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TECHNICAL SUPPORT FOR GEOPRESSURED-GEOTHERMAL WELL ACTIVITIES IN LOUISIANA

**ANNUAL REPORT
for the period
1 November 1984 to 31 December 1986**

**C. G. Groat
Program Coordinator**

September 1987

**Work Performed under Contract
DE-FC07-85NV10425**

**Louisiana State University
Office for Research
Louisiana Geological Survey
University Station, Box G
Baton Rouge, LA 70893**

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PREFACE

This report describes environmental monitoring activities carried out by Louisiana State University (LSU) under U.S. Department of Energy Contract DE-FC07-85NV10425 for the period 1 November 1984 through 31 December 1986. Other aspects of the LSU technical support program completed under prior contracts were covered in final form in reports preceding this one. During the contract period, the Louisiana Geological Survey, aided by subcontractors, monitored microseismic activity, land-surface subsidence, and surface and ground-water quality at three designed geopressured-geothermal test well sites in Louisiana and Texas. Don Stevenson supervised microseismic monitoring activities, and Drukell Trahan coordinated water quality and land-surface subsidence studies. This is a progress report in the sense that it discusses program components, provides raw data, and presents preliminary interpretations. The environmental monitoring program continues and will be the subject of subsequent annual reports.

C. G. Groat

WATER QUALITY MONITORING

by

D. B. Trahan

ABSTRACT

The effects of geopressured-geothermal development on water quality surrounding and underlying DOE test sites can be determined only after careful consideration of temporal and spatial variations caused by natural and man-made processes. In southwestern Louisiana, the processes to be considered include runoff and tidal exchange. These processes form pathways in the hydrosphere for the migration of contaminants from such activities as agriculture, petroleum development and waste disposal.

Statistics of monthly and quarterly observations using FACTOR (SAS Institute, Inc., 1982) indicate natural mixing of fresh water and seawater as the primary source of variation in all natural waters at Gladys McCall and in ground waters at Sweet Lake. The effect of saltwater intrusion is minor in Sweet Lake surface waters and in all Parcperdue waters.

In some instances, data sets were too sparse or of too short a duration for an affective analysis. However, drilling fluid contamination has been indicated at all sites. This contamination has been mostly derived from historical activities, especially at Gladys McCall, where abandoned oil and gas pits have remained for decades. Drilling fluid contamination from geopressured-geothermal development has been strongly indicated at Sweet Lake due to anomalous concentrations of drilling fluid components in surface runoff and in ground waters during drilling and due to a relative lack of historical activities in the hydrologic regime.

INTRODUCTION

Variabilities in surface water chemistries can be ascribed to a number of causes. Climatic processes such as rainfall, seasonal warming and cooling, and barometric pressure changes are mostly temporal. Tidal exchange and land-surface runoff, although controlled by short- and long-term precipitation extremes and longer-term solar cycles, thus temporal, may vary spatially as well. Tidal exchange in the Louisiana Gulf Coastal Plain of southwestern Louisiana occurs from the south and land-surface runoff from the north. Runoff, and tidal exchange to a lesser degree, depending on the extent to which they have been controlled, may be mechanisms by which point-source contaminants are carried from localized domestic activities in agriculture, petroleum development and waste disposal. Agriculture may also impart a temporal variability to water chemistries due to the seasonal nature of tilling, planting, chemical spraying and harvesting.

Ground waters may also exhibit some chemical variability due to seasonal changes depending on their distance from a point of surface water recharge or the direction of groundwater flow. Flow in a discharging groundwater aquifer may be from above, below or along the aquifer depending on head distributions. Groundwater samples from southwestern Louisiana geopressured-geothermal prospects are taken at various depths from aquifers below sea level. Piezometric heads, in addition, are at or near sea level (Whitman and Kilburn, 1963). For this reason, seasonal rainfall and tidal extremes may influence the chemical variability of ground waters. Surface recharge to these aquifers typically occurs far to the north. There are some locations with limited interconnection of surface and groundwaters in the southern part however groundwater discharge is more likely in these areas (Harder et al., 1967). In addition, groundwater flow is slow so that recharge effects are not immediate. Tidal effects however, may be more immediate due to the close proximity of ground waters to the

freshwater/saltwater interface laterally as well as with depth (Harder, et al., 1967).

The saturation state of natural waters may affect the ability of the waters to undergo change due to mixing with allochthonous fluids and chemical reactions, thereby limiting chemical variability. The prime example in south Louisiana is of coastal waters that approach the chemistry of seawater due to saltwater intrusion. Constituents added to sea water are less likely to complex with other ions and may precipitate out, thereby affecting less change when compared to fresher waters.

RESULTS

Monthly elemental and physical data from surface and ground waters including elemental concentrations, chemical potentials, temperatures, and depths were factored using Statistical Analysis System's program for multivariate analysis, FACTOR (SAS Institute, Inc., 1982). This program statistically determines whether the variability of one element, species, or parameter is identical to the variability of other elements, species, or parameters and groups them according to the degree of correlation. The assumption in this test is that groups of ions will be related through chemical reactions and speciation in direct response to environmental factors and changes.

The analysis also provides a measure of the contribution of each parameter to its factor and the degree of variability explained by that factor. The factor contribution, not unlike a correlation coefficient, may be positive or negative, indicating the direction of correlation.

Results similar to those of a visual interpretation of concentration curves (Trahan, 1985) were obtained by the factor analysis. The first factor in all cases correlates parameters which are common reactants and products of the mixing of fresh water and seawater. This was demonstrated by the associa-

tion of calcium carbonate (CaCO_3), chloride (Cl), sodium (Na), boron (B) and sulfate (SO_4) by varying degrees depending on the proximity of the water to the coast. The association is more common in surface waters due to the masking effects of subsurface processes in ground waters and due to higher flow rates and more efficient mixing in surface waters. Furthermore, the order of factor contributions changes in analyses of coastal waters relative to upland waters; calcium carbonate being the dominant contribution in Parcperdue surface and ground waters and in Sweet Lake surface waters and sodium being the dominant contribution in Sweet Lake ground waters and all waters at Gladys McCall.

The second factor contribution in Parcperdue surface waters is very likely an indication of drilling fluid contamination as the contributing elements, barium (Ba), carbon (C), mercury (Hg) and ammonia (NH_4) are all common drilling fluid constituents (Fig. 1). The association of an increase in turbidity (TBTY) relative to increases in these constituents may reflect the over saturation of some species in solution, hence precipitation. The correlation of air temperature (TA), water temperature (TW), and dissolved oxygen (O_2) in group III would be expected in natural waters exposed to the atmosphere. The correlation serves to verify the validity of this statistical test. The correlation of day (D , julian) and sulfate (SO_4) in group IV is also representative of seawater intrusion. Seawater is higher in sulfate than fresh water, and would be expected to cause a temporal increase in sulfate concentrations as fresh waters convert to saline waters.

Ground water chemistries are, in general, more difficult to interpret, using any method due to the dynamics of groundwater transport and processes such as cation exchange and adsorption by clays in the matrix of the aquifer. Factor II in Parcperdue ground waters is likely representative of seawater intrusion as it illustrates a temporal increase in chloride content (Fig. 2). The source of arsenic (As) is uncertain. The third grouping of barium and

Figure 1. Factor groupings of elements and physical parameters for surface waters around the Parcperdue geopressured-geothermal prospect.

Figure 2. Factor groupings of elements and physical parameters for ground waters around the Parcedue geopressed-geothermal prospect.

ammonia again implies the presence of drilling fluids. Factor IV, suggesting that changes in ground water temperature are synchronous with changes in air temperature, suggests the possible interconnection of surface and ground waters at Parcperdue.

In Sweet Lake surface and ground waters, factor II may also represent seawater intrusion as well as other effects not well understood (Figs. 3 & 4). Factor III in surface waters again provides a test of the validity of these statistics by the expected correlation of air temperature and water temperature (Fig. 3). Drilling fluid constituents, carbon (C), barium (Ba), and lead (Pb) correlate in surface water factor IV, indicating contamination by drilling fluids.

Sweet Lake ground waters are more difficult to interpret. Besides the more obvious correlation of parameters in factors I and II which indicate saltwater intrusion, other correlations cannot be readily identifiable with their effects (Fig. 4). Another contribution to the correlation of parameters in factors I and II and correlation of sodium and sulfate in factor VII may be brine leakage from the disposal well noted in early 1982.

The parameters which correlate in factor I for Gladys McCall surface and ground waters are likely indicative of seawater intrusion and mixing (Figs. 5 & 6). A notable observation in surface waters, also obvious from a visual interpretation of concentration curves, is a negative correlation of concentrations with julian date. This indicates a decrease in constituents with time, the opposite of what would be expected as a result of saltwater intrusion. Ion adsorption, chelation or precipitation may be indicated in this case. Drilling fluid contamination may be responsible for the grouping of carbon (C), cadmium (Cd), lead (Pb) and mercury (Hg) in surface water factor II, but the contamination may not necessarily come from the geopressured-geothermal well. The area has been used for oil and gas development for many years and the Gladys McCall

Figure 3. Factor groupings of elements and physical parameters for surface waters around the Sweet Lake geopressured-geothermal prospect.

Figure 4. Factor groupings of elements and physical parameters for ground waters around the Sweet Lake geopressured-geothermal prospect.

Figure 5. Factor groupings of elements and physical parameters for surface waters around the Gladys McCall geopressed-geothermal prospect.

Figure 6. Factor groupings of elements and physical parameters for ground waters around the Gladys McCall geopressedured-geothermal prospect.

impoundment has enclosed many wells. It is likely that these elements are periodically leached and dissolved from oil and gas field storage and disposal pits buried at various locations in the impoundment. Other factors may also represent these and other effects, notably arsenic and barium in surface water factor VI and barium and ammonia in ground water factor IV which may indicate contamination from drilling or brine production. Sulfate (SO₄) and the calcium/magnesium ratio (RT) in surface water factor VII may indicate seawater intrusion and mixing. The correlation of air temperature and water temperature in ground water factor IV leads to some speculation that ground waters at Gladys McCall are interconnected with surface waters in the vicinity (Fig. 6).

Further testing of these results may be provided by a similar analysis of shorter periods of data. Each data set was subdivided into smaller sets corresponding to periods of no activity, drilling, and production at the geopressured-geothermal well and to location. Each subset was then subjected to a factor analysis. In some instances, the total observations in a subset were too few for an effective analysis. These subsets were eliminated from the analysis.

The factor analyses of subsets offer an interpretation of the contributions of the elements and physical parameters temporally and spatially. The long-term general trends observed in the first factoring, can thus be ascribed to short-term variations and more knowledge of proximity to the source(s) of variation. In this interpretation, more emphasis will be placed on the existence of potential factors attributable to geopressured-geothermal development. Most importantly, temporal and spatial baselines can be developed. The period of no activity can be considered the temporal baseline for it best determines the typical quality of water prior to geopressured-geothermal development. The sample location designated as the spatial baseline will be the location farthest removed from the geopressured-geothermal well or out of the flow path of

potential contaminants from the well. This sample site presumably best represents the quality of water in the area assuming that the geopressured-geothermal well is non-existent.

The most limiting variable in this analysis is the frequency and duration of sampling in sample subsets. A series of samples in a subset may be taken during a time when rainfall (hence runoff), tidal exchange and/or temperature were higher (or lower) than during other sample series. For this reason, much more emphasis and certainty can be placed on interpretations based on subsets containing the most observations. At Parcperdue, a similar number of observations is available for surface water samples taken during the period of no activity prior to geopressured-geothermal development and for samples taken during drilling of the geopressured-geothermal well (Table 1). The variability in numbers of observations is not as clear-cut in ground waters at Parcperdue. Observations were discontinued at some observation wells and were replaced by observations in deeper wells closer to the geopressured-geothermal well. The most effective analysis will utilize data from the 100 ft. well prior to geopressured-geothermal development (S100NA), from the 180 ft. well during drilling of the geopressured-geothermal well (L180DRIL) and from the 90 ft. well during production from the geopressured-geothermal well (D90PROD) (Fig. 7). Although these wells tap the same aquifer (Fig. 8), some variability will probably result from their inconsistent depths.

In Sweet Lake surface waters, greater numbers of observations are available during drilling and production from the geopressured-geothermal well (Table 1). Little emphasis can be placed on the background determinations derived during periods of no activity. In Sweet Lake ground waters, numbers of observations are relatively consistent at all sample locations during drilling, during the first production at the geopressured-geothermal well, and during

OBSERVATION WELL

1 - L180 3 - D130
 2 - D90 4 - NOT REFERENCED
 S50 & 100 OFF INSET TO WEST

SURFACE WATER STATION

LEFT TO RIGHT:
 LEBR LEBG BPP

Figure 7. Surface hydrology and water sample locations around the Parcperdue geopressedured-geothermal prospect. Closed circles represent surface water sample locations.

Figure 8. The geology and general chemistry of water-bearing stratigraphic units below the Parcperdue geopressured-geothermal prospect. Letter/number combinations and numbers refer to the locations of well logs. The heavy line at top marks the position of sea level.

SURFACE WATERS

<u>PARCERDUE</u>		<u>SWEET LAKE</u>		<u>GLADYS MCCALL</u>	
BPPNA	12	SWBRNA1	4	GLLKDRIL	28
LEBCNA	12	SWSQNA1	4	GLBRDRIL	28
LEBRNA	12	SWSWNA1	4	GLHGDRIL	25
BPPDRIL	15	SWBRDRIL	9	GLLKPROD	4
LEBCDRIL	13	SWSQDRIL	9	GLBRPROD	4
LEBRDRIL	13	SWSWDRIL	9	GLHGPROD	4
BPPPROD	5	SWBRPROD	8		
LEBCPROD	4	SWSQPROD	8		
LEBRPROD	4	SWSWPROD	8		
		SWBRNA2	3		
		SWSQNA2	3		
		SWSWNA2	3		

GROUND WATERS

<u>PARCERDUE</u>		<u>SWEET LAKE</u>		<u>GLADYS MCCALL</u>	
S50NA	8	SWEL1DRL	8	GL310DRL	27
S100NA	12	SWEL2DRL	8	GL660DRL	27
L180NA	4	SWEL3DRL	8	GL310PRD	4
D90DRIL	4	SWL1PRD1	8	GL660PRD	4
D130DRIL	6	SWL2PRD1	8		
L180DRIL	13	SWL3PRD1	8		
D90PROD	9	SWEL1NA	8		
S100PROD	2	SWEL2NA	8		
L180PROD	6	SWEL3NA	6		
		SWL1PRD2	2		
		SWL2PRD2	2		
		SWL3PRD2	3		

Table 1. Temporal and spatial subsets of water quality data for surface waters and ground waters at geopressured-geothermal prospects and numbers of observations.

shut-in following first production (Table 1). Observations during the second production from the well are too few for conclusive results.

The best results may be obtained from analyses of surface and ground waters at Gladys McCall during drilling of the geopressured-geothermal well. Over 25 observations were made of water chemistries during this period (Table 1). Although the numbers of observations during production are too few for conclusive results at this time, the data collection at this site has continued and should be available soon for inclusion in this analysis.

During the period of no activity at the Parcperdue geopressured-geothermal test site, the ranked factor groupings (Table 2) indicate mixing of fresh water and seawater as the primary and secondary source of variation in Leblanc Ditch near the Vermilion river (LEBRNA) and the primary source about 3.5 miles upstream (LEBCNA) (Fig. 7). The correlation of turbidity (TBTY), carbon (C), and barium (Ba) upstream may indicate well drilling residues from a source other than geopressured-geothermal development. The correlation of air temperature (TA) and water temperature (TW) consistently in all three sample locations, as in the general factoring, can be considered a test of the analysis. This association would be expected in surface waters in contact with the atmosphere. This association may be masked in other locations and at other times by the greater influence of other sources of variation. At Bayou Parcperdue, (BPPNA, BPPDRIL AND BPPPROD), fewer elements fall into factor groupings, probably due to the fact that the stream is intermittent as attested to by field investigations during dry conditions (Fig. 7). The stream is therefore most affected by runoff from the surrounding uplands which may render contaminants from a number of sources. Residues from agricultural applications and petroleum development would not be considered uncommon.

Considering the period of no activity as a temporal baseline and Bayou Parcperdue the spatial baseline (Bayou Parcperdue is farthest removed from the

BPPNALEBCNALEBRNA

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
Na	Mn	TA	Ba	Ca	TBTY	TW	O ₂	SC	SO ₄	TA	DT	Ba
pH	As	TW	TBTY	CaCO ₃	C	TA	pH	Mg	D	TW	RAIN	TBTY
SC			C	SC	Ba			Na				
Mg				Na				CaCO ₃				
CaCO ₃				Cl				Ca				
Cl				Mg				Cl				
Ca				RT				Mn				
				K				K				
								NH ₄				

BPPDRILLEBCDRILLEBRDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
K	Hg	Mn	RAIN	Cl	RT	Mn	Ba	SO ₄	Na	TBTY	K	RAIN	DT
Mg	Ba	Ca	DT	Na	TBTY	TW	RAIN	D	CaCO ₃	B	pH	TA	SO ₄
Na	NH ₄			B		TA			Mg				
B	C			SC					Ca				
Cl				Mg					SC				
TBTY				As					Cl				
CaCO ₃				CaCO ₃									
				Ca									

BPPPRODLEBCPRODLEBRPROD

<u>1</u>	<u>2</u>	<u>3</u>		
As	SC	TW	Data	Data
SO ₄	B	pH	Insufficient	Insufficient
O ₂	RT	DT		
D	NH ₄	TBTY		
RAIN	Ca	Mn		
	CaCO ₃	K		
	Na	Cl		
		TA		
		C		

Table 2. Factor groupings in temporal and spatial subsets for elements and physical parameters in surface waters around the Parperdue geopressured-geothermal prospect. Negative correlates are indicated in bold-face type.

test site along drainage), statistics indicate no change above the baselines which can be attributed to geopressured-geothermal drilling but potentially to drilling from other sources and fresh water/seawater mixing. This analysis cannot define the effects of geopressured-geothermal production on these waters due to a lack of data.

A lack of data in Parcperdue ground waters may also inhibit this analysis due to the fact that wells sampled at the beginning of the program were substituted with other deeper wells closer to the test site (Table 3). The spatial baseline best represented by the data is the completion depth of observation wells. It is best suited for designation as the baseline considering the direction of potential fluid migration from the subsurface production flow system or from the disposal of fluids at the surface.

The results from ground waters indicate high degrees of temporal and spatial variability (Table 3). The correlation of barium (Ba), carbon (C), and ammonia (NH₄) at the 50 ft well prior to geopressured-geothermal development (S50NA) does not indicate drilling fluid contamination as would be implied upon first inspection because the correlations are negative. A consistent correlation for calcium (Ca), magnesium (Mg), calcium carbonate (CaCO₃) and the calcium/magnesium ratio (RT) would be expected because these variables are interdependent. In the more general analysis, a correlation between air temperature and water temperature indicated an interconnection of ground waters with the surface. The lack of correlation in this analysis does not negate the previous results, but rather implies that a longer series of data was necessary to detect it.

The factor groupings of Sweet Lake surface water chemistries tend to exhibit much more variability than Parcperdue surface water chemistries probably due to the greater contributions of seawater mixing and agricultural runoff (Table 4). The site is on the edge of the prairie terrace bordering the

S50NA

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Ba	Na	Mn	Cl
C	pH	B	TBTY
NH ₄	Mg	TA	
As	CaCO ₃		
D	Ca		
K			

S100NA

<u>1</u>	<u>2</u>	<u>3</u>
Ca	TW	C
CaCO ₃	Mn	D
RT	TA	Ba
RAIN		
pH		

L180NA

<u>1</u>	<u>2</u>
As	O ₂
pH	K
NH ₄	Mn
RAIN	CaCO ₃
TA	B
Cl	TBTY
TW	Na
Ca	
SC	
Ba	
RT	
Mg	
D	

D90DRIL

<u>1</u>	<u>2</u>	<u>3</u>
CaCO ₃	TA	C
Ca	As	Na
RT	NH ₄	Ba
O ₂	RAIN	TBTY
B	TW	
K	SC	
Cl	Mn	
Mg		
D		

D130DRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
NH ₄	CaCO ₃	K	Mn
B	Ca	Cl	SC
C	RT	O ₂	Na
TA	Mg		
D	As		
	RAIN		

L180DRIL

<u>1</u>	<u>2</u>	<u>3</u>
CaCO ₃	B	NH ₄
Ca	D	TA
RT	Mn	
Mg		

D90PROD

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Mg	O ₂	Ca	SC
D	TBTY	TW	TA
NH ₄	RAIN	CaCO ₃	K
B	Mn		
As	C		
RT	Ba		
CaCO ₃			

D130PROD

Data
Insufficient

L180PROD

<u>1</u>	<u>2</u>	<u>3</u>
D	Ca	RAIN
B	Mn	O ₂
TW	CaCO ₃	As
SC	Cl	NH ₄
Na	RT	TA
K	pH	
TBTY		
Ba		
Mg		

Table 3. Factor groupings in temporal and spatial subsets for elements and physical parameters in ground waters around the Parcperdue geopressed-geothermal prospect. Negative correlates are indicated in bold-face type.

SWBRNA1

<u>1</u>	<u>2</u>	<u>3</u>
SC	Ca	As
Hg	DT	O ₂
Na	pH	NH ₄
SO ₄	Ba	TA
RAIN	CaCO ₃	
Cl	C	
K	Mn	
B	TW	
Mg		
D		

SWSQNA1

<u>1</u>	<u>2</u>	<u>3</u>
RAIN	RT	DT
Ba	TBTY	Mn
SO ₄	TW	
K	O ₂	
As	TA	
CaCO ₃	D	
Hg	pH	
NH ₄	SC	
Mg	Cl	
B		
Ca		

SWSWNA1

<u>1</u>	<u>2</u>	<u>3</u>
Hg	TA	O ₂
CaCO ₃	DT	C
Mg	pH	NH ₄
SO ₄	TW	As
Cl		
Na		
SC		
Ba		
RAIN		
K		
Ca		
Mn		
D		

SWBRDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
CaCO ₃	SO ₄	RAIN	pH
Mn	Ba	TA	Hg
SC	TBTY	TW	Cl
Ca			
B			
Pb			

SWSQDRIL

<u>1</u>	<u>2</u>
SO ₄	pH
SC	TW
Cl	Ca
K	
CaCO ₃	
Na	
RAIN	

SWSWDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Na	RAIN	Pb	pH
Mg	O ₂	Cd	B
Cl	TA	As	
SC	TW		
CaCO ₃	DT		
K			
RT			

SWBRPROD

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
TA	K	O ₂	Na
SC	pH	Pb	B
Cl	SO ₄	Hg	Cd
D	C	Ba	RT
Mg	TBTY		
TW			
Ca			

SWSQPROD

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
K	TA	C	Cl
Mn	TW	SC	SO ₄
DT	B	Na	As
Mg	D		
CaCO ₃	Ca		
	Cd		

SWSWPROD

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
O ₂	Mn	K	C
TW	CaCO ₃	DT	As
D	Na		
Ca	SC		
TBTY	Ba		
B	SO ₄		
TA			

Table 4. Factor groupings in temporal and spatial subsets for elements and physical parameters in surface waters around the Sweet Lake geopressured-geothermal prospect. Negative correlates are indicated in bold-face type.

marshlands and hence, water chemistries are controlled by tidal exchange from the south (Fig. 9). This may cause a temporal variability controlled by numbers of observations and sampling frequency if samples taken during one geopressured-geothermal development phase were taken mainly during a low (or high) tidal stand or a greater (or lesser) amount of runoff than samples taken during a higher (or lower) tidal stand or during a period of lesser (or greater) runoff.

Drilling fluids may be responsible for correlations of sulfate (SO₄), barium (Ba) and turbidity (TBTY) in site drainage during drilling (SWBRDRIL). Since no other well activities are obvious in the drainage area, this contamination is most probably from the geopressured-geothermal well. Other correlations can be ascribed to other sources. The correlation of lead (Pb), cadmium (Cd) and arsenic (As) in Sweet Lake during drilling (SWSWDRIL), may be due to local contamination in Sweet Lake (southernmost on map, Fig. 9). This lake has been the site of oil and gas development for decades. Residues from development activities in the lake may be periodically leached and dissolved from bottom sediments. Air temperature and water temperature correlations are common, attesting to the effectiveness of this analysis.

As in ground waters from the Parcperdue geopressured-geothermal prospect, groundwater chemistries from the Sweet Lake prospect are highly variable due to the potential combined effects of saltwater intrusion, groundwater pumping and subsurface processes (Table 5). The correlation of mercury (Hg), sulfate (SO₄), barium (Ba), sodium (Na) and ammonia (NH₄) in observation well number 3 during drilling (SWEL3DRL) is potentially due to drilling fluid migration from the geopressured-geothermal well bore (Fig. 9). This observation well is the deepest of the sampled observation wells and is directly in the presumed groundwater flow path from the well. Drilling fluids heavier than ground water may flow preferentially to the deeper well. Correlations of air temperature

OBSERVATION WELL

1 - SWL1 & SWEL1

2 - SWL2 & SWEL2

3 - SWL3 & SWEL3

SURFACE WATER STATION

TOP TO BOTTOM:

SWBR SWSQ SWSW

Figure 9. Surface hydrology and water sample locations around the Sweet Lake geopressured-geothermal prospect. Closed circles represent surface water sample locations.

<u>SWEL1NA</u>				<u>SWEL2NA</u>				<u>SWEL3NA</u>			
<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Na	NH ₄	Mn	Pb	Cl	Mg	B	pH	RT	CaCO ₃	Mg	O ₂
As	Cl	Ba	Hg	D	Na	SC	As	TW	Mn	K	TA
SO ₄	TBTY	B	SC	TBTY	K	Pb	Ba	Ca	DT	Na	SO ₄
Mg	D	pH		RT	NH ₄		C	D	C	NH ₄	
Ca	TW			Ca				Cl	RAIN		
								B			
<hr/>											
<u>SWEL1DRL</u>				<u>SWEL2DRL</u>				<u>SWEL3DRL</u>			
<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Mg	Pb	C	NH ₄	DT	B	SO ₄	TBTY	Ca	TBTY	Hg	SC
As	Cd	SO ₄	B	TW	Mn	C	pH	Mn	Cd	SO ₄	O ₂
Mn	DT	RAIN	pH	Cl	Hg	CaCO ₃	Ba	RAIN	K	Ba	C
Ca	K	Cl	Na	D	SC	RT	Na	As	DT	Na	
TA	TBTY		CaCO ₃	K	NH ₄		Mg	B	pH	NH ₄	
Hg	Ba			As				Mg	TW		
RT	TW			TA				TA			
SC				Pb							
D				Cd							
<hr/>											
<u>SWL1PRD1</u>				<u>SWL2PRD1</u>			<u>SWL3PRD1</u>				
<u>1</u>	<u>2</u>	<u>3</u>	<u>5</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	
D	Ca	TBTY	Mn	Na	CaCO ₃	Pb	Mg	Ba	TBTY	Ca	
DT	RT	B	Na	Cl	Hg	pH	CaCO ₃	Cd	NH ₄	Na	
SO ₄	K		NH ₄	TBTY	SO ₄	C	Mn	As	TA		
Mg				Ca	RT	RAIN		K			
TW				O ₂	Mg			B			
TA				K	B						
<hr/>											
<u>SWL1PRD2</u>		<u>SWL2PRD2</u>		<u>SWL3PRD2</u>							
<u>1</u>		<u>1</u>		<u>1</u>							
Data		Data		Na	K						
Insufficient		Insufficient		TA	pH						
				RT	DT						
				NH ₄	B						
				CaCO ₃	Mn						
				Hg	Cl						
				Mg	O ₂						
				TBTY	RAIN						
				SC	SO ₄						
				TW	Ca						
				C							
				D							

Table 5. Factor groupings in temporal and spatial subsets for elements and physical parameters in ground waters around the Sweet Lake geopressured-geothermal prospect. Negative correlates are indicated in bold-face type.

and water temperature in Sweet Lake ground waters are uncommon. These waters are probably unconnected to nearby sources of recharge (Fig. 10).

The main factor grouping in Gladys McCall surface waters (Fig. 11) is probably due to saltwater intrusion since these waters are coastal and receive little runoff when compared to inland waters at Parcperdue and Sweet Lake (Table 6). The correlation is most obvious in surface water samples taken during drilling (GLLKDRIL, GLBRDRIL, and GLHGDRIL) probably due to a greater sampling frequency and duration than samples taken during production (GLLKPROD, GLBRPROD and GLHGPROD). The correlation of chromium (Cr), cadmium (Cd), lead (Pb), and to a lesser extent, mercury (Hg) in surface waters during drilling, may not be due to geopressured-geothermal development. The area around the Gladys McCall geopressured-geothermal well has been the site of oil and gas development for decades. Oil and gas well pits, which were buried in the area prior to regulations controlling waste disposal, may be susceptible to periodic flooding and the subsequent leaching and dissolution of constituents.

Similar correlations are, in general, not evident in surface waters sampled during production from the geothermal well (GLLKPROD, GLBRPROD and GLHGPROD). These samples exhibit much more variability than earlier samples probably due to a shorter and less frequent sample series (Table 1). The predictive capability of these analyses should improve with a continuation of sampling at the site. The correlation of air temperature and water temperature is an exception. Although the correlation is not as obvious in samples taken during production versus samples taken during drilling, the correlation is apparent in all sample subsets testifying to the validity of this analysis.

In general, ground waters at Gladys McCall (Fig. 12) should exhibit much less variability than any of the waters observed in this analysis (Table 7). This ground water is in a coastal zone where saltwater intrusion has attained a nearly maximum level due to a relative lack of freshwater recharge from the

Figure 10. The geology and general chemistry of water-bearing stratigraphic units below the Sweet Lake geopressured-geothermal prospect. Letter/number combinations refer to the locations of well logs. The heavy line at top marks the position of sea level.

OBSERVATION WELL

1 - GL310

2 - GL660

SURFACE WATER STATION

CLOCKWISE FROM TOP:

GLLK GLBR GLHG

Figure 11. Surface hydrology and water sample locations around the Gladys McCall geopressured-geothermal prospect. Closed circles represent surface water sample locations.

Figure 12. The geology and general chemistry of water-bearing stratigraphic units below the Gladys McCall geopressured-geothermal prospect. Numbers refer to the locations of well logs. The heavy line at top marks the position of sea level.

GLLKDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Ca	Cr	As	TA
Na	Hg		TW
CaCO ₃	Cd		
Mg			
Cl			
D			
SO ₄			
SC			
B			

GLBRDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
CaCO ₃	Cr	Mn	TBTY	TW
Na	Cd	O ₂	RT	TA
Ca	Pb	C		
Mg				
Cl				
SO ₄				

GLHGDRIL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Na	Cd	D	TA
K	Pb	O ₂	TW
Ca	Cr	DT	
Mg			
CaCO ₃			
Cl			
SC			

GLLKPROD

<u>1</u>	<u>2</u>	<u>3</u>
SO ₄	Ba	D
Mn	SC	TBTY
Ca	O ₂	pH
NH ₄	Cl	As
B	C	RAIN
RT	DT	
CaCO ₃	Na	
TW		
TA		
Mg		
K		
Na		

GLBRPROD

<u>1</u>	<u>2</u>	<u>3</u>
Mg	TBTY	DT
K	RT	B
Cl	NH ₄	C
Na	D	pH
Ca	As	
CaCO ₃		
Ba		
SC		
SO ₄		
TA		
TW		

GLHGPROD

<u>1</u>	<u>2</u>
Ca	D
Ba	DT
CaCO ₃	TW
SC	TBTY
Cl	RT
K	TA
Na	Hg
O ₂	pH
Mg	SO ₄
RAIN	Mn
As	NH ₄
C	
B	

Table 6. Factor groupings in temporal and spatial subsets for elements and physical parameters in surface waters around the Gladys McCall geopressured-geothermal prospect. Negative correlates are indicated in bold-face type.

GL310DRL

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Na	B	TW	Pb
SO ₄	DT	As	pH
Ca			
SC			
CaCO ₃			
Cl			
Mg			
Mn			

GL660DRL

<u>1</u>	<u>2</u>
Ca	TBTY
RT	RAIN
K	
Na	

GL310PRD

<u>1</u>	<u>2</u>
pH	Cl
Hg	C
RT	SO ₄
TBTY	DT
RAIN	D
Mn	NH ₄
SC	Na
As	K
B	CaCO ₃
TW	O ₂
Ba	Ca
Mg	TA
TA	

GL660PRD

Data
Insufficient

Table 7. Factor groupings in temporal and spatial subsets for elements and physical parameters in ground waters around the Gladys McCall geopressured-geothermal prospect. Negative correlates are indicated in bold-face type.

north, or from greater saltwater recharge from deeper aquifers. Therefore ground waters chemistries more closely approach that of sea water and will be less affected by contamination. Data are generally insufficient to support any firm conclusions.

SUMMARY

Although the potential effects from drilling fluid contamination are probable in natural waters from geopressured-geothermal prospects in southwestern Louisiana, most observed effects were most likely the result of activities other than geopressured-geothermal development. The notable exceptions were in Sweet Lake site drainage and in the deepest observation well during drilling of the geopressured-geothermal well when constituents common to drilling fluids were correlated. The effects of drilling and production at other geopressured-geothermal wells have not been substantiated due to the masking effects of salt-water intrusion, agricultural runoff, and potential contamination from other petroleum development activities. In some instances, observations of water chemistries were too few or of short duration. Continued observations may enable further analyses. Most of these results seem to be valid due to correlations expected from seasonal atmospheric processes.

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SUBSIDENCE MONITORING

by

D. B. Trahan

ABSTRACT

Analyses of repeated geodetic levelings for motion determinations must rely on assumptions based on somewhat arbitrary points of reference established outside of or in the network. Subsidence monitoring networks for geopressured-geothermal prospects in southwestern Louisiana however, were initially referenced to the regional differential motion associated with isostatic adjustments in the Gulf Coast geosyncline and areas to the north (Trahan, 1986). Trends associated with the large-scale differential compaction of alluvium were also detected. Further adjustments to local motions observed at Gladys McCall have also been made when necessary to tie-in partial surveys. These adjustments were based on the assumption that motion occurs at a linear rate at reference benchmarks.

Statistical analyses conducted in earlier studies have been misleading due to interpolation between data points in a network which, by necessity, is somewhat sparse by most standards. The present analysis relies on actual observations which, after adjustment, provide information on the motions of benchmarks relative to each other with time. Repeated motion observations provide the only statistics which are effective.

According to this analysis, benchmark motions may be oscillatory, with each benchmark capable of moving up or down relative to its neighbor although this motion is usually small. Larger-scale motions indicate that subsidence decreases from west to east and that anomalous subsidence accompanied the construction and drilling of the Gladys McCall test site. Subsidence from historical oil and gas development has not been verified.

An attempt to relate this subsidence to sea-level rise and erosion on the coast south of the Gladys McCall well was also inconclusive due to a lack of data. However, the continuation of temporal analyses may provide for a more complete comparison at some later time.

INTRODUCTION

Analyses of geodetic leveling data for motion determinations usually rely on a presumed motion at some reference point along the survey network. Normally, a benchmark in a presumably more stable region is held fixed (no movement) during the two or more epochs of surveying being used to determine motion. This assumption has obvious flaws in south Louisiana where the land surface has been determined to be subsiding in a number of studies (Holdahl and Morrison, 1974; Swanson and Thurlow, 1973 and Trahan, 1986). In past analyses of geodetic leveling data from geopressured-geothermal prospects, motion rates were referenced to the regional vertical geodetic network and an assumed rate of uplift in the Monroe uplift area in northeastern Louisiana (Trahan, 1986). This information was used to construct contour maps of motion velocities around geopressured-geothermal test sites and to relate the motions to geopressured-geothermal development, historical petroleum production, natural landform variations, and geologic processes (Trahan, 1985). This type of analysis may be misleading however, because of the varied amount of interpolation between survey points for different epoch comparisons. For example, a correlation of abnormal subsidence in contour maps to the location of the Gladys McCall well during drilling was not entirely conclusive. A visual interpretation of new adjustments (Table 1) discloses that the abnormal motion observed was actually much lower. The new adjustment relied on the assumption that key benchmarks were subject to constant motion. This type of analysis is not intended for use in determining land surface elevations but relative changes in elevation among

BENCHMARK	RATE M/YR 81-82	RATE M/YR 82-84	RATE M/YR 81-84	RATE M/YR 84-86	RATE M/YR 82-86	RATE M/YR 81-86	AVERAGE
P213	-0.01466				-0.01465	-0.01465	-0.01465
TIDAL2	-0.01699						-0.01699
TIDAL1	-0.01338						-0.01338
TT184	0.00000				-0.01470	-0.01327	-0.00932
Q213	-0.01690				-0.01622	-0.01628	-0.01646
R213	-0.01816				-0.01530	-0.01558	-0.01634
GM1	-0.02558				-0.01400	-0.01513	-0.01823
S213	-0.02651				-0.01431	-0.01549	-0.01877
GM2	-0.02489	-0.01414	-0.01582	-0.01413	-0.01414	-0.01518	-0.01638
T213	-0.02829	-0.01548	-0.01748	-0.01872	-0.01684	-0.01795	-0.01912
TT186	-0.03504	-0.01409	-0.01737	-0.01096	-0.01278	-0.01494	-0.01753
U213	-0.02976	-0.01547	-0.01770	-0.00720	-0.01200	-0.01372	-0.01597
GM3	-0.03342	-0.01439	-0.01737	-0.00906	-0.01195	-0.01422	-0.01673
MARSH						-0.01389	-0.01389
TT187						-0.01386	-0.01386
W213						-0.01469	-0.01469
X213						-0.01718	-0.01718
MILLER RM1						-0.01152	-0.01152
DOLAND RM2						-0.01609	-0.01609
DOLAND						-0.01663	-0.01663
Y213						-0.01667	-0.01667
GM18			-0.01615	-0.01481		-0.01564	-0.01553
GM19			-0.01637	-0.01363		-0.01533	-0.01511
GM20			-0.01593	-0.01203		-0.01445	-0.01413
GM21			-0.01548	-0.01219		-0.01424	-0.01397
GM23			-0.01548	-0.01215		-0.01422	-0.01395
GM22			-0.01560				-0.01560
WELLHEAD				-0.00999			-0.00999
AVERAGE	-0.02181	-0.01471	-0.01643	-0.01226	-0.01426	-0.01503	-0.01531

BENCHMARK	RATE M/YR 81-82	RATE M/YR 82-84	RATE M/YR 81-84	RATE M/YR 84-85	RATE M/YR 82-85	RATE M/YR 81-85	RATE M/YR 85-86	RATE M/YR 84-86	RATE M/YR 82-86	RATE M/YR 81-86	AVERAGE
GM3	-0.03341	-0.01439	-0.01737	-0.00906	-0.01234	-0.01450	-0.00906	-0.00906	-0.01215	-0.01422	-0.01455
GM4	-0.03065	-0.01464	-0.01715	-0.00948	-0.01266	-0.01450	0.00028	-0.00814	-0.01191	-0.01373	-0.01325
GM5	-0.02879	-0.01368	-0.01604	-0.01074	-0.01255	-0.01421	-0.00076	-0.00937	-0.01187	-0.01351	-0.01315
GM6	-0.03172	-0.01339	-0.01626	-0.02166	-0.01657	-0.01813	-0.00189	-0.01895	-0.01573	-0.01728	-0.01715
GM7	-0.03058	-0.01374	-0.01637	-0.01095	-0.01267	-0.01450	-0.00701	-0.01041	-0.01234	-0.01411	-0.01426
GM8	-0.02925	-0.01438	-0.01670	-0.00948	-0.01249	-0.01421	-0.01493	-0.01022	-0.01263	-0.01425	-0.01485
GM9	-0.02718	-0.01424	-0.01626	-0.01116	-0.01305	-0.01450	-0.01519	-0.01171	-0.01318	-0.01453	-0.01510
GM10			-0.01548	-0.01095		-0.01392	-0.01927	-0.01209		-0.01419	-0.01431
GM11			-0.01493	-0.01158		-0.01377	2.67702	0.35649		0.12592	0.51985
DRAKE			-0.02147	-0.01200		-0.01820	-2.72353	-0.38322		-0.15866	-0.55284
GM12			-0.01459	-0.25626		-0.09803	-4.36884	-0.81929		-0.31976	-0.97946
GM13			-0.01493								-0.01493
GM14						-0.01363					-0.01363
GM15			-0.01593	-0.17995		-0.07256					-0.08948
GM16			-0.01604	-0.00821		-0.01334					-0.01253
GM17						-0.00123					-0.00123
GM24			-0.01582								-0.01582
GM25											
Q357									-0.01169		-0.01169
AVERAGE	-0.03022	-0.01406	-0.01635	-0.01138	-0.01319	-0.01374	-0.00847	-0.01129	-0.01283	-0.01447	-0.01332

Table 1. Motion rates determined from geodetic leveling results adjusted for initial stability at benchmark TT184 located west of the Gladys McCall geopressured-geothermal prospect.

Figure 1. Benchmark locations in the Gladys McCall subsidence monitoring network.

benchmarks. It is also intended to test the variability of motion rates between benchmarks with time.

The Gladys McCall subsidence monitoring network is the most extensively surveyed to date. Relevelings have been planned for the site as well. The network consists of benchmarks spaced approximately 1 km apart along roadways surrounding and leading to the site (Fig. 1). Each benchmark consists of a steel rod driven to 100 ft or to refusal, usually about 60 ft. Leveling surveys at Gladys McCall were conducted in 1981, 1984 and 1985 by an LSU subcontractor and in 1982 and 1986 by the National Geodetic Survey (NGS) as part of a regional adjustment.

Another research directive is aimed at understanding relative sea level rise along the coast near the Gladys McCall geopressured-geothermal prospect. Subsidence is presumably a large component of sea level rise along much of the Louisiana coast. To delineate subsidence from sea level rise requires a knowledge of the variation between local sea level rise and global (eustatic) sea level rise. Data collected during our subsidence monitoring efforts may add insight to this pursuit.

All of these efforts may eventually lead to the successful modeling of subsidence from a number of causes including the depressurization of geopressured-geothermal reservoirs and the production of oil and gas. For this reason, a treatise on the subject is included as Appendix 3 to this report.

RESULTS

Two new adjustments have been made to observed motions in the Gladys McCall subsidence monitoring network. The first adjustment is based on a constant motion rate of -0.00228 m/yr for benchmark P213, the westernmost benchmark on Louisiana highway 82, which is part of the NGS regional network, and on a constant motion rate of -0.00177 m/yr for benchmark GM2 which connects the

Gladys McCall subsidence monitoring network to the regional line (Appendix 1). The motion at P213 was derived from the regional adjustment of leveling data conducted in an earlier analysis (Trahan, 1986) and the motion at GM2 was determined from the yearly motion observed from 1982 to 1984.

The second adjustment relied on the assumption that uplift has not occurred at any benchmarks in the network. For this adjustment, all motions were reduced by 0.01238 m/yr to bring benchmark TT184 to initial stability (Appendix 1, Table 1). Some motions in the new adjustment can be disregarded due to the fact that certain benchmarks were disturbed or destroyed. This includes motions at benchmarks GM6, GM11, DRAKE, GM12, GM15, and GM17. Average motions, according to the new adjustments and not including the disregarded motions, range from -9.32 mm/yr to -19.12 mm/yr (Table 1). When these data are plotted, the amount of variability between benchmark motions is obvious. In general, most observed motions fall within the range from -13.0 mm/yr to -18.0 mm/yr for benchmarks located along the NGS regional line (Highway 82) and the road leading to the well site (Fig. 2). Motions of benchmarks along the refuge access road east of the well site in general range from -12.0 mm/yr to -16.0 mm/yr (Fig. 3). Also obvious is a greater degree of certainty provided by benchmarks with the greatest numbers of observations.

Three groups of benchmarks yield results which are most acceptable in terms of numbers of observations. Benchmarks GM2-GM3, along the NGS regional line, each had 6 observations (Fig. 2); benchmarks GM18-GM23, along the well access road, each had 3 observations (Fig. 2); and benchmarks GM3-GM9, along the refuge access road, each had 10 observations (Fig. 3). The yearly motion rates for these benchmarks also exhibit much variability as do the relative motions between benchmarks within each group (Fig. 4). According to these results, subsidence decreased between 1984 and 1986 and is greatest toward the west. In addition, motions of adjacent benchmarks along highway 82 and along

Figure 2. A comparison of average motion rates observed at benchmarks along Louisiana highway 82 and the access road to the Gladys McCall well. Numbers of observations are indicated.

Figure 3. A comparison of average motion rates observed at benchmarks along the refuge access road and the beach east and south of the Gladys McCall geopressured-geothermal prospect. Numbers of observations are indicated.

Figure 4. Comparisons of yearly motion rates for benchmarks along selected leveling lines around the Gladys McCall geopressured-geothermal prospect. Dotted lines pass through missing data.

the refuge road seem to oscillate with time; one benchmark may subside more or less than its neighbor depending on the time of observation. The anomalous behavior of benchmark T213 should be disregarded. A disturbance of the benchmark was overlooked in the initial analysis and was only noticed recently in benchmark recovery notes provided by the NGS (Appendix 2). The parallelism of motion curves for the well access road implies homogeneity. Since the road is contained within a levee system, the substrata may be less susceptible to local variations caused by differences in moisture content, drainage and flooding. The temporal variations may also explain the observation in earlier studies (Trahan, 1985) that compactional subsidence occurred at the well site during drilling. Although earlier maps of contoured motion velocities were inconclusive due to interpolation, the new analysis may further substantiate the claim that abnormal subsidence was associated with the additional weight of drilling and testing equipment. However, the entire length of the well access road exhibits the greatest subsidence between 1981 and 1984 when compared to the other profiles, and the benchmarks around the well (GM20, GM21, GM23 and GM22) exhibit less subsidence than other benchmarks along the road. The preferred explanation is that strata under the road and well pad were compacted by equipment brought in to the test site but that compaction at the site was less because of the relative stability of the substrata provided by pilings driven before well-site construction.

The interpolations of past analyses (Trahan, 1985) also led to results indicating historical oil or gas production as a probable cause for subsidence in the area. The new results do not substantiate this conclusion. However, these potential effects cannot be excluded. Depressurization of oil or gas reservoirs over the 30+ years these reservoirs have been producing may have resulted in a broader subsidence encompassing all the fields or in areas of subsidence that are delimited by the structures which define them. A more

densely spaced subsidence monitoring network may be necessary to delineate the associated motions.

Motions of benchmarks along the beach south of the Gladys McCall well (benchmarks GM12 through GM17 and GM24) are of particular interest because of their proximity to the shoreline. These benchmarks serve as landmarks to the shoreline position through time and offer a point of reference for measuring relative sea level rise. Although only one useful motion observation is available for these benchmarks, the new adjustment indicates that subsidence generally decreases from west to east consistent with motions observed to the north (Fig. 5). These observed motions should be comparable to the relative position of sea level during the surveys. A combination of sea level rise and subsidence is reported responsible for about 40 ft/yr of shoreline retreat in the area. Because of this, part of the subsidence record in the area is contained in the record of shoreline retreat south of the Gladys McCall well. It is of importance to know how much of this land loss is due to subsidence versus sea level rise or erosion. This delineation will add much insight to the interpretation of the subsidence record.

The geodetic leveling data for these benchmarks were extended in 1982 and 1984 by surface profiles of the beach. North-south profiles were run across benchmarks spaced approximately 1 km apart along the shoreline and topographic maps were constructed of the data (Fig. 6). Missing profiles were a result of destruction of benchmarks due to erosion and non-recovery of benchmarks due to burial. These maps indicate the position of the shoreline and height of the berm in January 1982 and June 1984. The maps were constructed using SURFACE II, a statistical computer program which contours a best-fit multiple regression (Sampson, 1975). Some error results were probably due to interpolation between surface profiles. For example, localized mounds depicted south of benchmarks are probably mostly connected into a continuous mound which runs the

W

E

Figure 5. Motion rates for benchmarks along the beach south of the Gladys McCall geopressed-geothermal prospect from 1981-1984. Dotted lines pass through missing data.

JANUARY 1982

JUNE 1984

KEY

⊙ BENCH MARK

▨ SHELL

CONTOUR INTERVAL = .5' MSL

0 25 50 100 200 300 100 M 300 FT

0 1000 2000 3000 FT
0 300 600 900 M

Figure 6. Topography and near-shore bathymetry of the beach south of the Gladys McCall geopressured-geothermal prospect in January, 1982 and June, 1984. Some data lines were missing in 1984 due to benchmark destruction.

entire length of the map. However, individual profiles are accurately depicted and distances when compared along profiles are accurate. Elevations on the maps are relative to continental elevations to the north adjusted for presumed measured subsidence. The 0 ft (0 m) contour, normally considered consistent with sea level, is independent of sea level position. It indicates, instead, the amount of shoreface erosion that has occurred during the time interval portrayed. The most erosion has occurred south of benchmark GM12 and the least has occurred south of benchmark GM15. This is consistent with results obtained from cross-sections of the profiles (Fig. 7). Sea level has been indicated on the cross-sections, assuming that the edge of the berm marks the position of mean tide during the time of the survey.

The same profiles, adjusted to negate the effects of subsidence (Fig. 8), indicate a relative sea level fall between January 1982 and June 1984. This measured rate of relative sea level change serves as an additional test of the accuracy of subsidence data based on land-surface elevation changes. This relative fall may not exceed the maximum tidal range for the area. A maximum relative fall of 1 ft is observed at benchmark GM15.

Relative sea level is proposed by various investigators to be rising (Hicks and Shofnos, 1965; Nummedal, 1983 and Penland et al., in press). However, these interpretations of sea level change have been based on best-fit adjustments of yearly records of tidal data. Shorter period oscillations may occur due to a number of factors such as variations in winds, current, water density, atmospheric pressure, precipitation and river discharge (Chew, 1964). Accordingly, a major oscillation is seasonal. It produces a bimodal distribution of high tides during a calendar year with tidal minimums in January, July, and December. Maximums typically occur in May and September. This short period oscillation, as observed in mareographs from a number of sources (Hicks and

Figure 7. Beach profiles south of the Gladys McCall geopressured-geothermal prospect in January, 1982 and June, 1984 indicate relative shoreline retreat and subsidence referenced to a continental datum.

Figure 8. Beach profiles south of Gladys McCall in January, 1982 and June, 1984 adjusted vertically to negate the effects of subsidence. Heavy horizontal lines mark the presumed position of mean high tide.

Shofnos, 1965 and Penland et al., in press), may have a periodicity from 2 to 8 years.

With this in mind, it is not surprising to see relative sea level falling in the beach profile cross-sections for the short time interval portrayed. Assuming that sea level was falling during an intermediate oscillation, sea level recorded in June 1982 should be lower than that recorded in January 1984 (Fig. 8).

It has been presumed that subsidence is the rule rather than the exception in the northern Gulf of Mexico due to geosynclinal downwarping (Spooner, 1935), soft-sediment consolidation, and a host of other factors (Poland, 1972). Relative sea level curves do not seek to separate the effects of subsidence or other factors from records of sea level change. Therefore, some minimal or maximal subsidence rate may be derived from records of relative sea level change when compared to subsidence records which are presumed not relative. It is hoped that this adjustment can be extended inland to the Gladys McCall subsidence monitoring network and to other networks farther inland.

Eustatic sea level change should be nearly consistent for parallel tide station records along a coast, especially if the stations are close together and are observed during the same time intervals. In this way, the station exhibiting the least amount of rise (or fall) should measure the least subsidence (or uplift) and a value closest to the (actual) change in eustatic sea level.

As mentioned previously, changes in sea level follow a number of oscillations including that caused by variations in solar activity and that caused by seasonal effects. Records of yearly sea level change (Penland et al., in press) illustrate a variance of about 0.04 ft/yr. Superimposed on this record is a monthly sea level variation which may amount to about 0.30 ft/yr (Chew, 1964). These oscillations are smaller than the observed drop in sea level

(Fig. 8). An alternate explanation to the observed fall in sea level is the diurnal variation which may exceed 2 ft in the area (NOAA, 1981 and NOAA, 1983).

Deposition is another key factor in the analysis of the beach profiles. It is highly probable that deposition occurs behind the berm and for some distance inland. This is attested to by the "tail" of sediments behind benchmark GM12 (Fig. 8) and by the fact that the marsh surface is relatively higher near the beach than inland. Recent field observations have disclosed an increasing tendency for flooding at a line approximately midway between the beach and Grand Chenier ridge located two miles inland and parallel to these two landforms. The effect of the deposition is to potentially offset the effect of subsidence or relative sea level rise north of the beach. Of course, deposition occurs mainly during storm tides, which are mostly seasonal.

This sedimentation may cause compactional subsidence near the surface but theoretically it has no effect on observed benchmark heights. The benchmarks consist of steel rods driven to refusal, greater than 60 ft. Periodic measurements of the tops of the rods presumably record only those changes occurring below 60 ft. Beach profiles, however, should be affected by this sedimentation since measurements of the land surface were made relative to the benchmarks. The land surface and the sedimentation surface are, by definition, the same.

The comparison of beach profiles surveyed in 1982 and 1984 and adjusted to negate presumed subsidence indicates a relative sea level fall at benchmark locations (Fig. 8). This relative fall increases from benchmark GM16 to benchmark GM15 then decreases from benchmark GM15 to benchmark GM12, indicating that subsidence decreases from benchmark GM16 to benchmark GM15 and increases from benchmark GM15 to benchmark GM12. The analysis of geodetic leveling data correlates only partially to these results (Fig. 5). This analysis indicates that subsidence decreases slightly from benchmark GM16 to benchmark GM15 and

decreases a greater amount from benchmark GM15 to benchmark GM12. The disparity may be due to variations in sedimentation rates on the marsh surface behind the berm or in near-surface compactional subsidence of the marsh under the berm. A combination of increasing sedimentation and/or decreasing near-surface compaction from benchmark GM12 to benchmark GM15 may explain the discrepancy.

SUMMARY

A 1- to 2-mm/yr variability in subsidence rates for benchmarks in the Gladys McCall subsidence monitoring network is obvious from new adjustments of motion rates in the network. Motions in the network decrease during the survey period and vary between benchmarks depending on the time of surveying. The variability may be explained by a number of factors including historical fluid production and sediment compaction. In addition, more emphasis can be placed on motions determined from a greater number of observations. These results further substantiate the potential effects of soil loading by the weight of drilling equipment brought in to the Gladys McCall test site. Although the analysis of beach profiles does not provide additional conclusive results as to the range of subsidence rates possible, it does indicate that with additional data on absolute tidal ranges, sedimentation rates and geodetic motions, the discrepancies may be resolved.

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BENCHMARK	RATE M/YR 81-82	RATE M/YR 82-84	RATE M/YR 81-84	RATE M/YR 84-86	RATE M/YR 82-86	RATE M/YR 81-86
P213	-0.00228				-0.00228	-0.00228
TIDAL2	-0.00461					
TIDAL1	-0.00100					
TT184	0.01238				-0.00233	-0.00090
Q213	-0.00452				-0.00385	-0.00391
R213	-0.00578				-0.00293	-0.00321
GM1	-0.01320				-0.00163	-0.00276
S213	-0.01413				-0.00194	-0.00312
GM2	-0.01251	-0.00177	-0.00345	-0.00176	-0.00177	-0.00281
T213	-0.01591	-0.00311	-0.00511	-0.00635	-0.00447	-0.00558
TT186	-0.02266	-0.00172	-0.00500	0.00141	-0.00041	-0.00257
U213	-0.01738	-0.00310	-0.00533	0.00517	0.00037	-0.00135
GM3	-0.02104	-0.00202	-0.00500	0.00331	0.00042	-0.00185
MARSH						-0.00152
TT187						-0.00149
W213						-0.00232
X213						-0.00481
MILLER RM 1						0.00085
DOLAND RM 2						-0.00372
DOLAND						-0.00426
Y213						-0.00430
GM18			-0.00378	-0.00244		-0.00327
GM19			-0.00400	-0.00126		-0.00296
GM20			-0.00356	0.00034		-0.00208
GM21			-0.00311	0.00018		-0.00187
GM23			-0.00311	0.00022		-0.00185
GM22			-0.00323			
WELLHEAD				0.00238		

BENCHMARK	RATE M/YR 81-82	RATE M/YR 82-84	RATE M/YR 81-84	RATE M/YR 84-85	RATE M/YR 82-85	RATE M/YR 81-85	RATE M/YR 85-86	RATE M/YR 84-86	RATE M/YR 82-86	RATE M/YR 81-86
GM3	-0.02104	-0.00202	-0.00500	0.00331	0.00003	-0.00213	0.00331	0.00331	0.00022	-0.00185
GM4	-0.01828	-0.00227	-0.00478	0.00289	-0.00029	-0.00213	0.01265	0.00423	0.00046	-0.00136
GM5	-0.01642	-0.00131	-0.00367	0.00163	-0.00018	-0.00184	0.01161	0.00300	0.00050	-0.00114
GM6	-0.01935	-0.00102	-0.00389	-0.00929	-0.00420	-0.00576	0.01048	-0.00658	-0.00336	-0.00491
GM7	-0.01821	-0.00137	-0.00400	0.00142	-0.00030	-0.00213	0.00536	0.00196	0.00003	-0.00174
GM8	-0.01688	-0.00201	-0.00433	0.00289	-0.00012	-0.00184	-0.00256	0.00215	-0.00026	-0.00188
GM9	-0.01481	-0.00187	-0.00389	0.00121	-0.00068	-0.00213	-0.00282	0.00066	-0.00081	-0.00216
GM10			-0.00311	0.00142		-0.00155	-0.00690	0.00028		-0.00182
GM11			-0.00256	0.00079		-0.00140	2.68939	0.36886		0.13829
DRAKE			-0.00910	0.00037		-0.00583	-2.71116	-0.37085		-0.14629
GM12			-0.00222	-0.24389		-0.08566	-4.35647	-0.80692		-0.30739
GM13			-0.00256							
GM14						-0.00126				
GM15			-0.00356	-0.16758		-0.06019				
GM16			-0.00367	0.00416		-0.00097				
GM17						0.01114				
GM24			-0.00345							
GM25										
Q357									0.00068	

Appendix 1. Motion rates determined from geodetic leveling results adjusted for constant motion at benchmark P213 located west of the Gladys McCall geopressured-geothermal prospect.

ACEN=AVC016 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--P 357 STATE-- COUNTY--
 QUAD--029092443 GSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--P 357 1982 OTHER CONTROL--
 LATITUDE = 294602N LONGITUDE = 0925030W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACEN=AVC073 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--P 213 STATE-- COUNTY--
 QUAD--029092443 GSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--IN DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--COPPER-CLAD STEEL ROD MONUMENTATION CODE--B
 STAMPING--P 213 1985 OTHER CONTROL--
 LATITUDE = 294552N LONGITUDE = 0925739W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

Appendix 2. National Geodetic Survey recovery notes for benchmarks in the Gladys McCall subsidence monitoring network.

ACR#AV0276 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--T1 184 USGS STATE-- COUNTY--
 QUAD--029092443 GSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--SURVEY DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--T1 184 STA LS 1932 R OTHER CONTROL--
 LATITUDE = 294540N LONGITUDE = 0925648W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION, THE DESCRIPTION IS ADEQUATE EXCEPT THE
 FENCE MENTIONED THEREIN HAS BEEN REMOVED.

ACR#AV0277 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--D 213 STATE-- COUNTY--
 QUAD--029092443 GSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--BM DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--D 213 1965 OTHER CONTROL--
 LATITUDE = 294528N LONGITUDE = 0925552W

***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACFI=AV0270 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--P 213 STATE-- COUNTY--
 QUAD--029092443 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--BM DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--COPPER-CLAD STEEL ROD MONUMENTATION CODE--6
 STAMPING--P 213 1965 OTHER CONTROL--
 LATITUDE = 294514N LONGITUDE = 0925456W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION, THE DESCRIPTION IS ADEQUATE EXCEPT
 ADD--0.18 METER (0.6 FT) EAST OF A CHAIN LINK FENCE.

ACFI=AV0510 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 1 LASU STATE-- COUNTY--
 QUAD--029092434 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--6
 STAMPING--LSU BM GM 1 6-1-81 OTHER CONTROL--
 LATITUDE = 294459N LONGITUDE = 0925403W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACCN=AV0250 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--S 213 STATE-- COUNTY--
 QUAD--029092434 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--BM DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STANDING--S 213 1965 OTHER CONTROL--
 LATITUDE = 294442N LONGITUDE = 092525W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACCN=AV0520 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 2 LASU STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STANDING--LSU BM GM 2 6-2-81 OTHER CONTROL--
 LATITUDE = 294434N LONGITUDE = 092522W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACEN=AV0521 ***** BENCH MARK DESCRIPTION *****

DESIGNATION--GM 18 LASU

STATE-- COUNTY--

QUAD--029002431 QSN--

LINE--

AREA--

LOCATED IN THE CITY OR TOWN OF--

MONUMENT BY--

YR--

CP--

MARK TYPE--FLANGE-ENCASED ROD

RECOVERY BY--NGS

YR--1986

CP--DCF

CONDITION--GOOD

SPECIFIC SETTING--STAINLESS STEEL ROD

MONUMENTATION CODE--B

STAMPING--LSU BN GM 18 1981

OTHER CONTROL--

LATITUDE = 294356N

LONGITUDE = 0925226W

***** RECOVERY DESCRIPTION *****

RECOVERED IN GOOD CONDITION. NEW DESCRIPTION FOLLOWS. 9.8 KM (6.1 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN GRAND CHENIER, THENCE 1.05 KM (0.65 MI) SOUTH ALONG A SHELL ROAD LEADING TO THE GLADYS MCCALL WELL SITE AND MARK ON THE RIGHT. IT IS 15.8 METERS (52.0 FT) SOUTH OF THE CENTER OF SHELL ROAD AND 1.8 METERS (6.0 FT) SOUTH OF A POWER LINE. NOTE--ACCESS TO DATUM POINT IS HAD THROUGH A 5-INCH LOGG CAP. A STAINLESS STEEL ROD SET TO THE DEPTH OF 25.6 METERS ENCASED IN A PIPE FLUSH WITH THE GROUND. 0.30 METERS BELOW SHELL ROAD. 0.4 METERS WEST FROM A WITNESS POST.

ACEN=AV0522 ***** BENCH MARK DESCRIPTION *****

DESIGNATION--GM 19 LASU

STATE-- COUNTY--

QUAD--029002431 QSN--

LINE--

AREA--

LOCATED IN THE CITY OR TOWN OF--

MONUMENT BY--

YR--

CP--

MARK TYPE--FLANGE-ENCASED ROD

RECOVERY BY--NGS

YR--1986

CP--DCF

CONDITION--GOOD

SPECIFIC SETTING--STAINLESS STEEL ROD

MONUMENTATION CODE--B

STAMPING--LSU BN GM 19 1981

OTHER CONTROL--

LATITUDE = 294333N

LONGITUDE = 0925220W

***** RECOVERY DESCRIPTION *****

RECOVERED IN GOOD CONDITION. NEW DESCRIPTION FOLLOWS. 9.8 KM (6.1 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN GRAND CHENIER, THENCE 2.0 KM (1.25 MI) SOUTH ALONG A SHELL ROAD LEADING TO THE GLADYS MCCALL WELL SITE AND THE MARK ON THE LEFT. IT IS 6.0 METERS (20.0 FT) EAST OF THE CENTER OF A SHELL ROAD AND 35.0 METERS (115.0 FT) SOUTHEAST OF THE SOUTHEAST END OF A BRIDGE. NOTE--ACCESS TO DATUM POINT IS HAD THROUGH A 5-INCH LOGG CAP. A STAINLESS STEEL ROD SET TO THE DEPTH OF 17.7 METERS ENCASED IN A PIPE PROJECTING 10 CENTIMETERS. 0.60 METERS BELOW SHELL ROAD. 0.4 METERS SOUTH FROM A WITNESS POST.

ACFM=AV0523 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 20 LASU STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU RM GM 20 1981 OTHER CONTROL--
 LATITUDE = 294244N LONGITUDE = 0925214W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACFM=AV0524 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 21 LASU STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU RM GM 21 1981 OTHER CONTROL--
 LATITUDE = 294244N LONGITUDE = 0925214W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACEN=AV0525 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--CP 23 LASU STATE-- COUNTY--
 QUAD--029002431 OSM-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--P
 STAMPING--LSU PM CP 23 1981 OTHER CONTROL--
 LATITUDE = 294244N LONGITUDE = 0025214W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ALFN=AV0557 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GLADYS MCCALL WELL LASU STATE--LA COUNTY--CAMERON
 QUAD--029002431 OSM-- LINE-- AREA--
 LOCATION-- 13.4 KM (8.3 MI) EAST OF GRAND CHENIER
 MONUMENT BY--MCA YR--UNK CP-- MARK TYPE--BOLT
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--UNSPECIFIED DEEP MONUMENTATION CODE--C
 STAMPING-- OTHER CONTROL--X
 LATITUDE = 294244N LONGITUDE = 0025214W

***** RECOVERY DESCRIPTION *****
 9.8 KM (6.1 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN
 GRAND CHENIER, THENCE 3.5 KM (2.2 MI) SOUTH ALONG A SHELL ROAD LEADING
 TO THE GLADYS MCCALL GEOTHERMAL WELL SITE AND THE MARK. THE MARK IS
 TOP OF BOLT ON THE SOUTH-SOUTHEAST SIDE OF WELL HEAD JUST EAST OF THE
 FIRST VALVE ABOVE GROUND ON THE SOUTH SIDE OF WELL.

ACIN=AV0512 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--N 357 STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY PY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STANDING--N 357 1982 OTHER CONTROL--
 LATITUDE = 294432N LONGITUDE = 0925218W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT AND ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACIN=AV0251 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--T 213 STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--RM DISK
 RECOVERY PY--NCS YR--1986 CP--DCF CONDITION--OTHER
 SPECIFIC SETTING--COPPER-CLAD STEEL ROD MONUMENTATION CODE--B
 STANDING--T 213 1965 OTHER CONTROL--
 LATITUDE = 294428N LONGITUDE = 0925203W

***** RECOVERY DESCRIPTION *****
 THE MARK WAS FOUND TO BE BENT AND IT WAS STRAIGHTENED BY THIS PARTY.
 ADD TO DESCRIPTION 0.91 METERS (3.0 FT) SOUTHEAST OF A FENCE POST WITH
 A WITNESS SIGN ATTACHED, 1.8 METERS (6.0 FT) WEST OF CENTER OF
 DRIVEWAY AND 0.15 METERS (0.5 FT) NORTH OF WITNESS POST. 0.62 METERS
 ABOVE HIGHWAY 12.

ACR=AV0282 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--TT 186 USGS STATE-- COUNTY--
 QUAD--022092431 OSM-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--SURVEY DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--TT STA 186 LS 1932 OTHER CONTROL--
 LATITUDE = 294416N LONGITUDE = 0925114W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION. THE DESCRIPTION IS ADEQUATE. A WITNESS
 POST WAS SET AT THIS TIME 0.30 METERS (1.0 FT) EAST OF MARK.

ACR=AV0283 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--U 213 STATE-- COUNTY--
 QUAD--022092431 OSM-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--BM DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--U 213 1965 OTHER CONTROL--
 LATITUDE = 294403N LONGITUDE = 0925008W

***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACRN=AVC527 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GN 3 LASU STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU PM GN 3 1981 OTHER CONTROL--
 LATITUDE = 294358N LONGITUDE = 0924952W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACRN=AVC528 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GN 4 LASU STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU PM GN 4 1981 OTHER CONTROL--
 LATITUDE = 294326N LONGITUDE = 0924058W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACR#AV0529 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 5 LASU STATE-- COUNTY--
 QUAD--029002431 OSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NCS YR--1956 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--R
 STAMPING--LSU RM GM 5 1981 OTHER CONTROL--
 LATITUDE = 294252N LONGITUDE = 092495W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT AND ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACR#AV0553 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--LM 6 LASU RESET 1986 STATE--LA COUNTY--CAMERON
 QUAD--029002431 OSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY--MCA YR--1986 CP-- MARK TYPE--OTHER
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--R
 STAMPING--LSU RM CM 6 1981 OTHER CONTROL--X
 LATITUDE = 294223N LONGITUDE = 092495W

***** RECOVERY DESCRIPTION *****
 14.2 KILOMETERS (8.8 MILES) SOUTHEAST ALONG STATE HIGHWAY 82 FROM THE
 POST OFFICE IN GRAND CENTER, THENCE 2.95 KILOMETERS (1.85 MILES)
 SOUTH ALONG PRICE LAKE ROAD (THE WEST BOUNDARY ROAD OF ROCKEFELLER
 WILDLIFE REFUGE) TO THE MARK ON THE LEFT, 4.87 METERS (16.0 FEET) EAST
 OF THE CENTER OF THE ROAD, AND ACCESS IS HAD THROUGH A 5-INCH LOGO
 CAP. NOTE--THE DATUM POINT HAS BEEN REMOVED, THE TOP OF THE ROD IS
 THE RESET CM. A STAINLESS STEEL ROD SET TO THE DEPTH OF 24.2 METERS
 ENCASED IN A PIPE FLUSH WITH THE GROUND. 0.6 METERS BELOW ROAD. 0.3
 METERS SOUTH FROM A WITNESS POST.

ACPN=AV0531 ***** BENCH MARK DESCRIPTION *****

DESIGNATION--GM 7 LASU STATE-- COUNTY--

QUAD--022092431 QSN-- LINE-- AREA--

LOCATED IN THE CITY OR TOWN OF--

MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD

RECOVERY BY--MGS YR--1986 CP--DCF CONDITION--POOR

SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B

STAMPING--LSU RM GM 7 1981 OTHER CONTROL--

LATITUDE = 294156N LONGITUDE = 0024954W

***** RECOVERY DESCRIPTION *****

RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
THROUGH A 5-INCH LOGO CAP.

ACPN=AV0532 ***** BENCH MARK DESCRIPTION *****

DESIGNATION--GM 8 LASU STATE-- COUNTY--

QUAD--022092431 QSN-- LINE-- AREA--

LOCATED IN THE CITY OR TOWN OF--

MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD

RECOVERY BY--MGS YR--1986 CP--DCF CONDITION--GOOD

SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B

STAMPING--LSU RM GM 8 1981 OTHER CONTROL--

LATITUDE = 294122N LONGITUDE = 0024954W

***** RECOVERY DESCRIPTION *****

RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
THROUGH A 5-INCH LOGO CAP.

ACIN=AV0523 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--C 257 STATE-- COUNTY--
 QUAD--029092431 DSM-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--C 357 1982 OTHER CONTROL--
 LATITUDE = 294112N LONGITUDE = 0925044W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACIN=AV0524 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GH 9 LASU STATE-- COUNTY--
 QUAD--029092431 DSM-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU BN CM 9 1981 OTHER CONTROL--
 LATITUDE = 294112N LONGITUDE = 0925044W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION EXCEPT ADD ACCESS TO DATUM POINT IS HAD
 THROUGH A 5-INCH LOGO CAP.

ACM=AV0554 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--CM 10 LASU STATE--LA COUNTY--CAMERON
 QUAD--029092431 OSM-- LINE-- AREA--
 LOCATION-- 17.8 KM (11.05 MI) EAST OF GRAND CHENIER
 MONUMENT BY--MCA YR--1981 CP--UKN MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU PM GN 10 1981 OTHER CONTROL--X
 LATITUDE = 294039N LONGITUDE = 0825057W

***** RECOVERY DESCRIPTION *****
 17.8 KM (11.05 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN
 GRAND CHENIER, THENCE 7.2 KM (4.5 MI) SOUTH ALONG THE WEST BOUNDARY
 ROAD OF THE ROCKEFELLER WILDLIFE REFUGE TO THE MARK ON THE LEFT SIDE
 OF A SMALL LEVEE. A STAINLESS STEEL ROD SET TO THE DEPTH OF 24.3
 METERS ENCASED IN A PIPE FLUSH WITH THE GROUND. ABOUT LEVEL WITH
 GROUND. 0.30 METERS SOUTH FROM A WITNESS POST.

ACM=AV0555 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--DRAKE 2 STATE--LA COUNTY--CAMERON
 QUAD--029092431 OSM-- LINE-- AREA--
 LOCATION-- 25.4 KM (15.8 MI) SE OF GRAND CHENIER
 MONUMENT BY--NGS YR--1979 CP--JRS MARK TYPE--TRI STA DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--COPPER-CLAD STEEL ROD MONUMENTATION CODE--B
 STAMPING--DRAKE 2 1979 OTHER CONTROL--HX
 LATITUDE = 294014N LONGITUDE = 0825057W

***** RECOVERY DESCRIPTION *****
 17.8 KM (11.05 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN
 GRAND CHENIER, THENCE 7.8 KM (4.85 MI) SOUTH ALONG THE WEST BOUNDARY
 ROAD OF THE ROCKEFELLER WILDLIFE REFUGE TO THE MARK ON TOP OF LEVEE.
 A COPPER-CLAD STEEL ROD SET TO THE DEPTH OF 6.1 METERS ENCASED IN A
 PIPE FLUSH WITH THE GROUND. 0.45 METERS ABOVE GROUND. 0.18 METERS
 WEST FROM A WITNESS POST.

ACPM=AV0556 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 11 LASU STATE--LA COUNTY--CAMERON
 QUAD--022092431 QSN-- LINE-- AREA--
 LOCATION-- 25.9 KM (16.1 MI) SE OF GRAND CHENIER
 MONUMENT BY--MCA YR--1981 CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--MCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING--LSU RM GM 11 1981 OTHER CONTROL--X
 LATITUDE = 294002N LONGITUDE = 0925054W

***** RECOVERY DESCRIPTION *****
 17.2 KM (11.05 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN
 GRAND CHENIER, THENCE 8.2 KM (5.1 MI) SOUTH ALONG THE WEST BOUNDARY
 ROAD OF THE ROCKEFELLER WILDLIFE REFUGE TO THE MARK ON THE LEFT SIDE
 OF A SMALL LEVEE. NOTE--ACCESS TO DATUM POINT IS HAD THROUGH A 5-INCH
 LOGO CAP. A STAINLESS STEEL ROD SET TO THE DEPTH OF 28.0 METERS
 ENCASED IN A PIPE FLUSH WITH THE GROUND. ABOUT LEVEL WITH GROUND.
 0.30 METERS SOUTH FROM A WITNESS POST.

ACPM=AV0557 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--GM 12 LASU RESET STATE--LA COUNTY--CAMERON
 QUAD--022092431 QSN-- LINE-- AREA--
 LOCATION-- 26.7 KM (16.6 MI) SE OF GRAND CHENIER
 MONUMENT BY--MCA YR--1981 CP-- MARK TYPE--FLANGE-ENCASED ROD
 RECOVERY BY--MCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--STAINLESS STEEL ROD MONUMENTATION CODE--B
 STAMPING-- OTHER CONTROL--X
 LATITUDE = 293946N LONGITUDE = 0925054W

***** RECOVERY DESCRIPTION *****
 17.2 KM (11.05 MI) EAST ALONG STATE HIGHWAY 82 FROM THE POST OFFICE IN
 GRAND CHENIER, THENCE 9.0 KM (5.6 MI) SOUTH ALONG THE WEST BOUNDARY
 ROAD OF THE ROCKEFELLER WILDLIFE REFUGE TO THE COAST AND THE MARK IN
 LINE WITH THE NORTH AND SOUTH LEVEE. NO STAMPING COULD BE FOUND ON
 MARK. NOTE--ACCESS TO DATUM POINT IS HAD THROUGH A 5-INCH LOGO CAP.
 A STAINLESS STEEL ROD SET TO THE DEPTH OF 30.4 METERS ENCASED IN A
 PIPE FLUSH WITH THE GROUND. 0.60 METERS ABOVE GROUND. 0.30 METERS
 EAST FROM A WITNESS POST.

ACEN=AV0204 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--MARSH STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YP-- CP-- MARK TYPE--TRI STA DISK
 RECOVERY BY--NCS YP--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STANDING--MARSH 1932 OTHER CONTROL--
 LATITUDE = 294346N LONGITUDE = 0924905W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION. THE DESCRIPTION IS ADEQUATE EXCEPT THAT
 THE FENCE HAS BEEN REMOVED AND THE MARK IS NOW 5.7 METERS (19.0 FT)
 WEST OF THE CENTER OF A SHELL ROAD AND 0.30 METERS (1.0 FT) LAST OF A
 WITNESS POST.

ACEN=AV0206 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--TIS 187 LS USGS 1965 STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YP-- CP-- MARK TYPE--SURVEY DISK
 RECOVERY BY--NCS YP--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STANDING--TIS 187 LS 1932 RESET 1965 OTHER CONTROL--
 LATITUDE = 294332N LONGITUDE = 0924755W

***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACID=AV0287 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--W 213 STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--RM DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--IN BASE OF A CATTLE GUARD MONUMENTATION CODE--D
 STAMPING--W 213 1965 OTHER CONTROL--
 LATITUDE = 294319N LONGITUDE = 0924657W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION. THE DESCRIPTION IS ADEQUATE EXCEPT ADD
 2.8 METERS (7.5 FT) EAST OF THE CENTER OF CAMERON PARISH ROAD 140.

ACID=AV0288 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--X 213 STATE-- COUNTY--
 QUAD--029092431 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--RM DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--COPPER-CLAD STEEL ROD MONUMENTATION CODE--B
 STAMPING--X 213 1965 OTHER CONTROL--
 LATITUDE = 294306N LONGITUDE = 0924551W

***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION. THE DESCRIPTION IS ADEQUATE EXCEPT THE
 MARK IS NOW 4.8 METERS (16.0 FT) NORTHWEST OF THE NORTHWEST CORNER OF -
 A SMALL PIC PEN. A COPPER-CLAD STEEL ROD SET TO THE DEPTH OF 26.8
 METERS ENCASED IN A PIPE FLUSH WITH THE GROUND. 0.20 METERS ABOVE
 GROUND.

ACPN=AV0291 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--HILLER RM 1 STATE-- COUNTY--
 QUAD--029092424 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--TRI STA REF DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--HILLER NO 1 1932 OTHER CONTROL--
 LATITUDE = 294246N LONGITUDE = 0924443W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACPN=AV0293 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--DOLAND RM 2 STATE-- COUNTY--
 QUAD--029092424 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--TRI STA REF DISK
 RECOVERY BY--NCS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--DOLAND NO 2 1955 OTHER CONTROL--
 LATITUDE = 294243N LONGITUDE = 0924404W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACPR=AV0227 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--DOLAND RM 1 STATE-- COUNTY--
 QUAD--020092424 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--TRI STA REF DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STANDING--DOLAND NO 1 1955 OTHER CONTROL--
 LATITUDE = 294246N LONGITUDE = 0924401W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACPR=AV0226 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--DOLAND STATE-- COUNTY--
 QUAD--020092424 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--TRI STA DISK
 RECOVERY BY--NGS YR--1986 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STANDING--DOLAND 1955 OTHER CONTROL--
 LATITUDE = 294244N LONGITUDE = 0924404W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACRM=AV0205 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--DOLAND AZ MK STATE-- COUNTY--
 QUAD--029092474 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--AZIMUTH DISK
 RECOVERY BY--MGS YR--1966 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CONCRETE POST MONUMENTATION CODE--C
 STAMPING--DOLAND 1955 OTHER CONTROL--
 LATITUDE = 294306N LONGITUDE = 0924353N
 ***** RECOVERY DESCRIPTION *****
 RECOVERED AS DESCRIBED.

ACRM=AV0205 ***** BENCH MARK DESCRIPTION *****
 DESIGNATION--Y 213 STATE-- COUNTY--
 QUAD--029092424 QSN-- LINE-- AREA--
 LOCATED IN THE CITY OR TOWN OF--
 MONUMENT BY-- YR-- CP-- MARK TYPE--RM DISK
 RECOVERY BY--MGS YR--1966 CP--DCF CONDITION--GOOD
 SPECIFIC SETTING--CUPPER-CLAD STEEL ROD MONUMENTATION CODE--R
 STAMPING--Y 213 1965 OTHER CONTROL--
 LATITUDE = 294232N LONGITUDE = 0924254W
 ***** RECOVERY DESCRIPTION *****
 RECOVERED IN GOOD CONDITION. THE DESCRIPTION IS ADEQUATE EXCEPT THAT
 THE WITNESS POST IS 0.30 METERS (1.0 FT) WEST. A CUPPER-CLAD STEEL
 ROD SET TO THE DEPTH OF 27.7 METERS ENCASED IN A PIPE FLUSH WITH THE
 GROUND. 0.30 METERS BELOW GROUND.

Appendix 3. A review of subsidence models applicable to geopressured-geothermal development.

Vertical movement of the lithosphere is a common problem associated with fluid withdrawal from subsurface formations. The vector movement, in most cases, is downwards by compaction (Gilluly and Grant, 1949; Fatt, 1958; Allen, 1968; and Geertsma, 1973) 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 have produced 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. (1980 a&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 modelling based on system thermal and mass transfer relationships. Other models which are more 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 modelling 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.

MODEL OF COMPACTION AND SUBSIDENCE

The most significant parameter effecting the compaction and resulting subsidence of a 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 reduced the ability of the reservoir to support the overlying strata. The strata 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:

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

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

(1 - ∞) = volume ratio of grains to total volume of sediment,

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

144 = one square foot in inches.

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

$$P = \frac{(1 - \infty) \times 2.7 \times 62.5 \times D + \infty \times 64 \times D}{144} \quad (2)$$

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 suare 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 the distribution and amount of pressure reductions. Structure contour maps of the producing reservoir indicated the thickness of reservoir sands. Mechanical properties of the involved sediments were determined in the laboratory using the relationship:

$$\frac{L_O - L_S}{L_O} \times E = P_S - P_O \quad (3)$$

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:

$$C = \frac{P_S - P_O}{L_S - L_O} \times \frac{1}{L_O} \quad (4)$$

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:

$$C_B = M C_m + C_g G \quad (5)$$

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 fluid pressure is depleted.

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

$$C_B = M(C_m - C_g) + C_g \quad (6)$$

Fatt (1958) also found that a relationship between C_B and G 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:

$$C_B = \frac{1}{V_B} \left(\frac{\partial V_B}{\partial P_e} \right) P_i \quad (7)$$

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:

$$C_{Pt} = \frac{1}{V_p} \left(\frac{\partial V_p}{\partial P_i} \right) P_e \quad (8)$$

- 2) Pseudo bulk volume compressibility:

$$C_{Bt} = \frac{1}{V_B} \left(\frac{\partial V_B}{\partial P_i} \right) P_e \quad (9)$$

- 3) Pore volume compaction:

$$C_P = \frac{1}{V_p} \left(\frac{\partial V_p}{\partial P_e} \right) P_i \quad (10)$$

- 4) Compressibility of total solid material:

$$C_r = \frac{1}{(V_B - V_p)} \left(\frac{\partial (V_B - V_p)}{\partial P} \right) \quad (11)$$

- 5) Net overburden pressure:

$$P_{ne} = P_e - nP_i \quad (12)$$

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 counteracting overburden pressure, formula 12 reduces to:

$$P_{ne} = gh(P_e - 0.85 P_i) \quad (13)$$

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:

$$C_B = \frac{1}{V_B} \left(\frac{\partial V_B}{\partial P_e - \frac{C_B - C_r}{C_B} \partial P_i} \right) \quad (14)$$

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 predominantly in the vertical plane, Geertsma (1973) characterized formation compaction by the vertical strain in the reservoir:

$$E_z = dz/z \quad (15)$$

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:

$$C_m = \frac{1}{z} \left(\frac{\partial z}{\partial p} \right), \text{ or } E_z = C_m dp \quad (16)$$

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:

$$\Delta H = \int_0^H C_m(z) \Delta p(z) dz \quad (17)$$

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 the 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:

$$\mu_z(r,0) = -\frac{1}{\pi} C_m (1 - \nu) \left(\frac{D}{(r^2 + D^2)^{3/2}} \right) \Delta p V \quad (18)$$

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

C_m = uniaxial compaction coefficient,

ν = Poisson's ratio,

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:

$$\mu_z(r,0) = -2C_m(1 - \nu) \Delta p \text{HR} \int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r) d\alpha \quad (19)$$

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

$$\mu_z(r,0) = -2C_m(1 - \nu) \Delta p \text{HA}(\rho, \eta) \quad (20)$$

Values for A can be obtained from tables such as that reproduced in Table 1. Further reduction of equation 20 can be accomplished by recalling equation 16, therefore:

$$\frac{\text{SUBSIDENCE}}{\text{COMPACTION}} = -2(1 - \nu)A \sim 1.5 A \quad (21)$$

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

TABLE 1—VALUES OF $A = R \int_0^\infty J_1(\alpha R) J_0(\alpha r) e^{-\eta \alpha} d\alpha$ FOR RANGES OF VALUES OF $\rho = r/R$ AND $\eta = D/R$
(after Geertsma, 1973)

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	0.1014	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

is able to compact. Teeuw (1971) provided the same formula for actual compaction as Geertsma (1973) 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:

$$C_m = 1/3 \left(\frac{1 + \nu}{1 - \nu} \right) (1 - \beta) C_B \quad (22)$$

where β = the ratio of rock matrix to rock bulk compressibility,

or C_{ma}/C_b .

State-of-the-art reservoir modeling studies of geothermal energy production have been reviewed extensively by Pinder (1979) and Miller et al. (1980 a&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. 1) to take advantage of their conception of problems associated with geothermal reservoir modelling. Strongest consideration is given to the idealization necessary in existing models which are based on assumptions of homogeneity, constant thickness, and other simplifications. Certainly, a most efficient

SOURCES OF ERROR

STAGE

FIGURE 1
GEOTHERMAL SUBSIDENCE PREDICTION PROCESS
(after Miller, et al., 1980a)

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,
- 5) Volume change, and
- 6) Pore volume compressibility.

Many of these parameters can be measured or estimated in the field or from well logs, i.e. 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 pressure, 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 (Whitman, 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 occurs, 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 ground water. Properly completed oil and gas wells may 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 a 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 gas 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.

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MICROSEISMIC MONITORING

by

D. A. Stevenson

ABSTRACT

Continuous microseismic monitoring networks have been established around U.S. Department of Energy (DOE) geopressured-geothermal design wells in southwestern Louisiana and southeastern Texas since summer 1980 to assess the effects well development may have had on subsidence and growth-fault activation. This monitoring has shown several unusual characteristics of Gulf Coast seismic activity. The observed activity is classified into two dominant types, one with identifiable body phases and the other with only surface wave signatures. During this reporting period 61 possible events were reported. Two of these are classified as local type I or body wave events; the remaining 59 are type II or surface wave events.

Origins of the type II events are still listed as unknown; however, little evidence is available to connect them with geopressured-geothermal well activity. We suspect sonic booms from military aircraft offshore.

The Gladys McCall well is the only prospect in production throughout this reporting period, with brine production levels averaging over 20,000 barrels per day. The two recorded type I events (magnitude <0.0) were both recorded by the Gladys McCall microseismic array. The locations and depths of the two events indicate possible associations with brine production at the Gladys McCall facility. However, with only two small coproduction events to work with it is impossible to speculate on their connection to well activity and growth-fault activation. It is believed that high volume, long-term testing remains the best test for coproduction seismicity and subsidence.

INTRODUCTION

Under DOE sponsorship the Louisiana Geological Survey and Louisiana State University have conducted baseline microseismic studies around the geopressured-geothermal design wells in Louisiana and Texas in order to assess the effects of well development on subsidence and growth-fault activation. The monitoring program was designed first to establish the nature of local seismic activity before production and second, to determine if well activities induce changes in the rates of local fault movement. This section describes the results obtained from microseismic monitoring during the two-year period January 1, 1985 to December 31, 1986.

During this reporting period four separate monitoring networks were in operation: Sweet Lake, Louisiana, Gladys McCall, Louisiana, Hulin, Louisiana, and Brazoria, Texas. The Sweet Lake network operated until April 30, 1986, which completed the final, post-production, phase of monitoring there. The Gladys McCall network has been in operation since summer 1980 and continues at present. The Hulin/Parcperdue and Brazoria networks went on line in October 1985 and operate today, collecting background seismic data before testing.

THE LOUISIANA AND TEXAS MICROSEISMIC MONITORING NETWORKS

The seismic networks that have been deployed by LGS/LSU are shown in figure 1. Operational status as of December 31, 1986 is presented in figure 2. Each network has consisted of from three to six short-period vertical component seismometers. To reduce the adverse effect of surface cultural noise on the data, seismometers are installed in boreholes up to 30 m (110 ft) deep. The seismic signals detected at each site within a network (fig. 3) are sent to the central recording facility at the LGS/LSU seismological laboratory in Baton Rouge via phone lines. Data received from the field are recorded in two different formats: first, the phone lines are fed directly into a 14-track

Figure 1. Microseismic network locations: Louisiana and Texas.

Operation Status of DOE Microseismic Recording Stations

Figure 2. Network status as of December 31, 1986.

Figure 3. Schematic of Typical Field Station Package.

programmable analog tape recorder together with a time code. The tapes allow us to digitize and save any signal of interest for further analyses and computer storage. Second, the phone signals are selectively demultiplexed into individual station signals and continuously recorded on visual drum recorders for daily analysis. It is from the paper drum records that we pick events for more detailed analysis and tape playback. Records are scanned daily to detect possible natural seismic activity. All events that are thought to be local microearthquakes are processed to obtain hypocenter locations and relative magnitudes. The hypocenter is determined by using computer algorithms similar to HYP071 (Lee and Lahr 1975). Magnitudes are calculated on the basis of event duration. Since a magnitude scale has not been developed for the Gulf Coast, the absolute values of computed magnitudes may not be valid. However, they do serve as good indicators of the relative size of events.

Magnitudes calculated for microearthquakes recorded at all the networks indicate that events have been small, less than 1.5. The exception to this is the magnitude 3.8 earthquake that occurred on 16 October 1983 to the northwest of the plugged and abandoned Sweet Lake prospect discussed in our 1983-84 report (Louisiana Geological Survey, 1985).

Gladys McCall Network

This six-station network has been in place since late summer 1980, operating continuously for the past six years. Figure 4 shows network station locations surrounding the prospect with an approximate 10-km diameter. Table 1 is a list of station coordinates. New broader band, better quality geophones were added to this network in 1984 to increase our detection threshold and allow us to record lower frequency signals. Since this addition, improved data quality and an increased detection threshold have resulted. We anticipate monitoring to continue at the Gladys McCall prospect through testing and at least one year after plug and abandonment.

Figure 4. Locations of Gladys McCall microseismic stations.

TABLE 1. Coordinates for Parcperdue, Sweet Lake, Rockefeller Refuge, and Pleasant Bayou seismic monitoring networks.

Station Name	North Latitude	West Longitude
HULIN/PARCPERDUE		
HFY	30°04'23.7"	91°58'55.5"
RHF	30°02'57.0"	92°00'25.5"
SSP	30°04'02.4"	92°03'15.3"
SWEET LAKE		
CPT	30°02'37"	93°12'47"
CPF	30°00'04"	93°08'02"
CLB	30°01'16"	93°08'43"
SFY	30°00'50"	93°10'56"
HWN	30°01'05"	93°05'19"
WLR	30°03'34"	93°07'41"
JCF	30°02'16"	93°07'01"
HWS	29°59'33"	93°05'17"
ROCKEFELLER REFUGE		
BCH	29°40'38"	92°53'19"
LEV	29°42'43"	92°52'54"
PLR	29°41'14"	92°50'00"
ALP	29°43'13"	92°48'32"
WRD	29°43'52.42"	92°52'19.43"
HQS	29°44'31"	92°52'27"
PLEASANT BAYOU		
DLF	29°10'29.4"	95°16'53.40"
EFF	29°15'53.4"	95°16'10.20"
GAR	29°20'13.80	95°18'21.60"

Pleasant Bayou Network

This four-station network (fig. 5, table 1) has been operating since October 1985 collecting microseismic background data in anticipation of a new testing program there. When that testing starts we will be deploying an additional two or three stations to augment our coverage of the area. Monitoring and data collection continues at present.

Hulin/Parcpardue Network

This three-station skeleton network is made up of stations within the old Parcpardue array. The purpose for continuing the data collection long after plug and abandonment is to provide long-term, relatively uninterrupted, background data for the prospective Hulin project. The Hulin well is located some 15 km south of the present stations (fig. 6, table 1). The Hulin/Parcpardue network now is fully operational and can be moved closer to the Hulin site with relatively little trouble.

Sweet Lake Network

The Sweet Lake stations were in operation until April 1986, almost two years after shut-in of the prospect. Station locations with respect to the well are in figure 7 and listed in table 1. All stations within this network have been removed and no data have been collected since April 30, 1986.

DATA ANALYSIS

The present microseismic networks, associated with geopressured-geothermal well development, are the first continuous seismic monitoring stations established in the Gulf Coast region. Interpretation and identification of the recorded seismic signals has been hampered by the lack of historical background data available for comparison.

As seen in previous reports (1983-1984), a vast majority of signals initially attributed to seismic activity around three of the Louisiana test wells

Microseismic Monitoring (Reference Map)

▲ Microseismic Station

Figure 5. Locations of Pleasant Bayou microseismic stations.

Figure 6. Locations of Hulin/Parcperdue microseismic stations.

Figure 7. Locations of Sweet Lake microseismic stations.

were actually signals derived from thunderstorms passing over or close by the seismic recording networks. It is only by identifying the sources of as many signals as possible that we can separate the possible well-induced activity from other human-induced or natural activity.

Types of Signals

Various signal sources have been tentatively identified through the course of this study, and as more data are collected, increasing numbers of signals are identified and catalogued. Geophysical exploration blasting continues to account for much of the activity (fig. 8) as does cultural noise such as the movement of vehicles along nearby roads.

In our last report (1983-1984) we noted periods of extremely regular seismic energy at the Gladys McCall network appearing every ten seconds. This energy took the form of short bursts 3 to 4 seconds in duration and continuing for periods of hours, during the day and night (fig. 8). The origin of these signals was listed as unknown at the time. We suspected that they were not natural, but human-induced. We have since discovered that the signals originate from large geophysical air-guns used in offshore oil exploration.

Distant Teleseisms from throughout the world are also recorded regularly by all networks. We tentatively identify and catalog all incoming teleseismic signals. A toll-free computer access number is used to match our signal arrival times against origin times from a list of worldwide earthquakes, issued weekly by the National Earthquake Information Service in Boulder, Colorado. We have over 50 cataloged and digitized Teleseisms from all over the world.

Two other types of signals have been recorded by the three networks: type I, or body wave events and type II, or surface wave, events. Type I events are classified as microearthquakes and typically are characterized by a P-wave arrival (primary compressional/dilatational), S-wave arrival (secondary, shear waves) and in some instances, a surface wave arrival. Type I events display P-

Figure 8. Regular type signals recorded at LEV within the Gladys McCall network, and two geophysical exploration blasts.

wave velocities ranging from 1.5 to 6.0 km/s (5000 to 20,000 ft/sec) and contain seismic signatures typical of microearthquakes reported throughout the world (fig. 9).

Type II events are signals consisting entirely of surface (Rayleigh) waves. They are characterized either by an impulsive or emergent first arrival. The apparent velocity with which these events traverse the networks is essentially sonic (0.35 km/s, or 1150 ft/s), and is similar to velocities of fundamental mode Rayleigh waves derived for a portion of the Gulf Coast in Texas. Because the sediment velocities in southern Louisiana are similar to those in coastal Texas, the initial conclusion was that the type II events may be attributed to leaking energy from microearthquakes within a near-surface low-velocity layer, which would tend to trap the seismic energy within it. However, the frequency and velocity range of the type II events is also occupied by acoustical transmissions through the air (thunder or sonic booms), and significant coupling of atmospheric acoustic and earth Rayleigh waves is very common.

Type II Microearthquake

In our 1983-84 annual report we demonstrated that most of the 1000+ documented Louisiana type II events were due to thunderstorms passing across the microseismic networks rather than some underground source. (Appendix I presents an analysis of some 1983 Texas data (Teledyne, 1983a and 1983b) with respect to thunderstorms in that region.) However, after removing all suspected events associated with thunderstorm activity from consideration there still remained a relatively small group of unidentified emergent and impulsive type II signals.

Station: LEV

85/02/14

00:23 (UTC)

**10
sec.**

Station: LEV

85/10/14

01:09 (UTC)

Figure 9. Type I microseismic event.

Emergent Type II Signals

These signals have been recorded by all microseismic monitoring networks with the majority of them showing up on the Rockefeller Refuge and Sweet Lake records.

Figure 10 is an example of such an event as recorded at the Gladys McCall and Sweet Lake networks. While the Sweet Lake network was in operation (through April 1986), many of the emergent signals were recorded by both Sweet Lake and Gladys McCall. This indicates to us that the signals are regional in extent. However, a few of the signals are confined to one network or another, which suggests a more localized source. In figures 11 and 12 numbers of events are plotted with respect to time of day and day of week, respectively. It is seen that most events take place during the afternoon and early evening hours on all days of the week. No events are recorded late at night. The fact that no signals appear late at night seems to indicate that this activity is probably not natural and it is unlikely that its origin is due to geopressured-geothermal well activity. The emergent character of these signals makes it impossible to determine a reliable first break for locating purposes. The source of these signals remains essentially unknown.

Impulsive Type II Events

The impulsive type II events constitute another small group of recorded signals not related to thunderstorm activity. Although they are common to all networks they seem to be local to each network with the majority of them recorded by the Hulin, Pleasant Bayou, and Sweet Lake networks. Within the two-year period covered by this report only 2 of 20 such signals have been recorded by the Gladys McCall network. Examples of this type event, as recorded at station SSP (within the Hulin network) and another event recorded at EFF (within the Pleasant Bayou network) are shown in figure 13. The signals do not appear to be similar in character. However, frequency plots of each

Sweet Lake Network

Gladys McCall Network

Figure 10. Emergent type II events recorded at Gladys McCall and Sweet Lake.

Emergent Type II Event

Figure 11. Numbers of events with respect to time of day.

EMERGENT TYPE II EVENT

Figure 12. Numbers of events with respect to day of week.

12/31/86
19:16:00 (UTC)

EFF

Pleasant Bayou Network

10/16/86
Parc Perdue Network

SSP

Parc Perdue Network

Figure 13. Impulsive type II events recorded at Hulin/Parcperdue and Pleasant Bayou.

signal (fig. 14) shows amplitudes differ, probably due to different subsurface structures along ray paths, but the same frequency peaks appear on each example. We interpret this to indicate that they may have a common source. They seem to originate from a southerly or Gulf direction regardless of which network is recording them. We suspect military aircraft operations or some other offshore activity.

Plots of activity with respect to time of day and day of week show a definite pattern (fig. 15 and 16, respectively). Most of these events occur between 8:00 am and noon on Tuesdays and Thursdays. No impulsive type II events have ever been recorded on Sundays or after 5:00 pm. Again, this does not point to natural activity, but rather to some sort of human-induced signal. The source of these signals still must be listed as unknown; however, it seems unlikely that these events are due to well activities.

Type I Events

Of the four geopressured-geothermal prospects, the Gladys McCall well is the only one to be in production through the reporting period. It is also the only seismic network to show any evidence of local type I microseismic activity. Two small suspected type I events on February 14 and October 10, 1985, (magnitude <0.0) have been recorded and located in the Gladys McCall area (figs. 5 and 9). The events' computed shallow depths (<2.0 km), and epicentral locations put them in close proximity to areas of possible influence by brine production and disposal. Additionally, the events took place at times of day that are well outside usual work hours, thereby making them likely candidates for natural events, as opposed to similar-looking geophysical exploration blasting.

We continue to review data daily for more evidence of well-induced coproduction microseismic activity. All such suspected events are reported in our monthly progress reports. With only two recorded type I events during this

Figure 14. Frequency plot of impulsive events from figure 13.

IMPULSIVE TYPE II EVENT

Figure 15. Numbers of events with respect to day of week.

IMPULSIVE TYPE II EVENT

Figure 16. Numbers of events with respect to time of day.

reporting period, it is impossible to derive information other than hypocentral locations at this time.

SUMMARY

Six years of microseismic monitoring data at USDOE geopressured-geothermal prospects in Louisiana and Texas have displayed many different and curious signal characteristics. Two main signal types have been reported from all networks. These include the type I, or body wave, events which more closely resemble microearthquakes reported from other areas of the world and type II, or Rayleigh wave, events that display characteristics more closely related to sonic waves.

Type II events are further classified into groups of emergent and impulsive signals. Both examples of type II events have been recorded by all networks with most emergent events being recorded at Gladys McCall and most impulsive events from the other networks. Emergent type II events exhibit mainly regional characteristics, while impulsive type II events appear to be local to the network recording it. We feel it unlikely that any of these events are related to well activity. Owing to their time of occurrence, they are suspected to be human-induced rather than natural in origin.

Included in the type I group are both local and teleseismic events. Teleseismic type I events have been recorded by all networks, however only Gladys McCall has shown any evidence of local type I activity. It is also the only well to produce continuously during this reporting period.

The Gladys McCall test program has evolved into the most productive of all Louisiana or Texas prospects producing large volumes of brine since November 1983. Average brine production rates of over 20,000 barrels per day have been regularly reported during this reporting period. The two local type I events that occurred in the Gladys McCall area were located at depths and in areas

that are probably within the area influenced by production. However, with the occurrence of only two small events, it is impossible to draw any meaningful conclusions about coproduction seismicity or growth fault movement from them.

Long term, high volume testing, such as that being done at Gladys McCall, remains the best test of whether microseismicity and growth fault activation will be induced by development of a single geopressured-geothermal prospect.

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APPENDIX 1

TEXAS PORTION

In our 1983-84 annual report it was determined that times of most reported Type II activity correlated extremely well with thunderstorms passing over or near the Louisiana microseismic recording networks of Sweet Lake, Gladys McCall, and Parcperdue. With this in mind, we examined events listed in the Teledyne Geotech quarterly report for the last six months of their Texas monitoring program (January to June 1983), and compared them with available weather data for the same period.

When attempting to match thunderstorms to suspected microearthquake activity we use hourly radar summary charts prepared by the National Weather Service office at Lake Charles, Louisiana. The radar summary charts do not necessarily record thunder and lightning strikes but they do indicate areas and intensities of rainfall with probable thunderstorms in a 400 km (250 mi) radius of Lake Charles, Louisiana. This radius easily encompasses the Louisiana and Texas USDOE geopressured-geothermal design wells. Only 1983 summary charts have been made available to us, making correlation with previous years impossible.

Comparing reported Texas events through the first six months of 1983 with radar summary charts reveals an extremely strong correlation to thunderstorm activity near the Pleasant Bayou, Texas, well, and the seismic recording network around it. Between January and March, 43 impulsive type II events were recorded by the Texas network. Of these, 35 (80%) coincided with local thunderstorm activity. From April to the end of the program in July, 30 impulsive type II events were reported. Sixteen of the 30 were attributed to operations at a chemical plant southeast of the network. Of the remaining 14, 7 were associated with thunderstorm activity in the area and 7 have no explanation.

In the entire six-month period all reported type II events not attributed to thunderstorm or chemical plant activity occurred during daylight or early evening hours and never on weekends. This pattern does not suggest natural origins for these signals, but they must remain as classified as unknown.

The thunderstorm-related type II activity displayed much the same characteristics in Texas as in Louisiana. Reported microseismic events would commence as thunderstorms began moving close to or over the network, with events subsiding as the storms moved out of the area or dissipated. For example, on March 23, 1983, 28 type II events were reported between the 3.5-hour period of 17:00 and 20:30 (UTC). Figures A-1 to A-7 show the hourly progression of a thunderstorm system as it approached the Pleasant Bayou microseismic monitoring network from the north, and eventually moved off to the east. The 28 events occurred when the most severe portion of the storm was closest to the network (figs. A-2 through A-6). The storm then moved off to the south and east by 02:30 (UTC) (fig. A-7), and no further events were reported for the next three days, when an event apparently originating from the chemical plant to the southeast was recorded.

This six-month sample of old Texas data seems to indicate a very strong correlation between thunderstorm activity and reported type II events at Pleasant Bayou. Correlation with previous years' data was not possible due to the unavailability of radar summary charts before 1983. Therefore, alternative explanations about the sources of previous years' seismic activity can not be offered. It does seem reasonable to assume that events reported in previous years contain some weather-related signals.

A-1 Radar summary chart 23 March, 1983, 1630 UTC

A-2 Radar summary chart 23 March, 1983, 1730 UTC

A-3 Radar summary chart 23 March, 1983, 1830 UTC

A-4 Radar summary chart 23 March, 1983, 1935 UTC

A-5 Radar summary chart 23 March, 1983, 2035 UTC

A-6 Radar summary chart 23 March, 1983, 2135 UTC

A-7 Radar summary chart 23 March, 1983, 2230 UTC

APPENDIX 2

List of recorded events from all networks

GMc = Gladys McCall; H = Hulin; SL = Sweet Lake; PB = Pleasant Bayou

Date	Time (UTC)	Recording Network	Comments
1984			
11/01	23:30	GMc	distant blasts?
	23:34	GMc	distant blasts?
11/02	17:46	GMc	distant blasts?
11/05	20:09	GMc	very emergent type I
11/09	22:47	GMc	poss. regional type I
11/13	00:50	GMc	noise?
11/16	05:48	GMc	offshore blasting
	05:49	GMc	offshore blasting
	05:50	GMc	offshore blasting
	05:55	GMc	offshore blasting
	05:56	GMc	offshore blasting
	05:57	GMc	offshore blasting
	05:58	GMc	offshore blasting
	05:59	GMc	offshore blasting
	06:17	GMc	offshore blasting
	11:49	GMc	impulsive type II
11/20	20:19	GMc	emergent type II
11/30	20:21	GMc	poss. event (or blast)
12/04	01:15	GMc & SL	emergent type II
12/07	01:48	GMc & SL	very emergent type II
12/09	16:28	GMc & SL	very emergent type II
1985			
01/04	01:52	GMc & SL	very ?able type II
01/22	00:58	GMc & SL	very ?able type II
02/08	22:30	GMc	too small
02/14	00:19	GMc	?able very small
	00:23	GMc	event? type I
02/19	13:08	SL	emergent type II
02/20	01:44	SL & GMc	emergent type II
03/06	13:03	SL	impulsive type II
03/08	20:22	SL	emergent type II
03/09	11:20	SL	impulsive type II
04/01	05:14	GMc	
04/14	15:56	GMc	blasting
04/20	17:12	GMc	much geophysical blasting during this time period
04/22	00:08	GMc	much geophysical blasting during this time period
04/29	13:46	SL	impulsive types II

Date	Time (UTC)	Recording Network	Comments
1985			
05/05	22:31	GMc	much geophysical blasting during this time period
05/10	18:06	SL	type II v. small
07/09	18:53	SL & GMc	v. small type II
07/09	21:11	GMc	v. small type II
09/19	13:21	GMc, SL, & H	type I teleseism (Mexico)
09/21	01:40	GMc, SL, & H	type I teleseism (Mexico)
10/23	01:09	GMc	type I event
10/24	11:09	GMc	emergent type II
11/20	01:08	GMc, SL, & H	type I teleseism (Greece)
12/08	21:00	GMc, & SL	emergent type II
12/16	02:48	GMc, SL, H, & PB	type I teleseism (Nicaragua)
12/23	05:23	GMc, SL, H, & PB	type I teleseism (NW Canada)
12/27	05:58	GMc, SL, H, & PB	type I teleseism (Sumatra)
12/28	18:51	SL	impulsive type II
	23:30	GMc, & SL	emergent type II
	23:30	GMc, SL, H, & PB	type I teleseism (Sumatra)
1986			
01/22	05:20	SL	impulsive type II
01/24	13:15	H	impulsive type II
	13:16	SL	impulsive type II
	13:17	GMc	impulsive type II
02/15	21:41	GMc, SL, H, & PB	type I teleseism (Guatemala)
03/02	05:50	GMc, SL, H, & PB	type I teleseism (Aleutian Islands)
03/07	23:13	PB	emergent type II
03/15	11:38	GMc, H, & PB	type I teleseism (Bolivia)
03/23	21:34	GMc, SL, H, & PB	type II emergent
04/10	13:01	GMc, SL, H, & PB	emergent type II
04/13	16:57	GMc	emergent type II
04/15	17:23	PB	emergent type II
04/16	00:48	GMc	emergent type II
04/19	15:43	PB	geophysical blasting
	15:46	PB	geophysical blasting
	15:50	PB	geophysical blasting
	15:52	PB	geophysical blasting
	15:55	PB	geophysical blasting
	15:57	PB	geophysical blasting
	16:40	PB	geophysical blasting
	16:43	PB	geophysical blasting
	16:46	PB	geophysical blasting
	16:52	PB	geophysical blasting
	16:54	PB	geophysical blasting
	17:10	PB	geophysical blasting
	17:13	PB	geophysical blasting
	17:16	PB	geophysical blasting
	17:19	PB	geophysical blasting

Date	Time (UTC)	Recording Network	Comments
1986			
04/30	07:10	GMc, SL, H, & PB	type I teleseism (Mexico)
05/01	14:53	PB	type I distant blast?
05/06	12:48	H	impulsive type II
	05:45	H	impulsive type II
05/07	22:57	GMc, H, PB	type I teleseism (Aleutian Islands)
05/30	06:18	H, & PB	type I teleseism (Costa Rica)
06/12	13:01	H	impulsive type II
	13:11	PB	impulsive type II
06/12	15:51	H	impulsive type II
	16:07	PB	emergent type II
06/14	21:42	PB	emergent type II
06/30	22:56	GMc, H, & PB	type I teleseism (Costa Rica)
07/02	12:30	H	impulsive type II (thunder?)
07/05	22:12	GMc, H, & PB	type I teleseism (Mexico)
07/08	09:25	GMc, H, & PB	type I teleseism (California)
07/13	09:15	GMc, H, & PB	type I teleseism (Mexico)
	13:52	GMc, H, & PB	type I teleseism (California)
07/15	12:44	H	impulsive type II
	15:40	H	impulsive type II
07/16	15:16	GMc	emergent type II
08/02	17:53	GMc, H, & PB	type I teleseism (Mexico)
08/03	20:04	PB	emergent type I regional
08/08	00:29	GMc	emergent type II
08/19	10:02	PB	impulsive type II
08/27	13:42	PB	emergent type II
08/29	20:16	GMc	emergent type II
08/30	21:40	GMc, H, & PB	type I teleseism (Romania)
09/12	00:06	GMc, H, & PB	type I teleseism (Greece)
10/10	17:53	H, & PB	type I teleseism (El Salvador)
10/16	15:59	H	impulsive type II
	16:01	GMc	impulsive type II
10/26	19:29	H, & PB	DOE "Bellmont" test
10/27	11:56	PB	emergent type II
10/30	01:41	GMc, H, & PB	type I teleseism (Fiji Islands)
11/04	00:50	GMc	emergent type II
11/09A	15:36	GMc	?able unknown type II
B	16:03	GMc	?able small unknown type II
11/12	trash		
11/14	18:58	GMc	type I distant blasts?
	19:10	GMc	type I distant blasts?
	20:30	GMc	type I distant blasts?
	21:35	GMc	type I distant blasts?
11/19	01:08	GMc	emergent type II
	01:10	GMc	emergent type II
11/20	13:35	H	impulsive type II
12/16	13:45	H	impulsive type II
12/31	19:15	PB	impulsive type II

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