DOE/ER/14278-4

**Energy Flux and Hydrogeology of Thermal Anomalies
in the Gulf of Mexico Basin -- South Texas Example**

Progress Report

September 1993 - August 1994

John M. Sharp, Jr.

**Department of Geological Sciences
The University of Texas at Austin
Austin, Texas 78712**

October 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**PREPARED FOR THE DEPARTMENT OF ENERGY
UNDER GRANT NUMBER DE-FG05-92ER14278**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Introduction

This report covers the period from 1 September 1993 through 31 August 1994. The last Annual Technical Progress Report was submitted in September 1993. In this period, we have focused our efforts on the following activities (more detailed descriptions of each effort are given in later sections):

1. Finalizing collection of radiogenic heat production data and evaluating results;
2. Evaluating petrographic controls on thermal conductivity;
3. Preparing paper on petrographic controls on thermal conductivity
4. Modeling one-dimensional heat conduction with sources;
5. Completing base geologic cross-section;
6. Acquiring pressure data to augment data base;
7. Putting map and well data into digital format for analysis;
8. Analyzing salinity, temperature, and fluid potential data for propensity of free convection;
9. Finalizing preliminary investigation into depressurization of reservoirs;
10. Presenting results at the Geological Society of America Annual Meeting in Boston, MA (October 1993);
11. Presenting results at the Annual Meeting of the American Association of Petroleum Geologists in Denver, Colorado (June 1994);
12. Preparing talk for the Geological Society of America Annual Meeting in Seattle, WA (October 1994);
13. Collaborating with project members of the DOE funded Global Basins Research Network who are working on a similar project in the Eugene Island Block in offshore Louisiana; and
14. Collaborating with others working on research in the Gulf of Mexico Basin or similar projects elsewhere:
 - 14.1. Drs. Land and Galloway of our Department,
 - 14.2. Dr. David Blackwell, Southern Methodist University, and
 - 14.3. K. Narayan and C. Simmons, CSIRO, Adelaide, Australia.

Project Status

The following shows the status of tasks as proposed in the original grant application:

Determination of core availability:	100%
Development ... procedures for manipulating ... databases:	100%
Acquisition of ... data to fill in and validate database:	100%
Development of geologic cross section:	100%
Performance of quality control check on pressure data:	99%
Mapping of potentiometric surfaces:	60%
Coding of heat-conduction model:	99%
Preliminary simulation of heat conduction:	90%
Collection of cores:	100%
Thermophysical measurements:	100%
Final simulation of heat conduction:	50%
Writing of paper on heat conduction study:	50%
Simulations of coupled heat and fluid flow:	40%
Writing of paper on regional hydrogeology:	20%
Continuation of coupled fluid, solute, and heat flow:	20%
Writing of paper on coupled fluid and heat transport:	20%

Summary of work completed since September 1993.

1. Finalizing collection of radiogenic-heat-production data and evaluating results:

We have collected the first radiogenic-heat-production data for the Gulf of Mexico Basin. Samples of Frio and Wilcox sandstones and mudrocks, and Stuart City limestones from south Texas were obtained from petroleum-well cores and cuttings. Heat production was calculated using the functions of Rybach (1988) and Huntley (1988) based on (1) alpha -particle decay counts measured on an alpha scintillation counter, (2) potassium concentrations measured by ICP or XRF (Land, Milliken, and Mack's DOE mudrock project, 1991-1994), and (3) direct bulk density measurements or estimates. Heat production is highest in the shales, moderate in the sandstones, and lowest in the limestones (Figure 1). Frio sandstones produce more heat than Wilcox sandstones and Frio shales produce more heat than Wilcox shales.

Huntley, D. J., 1988, The use of alpha counting for determining the heat production due to the uranium and thorium decay chains: *Applied geochemistry*, v. 3, pp. 653-656.

Rybach, L., 1988, Chapter 4.2 - Determination of heat production rate: in *Handbook of Terrestrial Heat-Flow Density Determination* (R. Haenel and others, eds.), Kluwer, Dordrecht, pp.125-142.

2. Evaluating petrographic controls on thermal conductivity.

Thorough analyses of petrographic variables and measured thermal conductivity show a strong relationship between porosity and thermal conductivity for sandstones with over 30% quartz, less than 15% calcite cement, and less than 20% clay matrix/cement (Figure 2). These petrographic criteria encompass most of the Frio and Wilcox sandstones in South Texas. About 90% of the variance in the thermal conductivity data can be explained by the linear relationship shown in Figure 2.

3. Preparing paper on petrographic controls on thermal conductivity

The first draft of this paper is near completion. This paper will be submitted to the AAPG Bulletin.

4. Modeling one-dimensional heat conduction with sources.

Coding of a one-dimensional, steady-state numerical model of heat conduction with sources was finalized. The model accounts for variable porosity, bulk density, rock-matrix thermal conductivity, effective thermal conductivity and radiogenic heat production with depth. Several parameterizations of thermal conductivity and porosity are available. A sample of preliminary results is shown in Figures 3 and 4.

5. Completing base geologic cross-section.

An interpreted cross-section acquired from Bill Galloway in our Department was augmented with information from the literature to complete the section.

6. Acquiring pressure data to augment data base

Additional pressure data were acquired to fill in our database in areas with little or no data (mostly in Brooks County which was missing in the early versions of our data base).

7. Putting map and well data into digital format for analysis.

Fault and salt dome locations were digitized from the Texas geologic and tectonic maps. The location of the cross section (from 4. above) along with electric log information were input into the database. Locations and additional data for wells sampled for radiogenic heat production and thermal conductivity were added. Digital Elevation Models were downloaded from the USGS INTERNET site. Digital production data were acquired from Dwight's Energy Data, Inc. and The Texas Railroad Commission to further evaluate effects of depressurization. We are using a senior geology major (Mr. Wolaver) to assist in the final digitizations.

8. Analyzing salinity, temperature, and fluid potential data for propensity of free convection.

Using a GIS system, salinity, temperature, major ion concentrations, and geologic information were evaluated spatially to identify areas conducive to free convection. Figure 5 is one of a series of maps depicting areas in which thermohaline Rayleigh numbers exceeded critical values for the onset of free convection (see attached abstract). Preliminary numerical modeling indicates that brines with total dissolved solids concentrations of over 100,000 ppm are unstable except in areas with very thick, extensive, low-permeability shales. Figure 6 depicts simulation^s conducted at CSIRO last spring. We are preparing a manuscript for submittal to a major geosciences journal (e.g., GSA Bulletin, AAPG Bulletin, Geochimica et Cosmochimica Acta).

9. Finalizing preliminary investigation into depressurization of reservoirs.

Our preliminary look into the depressurization of reservoirs indicates that depressurization is readily apparent in our database. Land subsidence due to this depressurization could be significant (see attached abstract and unpublished manuscript). This manuscript was submitted to Environmental Geology.

10. Presenting results at the Geological Society of America Annual Meeting in Boston, MA (October 1993);

A paper entitled "Significance of free convection in saline fluid migration, Frio Formation, South Texas" was presented by Merrie Smith and John M. Sharp, Jr. at the annual Geological Society of America meeting in Boston (October 1993).

11. Presenting results at the Annual Meeting of the American Association of Petroleum Geologists in Denver, Colorado (June 1994);

A paper entitled "Thermal conductivity and radiogenic heat production of sedimentary rocks from the Gulf of Mexico Basin (South Texas)" was presented at the annual American Association of Petroleum Geologists meeting in Denver (June 1994; see attached abstract).

Another talk not supported directly by this grant but closely related to this DOE-funded research was presented by Tom McKenna from UT and Bill Powell from Exxon Production Research Company. It is entitled "Evaluation of subsurface temperature in Eugene Island Block 330 and vicinity" (see attached abstract).

12. Preparing talk for the Geological Society of America Annual Meeting in Seattle, WA (October 1994);

We are preparing a talk (abstract included) entitled "Mapping the hydrogeology of sedimentary basins using a geographic information system and data from the petroleum industry" for the Geological Society of America Annual Meeting in Seattle, WA in October 1994.

13. Collaborating with project members of the DOE funded Global Basins Research Network who are working on a similar project in the Eugene Island Block, offshore Louisiana.

While on sabbatical from this research grant, Tom McKenna worked at Exxon Production Research Company (EPR) for 3 months. Research at EPR involved evaluating advanced techniques for interpreting subsurface temperatures and evaluating subsurface temperatures in the Eugene Island area. EPR is an industry sponsor of the DOE funded Global Basins Research Network project at Eugene Island. This unique opportunity allowed Mr. McKenna to compare and contrast Eugene Island thermal anomalies with the anomalies being analyzed in this research in South Texas. Collaboration with EPR researchers and members of the GBRN gave new insights into our research. Results of this research were presented to EPR researchers and was presented at the AAPG meeting in Denver (June 1994).

14. Collaborating with others working on research in the Gulf of Mexico Basin in our Department and with CSIRO scientists.

As suggested by the DOE-OPA review panel in July 1993, we have made a concerted effort to collaborate with other researchers in our Department. Currently we are working with Leo Lynch, a sedimentary petrographer, to aid in our petrographic interpretations for thermal conductivity prediction. We are working with Lynton Land, Larry Mack, and Kitty Milliken (sedimentary geochemists) to better determine the uranium and thorium content of shales and to couple fluid flow models with diagenetic models. Dr. Bill Galloway of our department has interacted in the preparation of synthetic stratigraphic cross sections, corresponding closely to Gulf of Mexico conditions.

Perhaps most enlightening is the Gulf of Mexico seminar organized by Lynton Land in the spring, 1994, semester. This seminar brought at least 10 researchers together twice weekly to share ideas on, among other topics, the origin and evolution of the Gulf of Mexico Basin, depositional and burial history, stratigraphy, fluid flow, geochemistry of formation waters, and sediment diagenesis.

In conjunction with K. Narayan and Craig Simmons (CSIRO in Adelaide, Australia), the computer program, SUTRA, has been utilized to investigate scenarios of free haline convection in the Gulf of Mexico Basin.

RADIOGENIC HEAT PRODUCTION South Texas, Gulf of Mexico Basin

Figure 1. Radiogenic heat production of sedimentary rocks from the South Texas, Gulf of Mexico Basin. Middle vertical line represents the mean heat production. The two outer vertical lines represent one standard deviation from the mean. The horizontal line represents the range of the data. (For muddy Stuart City Limestones, the vertical lines represent the two data points. Data for Wilcox sandstones are preliminary.)

Wilcox and Frio Sandstones South Texas, Gulf of Mexico Basin

Figure 2. Thermal conductivity as a function of porosity for water-saturated Wilcox and Frio sandstones ($> 30\%$ quartz, $< 15\%$ calcite, and $< 20\%$ clay), South Texas, Gulf of Mexico Basin. These petrographic criteria encompass most of the Frio and Wilcox sandstones in South Texas. Thermal conductivity was measured by the divided bar technique. Middle line is the best fit linear regression through the data. Outer lines represent the standard error of the regression.

Figure 3. Preliminary results from a one-dimensional heat conduction model with radiogenic heat. Solid lines represent geothermal gradients of 30 and 60 °C/km (for reference). Dashed line represents thermal regime when pores are filled with water. Dotted line represents thermal regime when pore are filled with gas. Note the significant increase in temperature due to gas saturation. In this example, porosity is an exponential function of depth, the rock matrix is 100% illite, thermal conductivity is a function of porosity and temperature, heat production is based on our shale measurements and a function of the bulk density of the rock, the surface temperature is 25 °C, and the basal heat-flow density is 40 mW/m².

Figure 4. Temperature-Depth profiles. These are the results of a one-dimensional, steady-state, heat-conduction model with an imposed heat-flow density of 40 mW/m^2 at the base of a 10 kilometer thick stratigraphic section and a surface temperature of 25°C . Results from two endmember models are shown. The pair of profiles on the right results from a stratigraphic section of sandstone. The profile with lower temperatures results from not including heat production and the higher temperature profile results from including heat production. Focussing on a particular depth (6 km), the minimum effect of including heat production is an increase in temperature of 17°C . The pair of profiles on the left results from a stratigraphic section of all shale. Again, the profile with lower temperatures results from not including heat production and the higher temperature profile results from including heat production. So at 6 km, the maximum effect of including heat production is an increase in temperature of 65°C . Also, with the increased geothermal gradient at the surface for the results including heat production, the surface heat flow increases 25% for the sandstone model and 45% for the shale model.

LEGEND

- + Na-Acetate beneath NaCl
- NaCl beneath NaCaCl
- △ NaCaCl beneath NaCaCl
- ★ Na-Acetate beneath NaCaCl
- ▲ NaCl beneath NaCaCl (diapir)

Figure 5. Location of wells at the 2000 and 3000 meter depth range in which the thermohaline Rayleigh numbers exceeded critical values indicating significant density inversions which could lead to free convection. Rayleigh numbers in this case were calculated assuming a layer thickness of 100 meters (a reasonable estimate of Frio sand thicknesses).

GM13C200 - t=1398 yrs

GM13C400 - t=3679 yrs

GM13C600 - t=5961 yrs

Figure 6. These SUTRA computer simulations depict free convection occurring in a sand/shale sequence. The upper 50-m thick sand layer has a concentration of 100,000 ppm from either salt dome dissolution or fluids upwelling along faulted zones. The underlying sedimentary sequence consists of 50m shale, 50m sand, 100m shale, and 50m sand. Shale permeability is 10^{-16} m^2 . The ratio of sand to shale permeability is 10^5 . Note that on geologically short time scales thermohaline convection is predicted to occur. This analysis is conservative in that only salinity-induced instabilities are evaluated.

Bibliography of publications and presentations relating to this project:

**Energy Flux and Hydrogeology of Thermal Anomalies in the Gulf of Mexico Basin -
South Texas Example**

PI: John M. Sharp, Jr.

Grant # DE-FG05-92ER14278

-
- Hill, D.W., 1993, Land Subsidence in the Big Hill and Fannett Fields of Jefferson County, TX; A Predictive Model; unpublished MA thesis, The University of Texas at Austin.
- Hill, D.W., 1993, A theoretical model for subsidence caused by petroleum production: Big Hill Field, Jefferson County, Texas: Proceedings, A.W.R.A.-A.I.H. Texas Hydrology Roundup, Austin, April 1993.
- Hill, D.W. and J.M. Sharp Jr., 1994, A theoretical model for subsidence caused by petroleum production: Big Hill Field, Jefferson County, Texas: unpub. manuscript submitted to Environmental Geology.
- Hill, D.W. and J.M. Sharp Jr., 1993, A theoretical model for subsidence caused by petroleum production: Big Hill Field, Jefferson County, Texas: Geol. Soc. America, Abs. with Programs (South-Central Section), v. 25, p. 14.
- McKenna, T.E., 1994, Mapping the hydrogeology of sedimentary basins using a geographic information system and data from the petroleum industry: Geol Soc America Abs. with Programs (Ann. Meeting), v. 26, n. 7, p. ?.
- McKenna, T.E., 1993, Hydrogeology of sedimentary basins: Proceedings, A.W.R.A.-A.I.H. Texas Hydrology Roundup, Austin, April 1993.
- McKenna, T.E. and W.G. Powell, 1994, Evaluation of subsurface temperature in Eugene Island Block 330 and vicinity: AAPG 1994 Annual Convention, Official Program, p. 212-213.
- McKenna, T.E., J.M. Sharp, Jr., and F.L. Lynch, 1994, Thermal conductivity and radiogenic heat production of sedimentary rocks from the Gulf of Mexico Basin (South Texas): AAPG 1994 Annual Convention, Official Program, p. 212.
- Smith, M.J. and J.M. Sharp, Jr., 1993, Significance of free convection in saline fluid migration, Frio Formation, South Texas: Geol Soc America Abs. with Programs (Ann. Meeting), v. 25, p. A244.

*abstracts & preprint
removed.
ds*