long-term forces. In addition, variations in subsurface geology or aquifer properties may cause local variations in the position of the interface. Discharge of shallow groundwater aquifers for domestic and industrial applications may also affect the position of the salt-water interface. Heavy pumping of aquifers produces deep cones of depression which alter groundwater flow patterns. As a result, the interface may move more rapidly toward pumping centers.

In general, water salinities in southwestern Louisiana increase downward through the stratigraphic column and outward toward the axis of the Gulf Coast Basin (1). The depth to saline water (250 ppm total dissolved solids TDS), although locally complex, in general decreases to the south from -2,000 ft (-610 m) MSL in northern Calcasieu Parish to mean sea level along the shoreline. The transition from fresh water to saline water is by no means abrupt. The gradient from the base of fresh water to the top of the slightly saline zone (1,000 ppm TDS) varies greatly but gradients from 4.9 to 12.2 m9/liter/m are common. Horizontal gradients along the tops of major sand units have been determined by (2). In the "upper sand unit" of the Pleistocene Chicot reservoir, the gradient between the 250 and 1,000 ppm isochlors is commonly between 0.04 and 0.16 mg/l/m. In the "500-ft" sand, the gradient is from 0.04 to 0.08 m9/l/m and in the "700-ft" sand, the gradient is from 0.05 to 0.16 m9/l/m/ Therefore, higher salinities are attained with depth than with horizontal distance per unit length.

Sweet Lake

Surface waters at the Sweet Lake test site which were observed through the environmental monitoring program have an average dissolved content of 880 m9/l based on a summation of the major cations and anions, Na, K, M9, Ca, Cl, NH4, Cd, and B (Table 6). The salinity of surface waters is higher than in the monitored Pleistocene sand and gravel unit which has an average dissolved solids content of 346 m9/l based on a sum of the concentrations of major cations and anions in wells sampled by the LSU monitoring program and the USGS. As expected, the salinity of groundwaters increases with depth. The dissolved solids content of a -950 ft (-290 m) MSL USGS observation is 2,130 m9/l and the average dissolved solids content of the Sweet Lake geopressured-geothermal brine is 148,000 m9/l (Table 6).

Concentrations of selected elements in the surface waters have seasonal variations which are a result of changes in climate (Table 6). The climate serves to increase fresh-water runoff during the "wet" seasons and increase tidal inflow during the "dry" seasons. Small-scale variations may also result from agricultural practices which should also be seasonal in nature. In general, concentrations of major cations and anions increase to the south from station L1 located on the prairie surface to station L3, located in the natural marshland lake, Sweet Lake (Fig.1).

The quality of groundwater at Sweet Lake is also seasonally variable due to movement of the salt-water interface in response to influx of fresh-water at the recharge source during "wet seasons and tidal influx during "dry" seasons (Fig. 11-18). The effect of the "dry" seasons may be more pronounced in the groundwaters due to increased pumping when farmers have to supplement surface irrigation sources with groundwater. In general, concentrations of major cations and anions increase with depth in the groundwaters. The groundwater observation program was not designed to characterize the natural horizontal variation in these waters. The wells are too closely spaced for such an analysis.

Rockefeller Refuge

The surface waters at Rockefeller Refuge are brackish. Their dissolved solids content when summing the concentrations of major cations and anions from project observations average 17,800 m9/1 (Table 4). This concentration is more than 6 times that of the shallowest average groundwater observation. In general, the salinity of groundwaters increases with depth in water quality observations conducted by the USGS (Table 4). The dissolved solids content of waters sampled through the environmental monitoring program are opposite this trend. The shallow Pleistocene sand and gravel has a higher average dissolved solids content (2,840 m9/1) than the deeper sand (2,131 m9/1), also Pleistocene and probably connected to the shallow sand some distance up the stratigraphic dip (2). The variation in chemistry between the two sands may be due to hydraulic connection of the shallow sand with gulf waters or recharge of the lower sand unit. A more plausible explanation is that well No. 1 produces water from the bottom of the shallow sand and well No. 2 produces from the upper to middle section of the lower sand. A salt-water interface in each sand would dip inland increasing to the north. This may also explain the lower salinities of USGS observations at an equivalent stratigraphic interval to the north.

The geothermal brine was produced from a depth of 15,500 ft (4724 The dissolved solids content of the brine is about 93,900 m9/1 when summing up the concentrations of major representative constituents. These major elements comprise 96 percent of the TDS content measured by laboratory methods (Table 4).

Major constituents in surface waters at Rockefeller Refuge vary seasonally (Fig. 11-18). A strong influence on this variability is undoubtedly tidal in nature as attested to by very high concentrations of major seawater constitutents (Fig. 8). The area is flat and very near sea level. Runoff from precipitation is therefore of minor importance. Concentrations of these elements in groundwaters also display seasonal variations due to the movement of the salt-water interface which is a response to a complex interaction between tidal change in the aquifer from the south and recharge from the north (Fig. 11-18). Some recharge to the Pleistocene aquifer may enter the Mermentau river system in and just north of the Chenier ridge complex, where the river system has scoured into the Pleistocene. Fresher recharge occurs about 100 miles north of the Rockefeller Refuge test site in Vernon Parish (3).

SUBSIDENCE

Subsidence is a very critical concern in south Louisiana where much of the land surface is very near sea level. Any increase in subsidence rates will result in increased urban flooding, loss of ecosystem habitat, and building foundation problems (5). Land loss is also a critical concern. In an area that is losing, by one estimate, up to 129 square kilometers per year, the subsidence component is probably most significant.

Subsidence in south Louisiana may result from any one of a number of phenomena ranging from the regional movement associated with deep crustal activity to soil compaction caused by loading or dewatering. The effect, if any, of geopressured-geothermal development will be to depressurize the geopressured aquifer. This depressurization would result in a negative head gradient from the surrounding shales into the aquifer. The dewatering and compaction of the shales, which follows can be transmitted to the surface as subsidence (6). In addition, subsidence may result from differential compaction across the growth faults which define the geothermal reservoir.

Past estimates of subsidence rates in south Louisiana vary greatly. The variation is due to differences in reference area and different assumptions based on sea level rise. Swanson and Thurlow (7) calculated rates between -0.5 and -4.3 cm/year by tieing in to a "stable" reference on the Florida coast. Holdahl and Morrison (8) calculated rates from -0.03 to -0.05 cm/year based on the stability of the Appalchian Mountains and an assumed 1 mm/year rate of sea level rise. In both cases, field leveling data from different surveying epochs were adjusted to account for their assumptions.

In earlier work for the DOE geopressured-geothermal project, subsidence networks were established around each of the test sites (9). These networks were designed to cover and extend beyond the area bounded by the subsurface growth faults which define each prospect. Leveling of first-order accuracy was used to tie in these networks to the existing National Geodetic Survey (NGS) regional network.

Before the effects of geopressured-geothermal development on subsidence rates can be determined, ideally a baseline of absolute existing subsidence rates should be established. Local adjustments were made on the site networks at the beginning of the DOE project to determine relative movements (9). A nearby reference benchmark at each site was assumed stable (zero movement), therefore subsidence rates measured along the lines were only meausurable relative to the "stable" benchmarks (Fig. 6). This analysis may be misleading since the reference benchmarks are probably not stable. Although earlier subsidence studies are disputable due to their differences, these studies are important for their common point; that the south Louisiana coast is subsiding. Therefore, subsidence rates at the geopressured-geothermal test sites are probably greater than those depicted in earlier studies (9).

In a more recent study, movements at the geopressured-geothermal test sites were adjusted to a different reference. The Monroe Uplift in northeastern Louisiana was shown by Schumm, Watson and Burnett (10) to be uplifting at a rate between +0.4 and +1.4 mm/year. They established this trend using geomorphic evidence which indicated that gradients and other characteristics of streams crossing the Monroe

Uplift and to adjust the movements at the geopressured-geothermal test sites to the known rate of movement of the Monroe Uplift. In so doing, more absolute subsidence rates in southwestern Louisiana have been determined (5).

Sweet Lake

The movement profile extends from Iowa, Louisiana north of the Sweet Lake test site to Creole, Louisiana to the south (Fig. 7). The Sweet Lake test site may be positioned at approximately the 25 km distance mark on the subsidence profile (Fig. 8). Movement along the line ranges from -0.3 to -0.03 m for the period 1965 to 1982. The shaded region in the profile is an error band corresponding to the +0.0004 to +0.0014 m/year range in movement of the Monroe Uplift.

Two correlations are evident in this profile. The topographic surface and the movement profile are inverted and the point of minimum subsidence is positioned coincidentally with the Prairie Marshland boundary and the Sweet Lake salt dome. The area of maximum subsidence may be associated with compaction of a buried Pleistocene Red River fluvial system or greater dewatering due to increased pumping for irrigation. The area south of the Prairie-Marshland boundary may be compacted less due to saturation as this area is under water most of the time or perhaps movement of the Sweet Lake salt dome has kept pace with subsidence rates.

Rockefeller Refuge

Movement at Rockefeller Refuge is represented by a profile which extends from Holly Breach, Louisiana to the west of the wildlife management area which is located just east of the test site (Fig. 9). In general, subsidence decreases from west to east from -0.15 to -0.05 m for the period 1965 to 1982. Anomalies occur in the profile at the positions of the existing Calcasieu and Mermentau Rivers. This subsidence is probably due to greater compaction of the younger sediements which comprise the river basins. Baseline subsidence at the Rockefeller Refuge test site between 1965 and 1982 was approximately -0.05 to -0.07 m. The test site is located at approximately the 64 km distance mark on the profile.

MICROSEISMICITY

Microseismicity may result from geopressured-geothermal development activities through enhanced or induced faulting (6). This faulting would occur as a result of slippage along the growth faults which define the prospect. Tensional stresses are created due to differential pore pressure declines along fault planes,resulting either from depressurization of the geothermal aquifer or pressurization and lubrication in the shallower disposal sands.

The growth faults which define the geopressured reservoirs are conducive to the localized natural compression of sandstone wedges in the Gulf Coast; a result of progradation of Tertiary and younger fluvial sands and silts onto older marine clays and evaporites (1). The growth faults are located where these thick sedimentary wedges have been deposited within the clays and salts. The fluvial wedges load and compress the marine sediments with progradation toward the center of the Gulf Coast Basin. Growth faulting is contemporaneous with deposition (1). Sediments are carried over the fault and are deposited on the downthrown side so that sediments on the downthrown side are thicker.

Movement along growth faults may continue for some time after deposition. Natural seismicity may be a result of this continued movement or could be due to other background sources within or away from the geopressured-geothermal test sites. Sources of natural background "noise" range from thunderstorms to distant crustal movements. Man-induced events may arise from oil field activities or highway travel.

Microseismic monitoring programs were initiated around each of the geopressured-geothermal test sites prior to development activities (1). A first phase of each program involved the operation of temporary seismometers to locate sources of background "noise" which could interfere with site-specific interpretations. The second phase involved the installation of permanent seismometers around each test site at locations strategic to the detection of growth fault movement. These seismometers are encased within boreholes to a depth of 11 m or more. Seismic signals are transmitted via radio signals and telephone lines to receiving stations where they are filtered and processed.

Sweet Lake

Seismic signals from the Sweet Lake geopressured-geothermal prospect are transmitted via telephone lines from telemetry packages at depths of 20 to 27 m below ground surface. Eight of these seismic stations are located radially around the test site (Fig. 1).

Continuous recording of seismic signals began in August of 1980. Through the period ending July, 1982, a total of approximately 450 seismic signals were recorded by the Sweet Lake microseismic moritoring array (4). Of these signals, about half may be attributable to natural events occuring outside the network and 20 percent of the signals may be due to natural events occuring within the network. The remaining signals either could not be located, were of unknown origin or were directly attributable to geophysical blasting. It is highly probable that most of the natural events were associated with the growth faults which are strewn across the Gulf Coast. Three events are correlable with earthquake activity in Alaska, Mexico, and Italy. The Jefferson Island, Louisiana salt dome collapse of November 20, 1980 produced a sequence of seismic activity that lasted for about 9 minutes. The events recorded within the network do not form any pattern in relation to the growth fault network which defines the prospect. Therefore, no microseismicity can be attributed to test well operation during the peroid of monitoring reported here.

Rockefeller Refuge

Eight permanent borehold seismometers were installed in June, 1981 at depths ranging from 11 to 15 meters (4). The seismometers were on-line via radio signals and telephone lines in July of 1981.

Between the period, July, 1981 through October, 1982, a total of 38 events have been recorded by the Rockefeller Refuge microseismic monitoring array. Of these events, about 45 percent were located outside the network and 10 percent were within the network. The remainder were either associated with oil field activities or were too small to locate. The natural events recorded at Rockefeller Refuge were also recorded by the Sweet Lake monitoring array. As mentioned previously, it is highly probable that these natural events were caused by natural growth fault slippage within the Gulf Coast subsurface. No events are directly attributable to test well operations.

REFERENCES

1. Bebout, D.G., Z. Bassiouni, D.R. Carver, C.G. Groat, R.H. Pilger, Jr. and F. M. Wrighton, 1982. Technical support for geopressured-geothermal well activities in Louisiana, annual report for the period November 1, 1980 to October 31, 1981; DOE/NY/10174-1, 378 p.
2. Harder, A.H., C. Kilburn, H.M. Whitman and S.M. Rodgers, 1967. Effects of ground-water withdrawals on water levels and salt-water encroachment in southwestern Louisiana; State of Louisiana, Department of Conservation, Geological Survey, Water Resources Bull. No. 10, 56 p.
3. Jones, P.H., A.N. Turcan, Jr. and H.E. Skibitzke, 1954. Geology and ground-water resources of southwestern Louisiana; State of Louisiana Department of Conservation, Geological Survey, Geological Bulletin No. 30, 285 p.
4. Wrighton, F.M., D. Bebout, D.R. Carver, C.G. Groat and A.E. Johnson, Jr., 1981. Technical support for geopressured-geothermal well activities in Louisiana, final report for the period September 27, 1978 to December 31, 1980; DOE/ET/27160, 211 p.

5. Trahan, D.B., 1983. A baseline for determining local, small scale vertical movements in Louisiana: Arizona Consulting Engineers Association, Symposium on Land Subsidence and Earth Fissures, in Press.

6. Gustavson, T.C., and C.W. Kreitler, 1976. Geothermal resources of the Texas Gulf Coast: Environmental concerns arising from the production and disposal of geothermal waters: University of Texas, Austin, Bus. Econ. Geology. Geol. Circ. 76-7, 35 p.

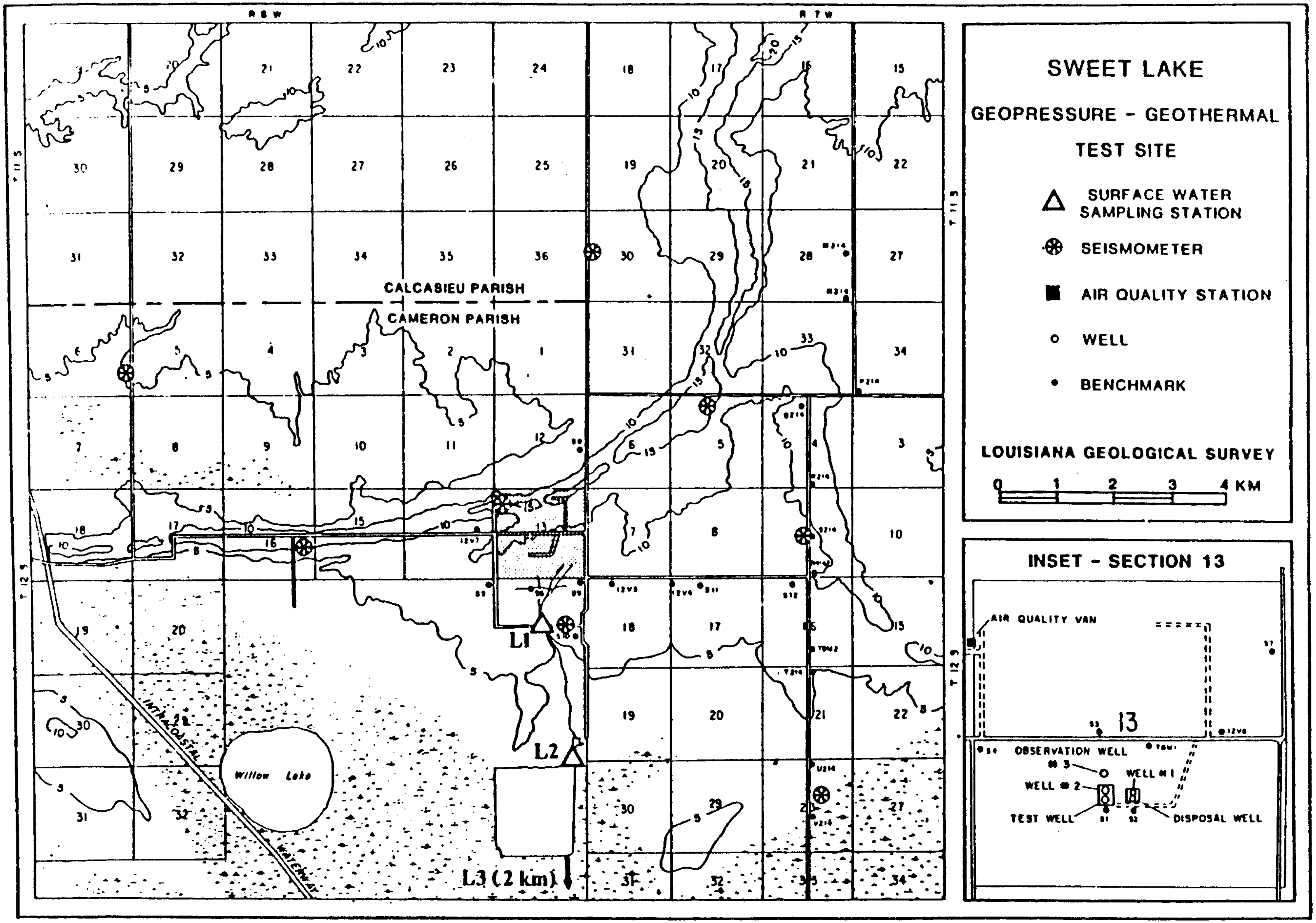
7. Swanson, R.L. and C. I. Thurlow, 1973. Recent subsidence rates along the Texas and Louisiana Coasts as determined from tide measurements. Jour. Geophysical Research, Vol. 78, No. 15, p. 2665-2671.

8. Holdahl, S.R., and N. C. Morrison, 1974. Regional investigations of vertical crustal movements in the U.S., Using Precise Releveling and Mareograph data, in R. Green, ed.. Recent Crustal Movements and Associated Seismic and Volcanic Activity: Tectonophysics, vol. 23, p. 373-370.

9. Trahan, D.B., 1982. Monitoring local subsidence in areas of potential geopressured fluid withdrawal, Southwestern Louisiana Trans., Gulf Coast Assoc. Geol. Soc. Vol. 32, p. 231-236.

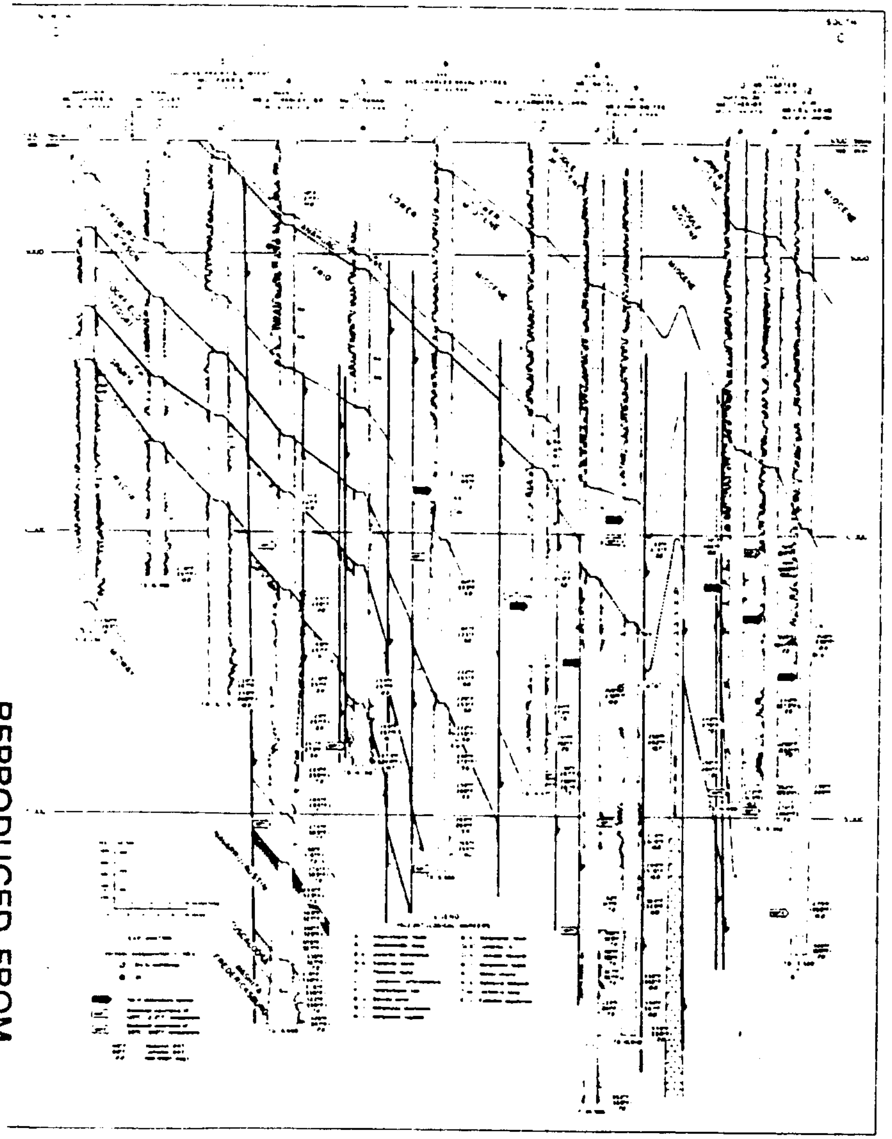
10. Schumm, S. A., C.C. Watson, and A. W. Burnett, 1982. Investigation of neotectonic activity within the lower Mississippi Valley Division: U.S. Corps of Engineers, Contract No. DACW38-80-C-0096. 158 p.

Fig. 1

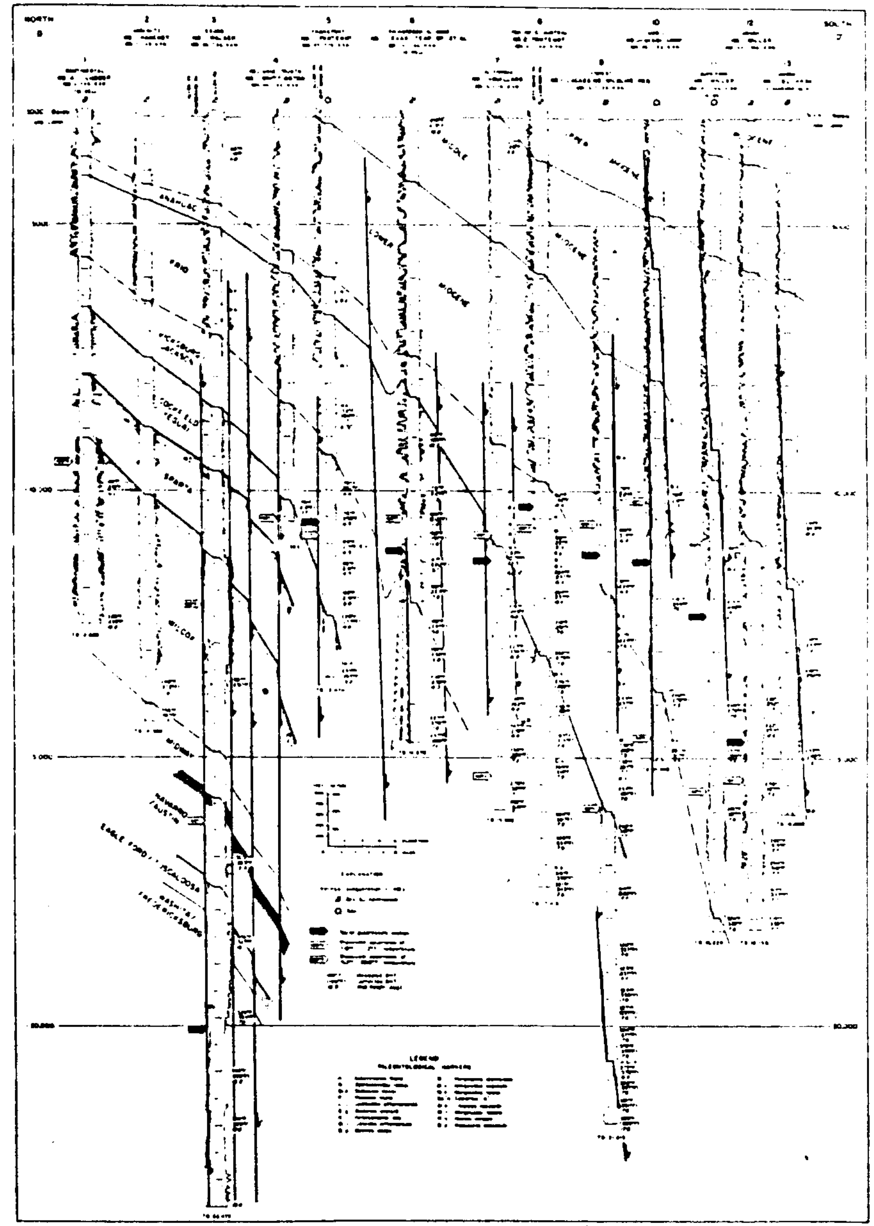


Area map of Sweet Lake geopressured-geothermal test site showing locations of parameter observation stations.

Fig. 2

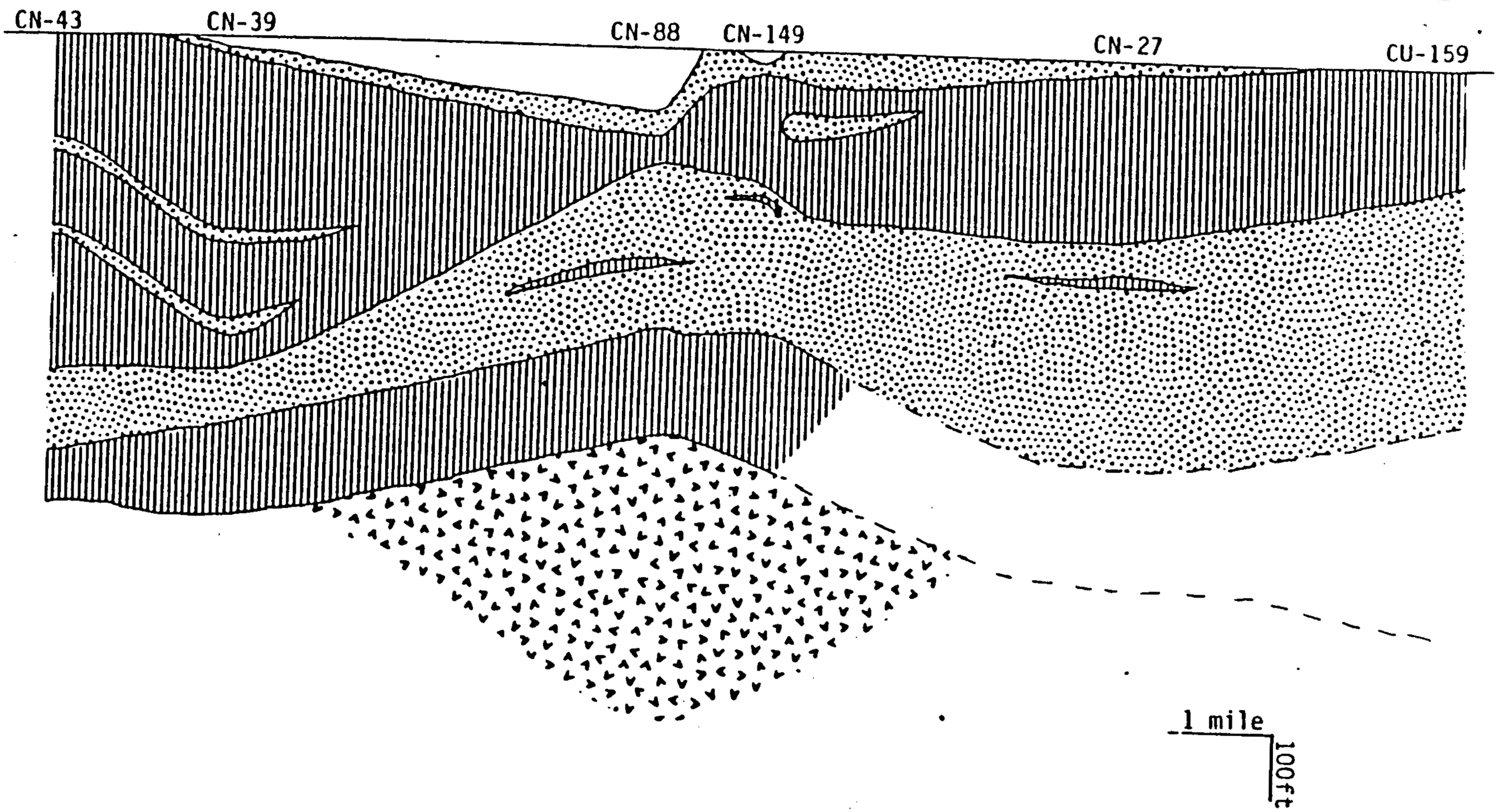


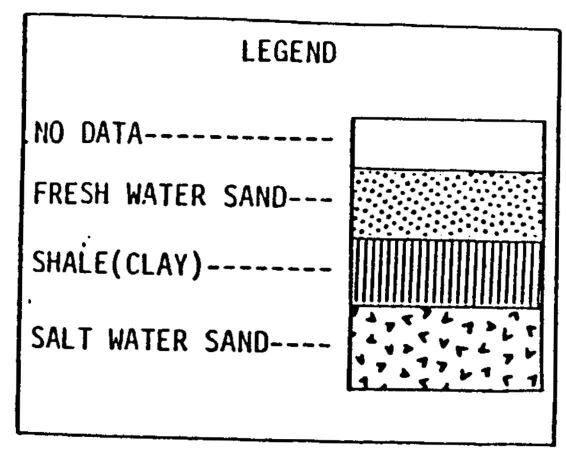
Dip section CC'. THROUGH Sweet Lake



Dip section DD'. THROUGH Rockefeller

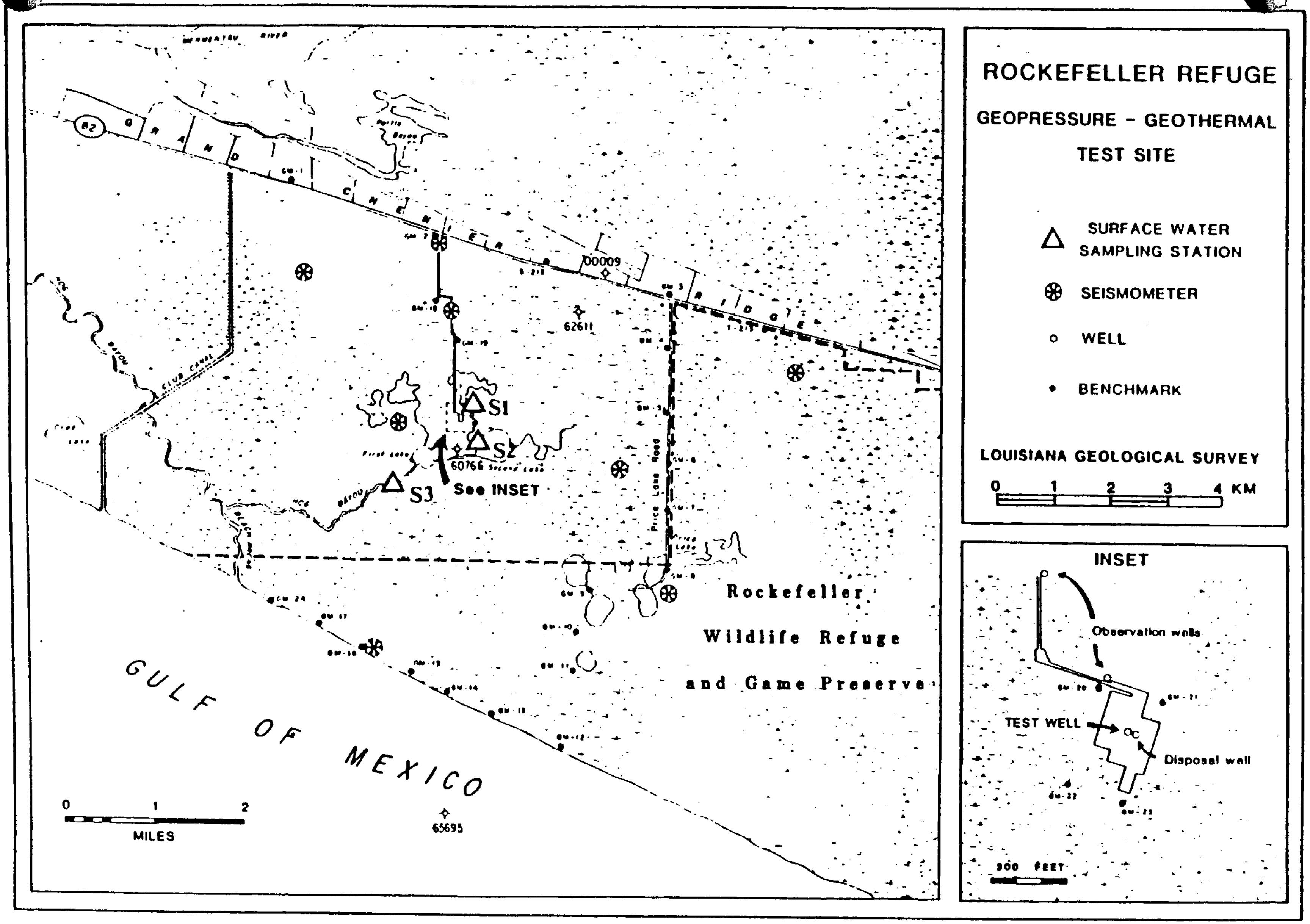
Fig. 3





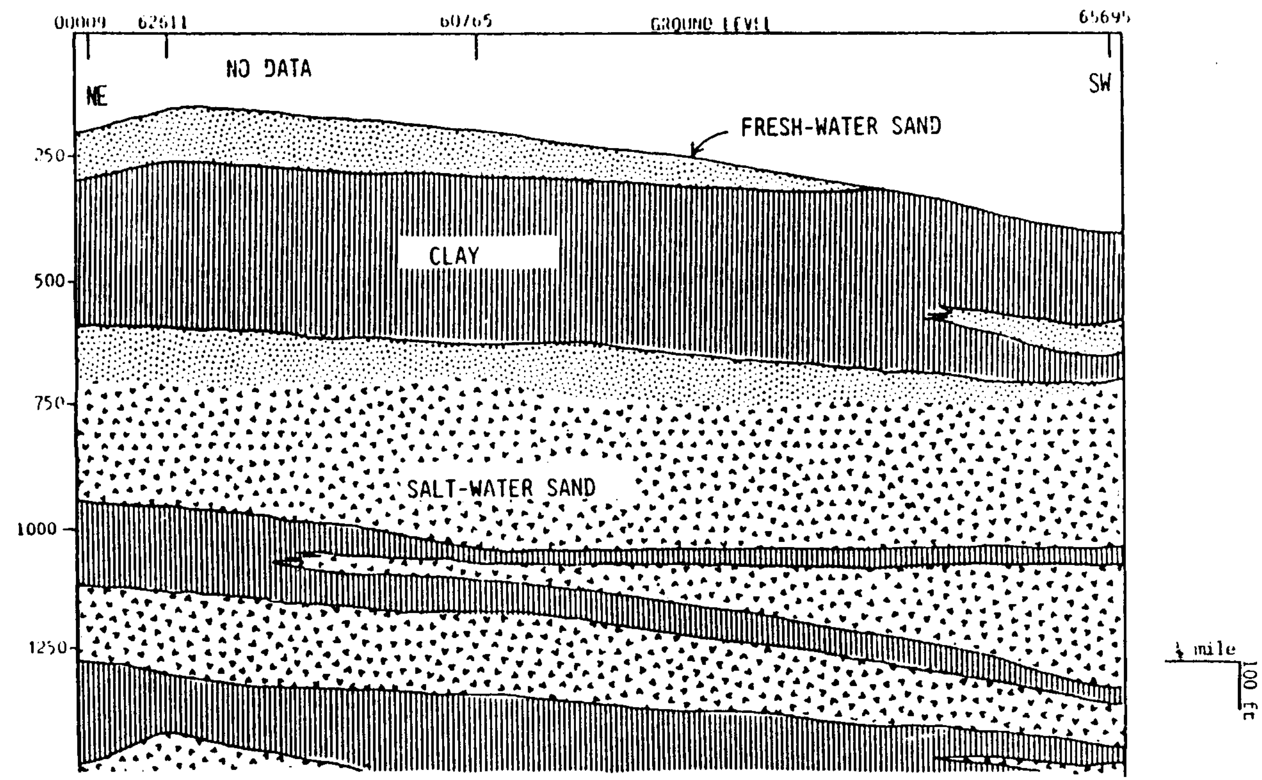
Stratigraphic cross-section through the Sweat Lake test site

Fig. 4



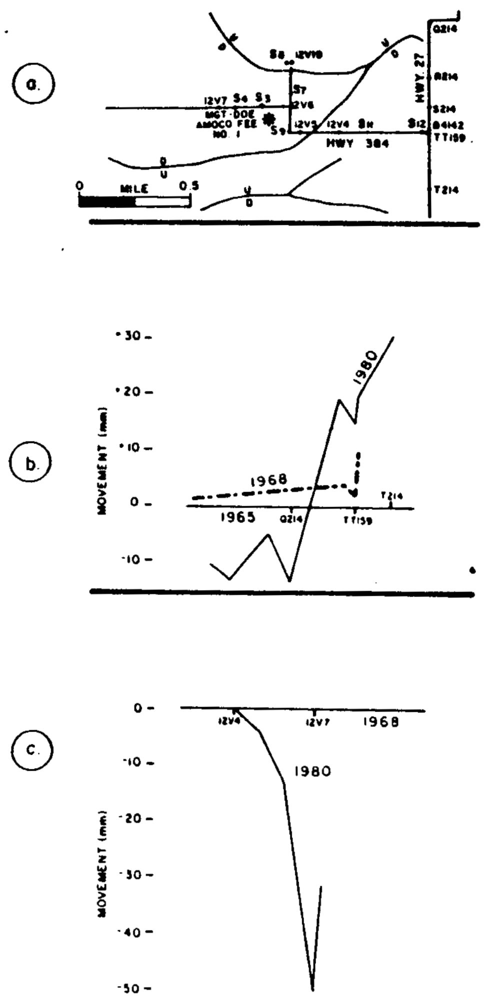
Area map of Rockefeller Refuge geopressured-geothermal test site showing locations of parameter observation stations.

Fig. 5

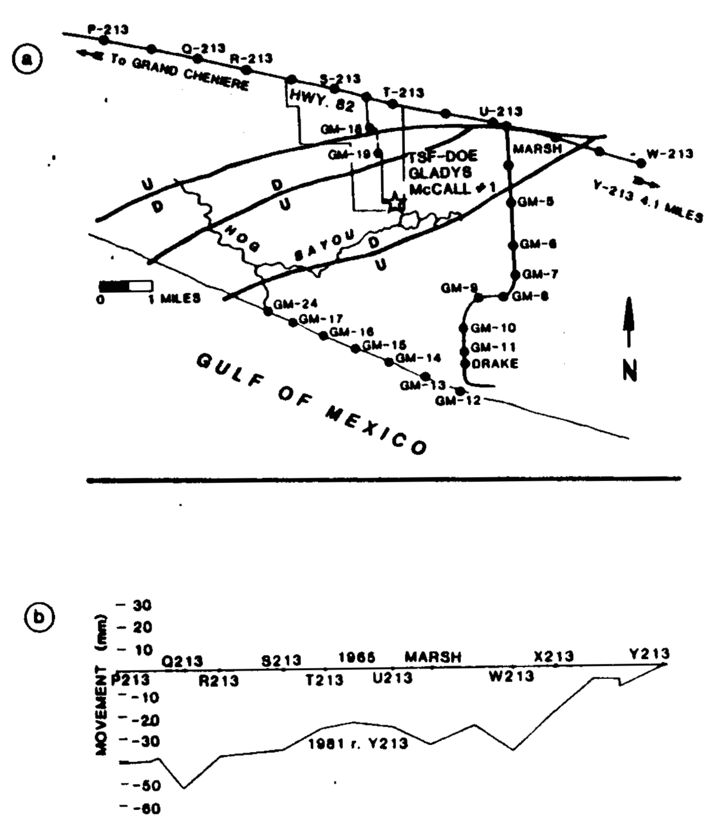


Characteristic stratigraphic cross section through the Gladys McCall test site (see Fig. 1 for well locations).

Fig. 6



a. The Sweet Lake geothermal fault block and historical leveling lines. b. Relative movement of benchmarks along Highway 27. c. Relative movement of benchmarks along Highway 384 and through the test site.



a. The Rockefeller Refuge geothermal fault block and historical leveling lines. b. Relative movement for benchmarks along Highway 82 north of the Gladys McCall design well site.

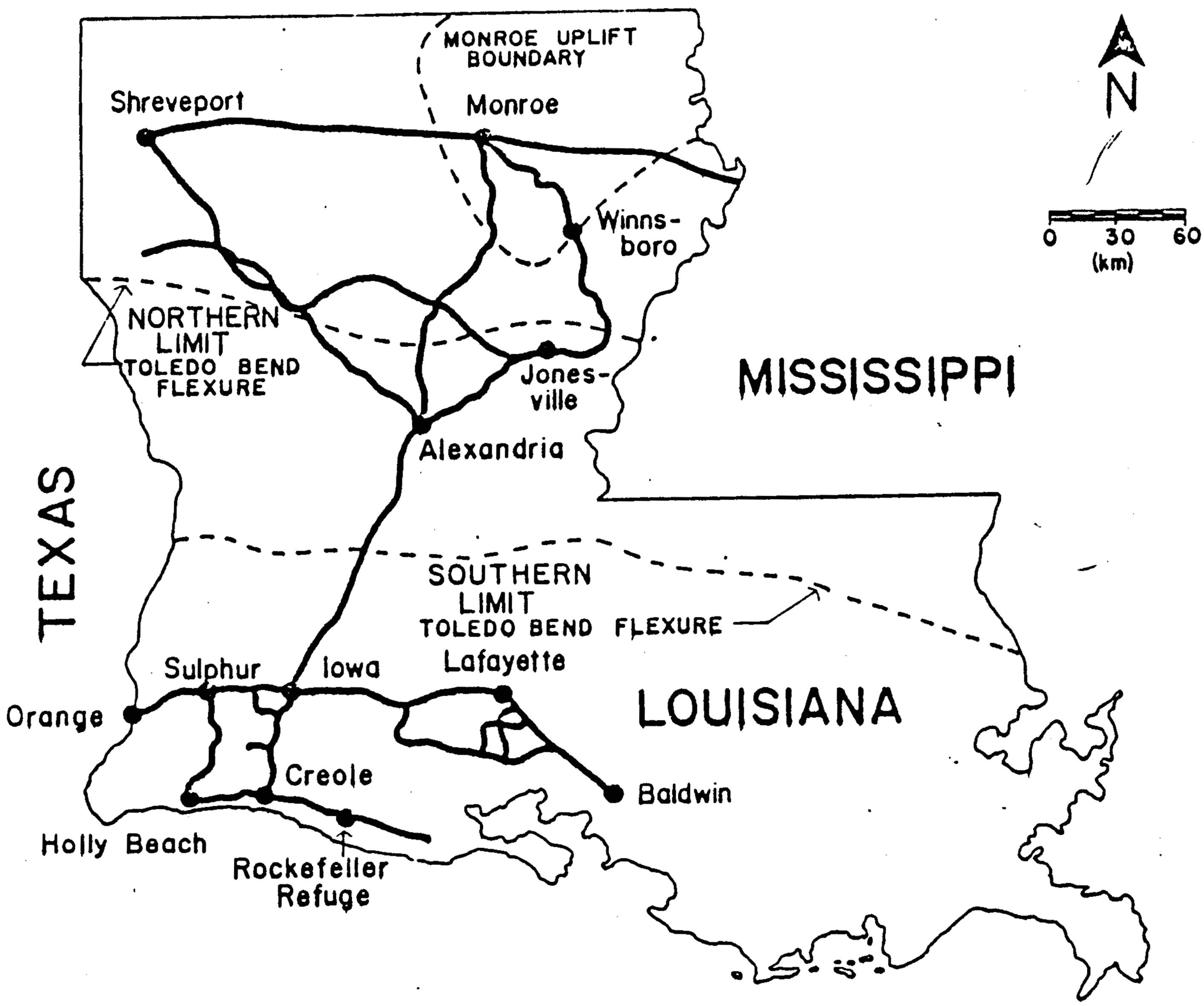


Fig. 7 The Louisiana first-order leveling network showing positions of major junctions and the boundary of the Monroe Uplift.

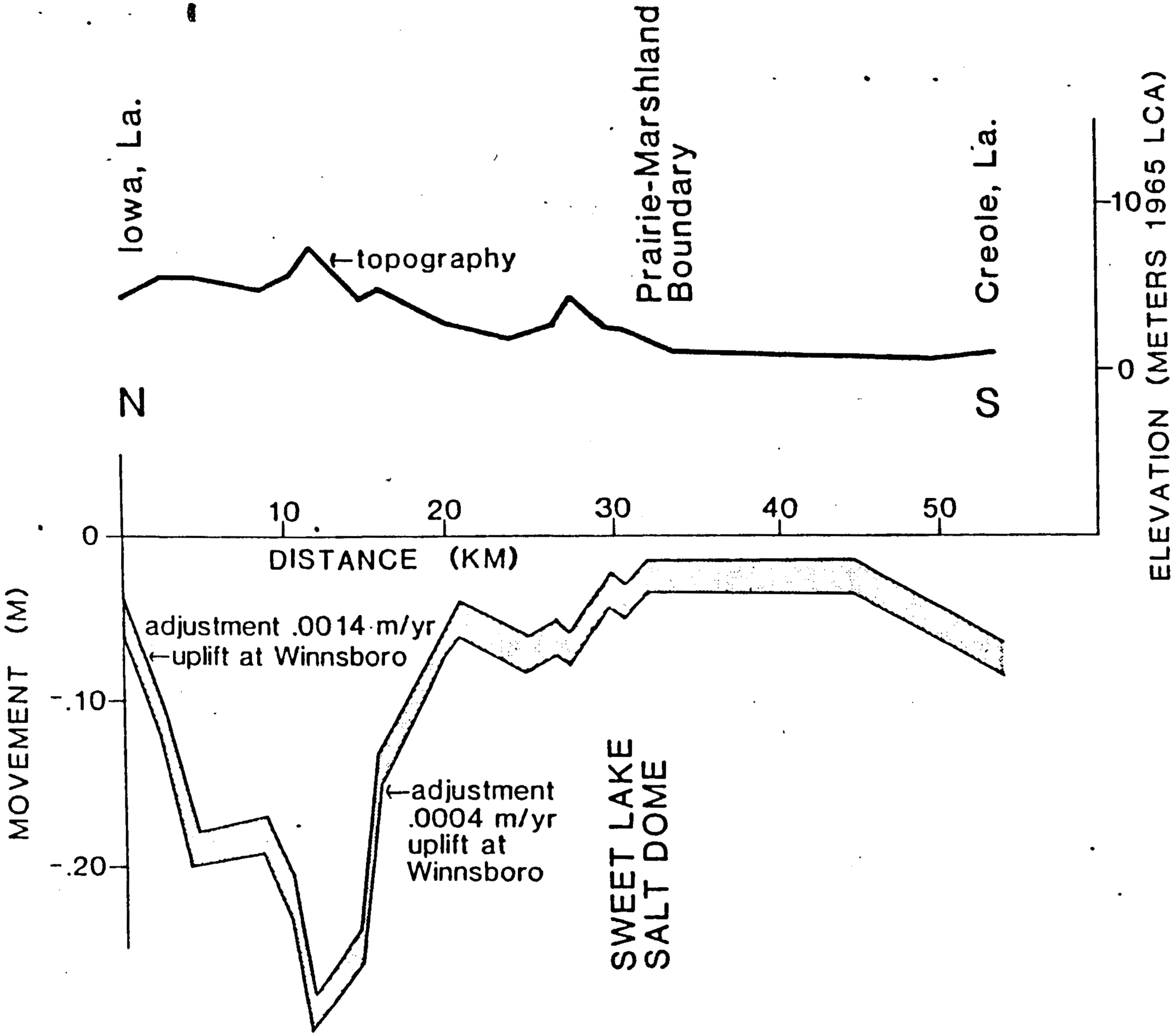


Fig. 8 Total absolute change in elevation based on movement of the Monroe Uplift, Iowa to Creole, Louisiana, 1965 to 1982. Geomorphic and structural features indicated for reference and correlation.

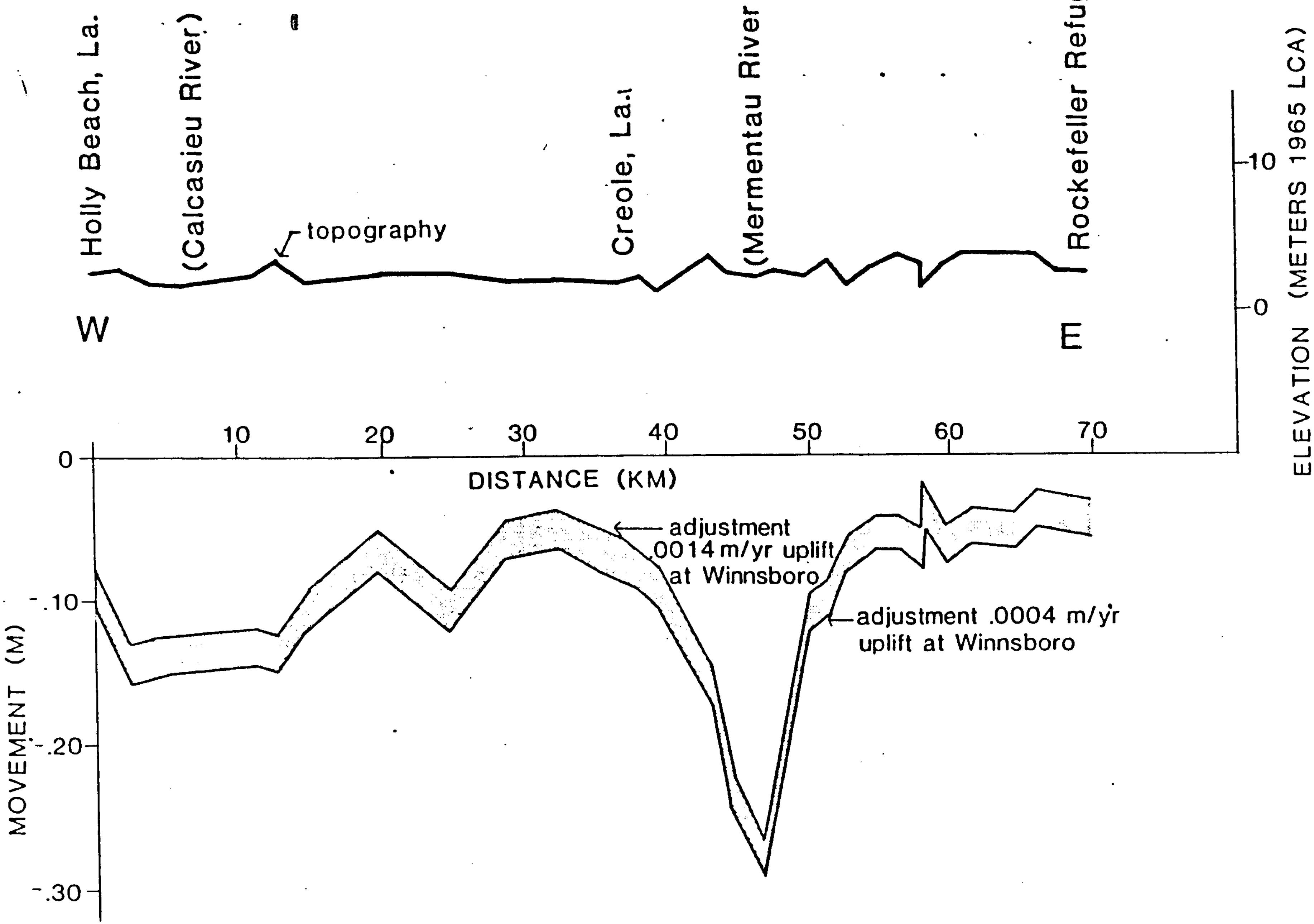


Fig. 9 Total absolute change in elevation based on movement of the Monroe Uplift, Holly Beach to Rockefeller Refuge, Louisiana, 1965 to 1982. Geomorphic features indicated for reference and correlation.

Table 6

Comparison of chemistry between the geopressured-geothermal brine and surface waters, Sweet Lake.

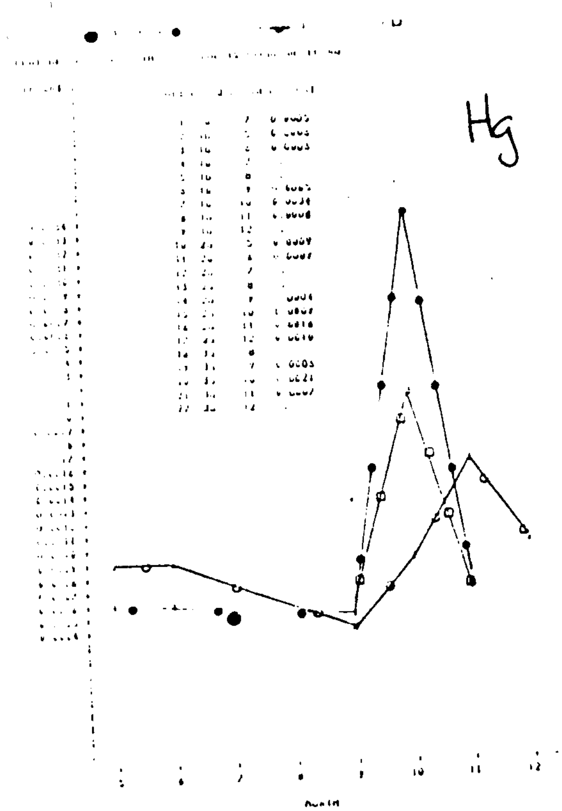
PARAMETER	BRINE AVERAGE	THIS STUDY--1982		U.S. GEOLOGICAL SURVEY--1948-1979	
		Surface	280-435 ft	280-450 ft	950 ft
TDS (ppm)	156,900			722	2,400
Na (ppm)	42,000	275	107	222	865
K (ppm)	1,690	17.400	2.100	5.40	7
Mg (ppm)	630	90	19	13	35
Ca (ppm)	11,200	25	31	29	3.40
Cl (ppm)	92,340	465	47	214	1,270
Sc (umhos)	162,000	1,604	564	1,180	4,270
pH	5.6 @ 50°C	7.300	7.900	8.10	7.600
HCO_3 (ppm)	317			314	301
NH_4 (ppm)	112	0.070	0.070		
Cd (ppm)	0.33	0.002	0.001		
B (ppm)	69	1.400	0.490	0.18	0.08

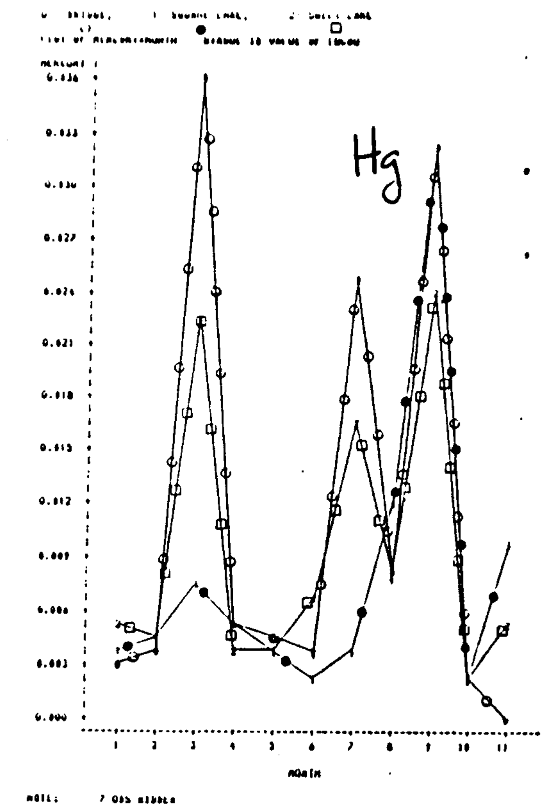
Table 7

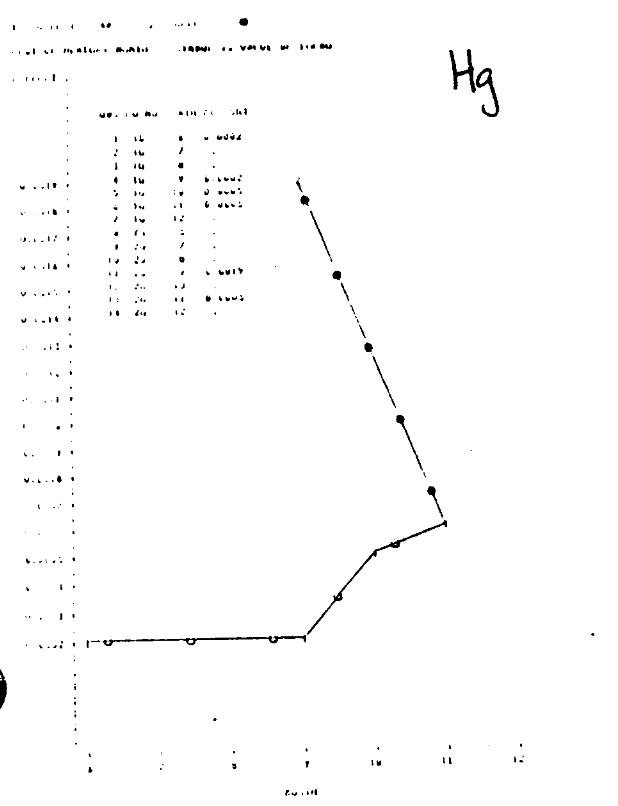
Comparison of surface and ground-water chemistries, Rockefeller Refuge.

PARAMETER	BRINE AVERAGE	THIS STUDY--1982			U.S. GEOLOGICAL SURVEY		
		Surface	310 ft	660 ft	1975 <400 ft	1955 460 ft	1974-75 >500 ft
TDS (ppm)	97,800				628	1,115	3,950
Na (ppm)	29,750	5,547	932	760	225	362	1,400
K (ppm)	430	165	12.160	4.287	3.5	4.05	8.0
Mg (ppm)	354	702	85	31	9.1	18	45
Ca (ppm)	4,040	199	106	45	18	46	90
Cl (ppm)	59,290	9,985	1,620	1,280	165	482	1,510
Sc (umhos)	NA	24,974	4,857	4,070	1,070	2,055	4,785
pH	NA	8.118	7.730	7.812	7.5	7.4	7.6
HCO_3 (ppm)	NA				394	388	288
NH_4 (ppm)	NA	0.198	1.435	1.010			
SO_4 (ppm)	1.000	1,241	83.200	9.860			
Cd (ppm)	0.015	0.003	0.002	0.001			
B (ppm)	36	1.049	0.321	0.195		0.080	

Figure 10


Rockefeller
Hg
Surface W.


Sweet Lake
Hg
Surfase W.


Hg
Ground W.

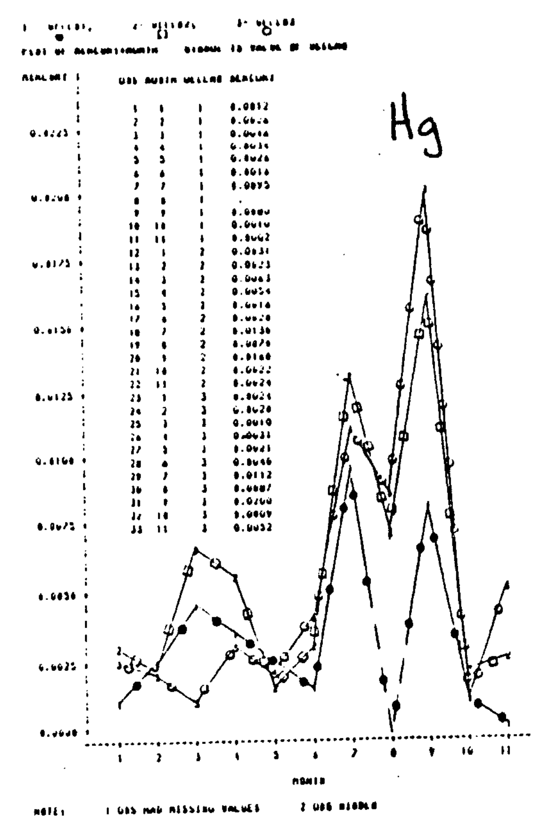
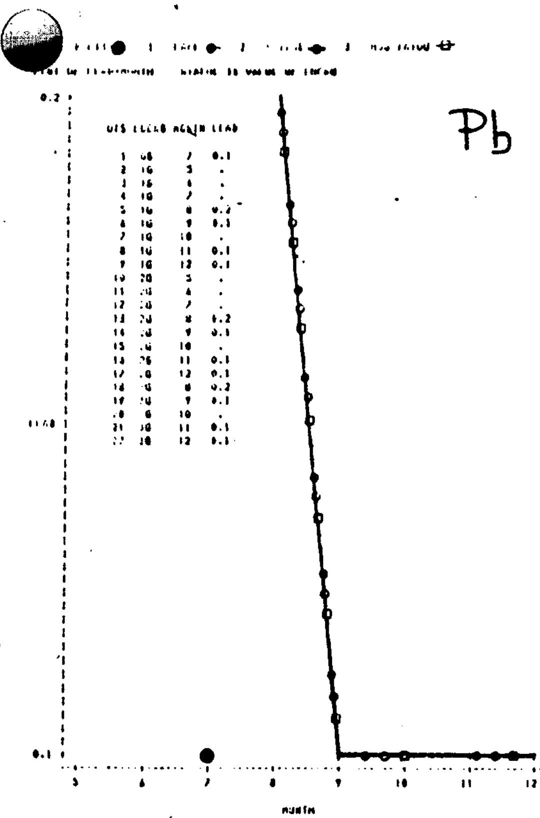
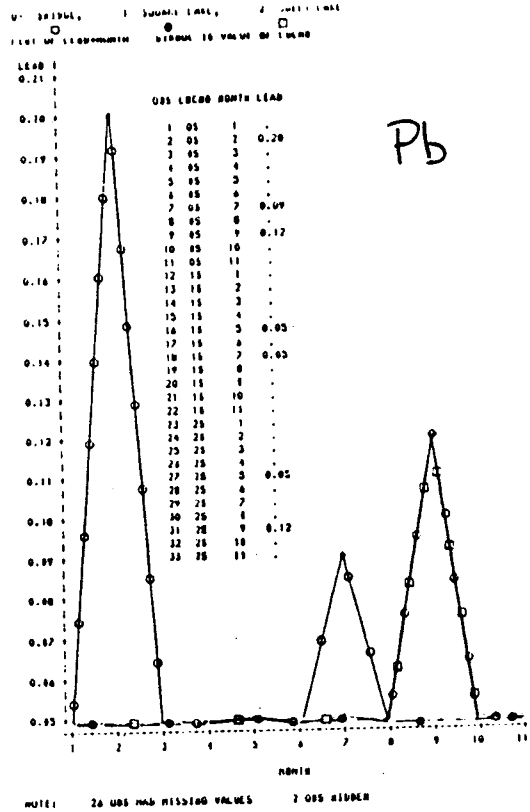
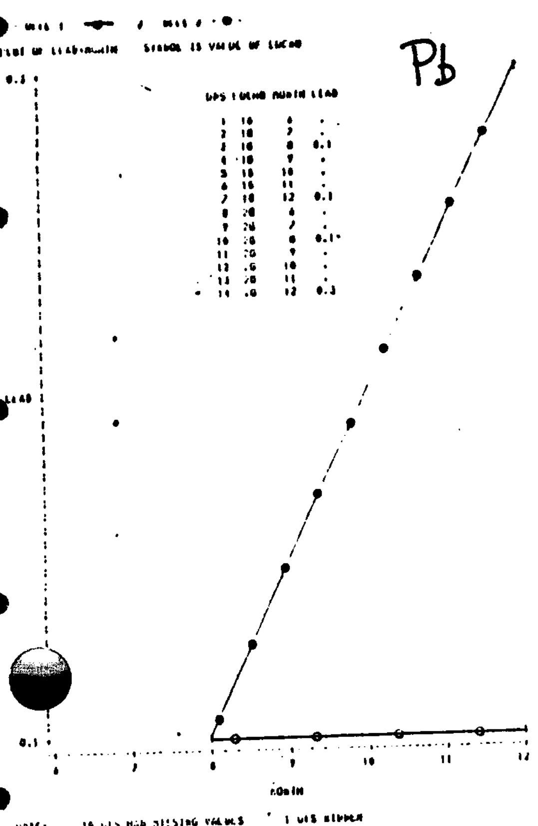

Hg
Ground W.

Figure 11







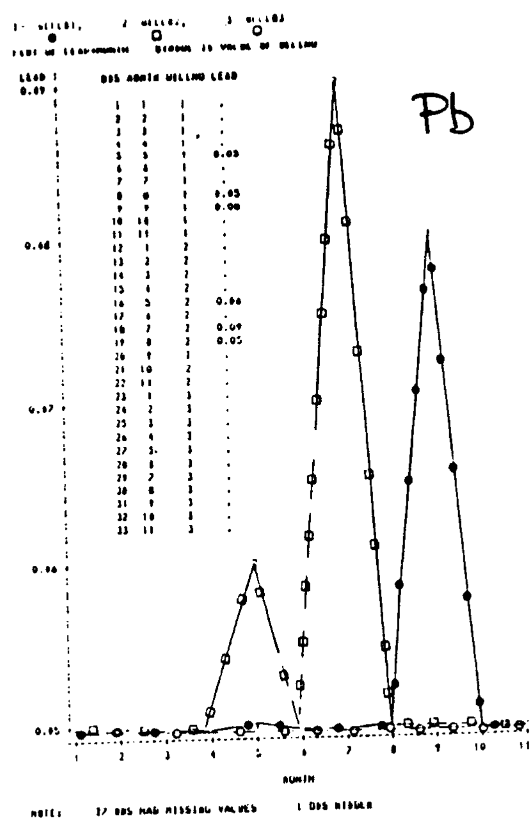
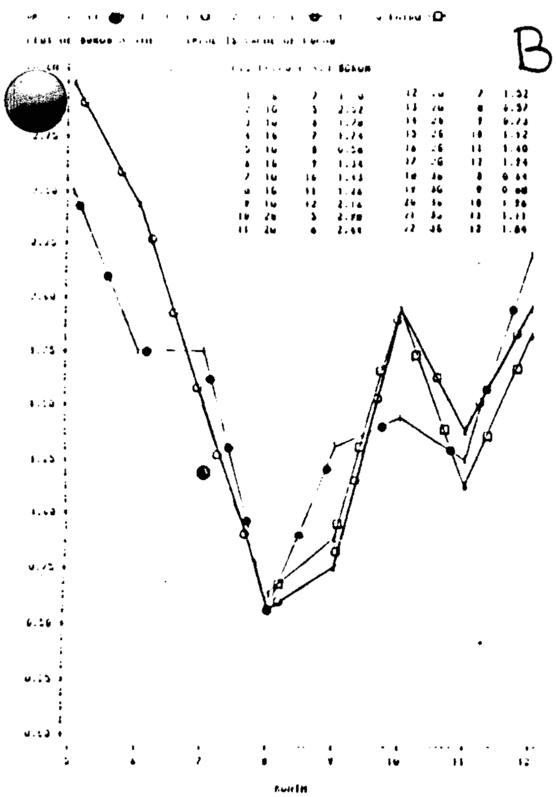
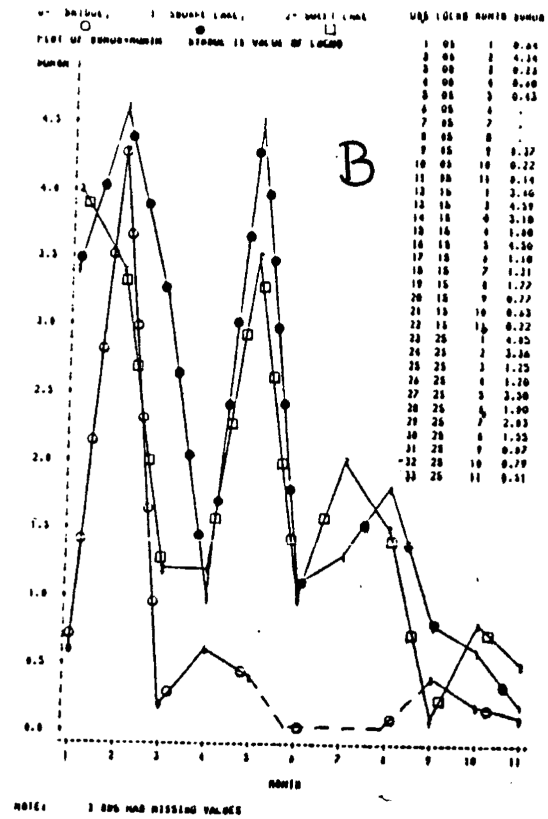
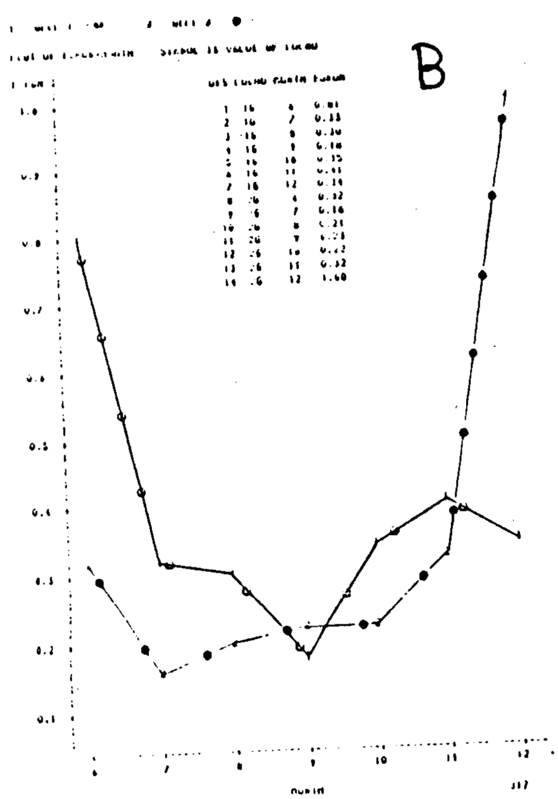


Figure 12







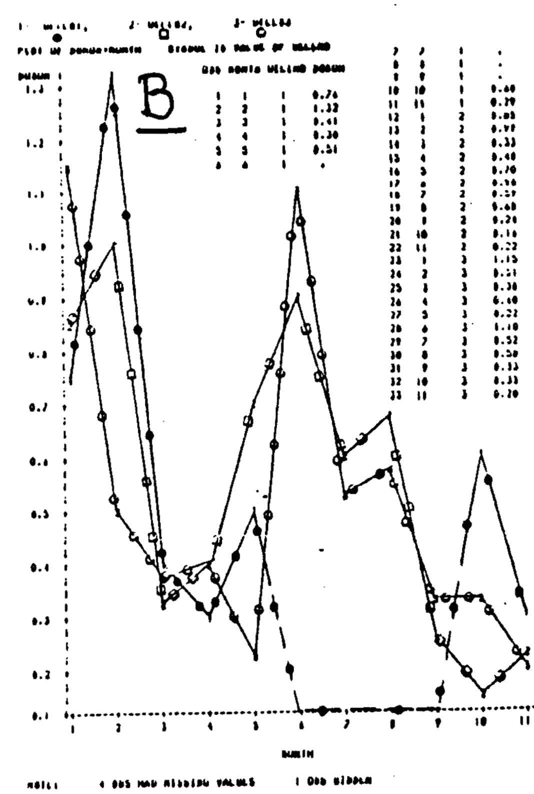
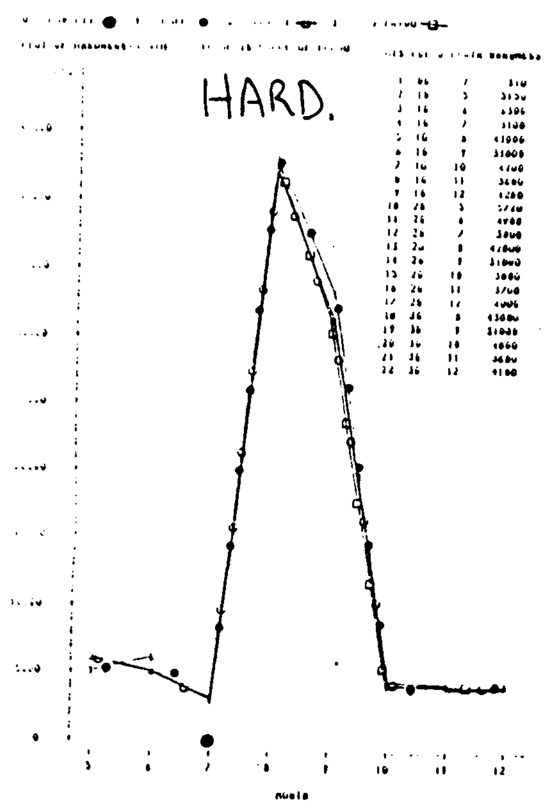
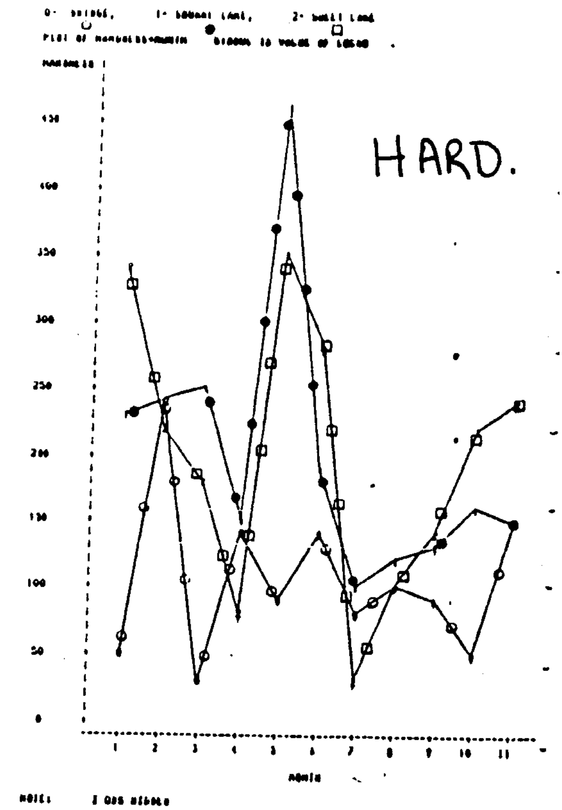
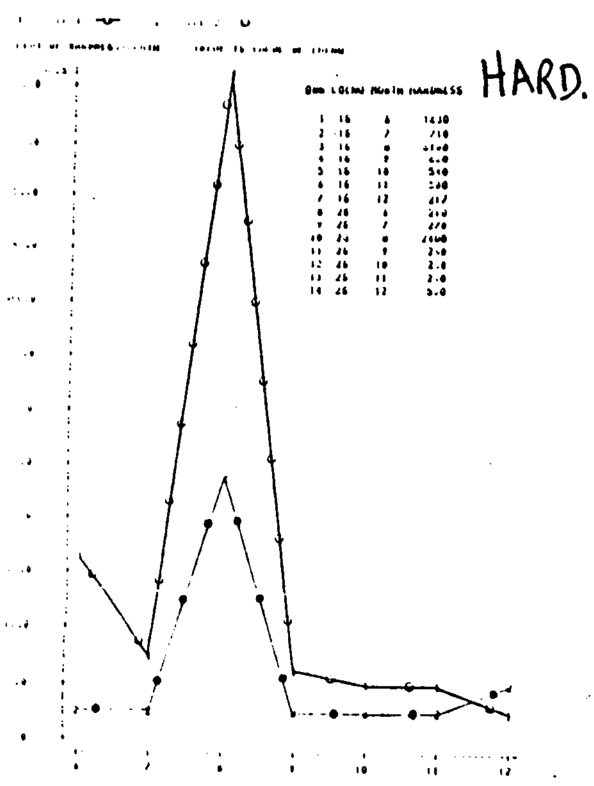


Figure 13







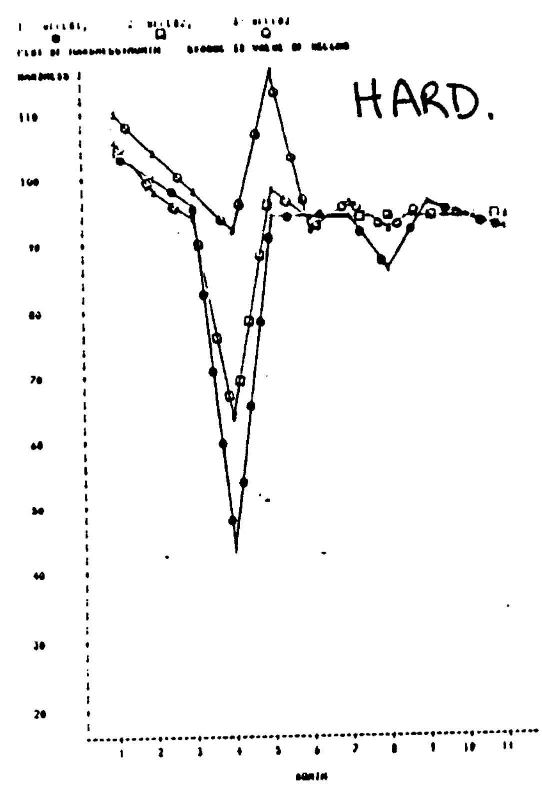
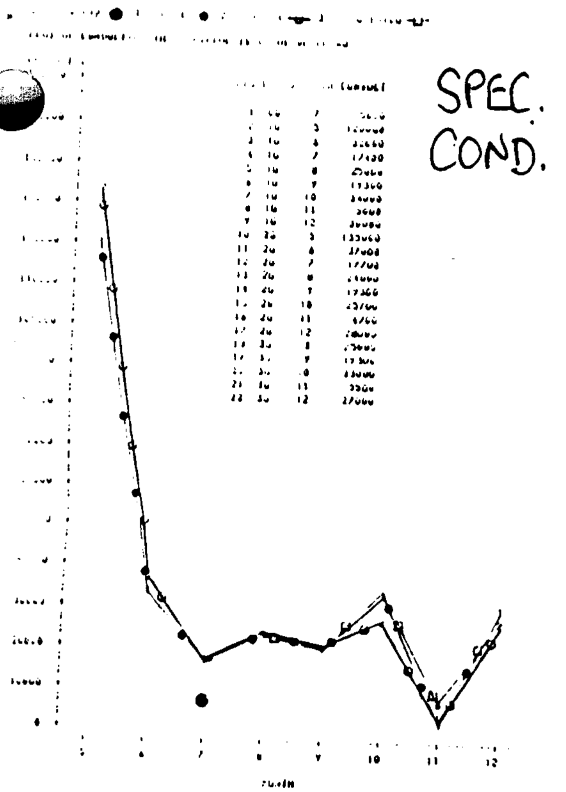
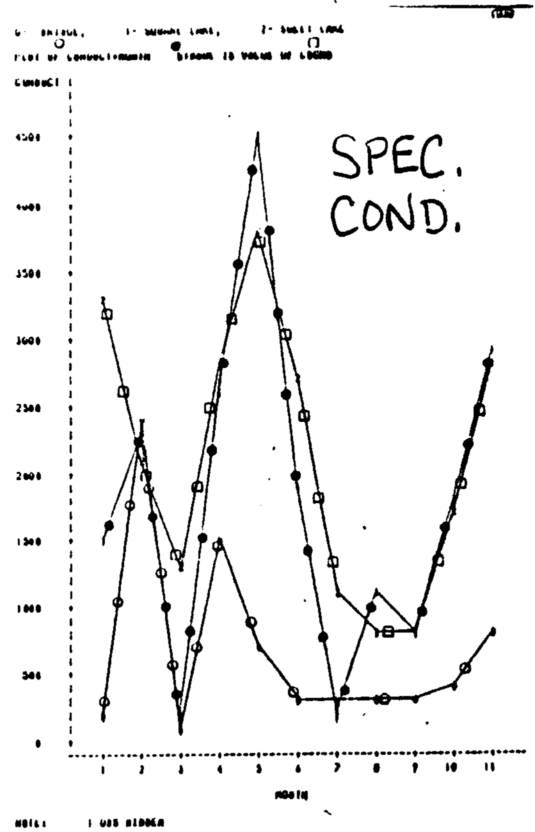
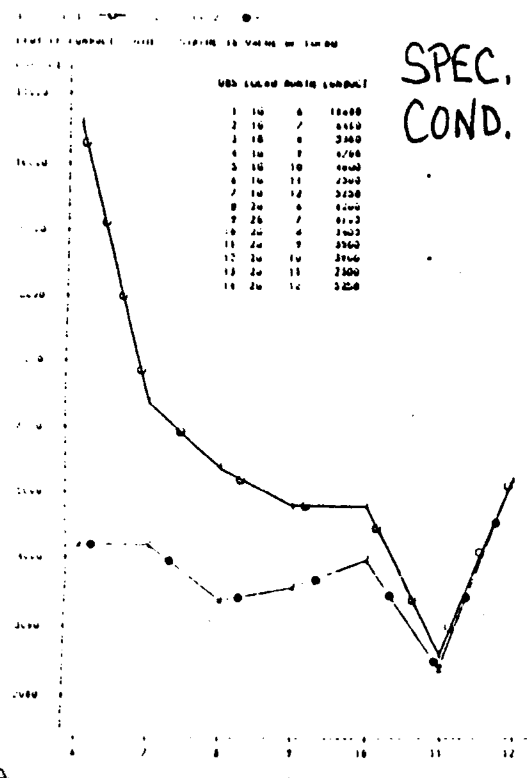


Figure 14







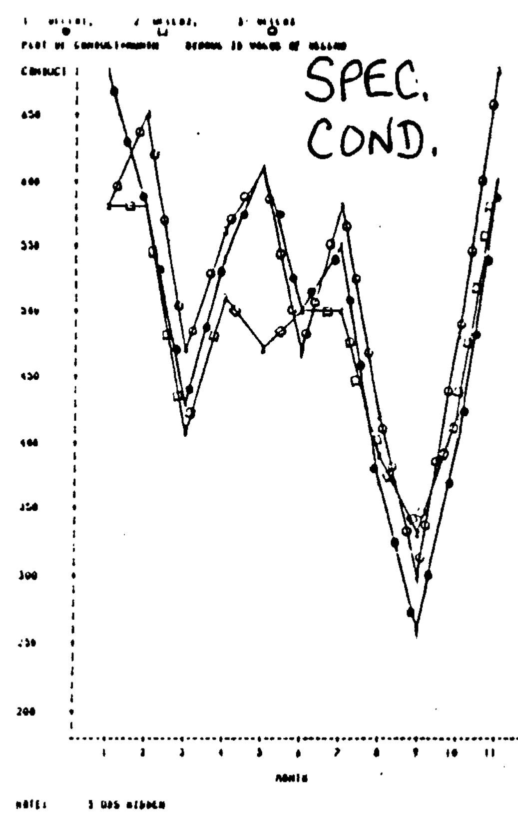
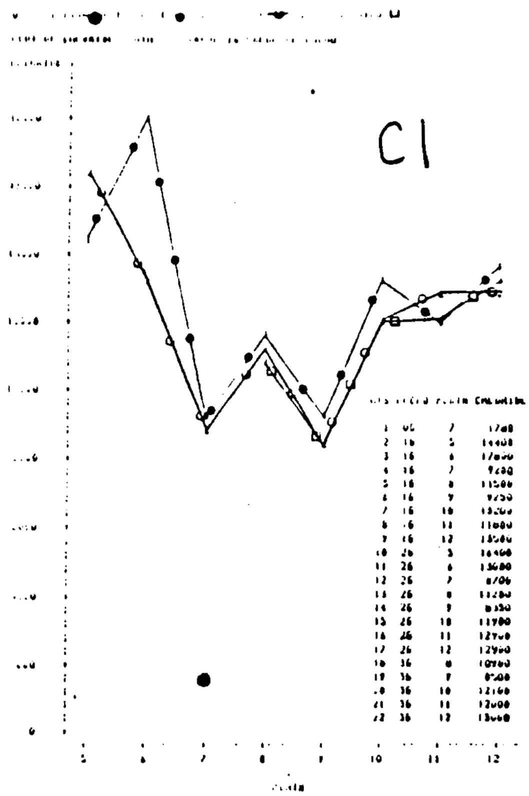
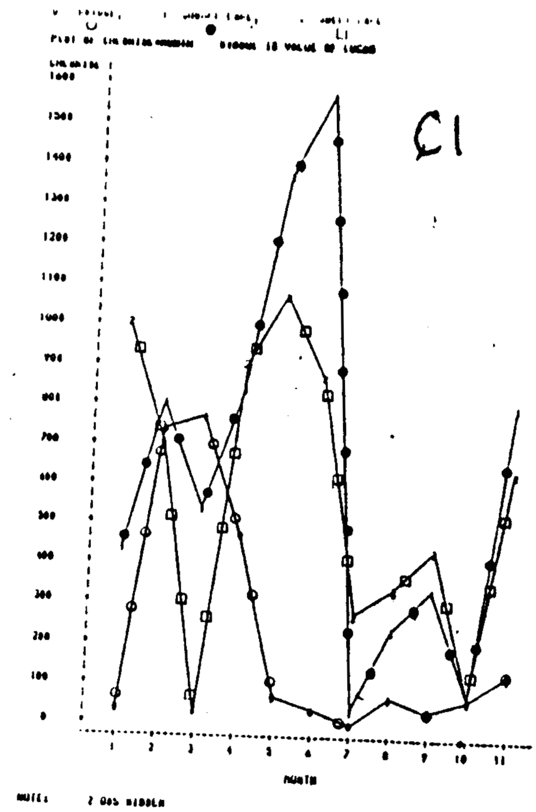
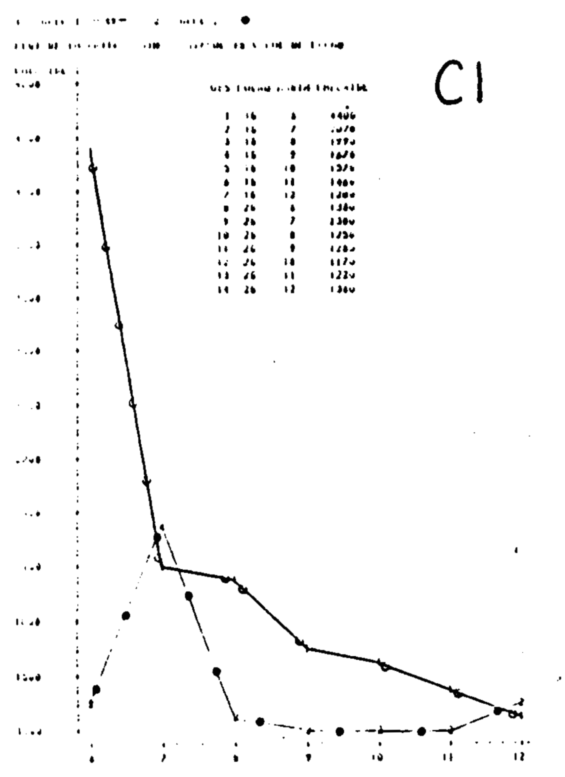


Figure 15







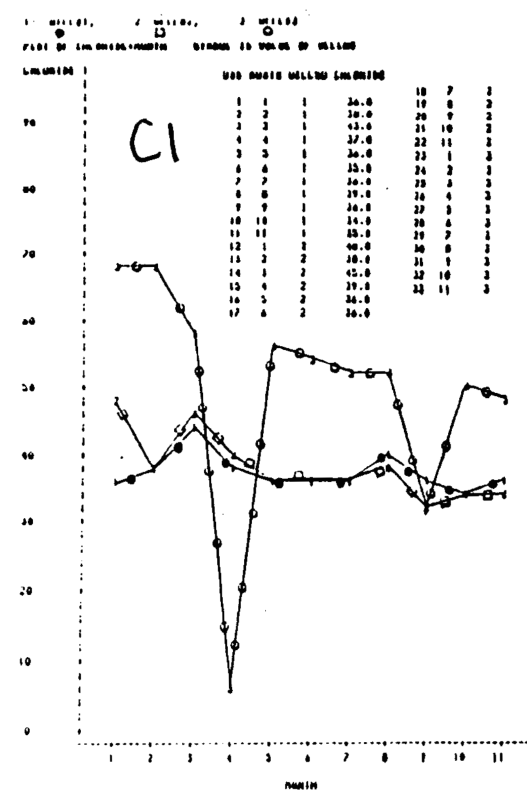
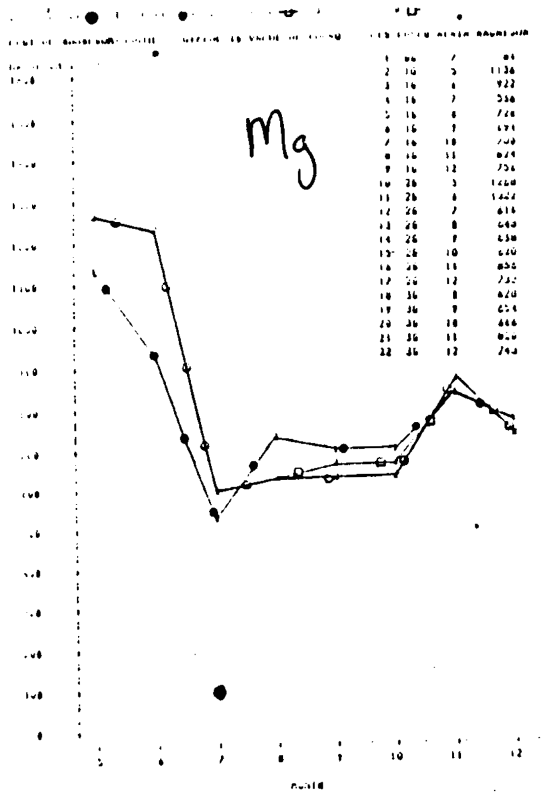
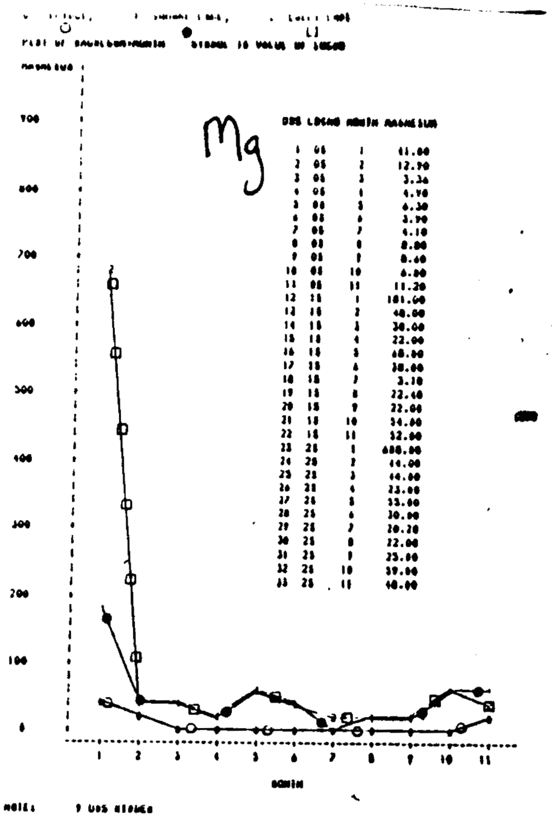
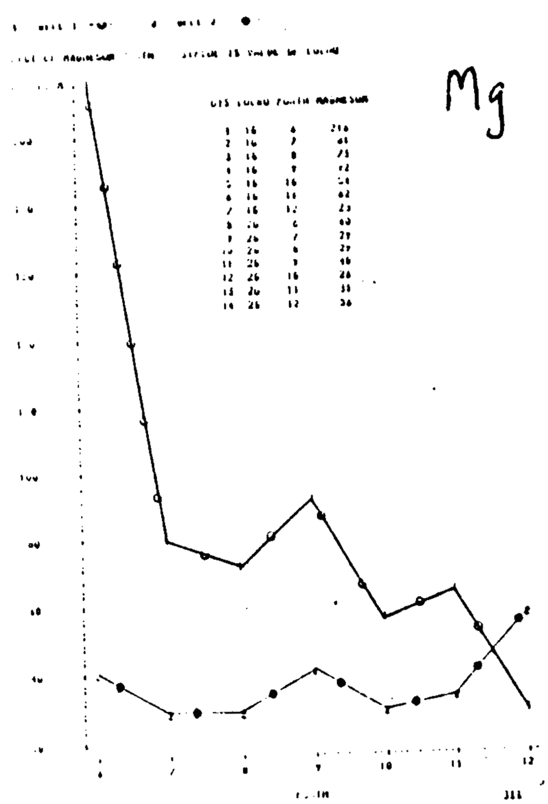


Figure 16







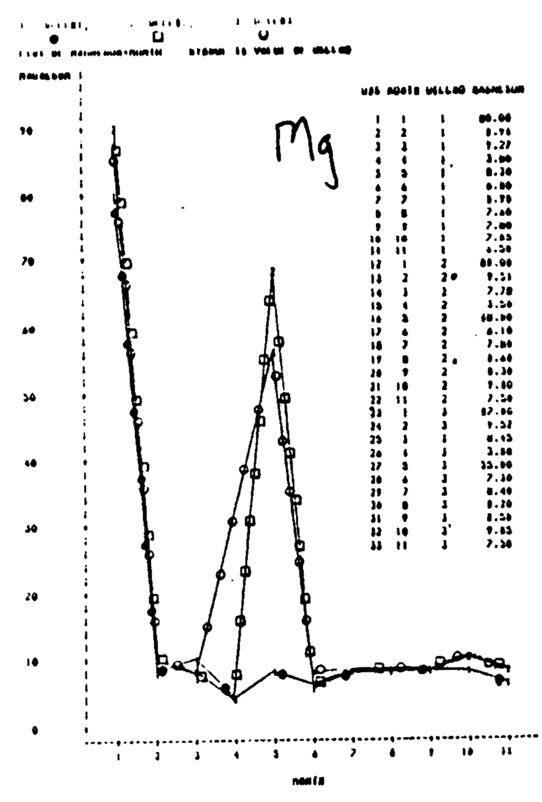
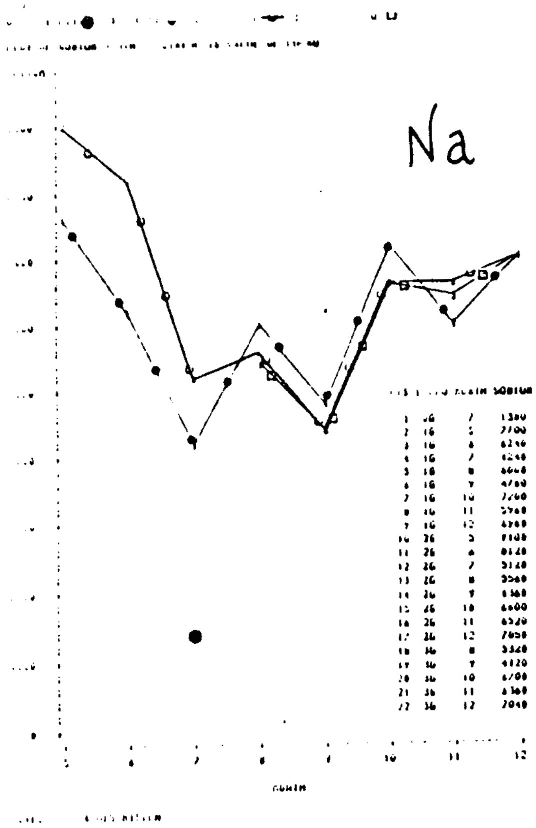
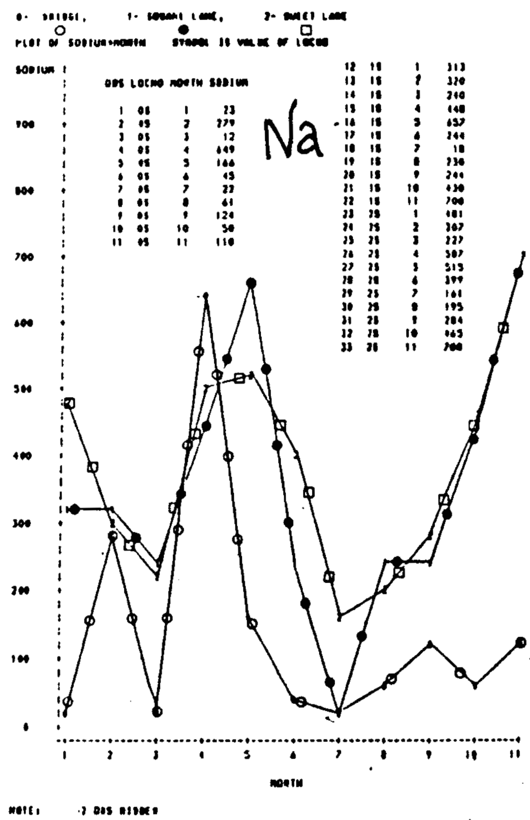


Figure 17


Na


PLOT OF SODIUM*MONTH SYMBOL IS VALUE OF LOCNO
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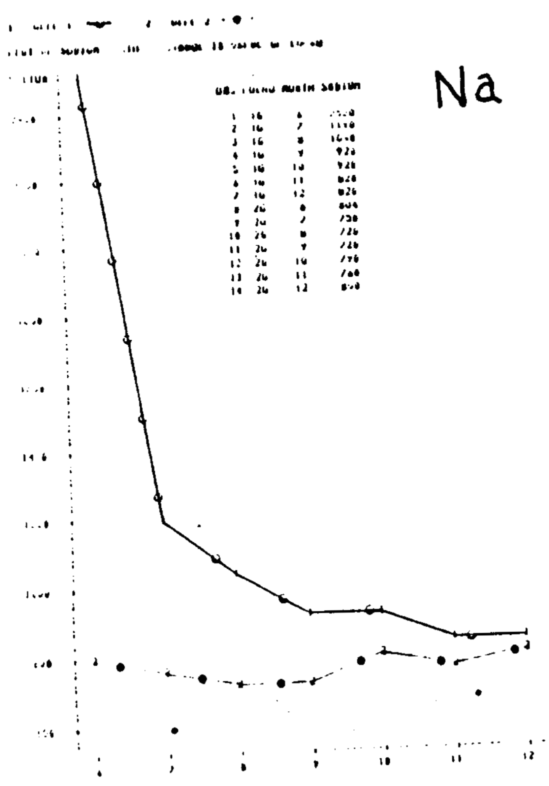
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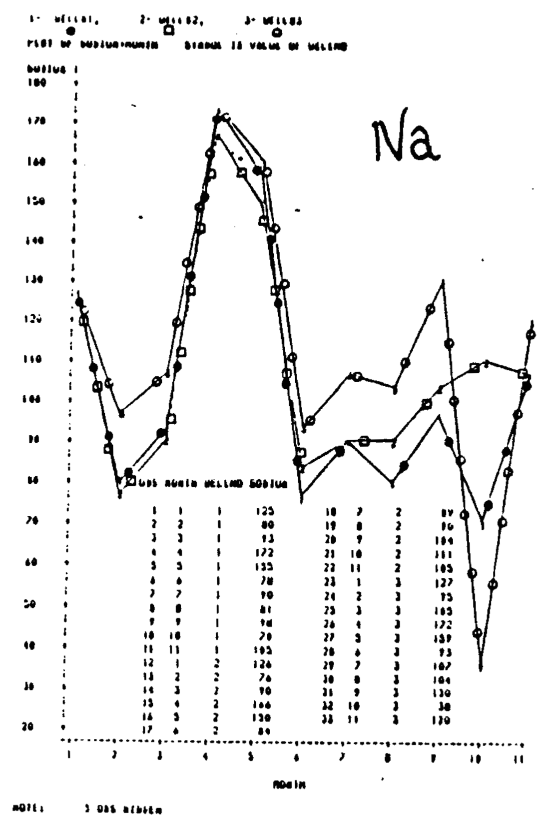
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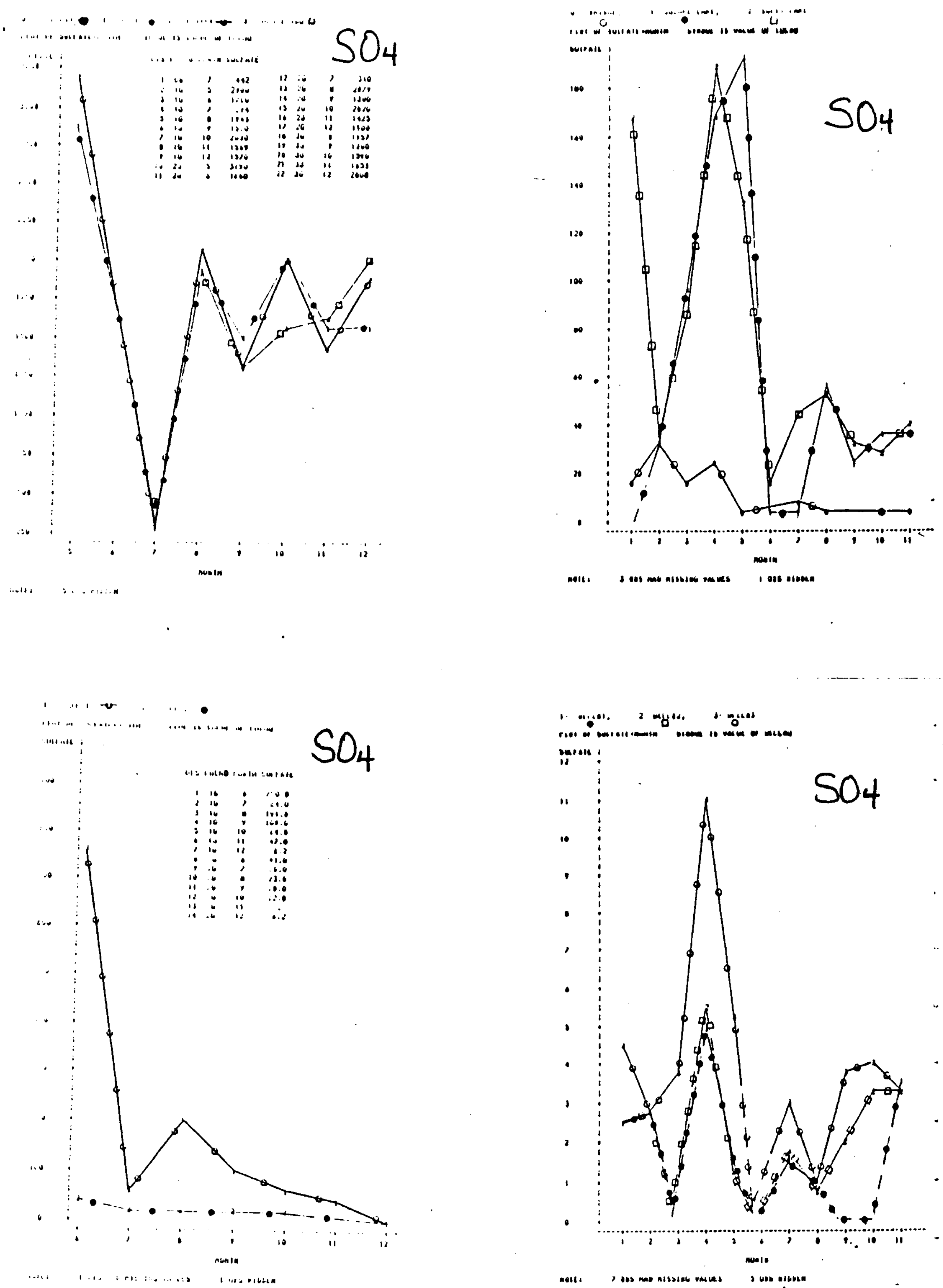
Figure 18



Vertical movement of the lithosphere is a common problem associated with fluid withdrawal from subsurface formations. The vector of movement, in most cases, is downwards by compaction (Gilluly and Grant, 1949; Fatt, 1958; Allen, 1968; and Geertsma, 1937) however, other work (Holzer, 1979) has shown that extraction of very large amounts of water may cause elastic expansion of the lithosphere underlying the producing reservoir thereby creating uplift.

Methods have been defined which attempt to measure and predict the amount and rate of movement above water, oil and gas reservoirs which are or were producing large amounts of fluids. In all attempts, the focus of research has been to model the reservoir of production with parameters that define the microscopic and macroscopic properties of the reservoir. It has been shown (Fatt, 1958; Geertsma, 1973) that the main factor in reservoir compaction is a reduction in pressure. Therefore, it is believed that most vertical movement will occur in strata associated with a reservoir where boundary conditions prevent the maintenance of pressure within the reservoir.

Cases for such a reservoir of fluid production exist in the Gulf Coast of Louisiana and Texas. Geopressure-geothermal reservoir brines are being tested by the U. S. Department of Energy for development of energy utilizing the high temperature, high pressure and dissolved methane characteristics of the geopressured resource. These reservoirs are trapped within faulted blocks of massive shales. Pressures in the reservoirs have been increased and maintained due to hydrostatic loading without release of pressure; the rate of fluid expulsion is slow due to very low permeabilities in the adjacent shales.

Models of geothermal subsidence have been extensively reviewed by Pinder (1979) and Miller et al. (1980a & b). These models are based mainly on geothermal production in California where the source of geothermal energy is hot rock. Their models are relevant to geopressure-geothermal reservoir modeling based on system thermal and mass transfer relationships. Other models which are mode applicable to Gulf Coast systems are those which have been developed for oil and gas systems. Where appropriate, hot-rock geothermal models will be taken into consideration. The emphasis here however, is on subsidence modeling above reservoirs which are producing fluids from sedimentary "rocks" like those in the Gulf Coast, these "rocks" can be described as soft, plastic, and brittle and in some cases may not even be classified as true rocks since they are unconsolidated.

MODELS OF COMPACTION AND SUBSIDENCE

As mentioned previously the most significant parameter effecting the compaction and resulting subsidence of the subsurface reservoir is reduction in pressure. This phenomenon was discussed in a case history for the Long Beach harbor area in California (Gilluly and Grant, 1949). Reductions in pressure in the Wilmington oil field were strongly correlated with subsidence of the land surface. Secondary factors considered were volume of fluid withdrawn, the thickness of fluid-saturated sands, and the spacing of producing wells. The reduction in pressures was a result of the lack of water influx through the reservoir boundaries. Assuming that the reservoir, in its natural state, was at hydrostatic equilibrium, a reduction in pore pressure within the reservoir increased the hydrostatic load on the reservoir. The strata above were then allowed to sink into the reservoir replacing the lost pressure and thereby maintaining a new hydrostatic equilibrium. This relationship was presented by the formula:

$$P = \frac{D \times 62.5 \times (1-\infty)\rho}{144}$$

where P = pressure on horizontal surface in lbs/in.

$(1-\infty)$ = volume ratio of grains to total volume of sediment,

ρ = density of grains comprising the reservoir corrected for the bouying effect of water, and

144 = one square in inches.

For an oil sand capped with a shale bed of low permeability, additional terms were incorporated into eq. 1:

$$P = \frac{(1-\infty) \times 2.7 \times 62.5 \times D + \infty \times 64 \times D}{144}$$

where 2.7 = specific gravity of sand grains, and

64 = the weight of one cubic foot of sea water.

These equations give the maximum load, per square inch. that can be placed upon an impermeable membrane at given depths.

To obtain the data necessary for calculations the authors relied on production data for distribution and amount of pressure reductions. Structure contour maps of the producing reservoir indicated thickness of reservoir sands. Mechanical properties were determined in the laboratory using the relationship:

$$\frac{L_o - L_s}{L_o} \times E = P_s - P_o$$

where L_o, P_o = original length and stress,

L_s, P_s = length and stress under load, and

E = Young's modulus.

This equation provides a basis for determining the shortening, within the elastic limit, of any material under load. The coefficient derived from this relationship is the compression modulus:

$$c = \frac{P_s - P_o}{L_s - L_o} \times \frac{1}{L_o}$$

This coefficient is related to grain shape, sorting, elasticity and depth of burial for a given reservoir material.

Another model of reservoir compaction was provided by Fatt (1958). Using the models, Fatt equated rock bulk compressibilities and rock composition:

$$c_B = M c_m + c_g G$$

where M = intergranular material content,

c_m = intergranular material compressibility,

G = grain content, and

c_g = grain compressibility.

This rock bulk compressibility is the volume change a reservoir undergoes as fulid pressure is depleted.

Since grain content is equal to the total volume of rock minus the intergranular material, the formula reduces to:

$$c_B = M(c_m - c_g) + c_g$$

Fatt (1958) also found that a relationship between and existed only when well sorted and poorly sorted sands were treated separately. Thus Fatt's measured compressibilities were a linear function of composition for a given grain shape and sorting.

The compressibility of porous rock is also a function of the applied external pressure and the pore fluid pressure related by the equation:

$$c_B = 1/V_B \left(\frac{\partial V_B}{\partial P_e} \right)_{P_i}$$

where P_e = external hydrostatic pressure,

P_i = pore fluid pressure, and

V_B = bulk volume.

Fatt (1958) also introduced many other relationships necessary in the analyses of compressibility data. These are:

1) Pore volume compressibility:

$$C_{pt} = 1/V_p \left(\frac{\partial V_p}{\partial P_i} \right)_{P_e}$$

where V_p = pore volume or porosity,

2) Pseudo bulk volume compressibility:

$$C_{BL} = 1/V_B \left(\frac{\partial V_B}{\partial P_i} \right)_{P_e}$$

3) Pore volume compaction:

$$C_p = 1/V_p \left(\frac{\partial V_p}{\partial P_e} \right)_{P_i}$$

4) Compressibility of total solid material:

$$C_r = \frac{1}{(V_B - V_p)} \left(\frac{\partial (V_B - V_p)}{\partial P} \right)$$

5) Net overburden pressure:

$$P_{ne} = P_e - n P_i$$

where n = a constant between .50 and 1.00 which takes into consideration that a given increase (or decrease) in internal pressure does not change the bulk volume or length of a reservoir the same as an equal decrease (or increase) in external pressure. Because the internal pressure in a formation is only about 85% effective in conteracting overburden pressure, formula 12 reduces to:

$$P_{ne} = gh \left(P_e - 0.85 P_i \right)$$

where g = acceleration due to gravity, and
h = depth of formation.

Geertsma (1973) stated that this same constant, n is a function of the bulk volume and the compressibility of the solid matrix. He derived the function:

$$C_B = \frac{1}{V_B} \left(\frac{\partial V_B}{\partial P_e - \frac{C_B - C_r}{C_B} \partial P_i} \right)$$

Geertsma also provided conditions for subsidence of the land surface above compacting oil and gas reservoirs:

1) A significant reduction in pressure must take place during production.

2) Production is effected from a thick vertical interval

3) Producing fluids are contained in loose or weakly cemented rocks, and

4) The reservoirs have a rather small depth of burial.

Considering that reservoirs deform predominatly in the vertical plane, Geertsma (1973) characterized formation compaction by the vertical strain in the reservoir:

$$E_z = dz/z$$

where E_z = formation compaction.

dz = change in height, and

z = initial height.

This is due to an increase in effective stress caused by a reduction in reservoir pore pressure under a constant overburden. The uniaxial compaction coefficient is therefore defined as the formation compaction per unit change in pore pressure:

$$c_m = 1/z\left(\frac{\partial z}{\partial p}\right) \quad \text{or} \quad E_z = c_m dp$$

Note the similarity between equation 16 and equations 7 through 10 which Fatt (1958) used to describe the compressibilities of the various constituents of the reservoir matrix.

Geertsma's (1973) final equation for reservoir compaction was derived assuming the uniaxial compaction coefficient constant for a given volume of reservoir.

$$\Delta H = \int_0^H c_m(z)\ \Delta p(z)\,dz$$

where ΔH = total reduction in reservoir height, and

$\Delta p = p_f - p_i$ (future minus initial reservoir pressure).

The reduction in reservoir pressure as a function of temporal and spatial variability depends on:

1) mobility,
2) solubility
3) density, and
4) compressibility of fluids, and
5) reservoir boundary conditions (faults, edge of bottom water, etc.).

The rate and degree of pore pressure reduction depends on:

1) Permeability distribution,
2) Location of wells, and
3) Production rate in relation to the rate of encroaching edge or bottom water.

The compaction coefficient depends on:

1) rock type,
2) degree of cementation,
3) Porosity, and
4) Depth of burial,

The number, size and shape of grain contacts controls deformation in sandstones. In limestones, the shape and strength of the rock skeleton controls deformation. Furthermore, compressibility in sandstones is related to the degree of cementation. In general, a transition from elastic to cataclastic occurs as the degree of cementation decreases. Well cemented rocks may rebound during unloading whereas loosely cemented rocks are permanently deformed due to crushing and rearrangement of grains. A good measure of degree of cementation is porosity since porosity also increases with decreasing cementation. Compressibility and porosity therefore, should be directly proportional.

The problem of compaction and subsidence above producing reservoirs can be treated as one of an isolated volume of reduced pore pressure in a variably porous, elastically deforming half-space with a traction-free surface (Geertsma, 1973). Homogeneity of the reservoir is implied. The nucleus of strain concept can then be applied where subsidence is due to a nucleus of strain of small but finite volume, V, under the influence of a pore pressure reduction, ΔP so that:

$$\mu_z(r,0) = -\frac{1}{\pi} c_m (1-\nu)\left(\frac{D}{(r^2+D^2)^{3/2}}\right)\Delta P V$$

where $\mu_z(r,0)$ = vertical displacement perpendicular to a free surface,

c_m = uniaxial compaction coefficient,

ν = Poisson's ration,

D = depth of burial of nucleus, and

r = radial distance from vertical axis through nucleus.

The subsidence above a disc-shaped reservoir can now be determined by integrating the nucleus solution over the entire reservoir volume. Since the reservoir is assumed to be homogeneous, c_m and ν are constant:

$$\mu_z(r,0) = -2 c_m (1-\nu)\Delta P H R \int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r)\, d\alpha$$

Bessel functions of 0 and 1st order are represented by the values of J_0 and J_1 respectively. With dimensionless ratios, $\rho = r/R$, $\eta = D/R$ so that the intergral reduces to:

$$\mu_z(r,0) = -2 c_m (1-\nu)\Delta P H A(\rho,\eta)$$

Values for A can be obtained from tables such as that reproduced in Table 8. Further reduction of equation 20 can be accomplished by recalling equation 16, therefore:

$$\frac{\text{Subsidence}}{\text{Compaction}} = -2(1-\nu)A \sim 1.5A$$

TABLE 8.—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 $\eta = D/R$

ρ	η = 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

Similar relationships were recognized by Teeuw (1971) in his analysis of laboratory compressibility data. He noted that with a decrease in reservoir fluid pressure, the effective vertical stress or the difference between overburden pressure and fluid pressure increases and the reservoir is able to compact. Teeuw (1971) provided the same formula for actual compaction as Geertsma (1978) which is represented by equation 16. However, his uniaxial compaction coefficient is related to Poisson's ratio, ν and the rock bulk compressibility, c_b directly:

$$c_m = 1/3\left(\frac{1+\nu}{1-\nu}\right)(1-\beta)c_b$$

where β = the ratio of rock matrix to rock bulk compressibility, or c_{ma}/c_b

As mentioned in the beginning paragraphs, state-of-the-art reservoir modeling studies of geothermal energy production have been reviewed extensively by Pinder (1979) and Miller et al. (1980a & b). These models however, focused on compaction and subsidence which may result from production of hot-rock geothermal energy in California. The models do have application to geopressure-geothermal subsidence since they too involve the parameters listed below:

1) fluid pressure and composition,
2) fluid flow,
3) temperature,
4) stress,
5) deformation, and
6) time.

Perhaps these models can be integrated with models of oil, gas and groundwater production for a more concise definition of geopressure-geothermal compaction and subsidence. These models are, however, too involved to be included here. One of their diagrams is reproduced (Fig. 19) to take advantage of their conception of problems associated with geothermal reservoir modeling. Strongest consideration is given to the idealization necessary in existing models which are based on assumptions of hemogeneity, constant thickness, and other simplifications. Certainly, a most efficient model would consider vertical and lateral variations in porosity, permeability, grain shape, size and sorting, temperature, pressure and a host of other parameters which influence reservoir compaction and subsidence. It should also be kept in mind that many of these parameters are interrelated.

SAMPLING HANDLING AND PREPARATION

Some sample handling problems and techniques were discussed by Newmann (1973). One of his primary concerns was for the preservation of in-situ rock properties for laboratory compressibility analyses. Problems are not as great for consolidated samples as for unconsolidated samples. The use of a rubber-sleeved coring tube can minimize the disturbance of unconsolidated samples and can help to maintain in-situ pressures and temperatures in consolidated and unconsolidated samples. Wrapping cores in foil and paraffin at the ground surface is a common practice in the oil industry. Studies that rely on existing data should be aware of these restraints.

The parameters to be measured include:

1) Porosity,

2) Overburden Pressure,

3) Pore Pressure,

4) Effective Pressure

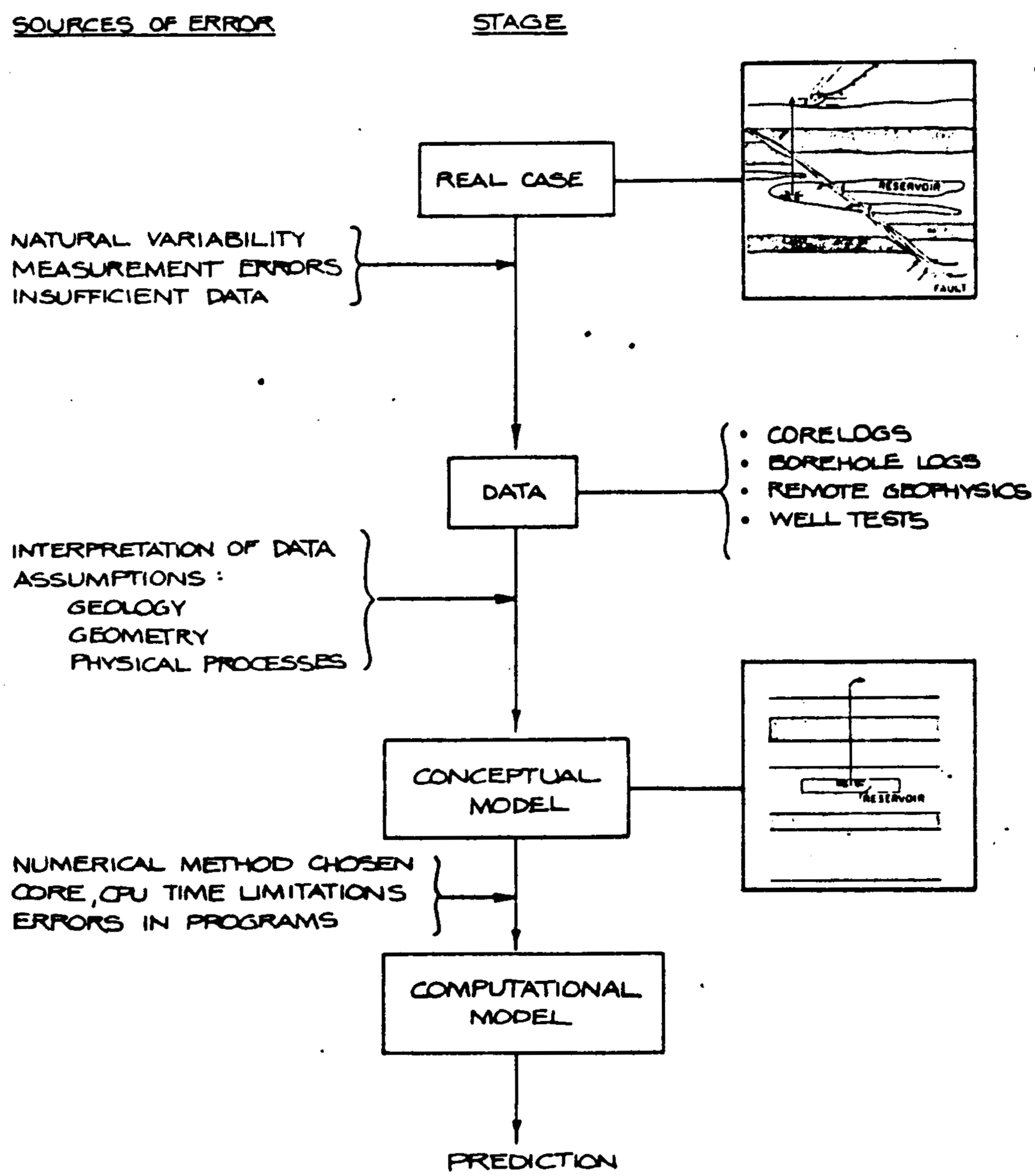


FIGURE 19
GEOTHERMAL SUBSIDENCE PREDICTION PROCESS

5) Volume change, and

6) Pore volume compressibility.

Many of these parameters can be measured or estimated in the field or from well logs, ie. porosity, overburden pressure, pore pressure, effective pressure, and volume changes. Pore volume compressibility is almost always measured in the laboratory based on the uniaxial compaction coefficient. Instruments used to measure these parameters include oedometer cells and triaxial cells (Teeuw, 1971) and potentiometers (Fatt, 1958). With these instruments, lateral deformation of the sample is prevented by the appropriate adjustment of lateral stress. The cells are designed as bombs which are capable of producing pressures, temperatures and/or stresses similar to in-situ reservoir conditions. Volume changes can be measured in the field with casing collar logging (Allen, 1968) where casing joint lengths are determined magnetically through time, or with extensometers (Whiteman, 1980). An extensometer consists of a pipe anchored down at depth below the stratigraphic interval of interest. The pipe is allowed to float freely within a casing which is also completed near the bottom of the interval. As compaction of the strata results, the land surface surrounding the top of the pipe subsides in relation to the pipe, thereby allowing direct measurement of the compacting interval. These extensometers can also be used as wells to monitor groundwater. Properly completed oil and gas wells my serve as existing extensometers for observations in deeper intervals.

SUMMARY

Geopressure-geothermal reservoirs are much like oil and gas reservoirs except for abnormally high temperatures and pressures and a mainly brine composition. Compaction and subsidence in producing reservoirs is due mainly to reduction in pressure which increases the effective vertical stress within the reservoir resulting in compaction. Other variables include the depth and thickness of the reservoir, well spacings, the size, shape, sorting and composition of mineral grains, flow characteristics, and the nature of boundary conditions.

Models of geopressure-geothermal subsidence should therefore rely mainly on, contributions from the oil and bas industry. Various models should be integrated to take into account all variables which define the reservoir under consideration. In addition, contributions from hot-rock geothermal areas may also be incorporated for consideration of temperature and mass-transfer relationships.

REFERENCES

1. Allen, D.R., 1968. Physical changes of reservoir properties caused by subsidence and repressuring operations: Journal of Petroleum Technology. V 20, No. 1, p. 23-29.
2. Fatt, I., 1958. Compressibilities of sandstones at low to moderate pressures: AAPG Bull., V. 42, No. 8, P. 1924-1957.
3. Geertsma. J., 1973. Land subsidence above compacting oil and gas reservoirs: Journal of Petroleum Technology, June, p. 734-744.
4. Gilluly, I, and U.S. Grant, 1949. Subsidence in the Long Beach harbor area, California: GSA Bull., V. 60, No. 3, p. 461-530.

5. Holzer, T.L., 1979. Elastic expansion of the lithosphere caused by groundwater depletion: Journal of Geophysical Research, V. 84, No. 89, p. 4689-4698.

6. Miller, I., W. Dershowitz, K. Jones, L. Myer, K. Roman, and M. Schauer, 1980a. Simulation of geothermal subsidence: Earth Sciences Division, Lawrence Berkeley Laboratory, University of California. LBL-10794, 160 p.

7. __________, 1980b. Detailed report on tested models, companion report 2 to simulation of geothermal subsidence; I.B.I.D. LBL-10837, 142 p., APP.

8. Newman, G.H., 1973. Pore-volume compressibility of consolidated, friable and unconsolidated reservoir rocks under hydrostatic loading: Journal of Petroleum Technology, v. 25, No. 2. p. 129-134.

9. Pinder, G.F., 1979. State of the art review of geothermal reservoir modeling: Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, LBL-9093, 144 p.

10. Teeuw, D., 1971. Prediction of formation compaction from laboratory compressibility data: Society of Petroleum Engineers Journal. V. 11, No. 3. p. 263-271.

11. Whiteman, C. D. Jr., 1980. Measuring local subsidence with extensometers in the Baton Rouge area, Louisiana, 1975-79: Louisiana Department of Transportation and Development, Office of Public Works, 18 p.

CHEMISTRY OF BRINE

CONTRACT SUMMARY
UNIVERSITY RESEARCH PROGRAM

Contractor: Southern University - Baton Rouge Campus

Investigator: Arnold W. Smalley

Scope of work: Establishment of an evnironmental assessment of the congeneration facilities installed in the Gladys McCall and Sweet Lake drilling sites located on the Southeastern Coast of Louisiana. Studies of changes in air and water quality, effects of waste disposal, and long-term structural changes due to reinjection of brine will be effected.

Specific Objective: Assessment of data related to chemistry of brine.

SUMMARY OF WORK

A preliminary environmental assessment of selected geopressure-geothermal prospect areas of the Louisiana Gulf Coast region (Figure 1) was prepared by the Institute for Environmental Studies of Louisiana State University (1). In the report, assessment was made on the basis of the nature and extent of the proposed testing activities in view of the environmental characteristics of each prospect area: land use, geology and geohydrology, air quality, water resources and quality, ecological systems, and naturel hazards.

The Department of Energy proposed to drill, complete and test at least one in a possible series of geopressured wells, and evaluate the feasbility of expanded operation over a period of approximately three years. The initial test program could eventually lead to the commercial production of natural gas, electricity and process heat.

The Louisiana Department of Natural Resources has formulated regulations concerning geopressured wells in this state (2), and such activities must be conducted with regard to the regulations, extra precautions being therefore followed which recognize the existence conditions of temperature, pressure, and volumetric flow rates to be encountered. Surface facilities were designed to allow for the collection of data on flow rates, fluid composition, gas content and composition, and temperature and pressure. The construction of two to four disposal wells for fluid reinjection was also considered. Restoration of the entire site is to be accomplished by back-filling and replanting with species native to the area, where possible.

Surface disruption the marsh portions of the prospect areas, an event most likely to occur, was considered to have highly destructive impacts. The apparent consequencies are: changes in existing hydrologic patterns, clarity and salinity parameters, with resulting impacts on fish and shellfish; possible blockage of migration of some species; and loss of marsh. These effects are essentially irreversible, and are already occurring extensively in the coastal marshes as a result of natural forces and human activity in particular, oil and gas activity. This impact was thus considered a high priority issue for Louisiana. The propagation of fish, shellfish and fur-bearers - the primary land use in the wetland protions of the prospect areas is considered the most vulnerable to imparts from the test program with the exception of community development and cultural resource sites.

Baseline data for the prospect areas under consideration were obtained from existing sources and compiled for the report (3). Three different qualities of ground water were reported for Rockefeller Refuge (Figure 2). Fresh ground water, which contained less than 250ppm chlorides; slightly saline water, defined as the containing from 1000 to 3000 mg/L dissolved solids; and moderately saline water, which contained 3000 to 10,000 mg/L of dissolved solids. Water which contained less than 1000 mg/L of dissolved solids was categorized as fresh. Due to the mode of measurement employed - resistivity record on electrical logs - ground water quality showed considerable variance from one site to another.

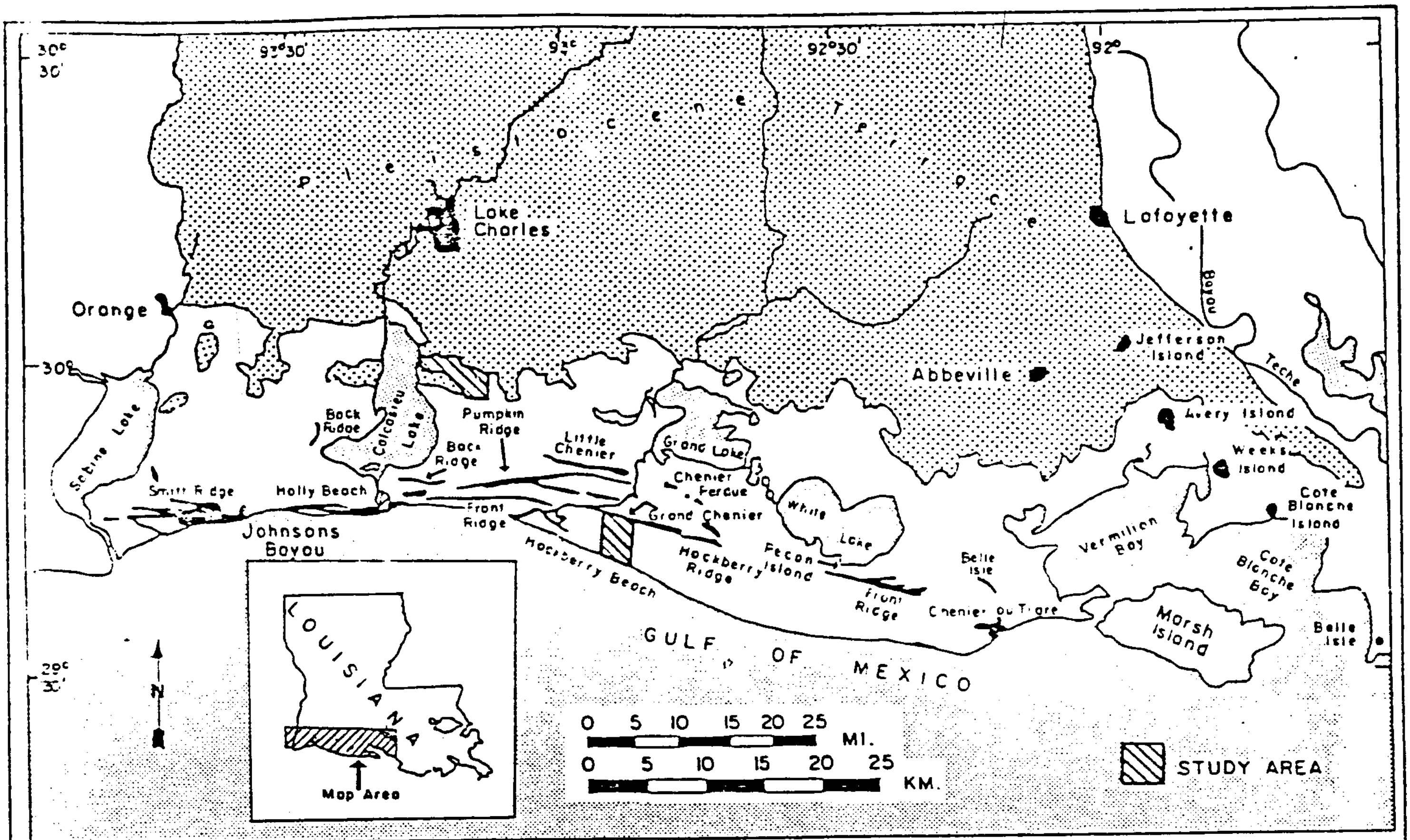
A number of inorganic contaminants were found in the brine from the Sweet Lake Operations; however, the preliminary report listed no data on possible organic contaminants. A reasonable if not valid explanation for this is the nonexistence of such information prior to the initiation of the drilling activity. Considering the location of the drilling site - in the midst of marshland - and its proximity to the Rockefeller Wildlife Refuge, subsequent studies should include such listing in order to accurately assess the impact of the geopressure - geothermal operation on the immediate environment.

No stations for water quality management are maintained within the prospect area by any of the agencies which regularly operate such facilities in Louisiana - i.e., the U.S. Corps of Engineers, the U.S. Geological Survey, and the Louisiana Stream Control Commission. However, a preliminary assessment of water quality conditions was made of the Rockefeller area Environmental Monitoring.

All phases of the environmental program were monitored by Groat, eta (4), except air quality, between November 1981 and October 1982. The major emphasis of their studies was to acquire a thorough understanding of the background data, which primarily consisted of those environmental impacts which have their origins in natural occurences or in cultural activities other than geopressure - geothermal energy development.

Water quality and to some extent, air quality can be affected by saltwater intrusion, drilling activities, and waste disposal; each of these activities may well contribute significantly to increases in the number and kinds of organic components in the environment surrounding the cogeneration facility.

The inclusion of data in the data base concerning these chemicals will result in more complete interpretations. The end product will be a comprehensive assessment of environmental impacts which result from the geopressure - geothermal process in Southwestern Louisiana.



MODIFIED AFTER NEWTON - 1972

FIGURE 20. Location map of Sweet Lake and Rockefeller Refuge study areas.

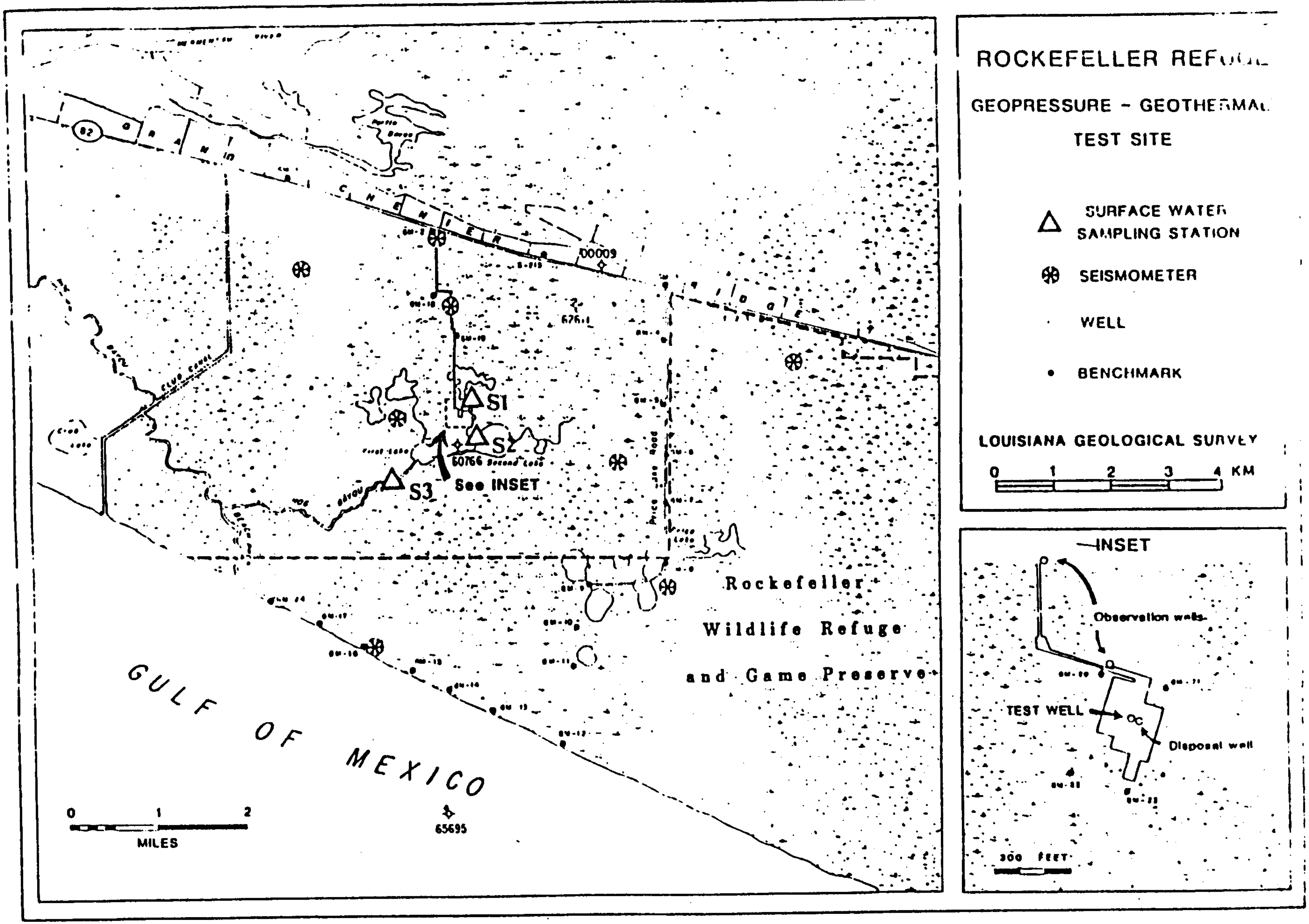


FIGURE 21. Area map of Rockefeller Refuge geopressured-geothermal test site showing locations of parameter observation stations.

TABLE 9

Chemical Analysis
Production Brine
T-F&S/DOE Gladys McCall # 1 Well
Sand Zone # 8
Sample--Raw Acidified Supplied by
T-F&S--November 1983

Alkalinity	NA
Alpha (gross)	40 pCi/L
Ammonia	NA
Arsenic	.013 mgAs/L
Barium	420 mgBa/L
Beta (gross)	340 pCi/L
Boron	36 mgB/L
Cadmium	.015 mgCd/L
Calcium	4040 mgCa/L
Chloride	59,290 mgCl/L
Chromium	.04 mgCr/L
Copper	.015 mgCu/L
Dissolved Solids	97,800 mg/L
Fluoride	.14 mgF/L
Gamma (gross)	------
Iron	14.0 mgFe/L
Lead	<.05 mgPb/L
Magnesium	354 mgMg/L
Manganese	2.1 mgMn/L
Mercury	.001 mgHg/L
pH	NA

Potassium	430 mgK/L
Radium	17 pCi/L
Radon (gas)	NA
Silica	100 mgSiO_2/L
Sodium	29,750 mgNa/L
Specific Conductance	NA
Specific Gravity	1.0639
Strontium	540 mgSr/L
Sulfate	<1 mg$SO_4^=$/L
Sulfide	NA
Suspended Solids	NA
Zinc	.29 mgZn/L

TABLE 10

Revised Chemical analysis
Production Brine
MG-T/DOE Amoco Fee # 1 well
Sweetlake Project
Sand Zone # 3-15248-15285 ft.
Sample Collected 11-23-83

Alkalinity	281 mgKCO$_3^-$/L	
Alpha (gross)	71 pCi/L	**
Ammonia	105 mgNH$_3$/L	
Arsenic	<.001 mgAS/L	
Barium	110 mgBa/L	**
Beta (gross)	1050 pCi/L	
Boron	50.6 mgB/L	
Cadmium	.004 mgCd/L	
Calcium	12,500 mgCa/L	**
Chloride	99,650 mgCl/L	
Chromium	.05 mgCr/L	**
Copper	.050 mgCu/L	
Dissolved Solids	168,900 mg/L	
Fluoride	.45 mgF/L	
Gamma (gross)	--------	
Iron	63.5 mgFe/L	
Lead	.008 mgPb/L	
Magnesium	700 mgMg/L	**
Maganese	9.9 mgMn/L	
Mercury	<.001 mgHg/L	

pH	5.20
Potasssium	990 mgK/L
Radium	210 pCi/L
Radón (gas)	.3 pCi/L
Silica	92 $mgSiO_2/L$
Sodium	41,800 mgNa/L
Specific Conductance	160,000 mhos/cm
Specific Gravity	1.1103
Strontium	1220 mgSr/L **
Sulfate	<1 $mgSO_4^{=}/L$
Sulfide	3 $mgS^{=}/L$
Suspended Solids	.25 mg/L
Zinc	2.25 mgZn/L

TABLE 11

Chemical Analysis
Production Brine
MG-T/DOE Amoco Fee # 1 well
Sweetlake Project
Sand Zone # 3 (15248-15285 ft.)
Sample Collected 11-30-83

Alkalinity	256 mgHCO_3^-/L
Alpha (gross)	80 pCi/L
Ammonia	170 mgNH_3/L
Arsenic	.014 mgAS/L
Barium	130 mgBa/L
Beta (gross)	1130 pCi/L
Boron	52.6 mgB/L
Cadmium	.007 mgCd/L
Calcium	13,400 mgCa/L
Chloride	99,900 mgCl/L
Chromium	.05 mgCr/L
Copper	.085 mgCu/L
Dissolved Solids	168,400 mg/L
Fluoride	.78 mgF/L
Gamma (gross)	-------
Iron	55.8 mgFe/L
Lead	<.05 mgPb/L
Magnesium	720 mgMg/L
Manganese	10.8 mgMn/L
Mercury	<.001 mgHg/L
pH	6.10

Potassium	860 mgK/L
Radium	224 pCi/L
Radon (gas)	-------
Silica	93 mgSiO_2/L
Sodium	46,750 mgNa/L
Specific Conductance	155,000 mhos/cm
Specific Gravity	1.1079
Strontium	1180 mgSr/L
Sulfate	<1 mg$SO_4^{=}$/L
Sulfide	.27 mg$S^{=}$/L
Suspended Solids	.56 mg/L
Zinc	1.47 mgZn/L

References:

1) A Preliminary Environmental Assessment of Selected Geopressured - Geothermal Prospect Areas: Louisiana Gulf Coast Region. Vol. I., Institute for Environmental Studies, LSU, 1978.

2) Louisiana Revised Statutes, 1978, 49: 213.1 - 49: 213-21 (Louisiana Coastal Resources Management Act, Act 361, July 14, 1978).

3) A preliminary Environmental Assessment, Ref. (1), Vol. II.

4) G.C. Groat, V.R. Van Sickle, D. Trahan, and L.T. Gorman, Environmental Monitoring, November 1981 - May 1982.

Final Report

Environmental Impact of Geopressure - Geothermal Cogeneration Facility on Wetland Resources and Socioeconomic Characteristics in Louisiana Gulf Coast Region

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WETLAND RESOURCES

Approximately 90.8% of the surface area of Cameron Parish is comprised either of wetlands or open water bodies such as lakes and canals (LaSPO,1972). Fresh to saltwater marshes cover 62.3% of the surface area while open water covers 28.5%. Elongated sandy ridges called "cheniers" parallel the coastline and are separated by large expenses of coastal marsh (Gosselink, et al., 1979). The coastal marshes range from freshwater in nontidal inland areas to intermediate, brackish and finally saline marshes in tidal areas near the coastline. Ponds, small lakes, and streams are interspersed throughout the marshy areas.

The saline vegetation type wetland which borders the Gulf of Mexico in Louisiana and Cameron Parish is subject to daily tidal fluctuations with water salinities averaging 18.0 ppt (range, 8.1 to 29.4 ppt); the soils have a lower organic content (mean, 17.5%) than fresher types (Chabreck, 1982). Dominant plant species are smooth cordgrass *Spartina alterniflora*, saltgrass *Distichilis spicata* and black rush *Juncus roemerianus*.

The brackish vegetation type is further removed from gulf waters, but is still subject to daily tidal action. Water depths are normally slightly deeper than in saline marshes and soils contain higher organic matter (mean: 31.2%). Water salinities average 8.2 ppt (range: 1.0 to 18.4 ppt). The brackish type marsh contains a greater plant species diversity than the saline type but is dominated by two perennial grasses, wiregrass (Spartina patens) and saltgrass. These grasses are among the most productive marsh species in the coastal zone (Gosselink et al., 1977).

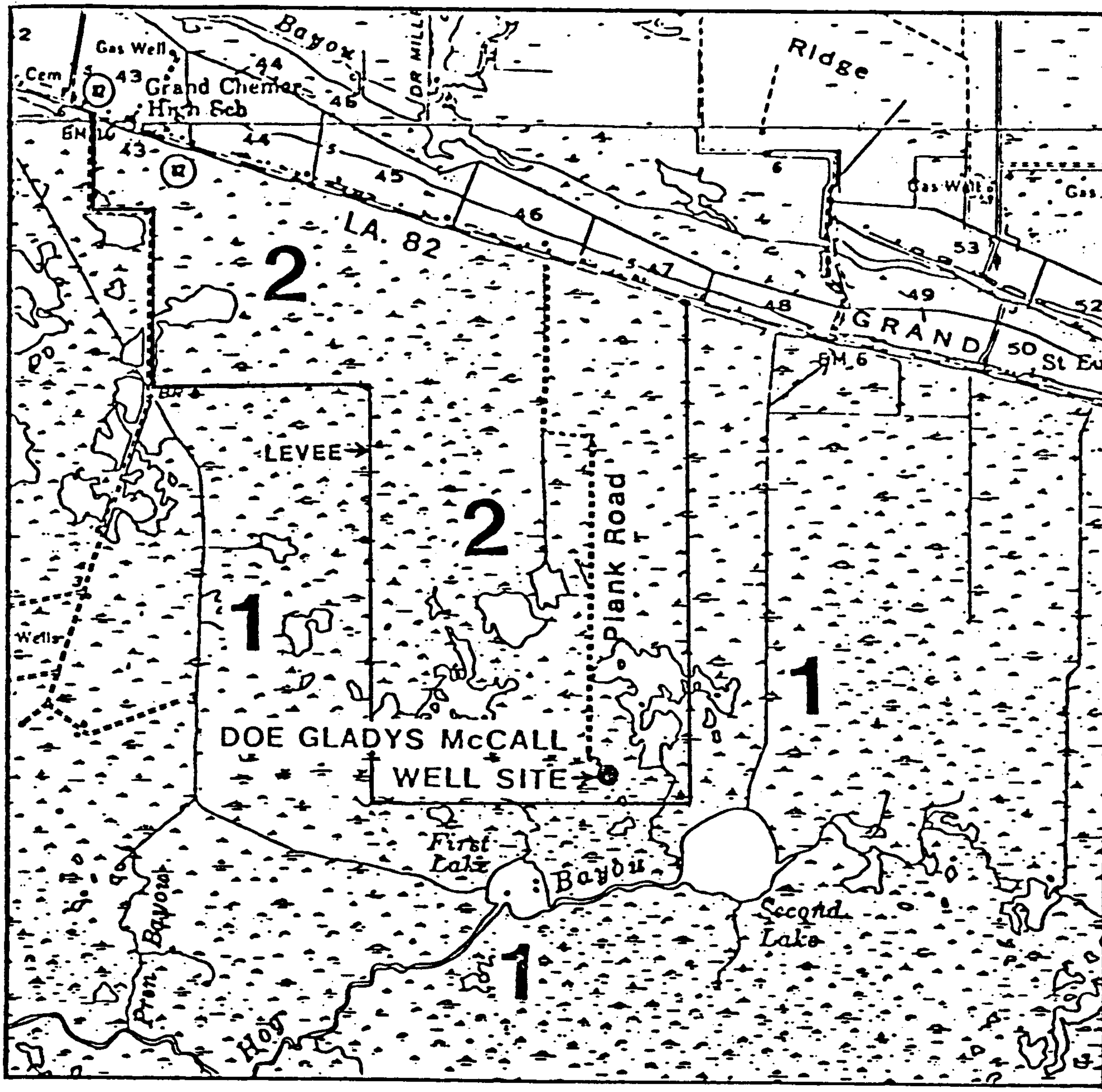
An intermediate vegetation type lies inland from the brackish type and receives some influence from tides. Water salinities average 3.3 ppt (range: 0.5 to 8.3 ppt). Water levels are slightly higher than in the brackish type, and soil organic content averages 33.9%. Plant species diversity is high, containing both brackish and freshwater species that are used as food by a wide variety of waterfowl and other herbivores. Spartina patens dominates intermediate marshes but is often accompanied by bulltongue (Sagittaria falcata), waterhyssop (Bacopa monnieri) and Roseau cane (Phragmites communis).

Fresh vegetation marsh is found inland from the intermediate type and lies south of the Prairie formation in Cameron Parish. This marsh type is free from tidal influence except during major storm surges associated with hurricanes. Water salinity averages 1.0 ppt (range, 0.1 to 3.9 ppt). Because of slow drainage, water depth and soil organic content (mean: 52.0%) in this marsh are the greatest of all marsh types. The fresh type is the most diverse and contains many plant species which are preferred foods of wildlife. Dominant plants include maidencane (Panicum hemitomon), spike rush (Eleocharis spp.), bulltongue, and alligator weed (Alternanthera philoxeroides).

The Gladys McCall well site is surrounded by brackish marsh wetlands (Fig.22). Within the impounded area encompassing the well site, wiregrass, saltgrass and saltmarsh bulrush are the dominant emergents (US DOE, 1981). A solid stand of soft stem bulrush (*Scirpus validus*) is present near the northern boundary of the impounded area. Widgeon grass (*Ruppia maritima*) is a common submergent species in ponds interspersed throughout the area. The natural brackish marsh outside the impounded area is also comprised mostly of wiregrass, saltgrass and saltmarsh bulrush.

Freshwater marshes are found approximately three km (1.8 miles) SSW of the Sweet Lake well site (Fig.23). Interspersed in these marshes are numerous freshwater ponds. Sweet Lake, with a surface area of approximately 810 hectares (2,000 acres), lies six km (3.6 miles) south of the well site. Dominant plant species in the freshwater marshes include maidencane, bulltongue, *Eleocharis* spp. and alligator weed.

The coastal wetlands of Cameron Parish support a large and diverse faunal assemblage including numerous fish and shellfish species, furbearers and other mammals, reptiles, amphibians, songbirds, wading birds, shorebirds and a vast population of wintering waterfowl. Fish and shellfish are the most important from a recreational and economic standpoint and are dependent on the coastal marshes as a fish nursery grounds. The most abundant fish species dependent on the marsh cover or productivity and detrital export



1 BRACKISH MARSH

2 IMPOUNDED BRACKISH MARSH

Figure 22. Marsh Vegetation in the vicinity of the Gladys McCall Well Site.

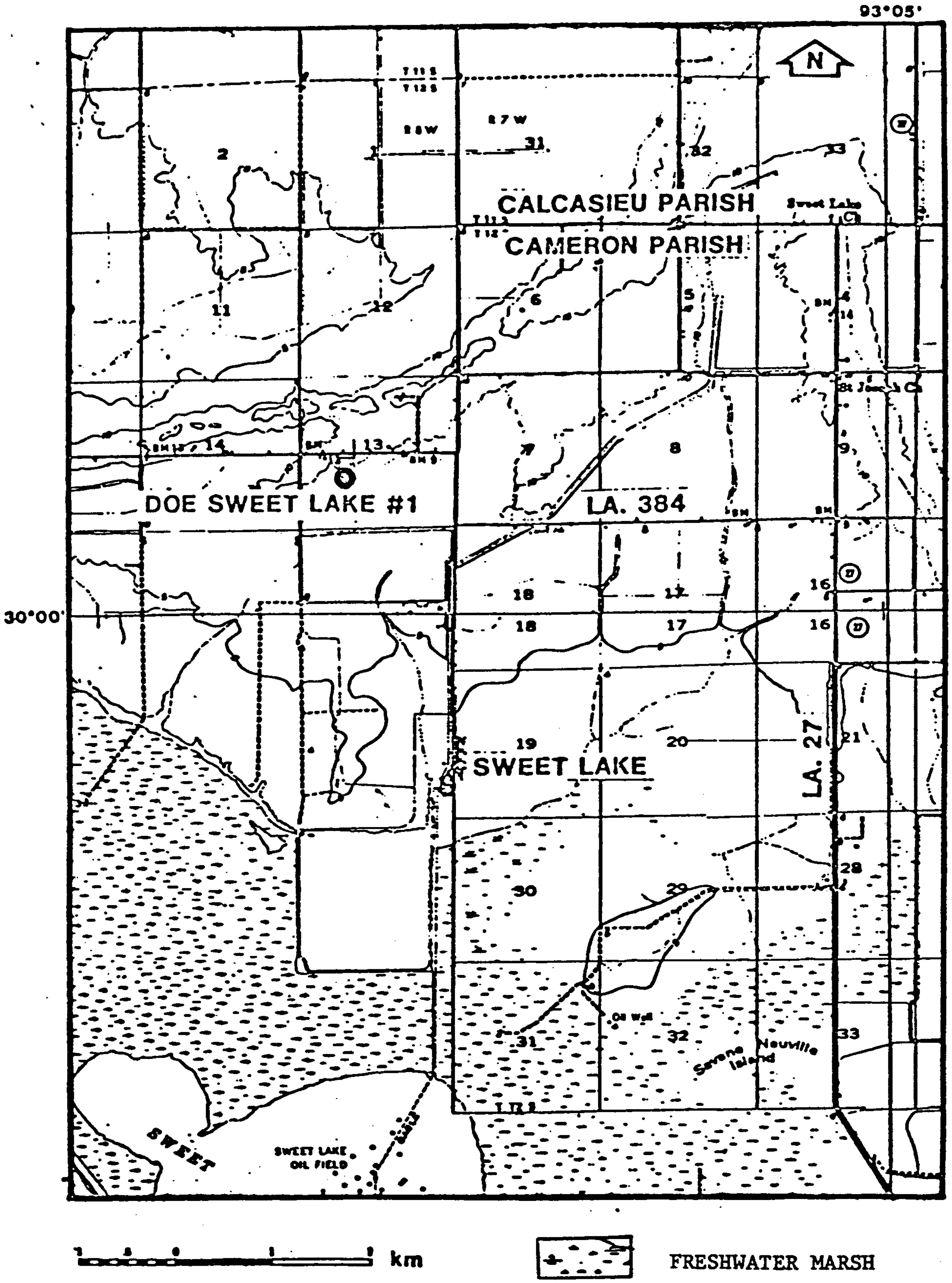


Figure 23. Marsh Vegetation in the vicinity of the Sweet Lake Well Site.

include Gulf menhaden (Brevoortia patronus), Atlantic croaker (Micropogon undulatus), bay anchovy (Anchoa mitchilli) speckled trout (Cynoscion nebulosus), spot (Leiostomus xanthurus), southern flounder (Paralicthys lethostigma), sand seatrout (Cynoscion arenarius), red drum (Sciaenops ocellata) and black drum (Pogonias cromis). Important shellfish include white and brown shrimp (Penaeus setiferus and P. aztecus) and blue crab (Callinectes sapindus). All of these species spawn in bays in the nearshore gulf waters and migrate into and utilize the estuarine marshes as nursery grounds (Wagner, 1981). The marshes utilized for nursery grounds are shallow, have low salinity, and provide food and protection for many post-larval and juvenile stages of fish and shellfish.

Mammals utilizing the coastal wetlands include a large and economically important contingent of furbearers, principally nutria, muskrat, mink and raccoon. Louisiana is the leading fur-producing state in the United States, with nutria the most important furbearer (O'Neil and Linscomb, 1977). Important game mammals of these marshes include white-tailed deer and swamp rabbits. Small mammals include a variety of mice, rat and shrew species.

Numerous species of snakes, lizards, turtles, salamanders, toads and frogs inhabit the coastal wetlands. Research conducted at the Rockefeller Wildlife Refuge has led to a managed commercial harvest of alligator hides in the Cameron and surrounding parishes. Bullfrogs also provide a commercial and recreational resource in freshwater marshes of the area.

The wetlands of Cameron Parish are noted for their abundant and diverse bird life, particularly during the winter months. Annual Audubon Christmas bird counts for Cameron Parish are among the highest in the nation (US DOE, 1980). On December 18, 1977, the Sabine National Wildlife Refuge Christmas bird count recorded 171 species and 56,787 individuals. These wetlands lie in the Mississippi migratory flyway and provide an overwintering area for most of these species. A large number of trans-gulf migrants pass through the area each spring and fall, sometimes stopping for a short rest period before crossing the Gulf of Mexico.

Of particular recreational and economic importance are the vast numbers of ducks and geese that winter in the Cameron Parish. Most of these waterfowl species rest and preen in the coastal marshes and feed in rice and soybean fields to the north. This resource allowed Cameron Parish hunter to annually harvest an average of 172,702 ducks and 36,978 geese (US DOE, 1981). Common waterfowl species utilizing the area include snow and white-fronted geese, gadwell, blackducks, ring-necked ducks, pintails, mallards, blue-winged teal, green-winged teal, shovelers, widgeon and mottled duck.

Many other bird species also frequent the area wetlands. Game birds include rail, gallinules, coots, snipe and mourning doves. The marshes and coastal waters are utilized by egrets, ibis, herons, gulls terns, sandpipers, skimmers, willets, boat-tailed grackles, red-winged black birds, marsh hawks and white pelicans.

The present or historical range of a number of endangered species includes study area wetlands. Among these are the American alligator (Alligator mississipiensis), southern bald eagle (Haliaetus leucocephalus) and the peregrine falcon (Falco peregrinus). The former species is a resident of the area marshes while the latter two species may pass through the area or spend a limited amount of time in search of food. The whooping crane (Grus americana), brown pelican (Pelicans, occidentalis), and red wolf (Canis rufus) historically inhabited the area wetlands but do not exist there now nor are they likely to reinhabit the area.

Three large wildlife refuges in Cameron Parish provide a haven for the abundant wildlife of the area. Sabine National Wildlife Refuge, is located about 16 km (10 mi) south and west of the Sweet Lake well site. It offers 57,853 ha (142,846 ac) of wetlands of which 13,487 ha (33,000 ac) are open water. The Lacassine National Wildlife Refuge is located about 16 km (10 mi) east of the Sweet Lake well site and 32 km (20 mi) north of the Gladys McCall well site. It offers 12,869 ha (31,776 ac) of mostly marsh habitat for outdoor recreational, fishing and hunting on a seasonal basis. The Rockefeller State Wildlife Refuge is located 3.2 km (2 mi) east of the Gladys McCall well site. This refuge contains 33,300 ha (85,000 ac) of wetland habitat, including large areas of coastal marsh and shallow water impoundments.

SOCIOECONOMIC CHARACTERISTICS

Cameron Parish is a very rural, sparsely populated parish with abundant undeveloped wetlands. It also has the distinction of being the largest of 64 parishes in Louisiana with 1,350,102 acres and the least populated with 9,336 residents (U.S. Dept. of Commerce, 1981). Agricultural lands comprise 106,704 acres most of which is devoted to rice and soybean cultivation while wetlands comprise 843,011 acres, nearly all of which is in coastal marshes. Lakes, bays, streams and other water surfaces comprise 384,826 acres. In contrast to the above large acreage categories, urban and built up lands comprise only 11,100 acres or less than 1% of the parish.

The economy of Cameron Parish is based primarily on extraction, transmission and processing of oil and natural gas. Agriculture, trapping and commercial fishing also contribute substantially to the economy. The village of Cameron has been the nations's leading commercial fishing port the past several years, with numerous landings of shrimp, crabs, oysters, finfish and menhadnen.

There are no large towns in Cameron Parish. The nearest large town and employment center is Lake Charles which lies about 10 miles north of the Parish. In 1980, there were 4,487 housing units in Cameron Parish, 3,020 households and 2,201 married couples (U.S. Dept. of Commerce, 1981). The parish is predominantly white (8,782) with blacks comprising the largest non-white segment of the population (524). The 1980 population increased 13.9% compared to 1970 and is projected to continue to grow at a moderately rate.

In March, 1981, there were 175 business concerns in Cameron Parish employing 2,858 people (U.S. Dept. of Commerce, 1983). The median annual employee payroll was 17,080 dollars. The major employers were the petroleum industry (690), business services (562) and transportation and public utilities (548). Regional median family income is about 11,750 dollars and is projected to increase to 15,500 dollars by 1990 (John Cody, IMCAL, pers. com., 1983).

The immediate surroundings of Gladys McCall and Sweet Lake well sites are very sparsely populated. The Gladys McCall site area is largely a natural marsh while the Sweet Lake site area is rural agricultural with rice and soybean fields predominating (Figs. 22 and 23). At the Gladys McCall site, the nearest residential and commercial developments are located about 3.7 Km (2.3 mi) north of the well along State Highway 82. At the Sweet Lake site, there are a few residences along State Highway 384 within 2 km (1.2 mi) of the well. A recreational center is also located along this highway, approximately 1.6 km (1 mi) west of the well. The nearest population concentration is in the town of Sweet Lake, located 3 km (2 mi) SSE of the well.

IMPACTS ON WETLANDS

Installation and operation of cogeneration facilities can be accommodated on the existing well pads and within existing well site levees. A small amount of wetland (less than one acre) would be lost in providing a power transmission line to the existing area electric utilities at the Gladys Mccall. Approximately 5 acres of tidal marsh would also be disturbed temporarily in providing a gas pipeline hook up from the Gladys McCall site to the north. No other disturbance of wetlands will result from the proposed construction of cogeneration facilities provided there are no major brine spills or additional injection wells required during the life of the project.

The presence of work crews and movement of men and equipment and increased noise levels during construction and operation of the facility could temporarily displace animals sensitive to flushing such as waterfowl, shorebirds, deer, and other native wildlife residing near the site. This should have no significant impact on the reproduction or size of any wildlife population as there are large amounts of similar wetland habitat in the adjacent areas for support of these sensitive wildlife.

A number of activities related to operation of the energy cogeneration facilities could result in impacts on wetlands. Potentially the most significant of these would be a major brine spill or blowout and land subsidence, which could result in a long term loss of wetland if substantial subsidence is induced by the projects.

These and other potential impacts on wetlands resulting from operation of the cogeneration facilities are the focus of the following paragraphs.

Accidental spills caused by blowouts, cracks in the well head or cogeneration facility or injection well piping, human error, and natural hazards (ie. hurricanes, floods, fault activation) could result in the release of toxic substances present in the geopressured fluids to wetlands in the vicinity of the well site. Most spills would be contained and cleaned up within the existing levee system encircling the wells and cogeneration facilities and deposited in a suitable landfill with no adverse effects on surrounding wetlands. Moreover, the potential for accidents and spills will be minimized by use of blowout preventers, safety valves, high pressure pipes and valves, and a spill prevention control and counter measure plan that would be installed and maintained at the cogeneration facility site. Nevetherless, blowouts, piping or injection well leaking or failure could occur, but will probably be short term until brought under control by countermeasures that would be taken in accordance with state and federal regulations for geopressured drilling.

In the event of a major spill which could not be contained within the levee system, substantial impacts could occur on the surrounding wetlands. In this regard, the Gladys McCall site has a much greater potential for impact on wetlands than the Sweet Lake site, since it is surrounded by wetlands and is subject to hurricane storm surges and flooding (U.S. DOE, 1981). Conversely, the Sweet Lake site is in an upland area not subject to storm surges or flooding, and the nearest wetlands are over three kilometers (1.8 miles) from the site (U.S. DOE, 1980). The extent of impact from an accidental spill would depend on the location, type of toxicants, size and duration of the spill, meteorological conditions and proximity and type of wetlands exposed to the spill. A blowout would be the most serious type of accident, with the capability of sending geopressured effluents several hundred meters (ERDA, 1976). Geopressured effluents are extremely hot, hypersaline solutions that may contain significant concentrations of toxic substances in the solid, liquid or gaseous form, any of which could cause lethal or sublethal effects on wetland biota. The constituents of the geopressured effluents and their concentration will determine their toxicity. The principal constituents in geopressured brines of the Sweet Lake and Gladys McCall Wells and other Gulf coast wells are listed in Table 12, along with recommended EPA criteria and average seawater concentrations.

Salinity

High salinity levels of brines from the Gladys McCall and Sweet Lake wells could pose a major potential toxicity problem for wetlands in case of an unconfined spill. These brines are 2.7-4.3 times more saline than average seawater as measured by total dissolved solids (Table 12). Salinity levels (TDS) of 97,800 and 155,000 mg/l have been recorded for brines of the Gladys McCall and Sweet Lake wells, respectively, while values of 39,000 mg/l are sufficient to kill *Spartina patens*, the most abundant marsh plant of the area

Table 12. Constituents of Geopressured Brines of Environmental Concern to Wetlands

Component (mg/l) except as noted	EPA Criteria for Water[1] Fresh Water Acute	EPA Criteria for Water[1] Fresh Water Chronic	EPA Criteria for Water[1] Marine Acute	EPA Criteria for Water[1] Marine Chronic	Average in Seawater	Sweet Lake #1 Well Brine (sand zone #3)[2]	Gladys Mccall #1 Well Brine (sand zone #8)[3]	Other Gulf Coast Well Brines[4]
Ammonia	0.02	NA	NA	NA	-	170	NA	4-100
Arsenic	0.440	NA	0.508	NA	0.003	0.014	0.013	0.0001-0.56
Barium	NA	NA	NA	NA	0.03	130	420	1.0-310
Bicarbonate	NA	NA	NA	NA	160	256	527	81-2,000
Boron	(0.750 for crop irrigation)				5	52.6	36	15-120
Cadmium	0.013*	0.0001*	0.059	0.0045	0.001	0.007	0.015	0.0001-0.770
Chloride					19,000	99,900	59,290	4,000-170,000
Chromium (Hexavalent)	0.021	0.0003	1.260	0.0180	-	0.05	0.04	-
Copper	0.0337*	0.0056	0.02	0.0040	0.003	0.085	0.015	0.0001-0.0052
Gross Alpha (pCi/l)	5 for drinking water[5]				_	80	40	-
Gross Beta (pCi/l)	15 for drinking Water[5]				-	1130	340	-
Iron	NA	1.0	NA	NA	0.01	55.8	14.0	0.1-160
Lead	0.2927*	0.0106*	0.6780	0.0250	0.00003	<0.05	<0.05	0.0001-83
Lithium	NA	NA	NA	NA	0.2	-	-	1.2-15
Magnesium	NA	NA	NA	NA	1,300	720	354	3.3-1,500
Manganese	NA	NA	0.1	NA	0.002	10.8	2.1	0.04-2.80

Table 12. Constituents of Geopressured Brines of Environmental Concern to Wetlands

Component (mg/l) except as noted	EPA Criteria for Water[1] Fresh Water Acute	Fresh Water Chronic	Marine Acute	Marine Chronic	Average in Seawater	Sweet Lake #1 Well Brine (sand zone #3)[2]	Gladys Mccall #1 Well Brine (sand zone #8)[3]	Other Gulf Coast Well Brines[4]
Mercury	0.004	0.0002	0.004	0.0000025	0.00003	<0.001	0.001	0.00001-0.0002
pH (Units)	6.5-9.0 fresh		6.5-8.5 marine		-	6.10	NA	5.9-7.4
Potassium	NA	NA	NA	NA	350	860	430	4.5-1,100
Radium	5 in drinking water[5]				-	224	17	-
Sodium	NA	NA	NA	NA	11,000	46,750	29,750	2,700-99,000
Strontium	NA	NA	NA	NA	7	1,180	540	4-1,400
Sulfate	NA	NA	NA	NA	2,700	1.0	1.0	0.6-700
Sulfide	0.002 fresh		0.002 marine		-	0.27	NA	0-3.9
Total Dissolved Solids	NA	NA	NA	NA	36,000	155,000	97,800	7,500-270,000
Zinc	0.4610*	0.0470	0.1700	0.0580	0.01	1.47	0.29	0.0008-45

[1]Quality Criteria for water, US EPA, 1976 with Revisions, Federal Register; 28 November 1980, Part V.

[2]Scientific Consulting and Analysis, Inc., sample collected 11-30-83.

[3]Scientific Consulting and Analysis, Inc., sample collected, Nov. 1983

[4]Gas Research Institute, Assessment of Potential Environmental Impacts of Geopressured Methane Development. March, 1980.

[5]CFR 40 Part 141 National Interim Primary Drinking Water Regulations.

*Criterion is based on water hardness of 92.6 mg/l in relation to EPA guidleines (FR 1623-3, Nov. 28, 1980.

(Palmissano, 1970). Marine organisms are adapted to salinity concentrations of 36,000 mg/l and estuarine organisms are usually able to tolerate a wide range of salt concentrations below this level at least temporarily. However, sudden, extreme changes in salinity as would be experienced with a brine spill would kill flora and fauna in and around the immediate area of contact. The greatest damage would occur in fresh waters and fresh marshes where native species usually have a low salt tolerance.

Larvae and juveniles of estuarine species are also less tolerant of salinity changes than adults. There is evidence that brine discharge has been a contributing factor to rapid marsh degradation north and west of the Hackberry salt dome in Calcasieu Parish (Gosselink et al., 1979) and would similarly degrade marshes exposed to potential brine spills that might result from the energy congeneration facility. Dilution and leaching are the main methods for mitigating elevated salinity levels caused by brine spills. Areas which receive daily tidal flooding will quickly return to natural levels while salinity impacts may persist indefinitely in the undiluted or confined areas (impounded wetlands).

Chloride is the principal anion contributing to brine salinity and sodium the principal cation. Other important cations are calcium, magnesium, strontium , and potassium. Excessive salinity levels can cause harm to organisms by lowering the diffusion pressure of water in a solution and increasing the osmotic potential, thereby making it difficult for water and nutrients to diffuse into plants and aquatic organisms. Lowered turgor pressure, increased respiratory demands and osmoregulatory failure or impairment result in lethal effects or slowed growth in the stressed organisms.

The dissolved constituents in the geopressured brine could increase in concentration as the fluids move through the energy extraction processes thereby further increasing salinity and toxicant concentrations. The cogeneration processes may involve hydraulic turbines, high and low pressure methane extraction, single or two stage flash steam turbines, binary cycle turbines, condensers and cooling towers. Wilson et al. (1977) evaluated the alteration of a geopressured brine of probable constitution that would result from a conceptual cogeneration facility and estimated that dissolved constituents could increase in concentration by 16-18% during processing and energy extraction. The additional processes and piping associated with the cogeneration facility would also increase the possibility for accidental spills.

In case of a brine spill in the wetlands, the hypersaline brine would sink to the bottom of any ponded water area due to greater density than fresh or brackish water. There it would infiltrate soils of the root zone and affect the aqueous environment of benthic organisms, gradually becoming more dilute as mixing with native water occurs. Clay fraction of the wetland soils with high ion exchange capacity would extend the persistence of the salts accumulated. Gravity flow, rainfall, runoff, and wind and total action would increase mixing and thus dilution of the brine, while impounded wetlands would be slow to return to background salinity concentrations.

Toxic Metals

Heavy metals and various trace elements are commonly found in geopressured waters in significant concentrations (Wilson, et al., 1977; Karkalits and Hankins, 1981; Mayer and Ho, 1977). Those particularly noted in the literature were barium, boron, cadmium, lead, lithium, strontium and zinc. Most of these elements appear to be high in either or both of the Gladys McCall or Sweet Lake brines as well, except lead (Table 12). Other heavy metals which have high concentrations for aquatic organisms in these wells include chromium, copper, manganese and radium.

Although barium is quite toxic to aquatic organisms, it readily forms highly insoluble carbonates and sulfates. Consequently, it is expected that barium ions released to natural waters will be quickly precipitated and removed by adsorption or sedimentation (McKee and Wolf, 1963). The U.S. EPA has recognized that the chemical properties of barium will usually preclude the existence of the toxic soluble form, making it unnecessary to impose restrictive criteria for disposal in freshwater or marine environments.

The cadmium concentration in brine from the Gladys McCall well (0.015 mg/l) exceeds slightly the EPA acute criterion for freshwater (0.013

mg/l) and is 375 times higher than the chronic criterion (0.00004 mg/l, Table 12). In addition to being highly toxic to both freshwater and marine organisms, this metal is quite mobile in the aquatic environment and is bioconcentrated by all organisms by factors ranging from 10^2 to 10^4 or more (Callahan, et al., 1979). Acid oxidizing conditions favor release of cadmium while increased salinity decreases its availability (Khalid, 1980).

Chromium exceeds the acute EPA criterion for freshwater organisms in brines from both wells by about 2 times but is below the criterion for marine organisms. Fish appear to be relatively tolerant of chromium, but some aquatic invertebrates are quite sensitive (U.S. EPA, 1976). The toxicity of the metal is known to vary with species, chromium oxidation state and pH. Acid oxidizing conditions favor the release of bioavailable chromium, which can be accumulated by marsh plants and aquatic organfsms (Gambrell, et al., 1978).

Copper exceeds the acute EPA criterion for freshwater and marine waters in the Sweet Lake brine, but is slightly below the marine waters criterion in brine from the Gladys McCall well (Table 12). Copper is one of the most mobile heavy metals in water and is readily bioaccumulated by marsh plants and animals (Callahan, et al., 1979). Copper is more available at low pH and oxidizing conditions (Gambrell, et al., 1978) and because of its tendency to be bioaccumulated, could be a persistent toxicant in brine spill areas.

Lithium causes chlorosis, burning and impaired growth at concentrations commonly found in geopressured brine (Table 12). Fish and other aquatic wildlife are much less sensitive to lithium than plants; thus no EPA criteria have been set for freshwater and marine organisms.

The EPA recommend limit for manganese is 0.100 mg/l for marine waters. This metal is present at levels of 10.8 mg/l in the Sweet Lake brine and 2.8 mg/l in the Gladys McCall brine. Mollusks may bioaccumulate manganese up to 12,000 times; hence, there is concern for accidental spills of brine with many times the recommended levels getting into the human food chain via shellfish. Manganese is not considered a problem in fresh waters due to low toxicity of the metal and low concentrations in fresh waters (U. S. EPA, 1976).

High levels of radium are present in the Sweet Lake brine (224 pCi/l), while the Gladys McCall brine is moderately high (17 pCi/l) when compared to the EPA gross alpha limit for human drinking water of 5 pCi/l (U.S. EPA, 1981). There are, however, no criterias for the protection of fresh and marine water organisms.

Strontium has mainly been of concern as a radionuclide in drinking water supplies, the strontium 90 standard being 8 pCi/l and the gross beta radioactivity standard being 15 pCi/l (U.S. EPA, 1981). For larger aquatic organisms, it has a relatively low order of toxicity, however Daphnia and other small protozoans are affected by

100-300 mg/l of strontium ions in water (McKee and Wolf, 1963). The high level of strontium in brines from the geopressured wells (544 and 1180 mg/l, Table 12 and the high gross beta radioactivity levels (340 and 1130 pCi/l) for these well brines indicates it may be harmful to aquatic organisms and is a radionuclide of concern.

The zinc concentration in the Gladys McCall well (0.290 mg/l) exceeds the EPA chronic criterion for freshwater organisms (0.047 mg/l) by 6 times, and for marine organisms by 5 times. Thus, a substantial spill with little dilution in wetlands could be harmful to marsh organisms effected by these concentrations. Zinc was found to be toxic to Pacific oyster larvae at 0.2 mg/l even for a short period of exposure (Brereton et al., 1973) and to be harmful to freshwater fish fry, especially cladoceran fish in soft water at levels of 0.0004 mg/l (U.S. EPA, 1976). The levels of soluble zinc and its availability to marsh plants would increase at a reduced pH and increased oxidation - reduction conditions (Gambrell et al., 1978).

A number of other metals may be harmful at concentrations experienced in geopressured brine, even though they are generally beneficial for plants and animals and have no criteria established for freshwater or marine organisms. These include iron, sodium, potassium and probably calcium. As mentioned earlier, these cations also contribute to the total dissolved solids of geothermal brine and thus may be harmful through increased salinity.

In summary, heavy metals and other trace elements availability in case of an accidental brine spill, would depend on oxidation-reduction conditions, pH and constituents of native waters and soils. The pH of these brines is slightly acidic (5.61 for the Sweet Lake well) which is slightly below the EPA recommended pH levels of 6.5-9.0 for freshwater organisms. The low pH in the brine could increase metal solubility and thus enhance initial availability to many organisms while adsorption and complexing with clays will cause these metals to persist in the marsh sediments. The alteration of reduced and oxidized conditions such as may be present at the marsh surface, makes marsh locations ideal for complexing and then solubilization of heavy metals and increases toxicity potential to resident organisims.

Non-metal Toxicants

Non-metal constituents of brine that are likely to adversely affect wetlands in an accidental spill include ammonia, bicarbonates, boron, bromine, hydrogen sulfide, methane and other associated hydrocarbons. Geopressured brines have virtually no dissolved oxygen. Ammonia, hydrogen sulfide, methane, other contained hydrocarbons and metals in reduced states will cause a high chemical oxygen demand and result in extremely low dissolved oxygen levels in the brine. Most of the methane and hydrocarbons will be removed during the gas extraction processes and some reoxygenation of the brine may occur during heat extraction processes and transport to discharge points. Depending at what point in the cogeneration processing a spill occurs, and the amount of reoxygenation, methane, ammonia, hydrogen sulfide and oxygen demanding compounds could have a short-term impact on affected wetlands. The EPA freshwater toxicity for ammonia is 0.02 mg/l (unionized) while the criterion for hydrogen sulfide is 0.002 mg/l. These limits are exceeded by many times in the geopressured brines (Table 12). The ecological significance of brine spills with these low dissolved oxygen and high chemical oxygen demand characteristics will depend on the size of the area affected, the amount and duration of oxygen reduction, and the tolerance level and mobility of wetland organisms.

High levels of bicarbonates (total alkalinity) are present in brines in both the Gladys McCall (527 mg/l) and the Sweet Lake wells (256 mg/l). Bicarbonates contribute mainly to the overall salinity of the brine and thus would have their greatest effect on freshwater wetlands in case of a spill. Ninety-five percent of waters that produce good fish populations have less than 180 mg/l of bicarbonates (McKee and Wolf, 1963).

Boron is principally of concern to plants which may be sensitive to soluble boron in concentrations as low as 0.5 mg/l (USDA, 1954), whereas concentrations of 2,000 mg/l are apparently not harmful to fish (McKee and Wolf, 1963). The U.S. EPA has not set any criteria for freshwater or marine waters in recognition of the low toxicity to animal life of this element. Nevertheless, marsh plants upon which the aquatic ecosystem is based, may experience severe growth decline or die off from accidental brine spills with 36 mg/l boron such as that tested for the Gladys McCall well brine (Table 12).

Bromine, like other halogens, is an antiseptic and disinfectant. In toxicity studies concentrations of 10 mg/l killed Daphnia magna, while goldfish were killed at 20 mg/l (McKee and Wolf, 1963). The concentration of bromine at the two wells is not known at present, but other geopressured wells of the Gulf coast commonly have 40 mg/l or more of bromine (Table 12).

Temperature

The high temperature of geopressured fluids is another characteristic of brine that would be harmful to wetlands affected by an accidental spill. Geopressured fluids at the well head range up to 149° (300°F) while brine that has been processed through cogeneration facilities is likely to be 60-90°C (140-194°F) (Marsden and Kozokawa, 1978). These temperatures are sufficient to denature protein and would therefore be expected to cause death of most marsh vegetation and wetland organisms in the immediate vicinity of any spill. Mixing with native wetland waters would ameliorate the harmful effects of temperature, but synergistic effects of temperature with salinity and toxicity of brine constituents would probably be offsetting, widening the area of wetlands effected. The temperature effects would be strictly short-term, and would terminate shortly after the source of any spill is brought under control.

In conclusion, there are many constituents of the geopressured brines of the Gladys McCall and Sweet Lake wells of concern to the area wetlands. Toxicities of individual constituents are compounded by high salt concentrations, high temperatures, low dissolved oxygen and high chemical oxygen demand. Some of the constituents have an acute short-term toxicity while others, particularly heavy metals, may be both toxic and persistent and subject to bioconcentration. Dilution and dispersion will reduce effluent concentrations where tidal mixing occurs but impounded wetlands may retain lethal and sublethal concentrations in their sediments for extended periods.

Subsidence

Subsidence or apparent sea level rise is on the order of 1.2 cm/yr in South Central Cameron Parish (Baumann and DeLaune, 1981). Marshes of the area are accreting at an average rate of about 0.7 cm/yr for a net vertical loss to subsidence of about 0.5 cm/yr. Between 1955 and 1978, shoreline erosion amounted to about 40 feet per year in South Central Cameron Parish with a net land loss of approximately 1% per year (van Beek and Meyer-Arendt, 1982).

The Sweet Lake well site is located on an upland sandy ridge at about 12 feet elevation MSL. Any subsidence resulting from geothermal-geopressure development would not be expected to significally effect any marshes or wetlands in the vicinity of the site. However, the Gladys McCall well site is surrounded by marshes and any subsidence induced by fluid withdrawal could significantly impact these wetlands as well as open water areas and subsequent shoreline erosion rates of marshes in the area. Janssen and Carver (1981) have estimated that full-scale development of the Parcperdue well in nearby Vermilion Parish could produce a total subsidence in the neighborhood of 0.004 feet at the well head with lesser subsidnece at concentric distances from the well site. Such small subsidence would have little impact on marsh loss. However, little quantitative data is presently available that is specific to geothermal-geopressure induced subsidence at the Gladys McCall well. Until such information becomes available, it will not be possible to estimate marsh and wetland impacts from induced subsidence at this site.

SOCIOECONOMIC IMPACTS

The expected work force for installation and operation of the proposed cogeneration facilities and associated wells will consist of 6-7 persons at any given time (Jonne Berning, pers.comm., Dec., 1983). Most of these workers are expected to come from the Lake Charles area which has large pool of well-trained workers in the construction and petroleum extraction industries, the well sites being approximately 20 and 50 miles, respectively from Lake Charles by state highway.

Because travel distance is not a limitation and few workers would be involved, no significant relocation of families is expected from the project and impacts on public services would be minor and insignificant. A small positive economic benefit could result from energy generation from the facility, providing there are no major accidents and no additional wells are needed for brine injection or energy extraction.

A major brine spill or well blowout resulting in an uncontrolled release of brine and gases could cause evacuation of houses and businesses in the area of impact. In the Tigre Lagoon accident, brines were carried a distance of 610 m (2000 ft) (ERDA, 1976). At the McCormak oil and gas well, maximum drift of fluid was 1840 m (6000 ft). Because of the rural character near the two wells under consideration here, relatively few people would be adversely affected by a major accidental spill. A major spill at the Sweet Lake well would pollute agricultural fields in the vicinity for 10 or more years with unexceptably high levels of salinity (US DOE, 1980).

BIBLIOGRAPHY

Baumann, R.H. and R.D. DeLaune. 1981. Sedimentation and apparent sea-level rise as factors affecting land loss in coastal Louisiana. Proceedings of the conference on coastal erosion and wetland modification in Louisiana: causes, consequences and options. Baton Rouge, Louisiana, Oct. 5-7. Pages 2-13.

Berning, J. Dec., 1983. Operations ard Testing Manager, Technadril-Fenix and Scisson. Pers. Comm.

Brereton, A.H., I. Thornton, and J.S. Webb. 1973. Effect of zinc on growth and development of larvae of Pacific oyster, Crossostrea. Marine Biology 9:96-101.

Callahan, M.A., M.W. Shimak, N.W. Gabel, I.P. May, C.F. Fowler, J. R. Freed, P. Jennings, R.L. Dufree, F.C. Whitmore, B. Moestri, W. R. Mabey, B.R. Holt, and C. Gould. 1979. Water-related environmental fate of 129 priority pollutants, Vols. I and II. EPA-440/4-79-029, U.S. Environm. Protection Agency, Washington, D.C. 1229 pp.

Chabreck, R.H. 1972. Vegetation, water and soil characteristics of the Louisiana coastal region. Bul. No. 664, Louisiana Agric. Exp. Stn., Louisiana State Univ., Baton Rouge. 72 pp.

Chabreck, R. H. 1982. THe effect of coastal alteration on marsh plants. Pages 92-98 in Proceedings of the conference on coastal erosion and wetland modification in Louisiana: causes consequences, and options. FWS/OBS-82159. Baton Rouge, Louisiana.

Cody, J. 1983. Planning Director, Imperial Calcasieu Regional Planning and Development Commission. pers. com.

Energy Research and Development Administration. 1976. An environmental assessment of proposed geothermal well testing in the Tigre Lagon oil field, Vermilion Parish, Louisiana. Washington, D.C.

Gambrell, R.P., R.A. Khalid, and W. H. Patrick, Jr. 1978. Disposal alternatives for contaminated dredged material as a management tool to minimize adverse environmental effects. Tech. Rep. DS-78-8, U. S. Army Engineer Waterways Exp. Sta., Vicksburg, Mississippi. 148 pp.

Gas Research Institute. 1980. Assessment of potential environmental impacts of geopressured methane development, final report for 1979. Chicago, Illinois.

Gosselink, J. G., C.S. Hopkinson, Jr., and R. T. Parrondo. 1977. Comman marsh plant species of the Gulf coast area. Vols. I and II. Technical Report D-77-44, U. S. Army Engineers Waterways Exp. Stn., Vicksburg, Miss. 202 pp.

Gosselink, S. M., C. L. Cordes and J. H. Parsons. 1979. An ecological characterization study of Chenier Plain coastal ecosystem of Louisiana Texas, Vol 1. U. S. Fish and Wildlife Service, Office of Biological Services FWS/OBS-78/79. 302 pp.

Janssen J. C. and D. R. Carver. 1981. A computer program for predicting surface subsidence resulting from pressure depletion in geopressured wells: subsidence prediction for the Dow test well No. 1, Parcperdue, Louisiana. Proceedings, 5th geopressured-geothermal energy conference. Louisiana State University, Baton Rouge, Louisiana Oct. 13-15, 1981. Pages 281-284.

Karkalits, O.C. and B.E. Hankins. 1981. Chemical analysis of gas and brine from MGT-DOE Sweet Lake Design Well. Proceedings, 5th conference, geopressured-geothermal energy. Baton Rouge, Louisiana. Pages 331-334.

Khalid, R. A. 1980. Chemical mobility of cadmium in sediment water systems. In cadmium in the Environment, Part I. J. O. Nriagu, ed. John Wiley & Sons, Inc., New York, Newy York. Pages 257-304.

U. S. Dept. of Commerce, Bureau of the Census. 1981. General population characteristics: Louisiana. 1980.

U. S. Dept. of Commerce, Bureau of the Census. 1983. County business patterns, 1981. Louisina. CBP-81-20 p. 38.

U. S. Dept. of Energy. 1980. Environmental assessment, Sweet Lake No. 1, Cameron Parish, Louisiana geothermal energy geopressure subprogram.

U. S. Dept. of Energy, 1981. Environmental assessment, Gladys McCall well site, Cameron Parish, Louisiana. Geothermal energy geopressure program. DOE/EA-0134.

U. S. Environmental Protection Agency. 1976. Quality criteria for water, EPA-440/9-76-023, U. S. Environmental Protection Agency, Washington, D.C. 501 pp.

U. S. Environmental Protection Agency. 1980. Water quality criteria documents; availability. Federal Register 45 (231): 79317-79379.

U. S. Environmental Protection Agency. 1981. National interim primary drinking water regulations CFR Part 141. pp 309-354.

Louisiana State Planning Office. 1972. Land use data analysis (LUDA) program, USGS Survey. One page.

Marsden, S.S. and N. Kozokaowa. 1979. A plan for the long-term environmental assessment of geopressured resource development in the Louisiana Gulf coast region. Institute for Environmental Studies, Louisiana State University, Baton Rouge.

Mayer, J. F. and C. L. Ho. 1977. Trace metals in selected aquatic environments of Louisiana coastal zone. Coastal Studies Institute, Louisiana State University, Baton Rouge.

McKee, J. E., and H. W. Wolf. 1963. Water quality criteria. State water resources control board, California. Publ. 3-A, 1971.

O'Neil, T., and G. Linscombb. 1975. The fur animals, the alligator, and the fur industry in Louisiana. Louisiana Wildlife and Fisheries Commission, New Orleans. Wild. Educ. Bull. 106. 66 pp.

Palmissano, A. W. 1970. Plant community-soil relationship in Louisiana coastal marshes. Unpublished Ph.D. dissertation, Louisiana State University, Baton Rouge.

U. S. Dept. of Agriculture. 1954. Diagnosis and improvement of saline and alkali soils. Agriculture Handbook No. 60.

van Beek, J. L. and K. J. Meyer-Arendt. 1982. Louisiana's eroding coastline: recommendations for protection. Coastal Environments, Inc., for Louisiana Department of Natural Resources, Coastal Management Section. 49 pp.

Wagner, P. R. 1981. Biological resources. Mississippi deltaic plain regional ecological atlas. FWS/OBS-81/16. Narrative of Map F. Pages 75-96.

Wilson, J. S., J. R. Hamilton, J. A. Manning and P.E. Muehlberg. 1977. Environmental assessment of geopressured waters and their projected uses. Industrial environmental research laboratory, US EPA. 600/7-77-039.