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DOE Grant # DE-FG05-92ER14278
Energy Flux and Hydrogeology of Thermal Anomalies in the Gulf of Mexico Basin -- South Texas Example

PI: John M. Sharp, Jr.

Brief Progress Report
March 1994

Introduction

This report covers the period from 1 September 1993 through 28 February 1994. The last Technical Progress Report was submitted in September 1993. In this period, we have focused our efforts on the following activities (a more detailed description of each effort is given in a later section):

1. Finalizing collection of radiogenic heat production data;
2. Evaluating petrographic controls on thermal conductivity;
3. Modeling one-dimensional heat conduction with sources;
4. Completing base geologic cross-section;
5. Acquiring pressure data to augment data base;
6. Putting map and well data into digital format for analysis;
7. Analyzing salinity, temperature, and fluid potential data for propensity of free convection;
8. Finalizing preliminary investigation into depressurization of reservoirs;
9. Preparing presentations for AAPG meeting in Denver;
10. Presenting results at the Geological Society of America Meeting in Boston (October 1993);
11. 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; and
12. Collaborating with others working on research in the Gulf of Mexico Basin in our Department and with CSIRO scientists in Adelaide, Australia.

Self- Evaluation of progress on goals for last 6 months as proposed in last Technical Progress Report (September 1993):

1. Complete filling in temperature and pressure databases:	COMPLETED
2. Complete geologic cross section:	COMPLETED
3. Continue validating database:	COMPLETED
4. Integrate pressure, temperature, and salinity data in GIS:	PARTIALLY COMPLETED
5. Finish coding 1-D simple models:	COMPLETED
6. Finish preliminary 1-D modeling:	NEARLY COMPLETED
7. Sample drill cuttings for heat-flow density calculation:	DEFERRED (not originally proposed)

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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:	90%
Mapping of potentiometric surfaces:	60%
Coding of heat-conduction model:	50%
Preliminary simulation of heat conduction:	80%
Collection of cores:	100%
Thermophysical measurements:	100%
Final simulation of heat conduction:	25%
Writing of paper on heat conduction study:	15%
Simulations of coupled heat and fluid flow:	10%
Writing of paper on regional hydrogeology:	0%
Continuation of coupled fluid, solute, and heat flow:	20%
Writing of paper on coupled fluid and heat transport:	0%

Summary of work completed over last 6 months.

1. Finalizing collection of radiogenic heat production data.

Measurements of radiogenic heat production on Frio and Wilcox sandstones and mudrocks, as well as Stuart City limestones are finished. Preliminary results are shown in Figure 1 .

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. Modeling one-dimensional heat conduction with sources.

Coding of a one-dimensional numerical model of heat conduction with sources was finalized. The model allows 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 Figure 3.

4. 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.

5. 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).

6. 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.

7. 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 4 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 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.

8. 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).

9. Preparing presentations for AAPG meeting in Denver.

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

Another talk not supported by this grant but closely related to this research also is being prepared 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).

10. Presenting results at the Geological Society of America Meeting in Boston (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. 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 will be presented at the AAPG meeting in Denver (June 1994).

12. 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.

Perhaps most enlightening is the Gulf of Mexico seminar organized by Lynton Land this spring semester. This brings 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 (CSIRO in Adelaide, Australia), the computer program, SUTRA, has been utilized to investigate scenarios of free haline convection in the Gulf of Mexico Basin.

Goals for the next six months (through 31 August 1994).

1. Prepare and present two papers at AAPG in Denver.
2. Prepare manuscripts on thermal conductivity and radiogenic heat production of sedimentary rocks, and reservoir depressurization for publication.
3. Finalize inputting data into the GIS including pressure, temperature, faults, fluid salinity, and a gridding system.
4. Move from 1-D to 2-D modeling of heat conduction.
5. Integrate temperature, pressure, and salinity data in GIS to map potentiometric surfaces.
6. Finalize 2-D SUTRA numerical models to investigate the controls on the development of thermal and salinity driven convection cells in the Gulf of Mexico Basin and their possible impact on sediment diagenesis.
7. Prepare abstract(s) and draft of paper on the development of thermal and salinity driven convection cells in the Gulf of Mexico Basin

Bibliography of publications and presentations relating to this project:

Hill, D.W., 1993, Land Subsidence in the Big Hill and Fannett Fields of Jefferson County, TX; A Predictive Model; unpublished M.A. 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., 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., 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 Abstracts with Programs (Ann. Meeting), in press.

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 Abstracts with Programs (Ann. Meeting), in press.

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.

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.

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

Figure 4. 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). We are currently working on a method of estimating sandstone thicknesses based on location within a particular depositional system.

Type abstract (not to exceed 250 words) on this form (and attach paper if you have a computer printer. Please double-space, and do not justify. NO ILLUSTRATIONS, REFERENCES OR ABBREVIATIONS. NOTE: The content of your abstract is your responsibility. Please check it carefully.

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Affiliation (employer): The University of Texas at Austin Office Fax: (Area Code) 512-471-9425 Telex:
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Author(s) (family name first): McKenna, Thomas E., J. M. Sharp, Jr., and F. L. Lynch
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Thermal conductivity and radiogenic heat production of sedimentary rocks from the Gulf of Mexico Basin (South Texas)

T. E. McKenna, J. M. Sharp, Jr, and F.L. Lynch, The University of Texas at Austin, Department of Geological Sciences (61140), Austin, Texas, 78712

Thermal conductivity and alpha-particle emission (for calculation of radiogenic heat production) were measured on over 100 sedimentary rock samples from the South Texas portion of the Gulf of Mexico Basin. These are the first reported radiogenic heat calculations for the Gulf of Mexico Basin and the first thermal conductivity measurements for the Texas area. Detailed petrology and/or whole-rock analyses were available for most of the samples. Thermal conductivity is inversely proportional to porosity and directly proportional to quartz content. Wilcox sandstones have a higher thermal conductivity than Frio sandstones with similar porosities because of the increased quartz content of Wilcox sandstones. Ranges of thermal conductivities are: for Wilcox sandstones, 3 to 6 W/m/K for porosities of 3% to 20%; for Frio sandstones, 2 to 3 W/m/K for porosities of 13% to 30%; and for Stuart City limestones, 3 to 3.5 W/m/K for porosities from 0% to 7%. Ranges of radiogenic heat production are: for Frio shales, 1.2 to 2.3 $\mu\text{W}/\text{m}^3$; for Wilcox shales, 0.8 to 2.0 $\mu\text{W}/\text{m}^3$; for Frio sandstones, 0.6 to 1.6 $\mu\text{W}/\text{m}^3$; and for Stuart City limestones, 0.1 to 1 $\mu\text{W}/\text{m}^3$. Steady-state, one-dimensional heat conduction models suggest that radiogenic heat production can contribute significantly to overall heat-flow density, especially in shale rich parts of the basin where thermal conductivity is relatively low.

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No 9549

SIGNIFICANCE OF FREE CONVECTION IN SALINE FLUID MIGRATION, FRIO FORMATION, SOUTH TEXAS.

SMITH, Merrie J., SHARP, John M., Jr., Dept. of Geological Sciences,
Univ. of Texas at Austin, Austin, TX 78713-7909.

Evaluation of geochemical data from the Oligocene-aged Frio Formation of the Texas Gulf Coast reveals the presence of formation waters with high salinities (Ave. 50,000 ppm) overlying relatively low salinity waters (Ave. 20,000 ppm). The vast difference in salinity coupled with an increase in temperature with depth create situations in which very buoyant waters are beneath relatively dense waters. Such instabilities have led us to hypothesize that sub-kilometer scale thermohaline convection may periodically occur in the Frio Formation. These convective cells may provide the many pore volumes of water necessary to explain diagenetic effects within the Gulf of Mexico basin.

Because of the vast spatial variation in geochemical and stratigraphic data in the Frio Formation, a Geographic Information System (GIS) was used to link information such as permeability, temperature, salinity, layer thickness, etc., with a geographic location. This database was then used to calculate thermohaline Rayleigh numbers, an indicator of the propensity of two waters to convect.

Results indicate free convection is likely in two distinct locations within the Frio. One such site is within the Houston Diapir Province, where dense waters appear to migrate up the flanks of salt domes. The second location is within the lower segment of the San Marcos Arch and may be related to periodic migration of saline fluids along growth faults.

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No 21718

A THEORETICAL MODEL OF SUBSIDENCE CAUSED BY PETROLEUM PRODUCTION: BIG HILL FIELD, JEFFERSON COUNTY, TEXAS

HILL, David W. and SHARP, John M., Jr., Dept. of Geological Sciences,
Univ. of Texas at Austin, Austin TX 78712

In the Texas Gulf Coastal Plain, there is a history of oil and gas production extending over 2 to 5 decades. Concurrent with this production history, there has been unprecedented population growth accompanied by vastly increased groundwater demands. Land subsidence on both local and regional bases in this geologic province has been measured and predicted in several studies. The vast majority of these studies have addressed the problem from the standpoint of groundwater usage while only a few have considered the effects of oil and gas production.

Based upon field-based computational techniques (Helm, 1984), a model has been developed to predict land subsidence caused by oil and gas production. This method is applied to the Big Hill Field in Jefferson County, Texas. Inputs include production data from a series of wells in this field and lithologic data from electric logs of these same wells. Outputs include predicted amounts of subsidence, the time frame of subsidence, and sensitivity analyses of compressibility and hydraulic conductivity estimates. Depending upon estimated compressibility, subsidence, to date, is predicted to be as high as 20 cm. Similarly, depending upon estimated vertical hydraulic conductivity, the time frame may be decades for this subsidence.

These same methods can be applied to other oil/gas fields with established production histories as well as new fields when production scenarios are assumed. Where subsidence has been carefully measured above petroleum reservoirs, the model may be used inversely to calculate sediment compressibilities.

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To test the hypothesis that elevated temperatures in the Eugene Island 330 area result from fluid flow in a large growth-fault system, we investigate the temperature structure in the vicinity of this fault system using a set of reliable subsurface temperature data. The data compilation includes over 1000 temperature measurements from pressure recovery tests and well logs; of these, only 5% are reliable measures of formation temperature. We cannot resolve spatially-restricted thermal anomalies along the faults because of the limited distribution of reliable measurements.

A temperature difference of approximately 10°F (6 °C) is observed at reservoir depths (6,000–9,000 ft; 1,800–2700 m) across the fault in Eugene Island Block 330 and vicinity. A one-dimensional model of transient heat conduction indicates that up to 80% of this temperature difference is due to the increased sedimentation rate on the downthrown side of the fault. Mobile salt below the sediments on the footwall side of the fault may also contribute to higher temperatures there because it is a good heat conductor. The temperature difference that we observe (1) is similar in magnitude to previous interpretations, (2) can be explained by sedimentation differences and thermal conductivity contrasts, and (3) does not reflect heat transport by fluid flow in the faults.

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