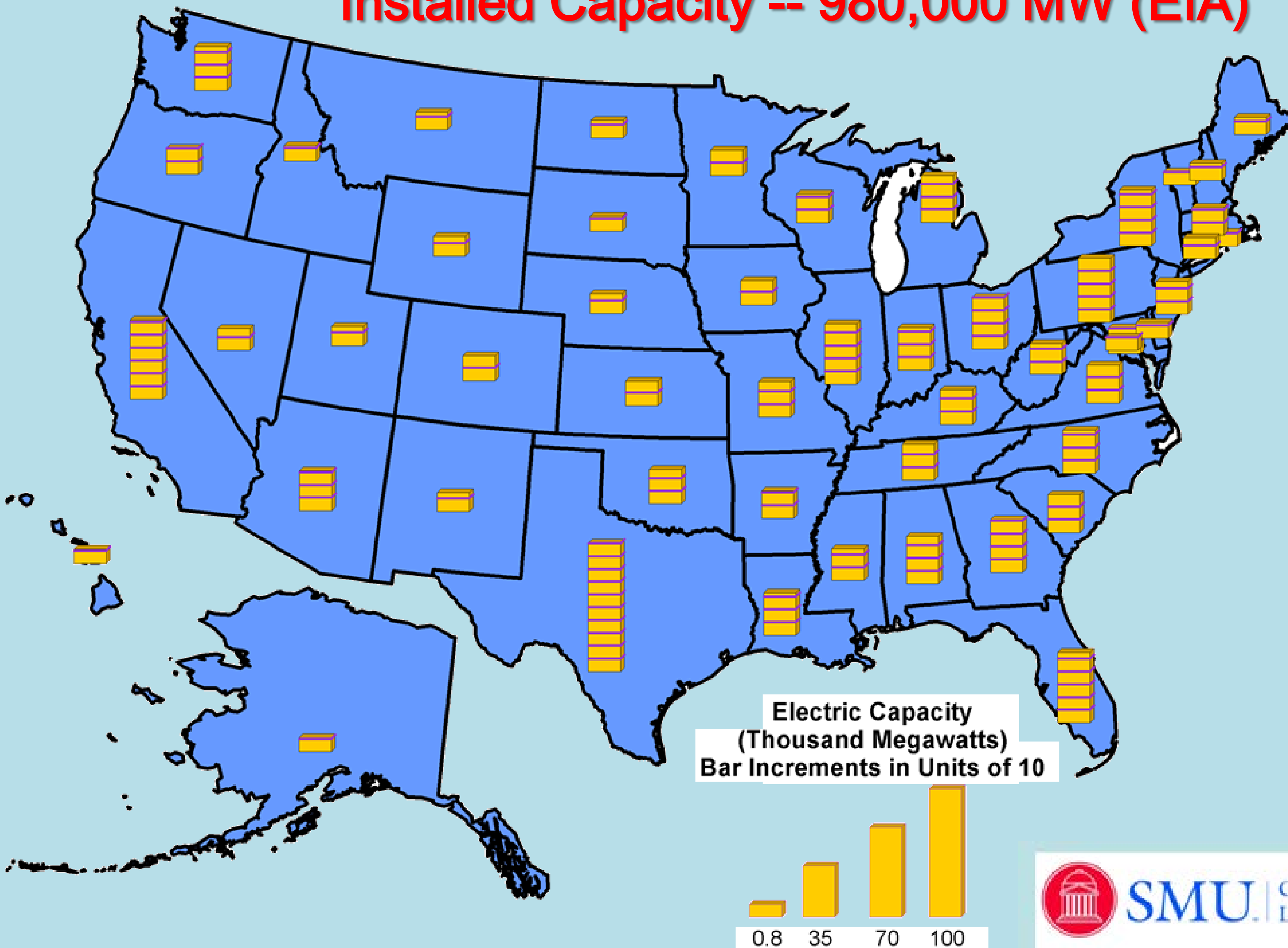
Introduction and Overview of Geothermal Resources

David Blackwell & Maria Richards
SMU Geothermal Laboratory

NSF Workshop: Geothermal Potential of Sedimentary Basins
Salt Lake City
November 7, 2011

Why Geothermal?

Installed Capacity -- 980,000 MW (EIA)



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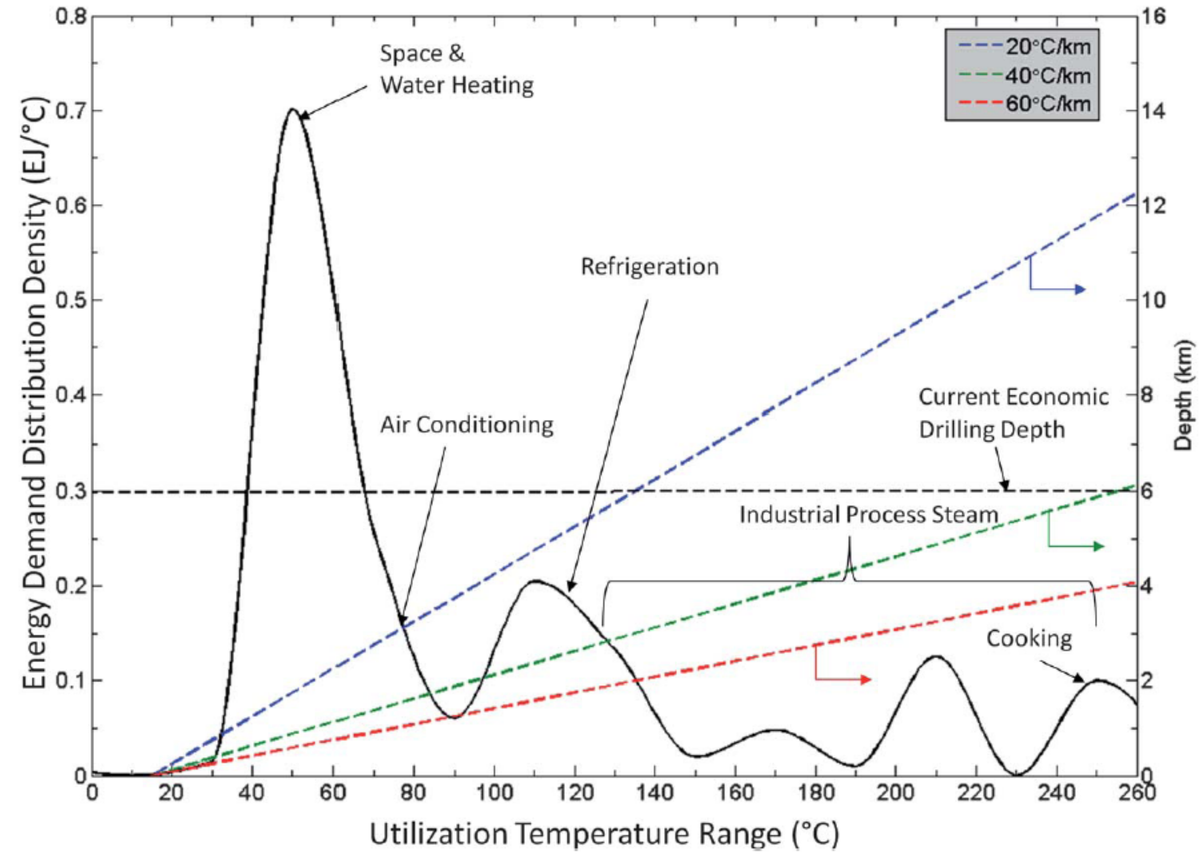

Fig. 6 Continuous approximation of the energy demand distribution density with Electrical System Energy Losses (ESEL). The energy demand is normalized by the temperature, *i.e.* the total area under the curve represents the total thermal energy demand. The scale on the right-hand side indicates the depth needed to achieve the corresponding temperature for three different temperature gradients (20, 40, 60 °C/km). The dashed horizontal line presents the current maximum economic drilling depth.

The thermal spectrum of low-temperature energy use in the United States†

Don B. Fox,[a] Daniel Sutter[ab] and Jefferson W. Tester*[a]

Energy &
Environmental Science

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www.rsc.org/ees

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“Green” Electrical Resources

- Geothermal
- Wind
- Solar
- Biomass
- Coal-CO_2 sequestration

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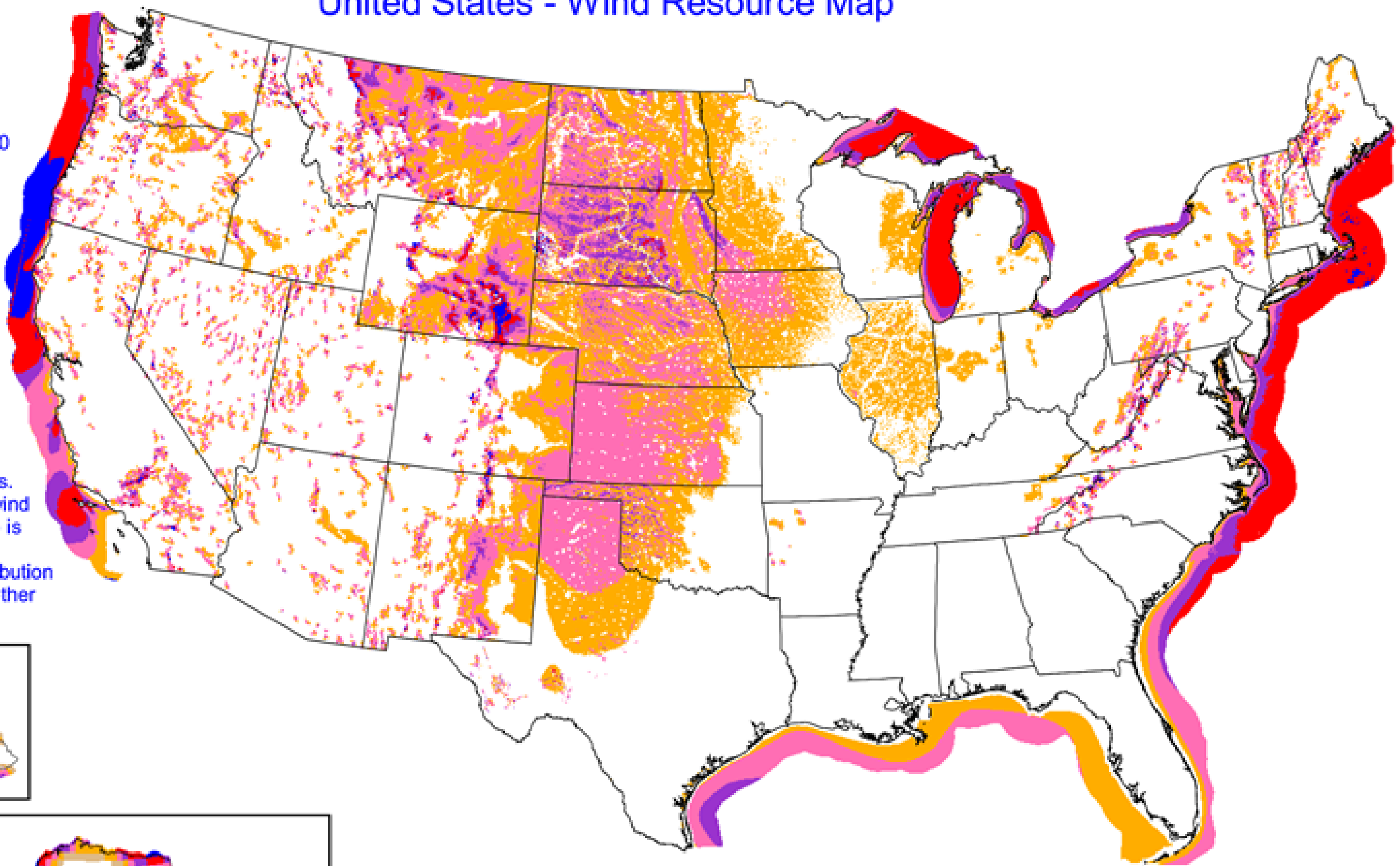
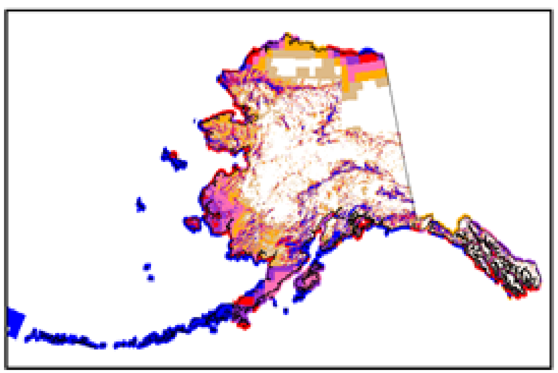
United States - Wind Resource Map

This map shows the annual average wind power estimates at 50 meters above the surface of the United States. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.





Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory

Wind Energy, Texas Style

- 9,000 MW installed
- 3 to 8% load Factor
- Delivery Problem-Power Lines
- Availability Problem
- Deregulated Power
- Ownership and Construction
- Energy Density

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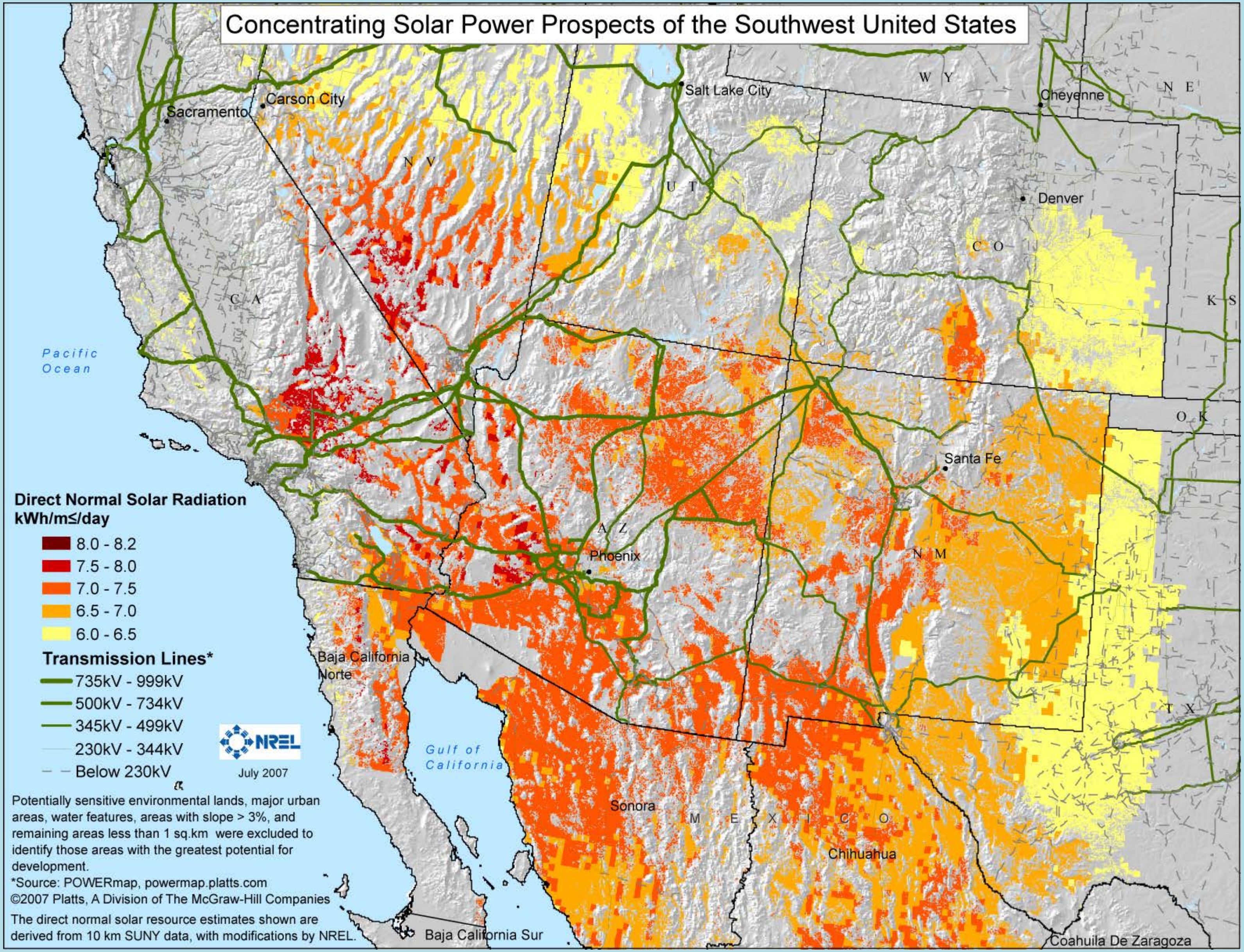
Solar Power

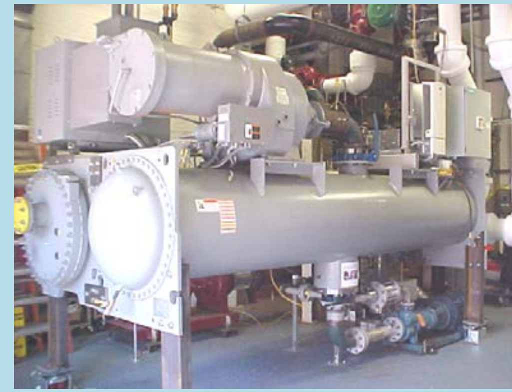


Concentrating Solar Power Prospects of the Southwest United States
Direct Normal Solar Radiation
kWh/m≤/day
8.0 - 8.2
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
Transmission Lines*
735kV - 999kV
500kV - 734kV
345kV - 499kV
230kV - 344kV
Below 230kV
NREL
July 2007
Potentially sensitive environmental lands, major urban areas, water features, areas with slope > 3%, and remaining areas less than 1 sq.km were excluded to identify those areas with the greatest potential for development.
*Source: POWERmap, powermap.platts.com
©2007 Platts, A Division of The McGraw-Hill Companies
The direct normal solar resource estimates shown are derived from 10 km SUNY data, with modifications by NREL.
Sacramento
Carson City
Salt Lake City
Cheyenne
Denver
Santa Fe
Phoenix
Pacific Ocean
Gulf of California
Baja California Norte
Baja California Sur
Sonora
Chihuahua
Coahuila De Zaragoza
M E X I C O
NV
UT
WY
NE
CO
KS
OK
CA
AZ
NM
TX

From Hot Water to Hydrogen

Bringing Geothermal Power to Alaska

CHENA HOT SPRINGS RESORT Alaska



Cascading Thermal Usage Presented by: **Bernie Karl**

SMU Geothermal Conference June 12th, 2007

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Types of Unconventional Resources

- Basement EGS-Hot Dry Rock
- Basement EGS Hot Wet Rock? (Landau & Insheim)
- Thick Sediments in high heat flow areas
- Hydrothermal Margins
- Geopressure-Gulf Coast/East Texas
- Tight gas sands-Gross Schoenbeck, Germany
- Coproduced-Green Oil Fields-Teapot Dome
- Heating and Cooling Applications Everywhere

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Week of Sept. 5, 2005/US$10.00

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International Petroleum News and Technology / www.ogjonline.com

Geothermal electric power supply possible from Gulf Coast, Midcontinent oil field waters

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US Army Engineer Research & Development Center
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Southern Methodist University
Dallas

Christopher Moyes
P. Dee Patterson
Moyes & Co. Inc.
Dallas

The rising price of el
and the current high pri
carbons have changed th
outlook in the US in a m

Several methods of ge
system development pre
unprofitable may be viab
ent time, especially in th
higher electricity prices,
new state portfolio stand

Coast and Midcontinent states possess few, if any, conventional electrical grade geothermal hydrothermal resources. However, states such as Texas, Louisiana, Mississippi, Alabama, and even Arkansas do possess thousands of wells that reach depths where temperatures are 250° F. to more than 400° F.

Some of these wells (or sites) are candidates for exploitation of geopressured geothermal resources, already proven feasible at prices similar to those existing today.[1] Others are candidates for more conventional geothermal exploitation similar to the geothermal sites currently producing electrical power in the Great Basin of Nevada.

Still others are candidates for enhanced geothermal system (EGS) development whereby either fluid is introduced, and-or permeability is enhanced, to artificially generate geothermal reservoirs capable of sustained electrical power production (see http://www.eere.energy.gov/geothermal/egs_technology.html).

The problem with development in this setting is that drilling characteristics, stress situations, and lithologic details remain poorly constrained and the water supply is uncertain.

Since most economic geothermal wells flow at 1,000-5,000 gpm, the probability of obtaining similar flow rates, even in stimulated bedrock reservoirs, is low, not to mention geographically restricted.

Second, the energy required to pump the fluid to the surface will generally be a significant fraction of the energy obtained by passing the fluid through a heat exchanger.

Ignoring other issues such as the availability of high background temperatures, infrastructure, and proven reservoir, the two main problems stated above are sufficient to slow the widespread use of EGS-type reservoirs and therefore the widespread utilization of geothermal electrical power production.

Thus the impediments to large-scale development are: Drilling conditions are uncertain; field development costs are high; water supplies are questionable, development costs are difficult to quantify, and, so far at least, energy companies with large capital resources are not involved.

So as currently envisaged, EGS-type situations in the western US are unlikely to generate significant electricity in the US in the immediate future.

COST COMPONENTS FOR CONVENTIONAL HYDROTHERMAL DEVELOPMENT — Table 1

Existing Gulf Coast waterflood field conditions
- Many wells with BHTs at over 250° F. at 15,000 ft or less
- Water produced from wells, stripped of hydrocarbons, and reinjected (paid for by disposer)
- In-place infrastructure of power lines, roads, pipelines
- Possible continued stripping of gas and oil in otherwise noneconomic wells

Direct costs to develop a Texas waterflood field
- Build power station
- Minor surficial infrastructure upgrades (i.e., insulating surface collection pipes)

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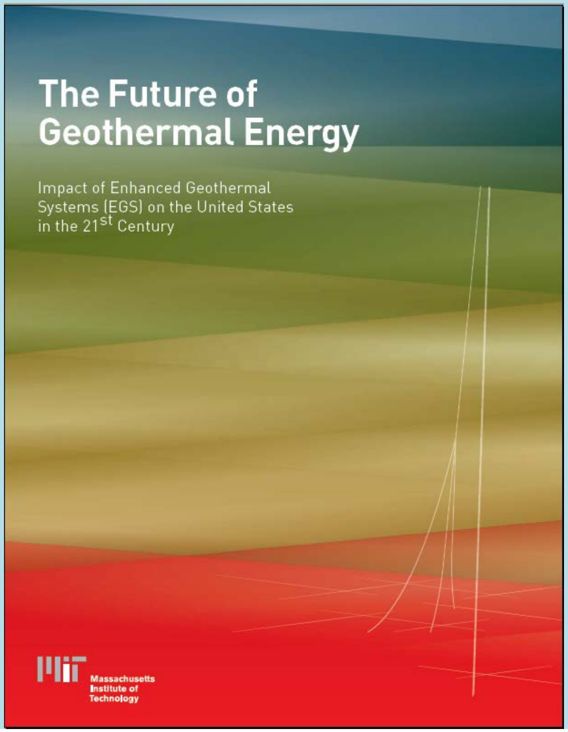
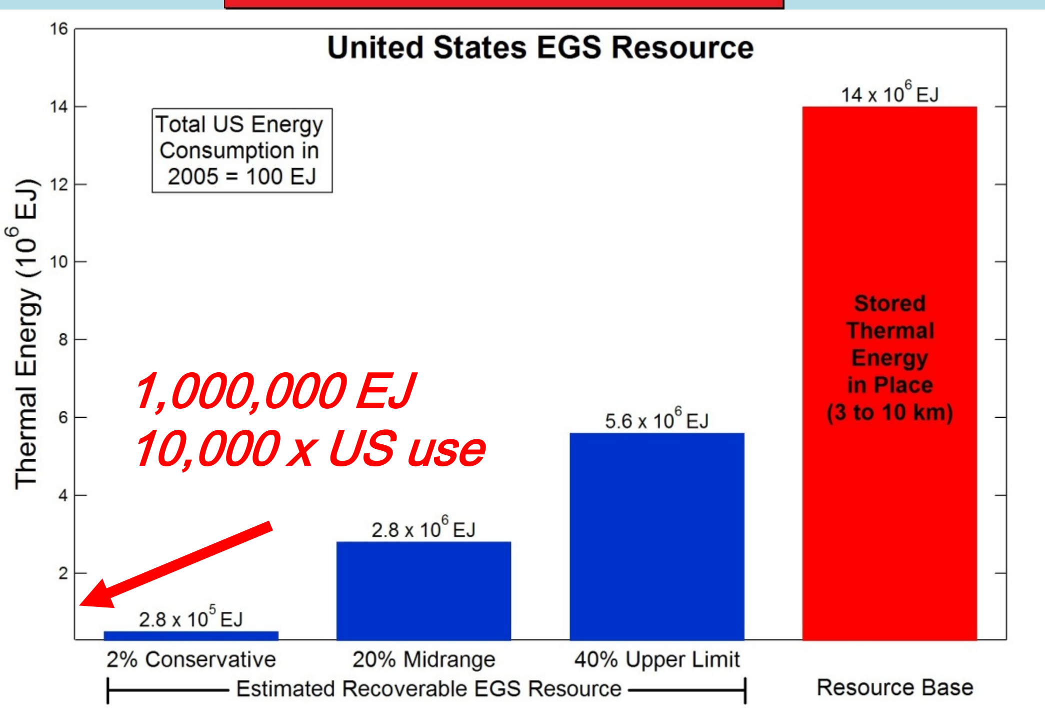


PREVIOUS WORK:

Geopressure Geothermal

Low Temperature



THE EGS SYSTEM

Introduction of water into rock of limited permeability (either tight sediment or basement) in a controlled fracture setting so that this water can be with-drawn in other wells for heat extraction, *i.e. heat mining*

Scenarios for Electrical Development in Sedimentary Basins

Coproduced fluids
Geopressure fluids
Sedimentary EGS

These are briefly described, resource base discussed, and examples of development given for each category

The resource base for these 3 types of geothermal development is briefly summarized: HUGE!

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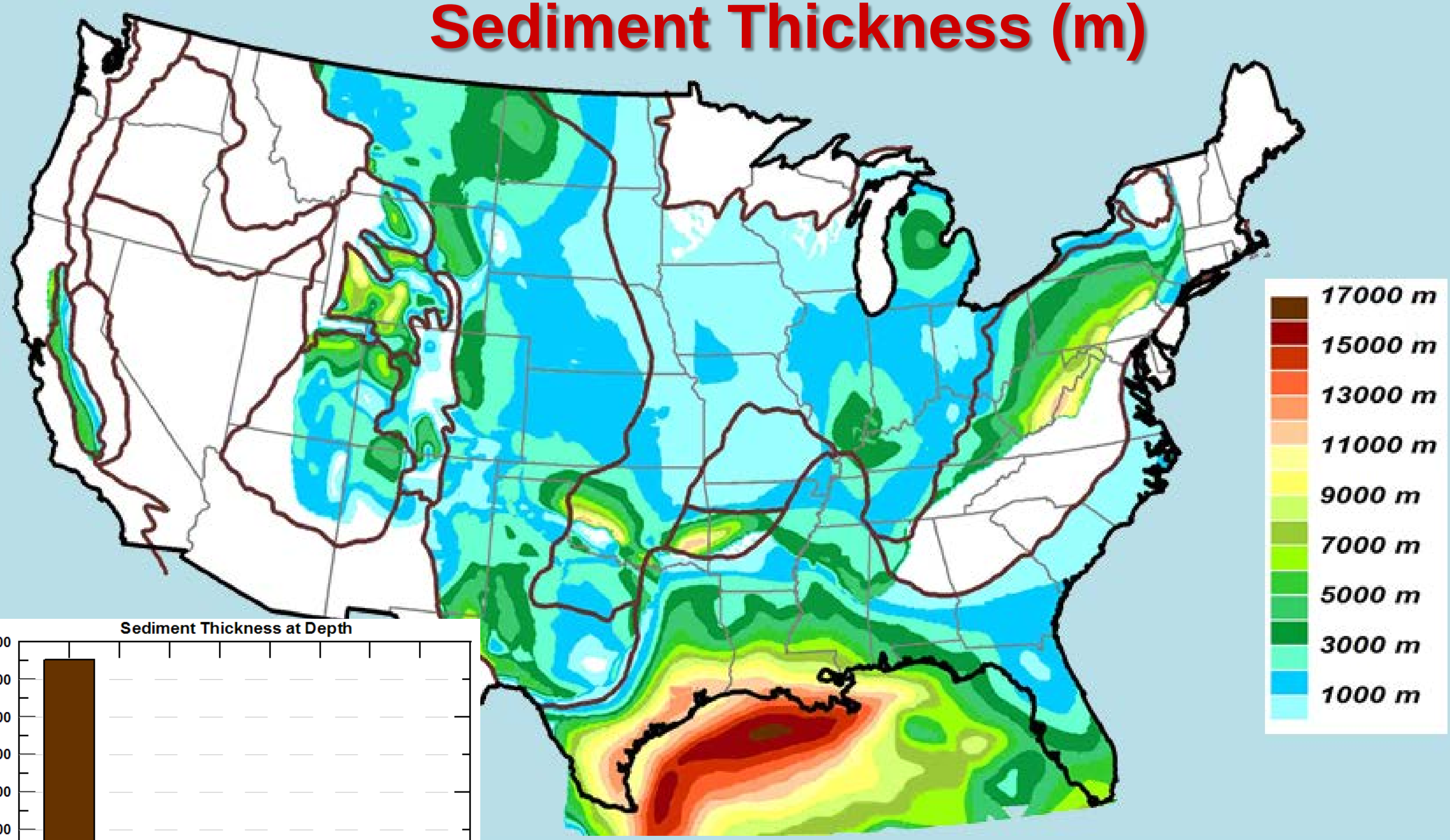
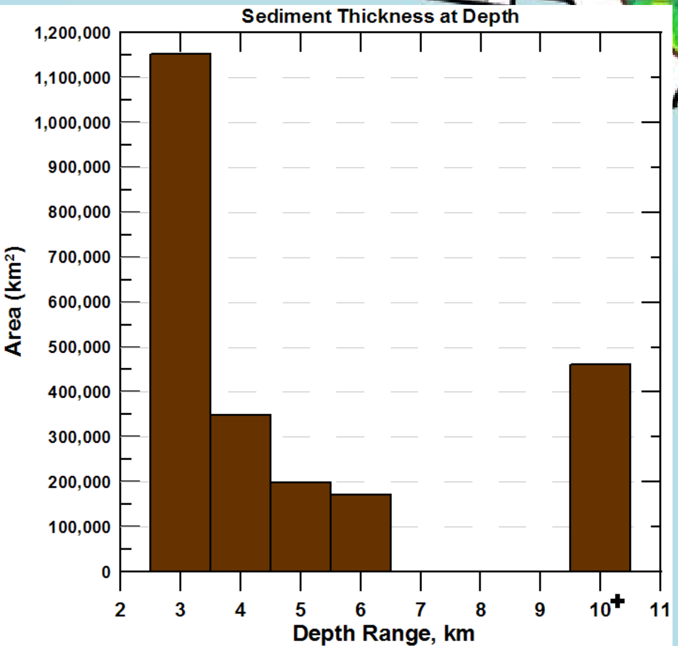
Sediment Thickness (m)





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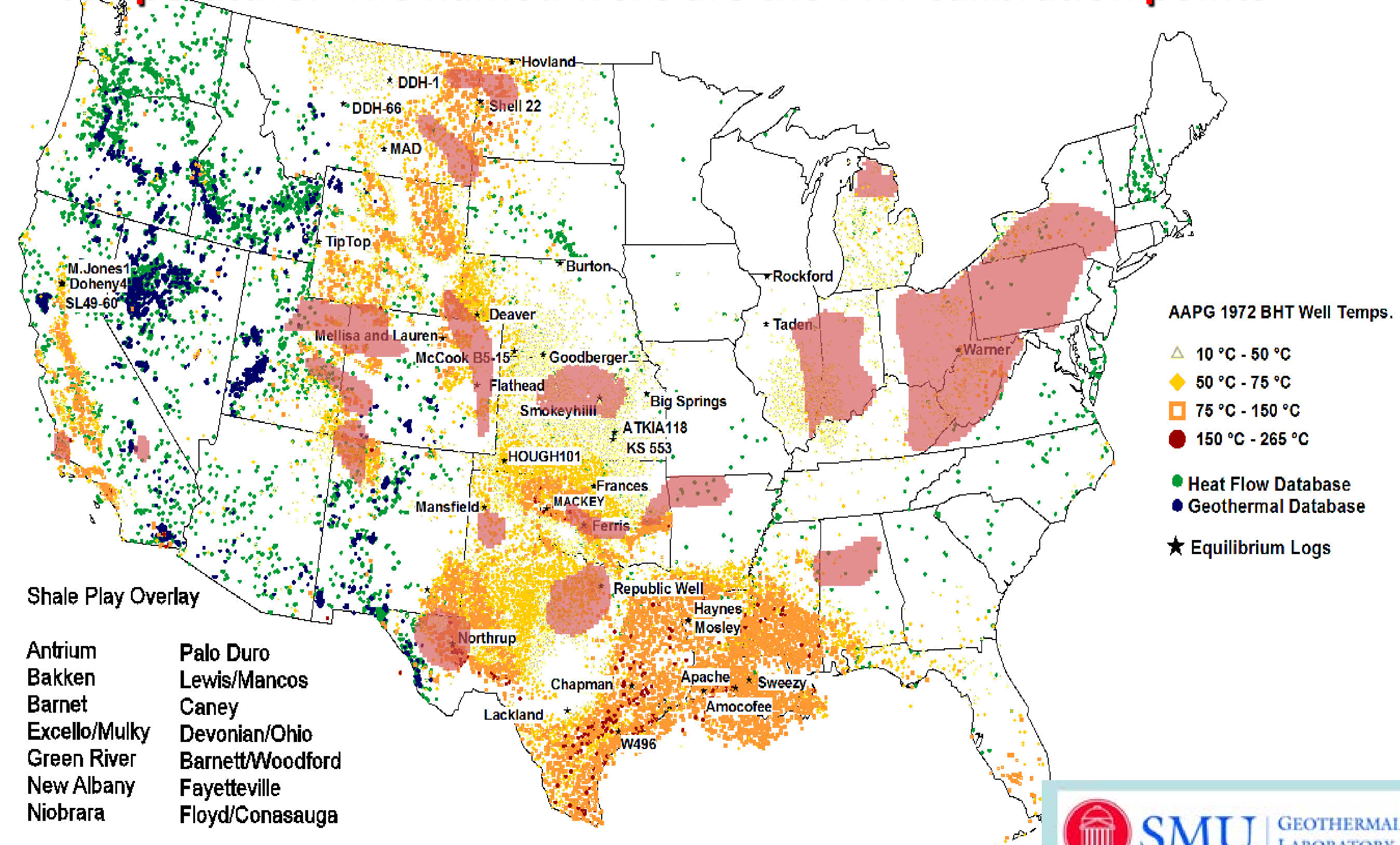
US heat flow map data sites including sites of wells with BHT data in the AAPG data base. BHT symbols are based on depth and temperature. The named wells are the BHT calibration points



Heat flow, and Shale Gas Plays

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A Protocol for Estimating and Mapping the Global Potential for EGS

HOT DRY ROCKS
Geothermal Energy Consultants

GEOWATT AG

Graeme Beardsmore — HDR (Australia)
Ladislaus Rybach — GeoWatt (Switzerland)
David Blackwell — SMU (Texas)
Charles Baron — Google.org (California)

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google.org

GRC *Transactions*, Vol. 34, 2010

A Protocol for Estimating and Mapping Global EGS Potential

Graeme R. Beardsmore[1], Ladislaus Rybach[2], David Blackwell[3] and Charles Baron[4]

[1]Hot Dry Rocks PL, South Yarra, Australia
[2]Geowatt AG, Zürich, Switzerland
[3]Southern Methodist University, Dallas TX
[4]Google.org, Mountain View CA
graeme.beardsmore@hotdryrocks.com

1. Grid geographic region into 5' x 5' cells.	Each cell becomes a node in the regional resource estimate. A temperature vs depth profile to 10 km depth will be derived for each cell.
2. Create sediment thickness (depth to basement) map.	From well-basement intersections, seismic interpretations, potential field inversions etc.
3. Populate sediment thermal properties	Thermal conductivity (K_S) and heat generation (A_S). Include depth variation if known. From measurements if available. Else, estimate from lithological mixing and age if possible. Else, estimate from age and basin setting. Else, global averages.
4. Populate basement thermal properties	Thermal conductivity (K_B) and heat generation (A_B). From measurements and geochemical data if available. Else, estimate from lithology. Else, global averages.
5. Create surface temperature map.	Mean average annual surface air temperature
6. Create surface heat flow map.	Average real data in 5' x 5' cell where available. Else, for Q_0 use BHTs and average conductivity if available. Else, assign by tectonic age. Else, use $Q_0 = 0.032 + b \times A_B + S \times A_S$.
7a. Derive temperature and heat flow at sediment-basement interface (S < 4,000 m)	$T_S = T_0 + [(Q_0 \times S) / K_s] - A_s (S^2 / 2.K_s)$; $Q_S = Q_0 - S \times A_S$
7b. Derive temperature and heat flow at sediment-basement interface (S > 4,000 m)	$T_S = T_{4km} + [(Q_0 - 4000.A_s) \times (S-4000) / K_B] - A_s \times (S-4000)^2 / 2.K_B)$; $Q_S = Q_0 - S \times A_S$
8. Derive T at depth X, between 3,000 m – 10,000 m.	$T_X = T_S + (Q_S \times (X-S) / K_B] - A_B \times ((X-S)^2 / 2.K_B)$

Figure 3. General process for estimating the temperature profile of the crust to 10,000 m depth.

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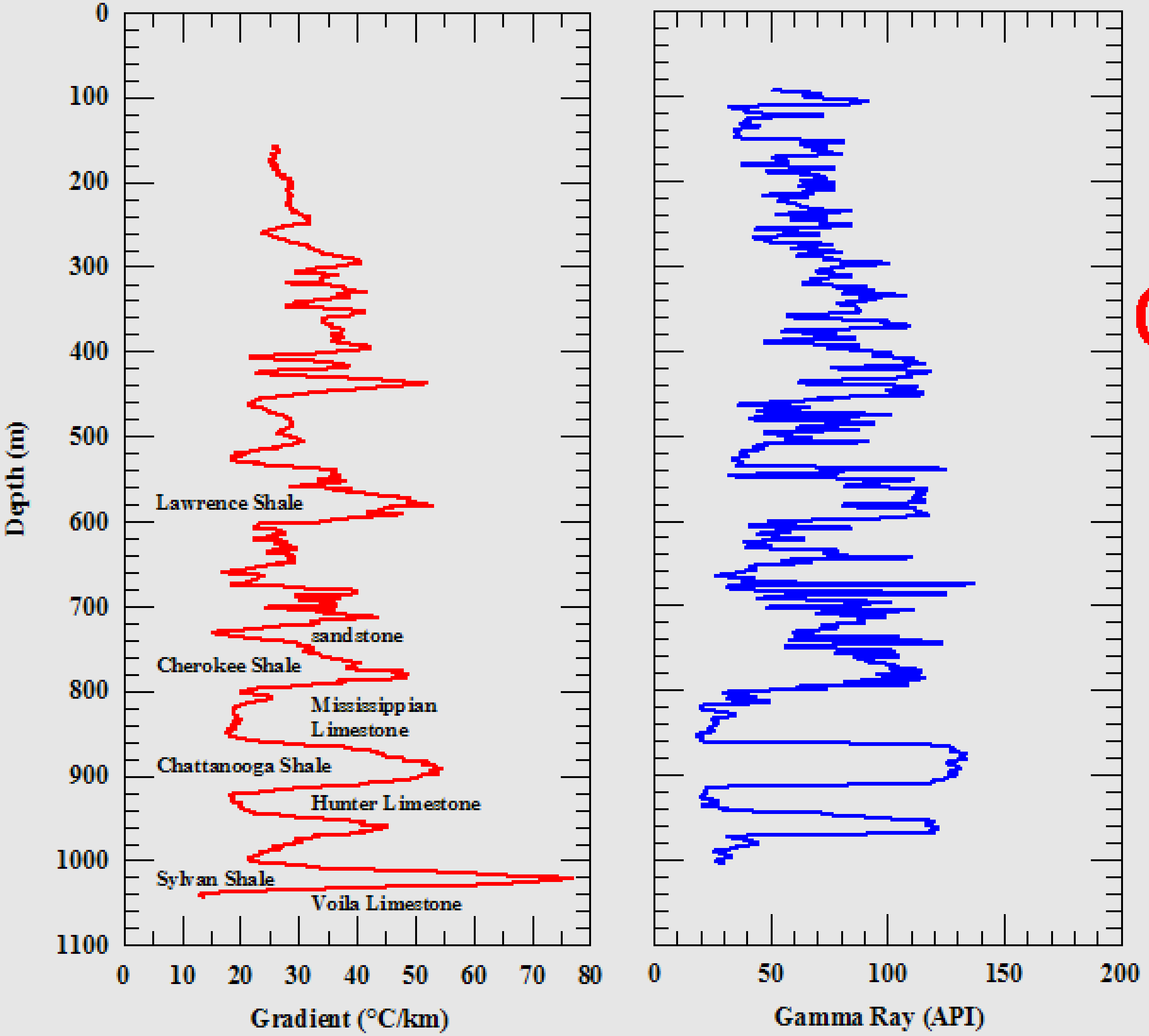
Smoky Hill Kansas Gradient and Gamma Logs



$$Q=K*(dT/dZ)$$

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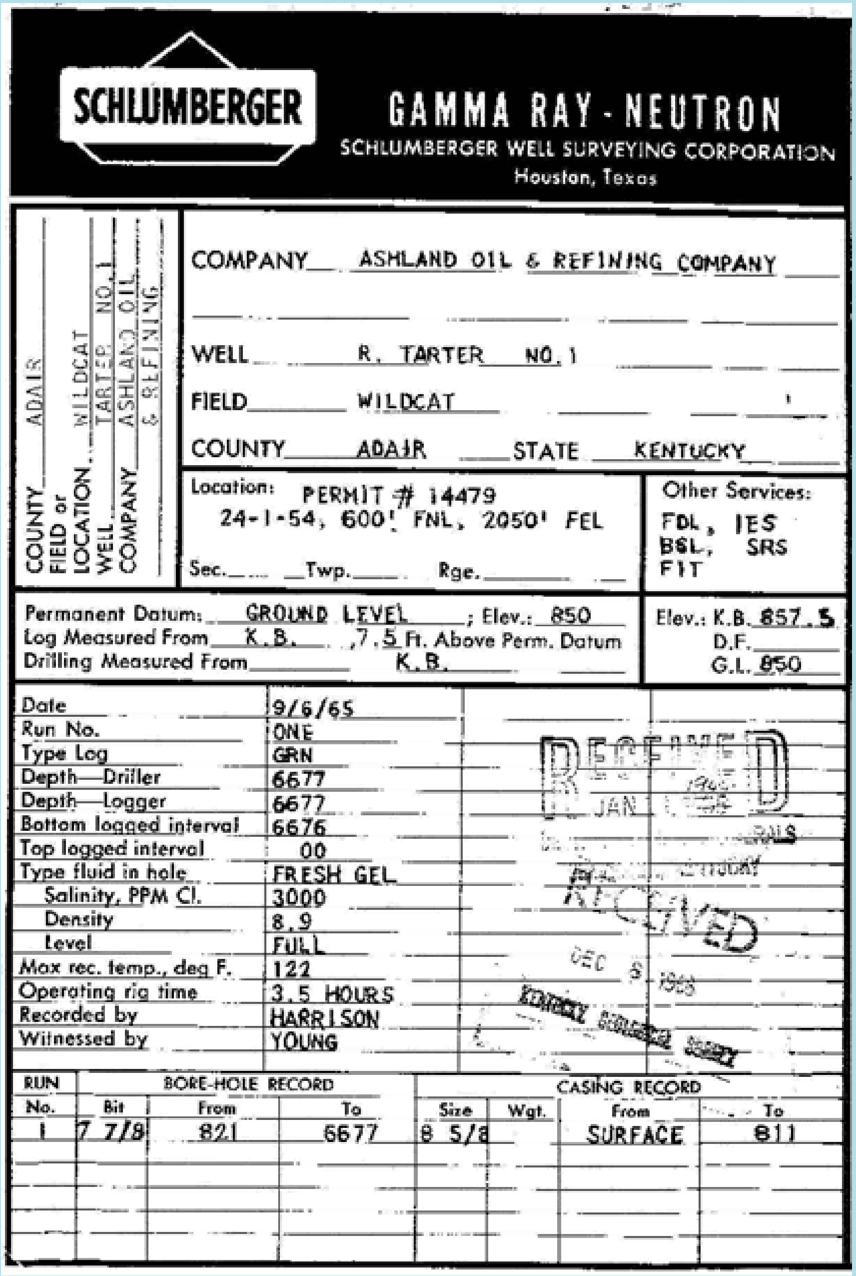
Bottom Hole Temperatures



SCHLUMBERGER

GAMMA RAY - NEUTRON

SCHLUMBERGER WELL SURVEYING CORPORATION

Houston, Texas

COUNTY ADAIR
FIELD or LOCATION WILDCAT
WELL TARTER NO. 1
COMPANY ASHLAND OIL & REFINING

COMPANY ASHLAND OIL & REFINING COMPANY

WELL R. TARTER NO. 1

FIELD WILDCAT

COUNTY ADAIR STATE KENTUCKY

Location: PERMIT # 14479
24-1-54, 600' FNL, 2050' FEL

Sec. Twp. Rge.

Other Services:
FDL, IES
BSL, SRS
FIT

Permanent Datum: GROUND LEVEL ; Elev.: 850
Log Measured From K.B. 7.5 Ft. Above Perm. Datum
Drilling Measured From K.B.

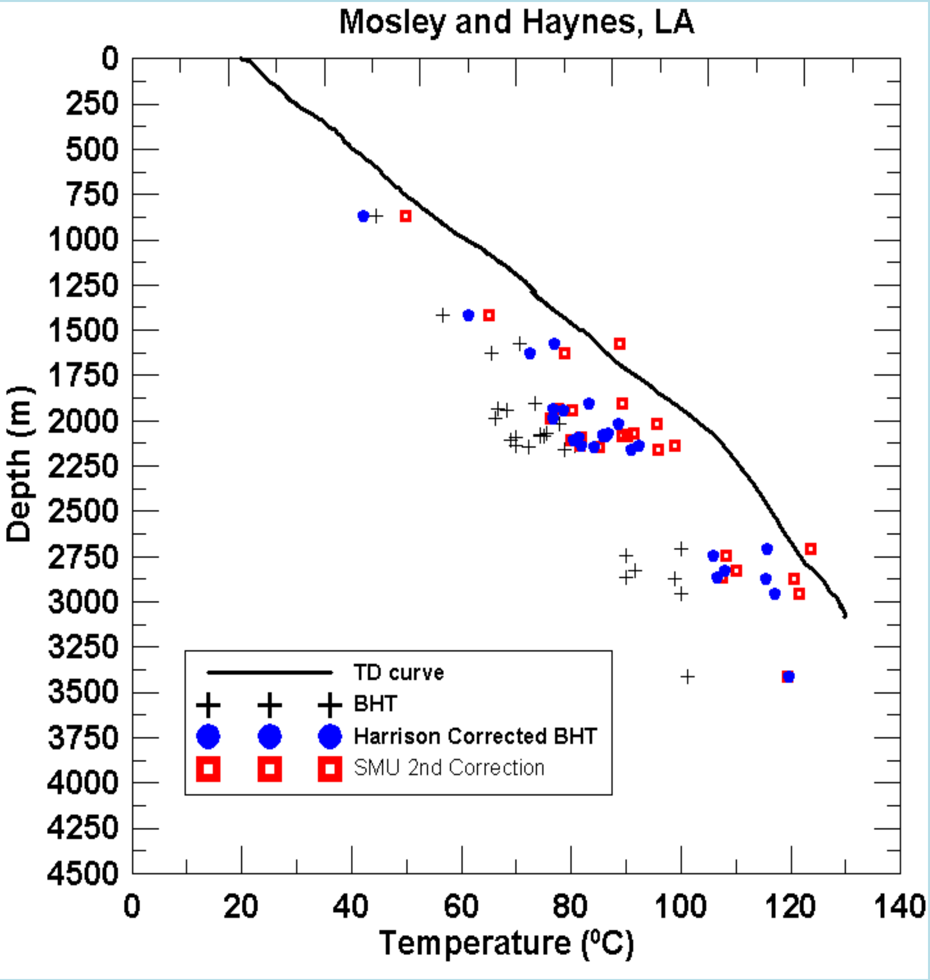
Elev.: K.B. 857.5
D.F.
G.L. 850

Date	9/6/65
Run No.	ONE
Type Log	GRN
Depth—Driller	6677
Depth—Logger	6677
Bottom logged interval	6676
Top logged interval	00
Type fluid in hole	FRESH GEL
Salinity, PPM Cl.	3000
Density	8.9
Level	FULL
Max rec. temp., deg F.	122
Operating rig time	3.5 HOURS
Recorded by	HARRISON
Witnessed by	YOUNG

RECEIVED JAN 1966

RECEIVED DEC 1965

RUN No.	BORE-HOLE RECORD Bit	From	To	CASING RECORD Size	Wgt.	From	To
1	7 7/8	821	6677	8 5/8		SURFACE	811



BHT Calibration

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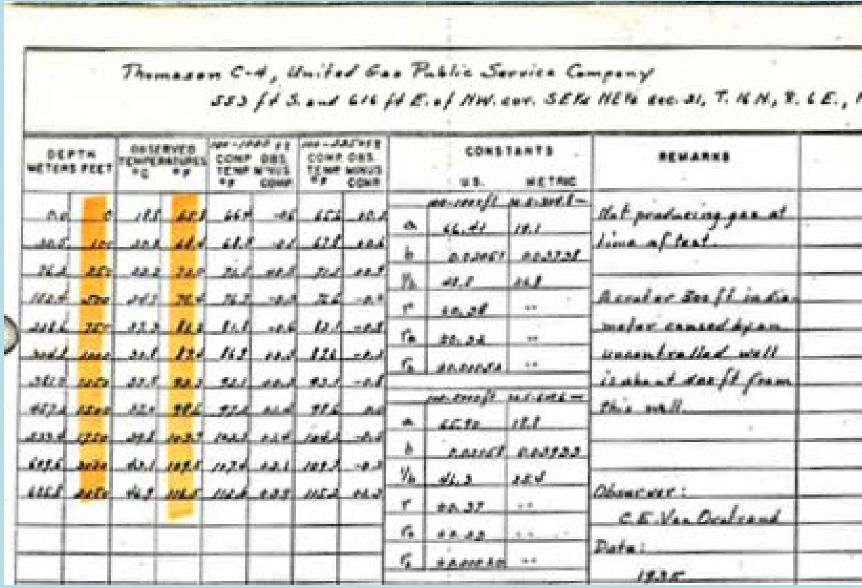


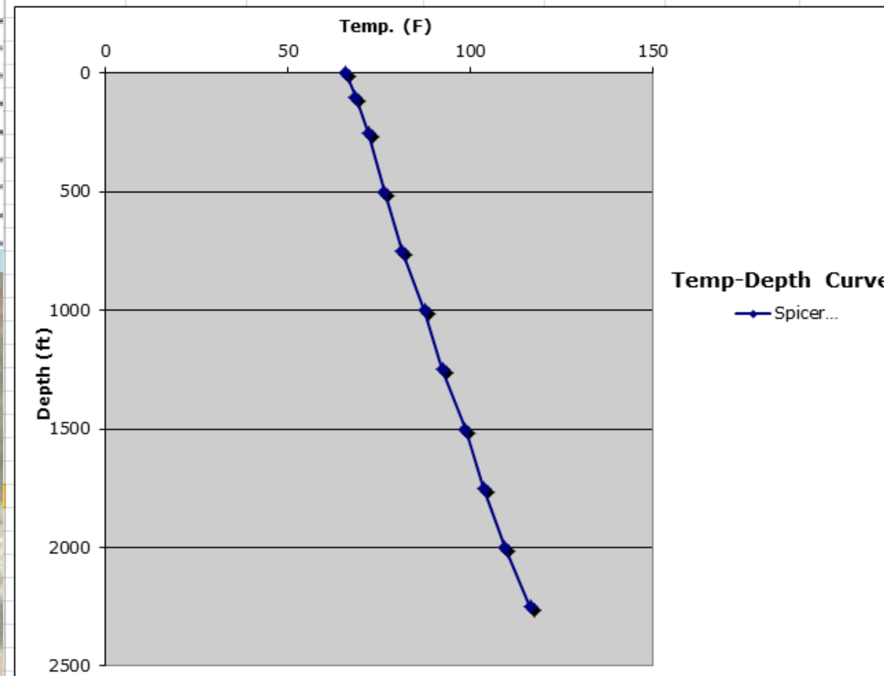
Depth (ft)	Temp. (F)	Gradient (F/1000ft	Depth (m)	Temp. (C)
0	65.8	-	0.0	18.8
100	68.4	26.0	30.5	20.2
250	72	24.8	76.2	22.2
500	76.4	21.2	152.4	24.7
750	81.2	20.5	228.6	27.3
1000	87.4	21.6	304.8	30.8
1250	92.3	21.2	381.0	33.5
1500	98.6	21.9	457.2	37.0
1750	103.7	21.7	533.4	39.8
2000	109.5	21.9	609.6	43.1
2250	116.5	22.5	685.8	46.9

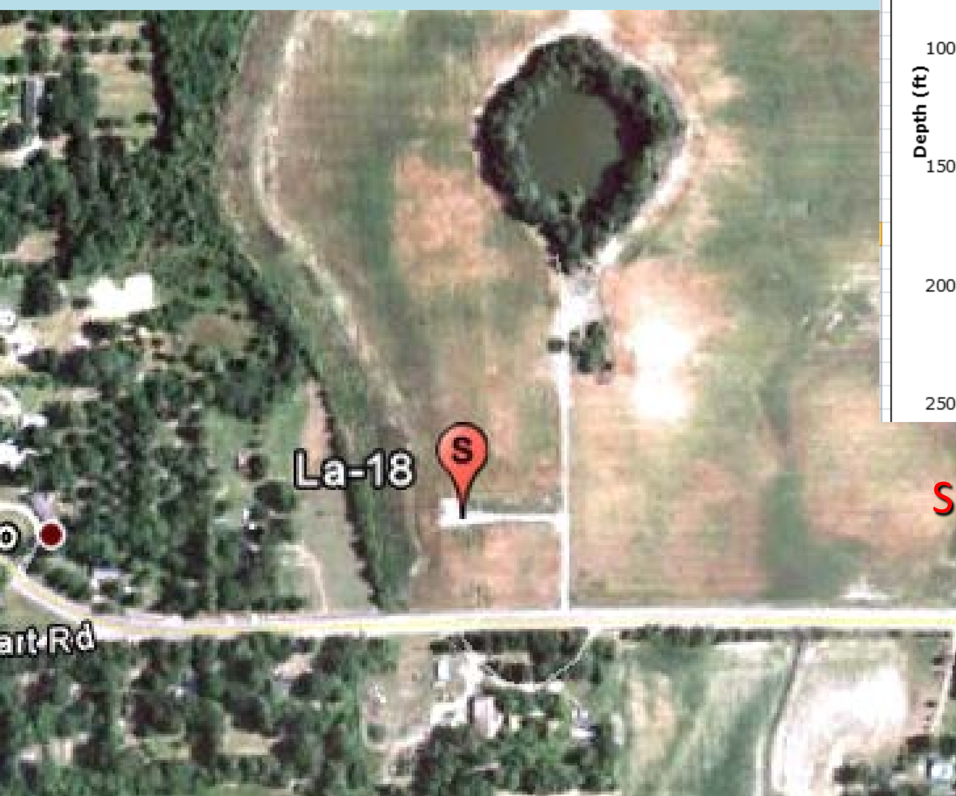
La-18

Thomason C-4, United Gas Public Service
Richland Gas Field
Monroe, La

not producing gas at time of test

a crater 300 ft in diameter cause by an uncontrolled well is about 400 ft from thi
well





Spicer USGS Open File (1964)

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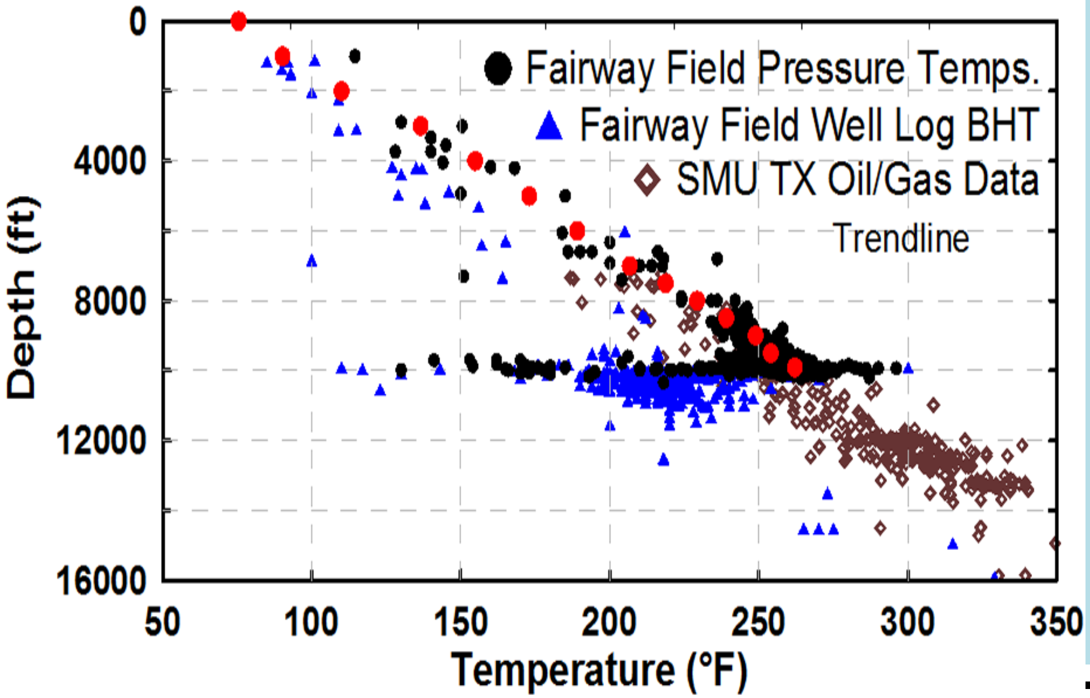
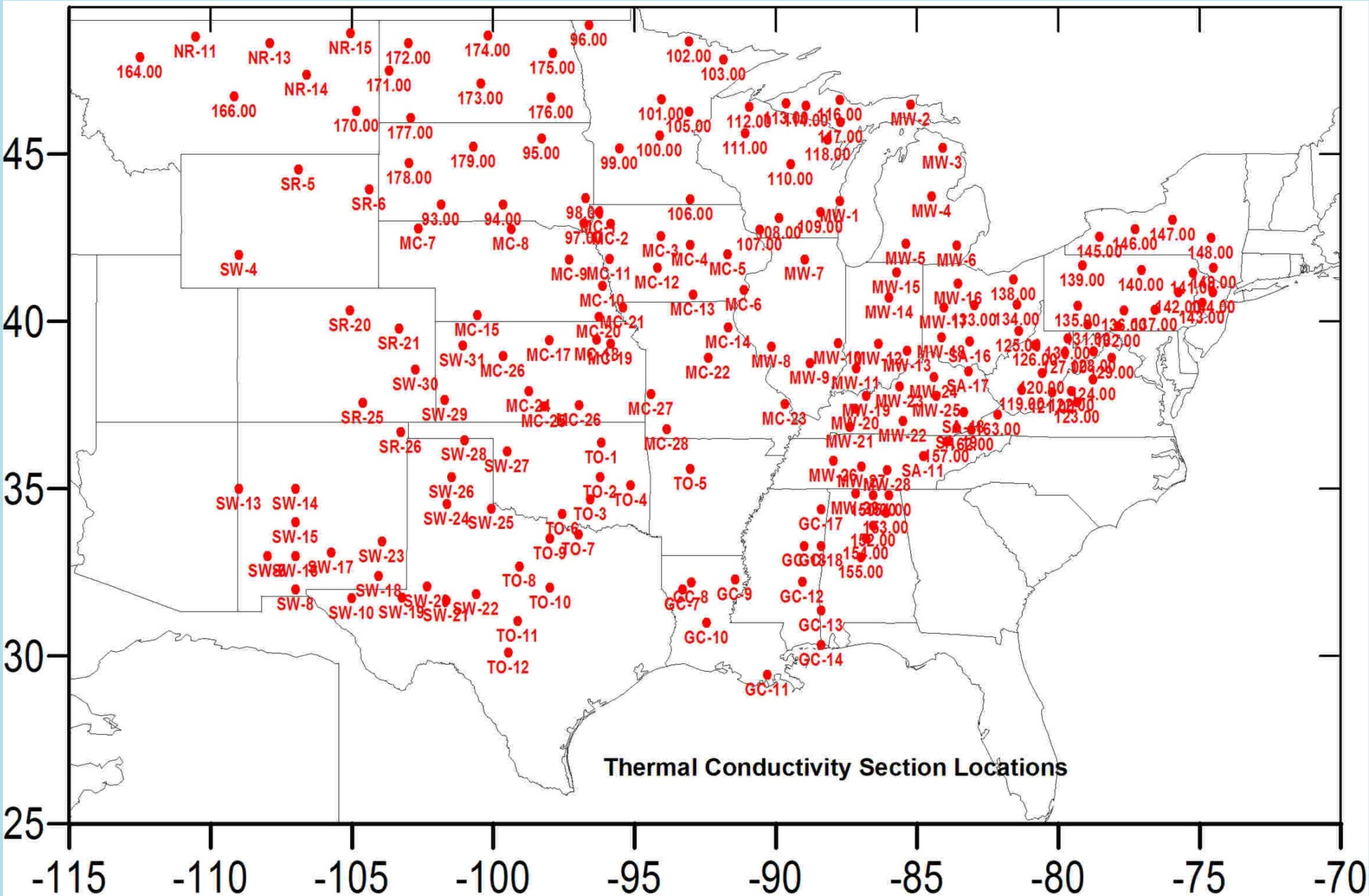
Blackwell, Richards, and Stepp, (2010) Texas SECO

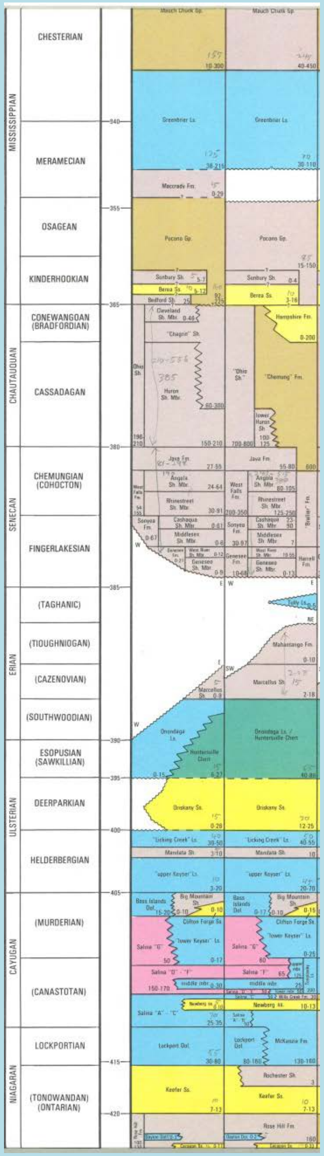


Depth Range Feet	Number of Wells	Average Uncorrected Temperature °F	Average Corrected Temperature °F	Maximum Corrected Temperature °F
12,000 - 13,000	879	263	299	363
13,000 - 14,000	628	283	320	430
14,000 - 15,000	330	304	340	423
15,000 - 16,000	159	306	349	420
16,000 - 17,000	107	319	361	422
17,000 - 18,000	60	319	358	454
18,000 - 24,000	46	362	402	544



COSUNA Strat Column Locations

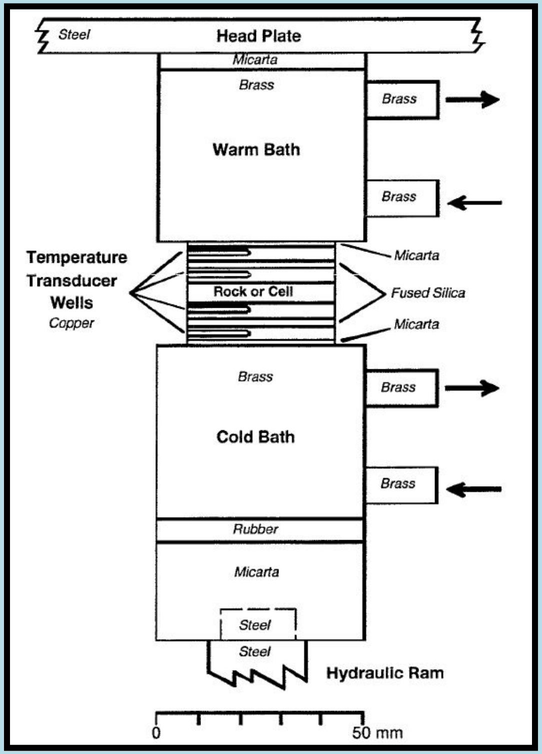
Conductivity Model for BHT Sites



- Lithology based on AAPG's Correlation of Stratigraphic Units of North America (COSUNA) seen on left, scaled to sediment thickness
- Measured conductivities for a formation used when available, otherwise values from the table below used

Rock Type	Thermal Conductivity*
Dolomite	4.4
Limestone	2.9
Sandstone	4.2
Shale	1.4
Unconsolidated Sediment	1.2
Evaporites	4.7
Conglomerate	4.0
Limestone/Shale	2.0
Coal	0.6
Chert	4.0

*Table adapted from Gallardo and Blackwell (1999)



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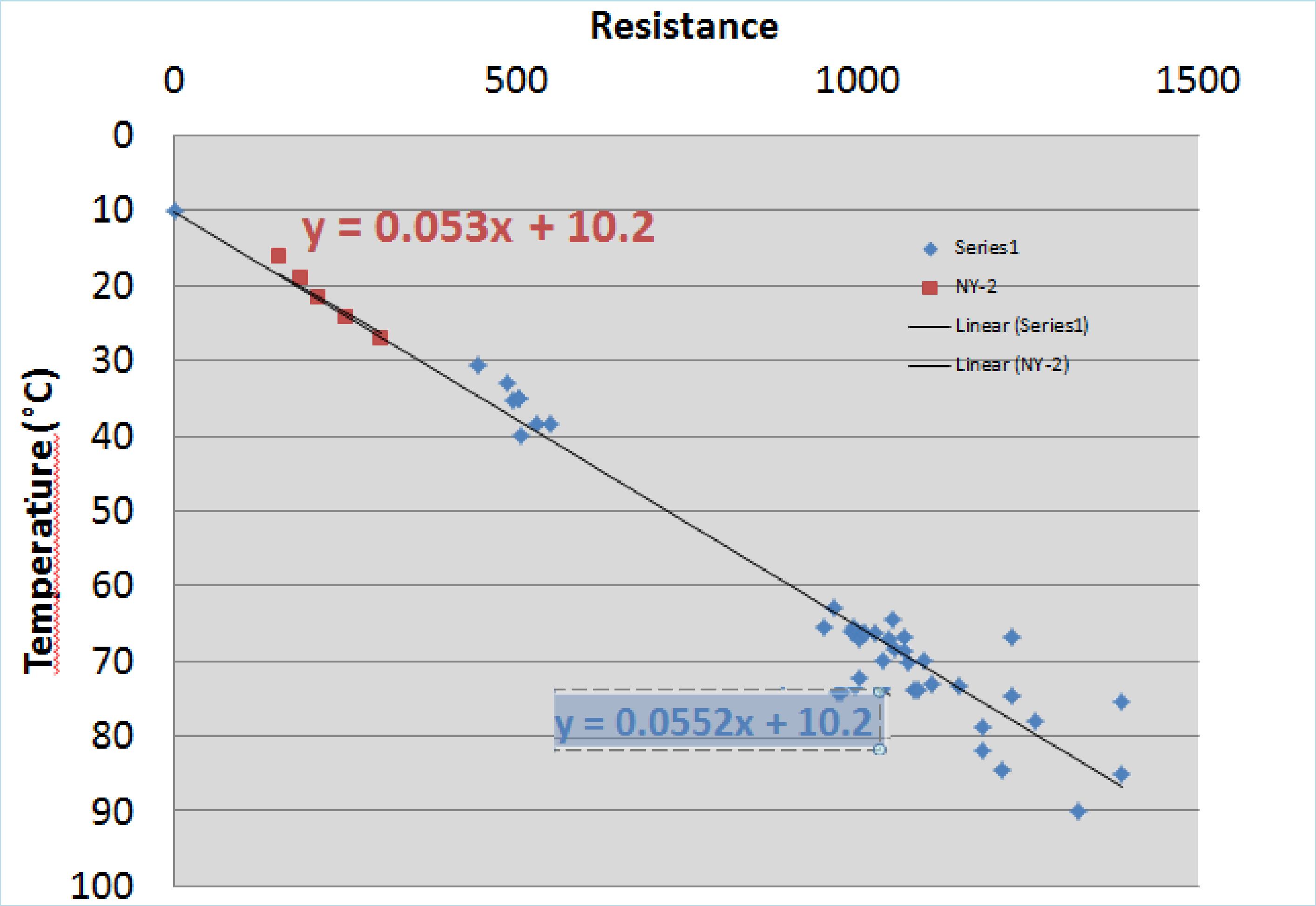

- Bullard Plots of BHT data in the area of Spicer equilibrium temperature depth wells
- Error Calculation

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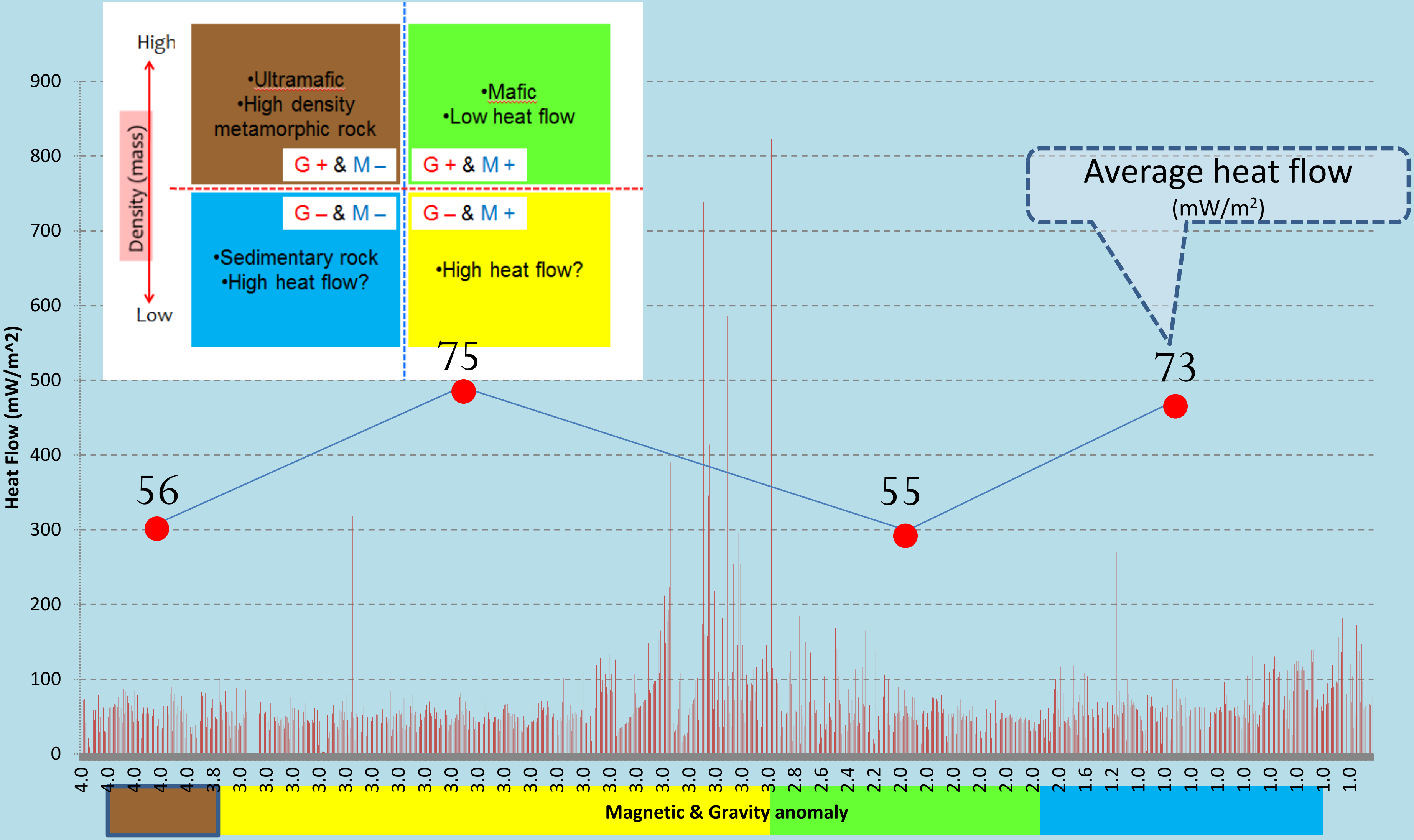

Correlation of Magnetic & Gravity Anomaly with Heat Flow

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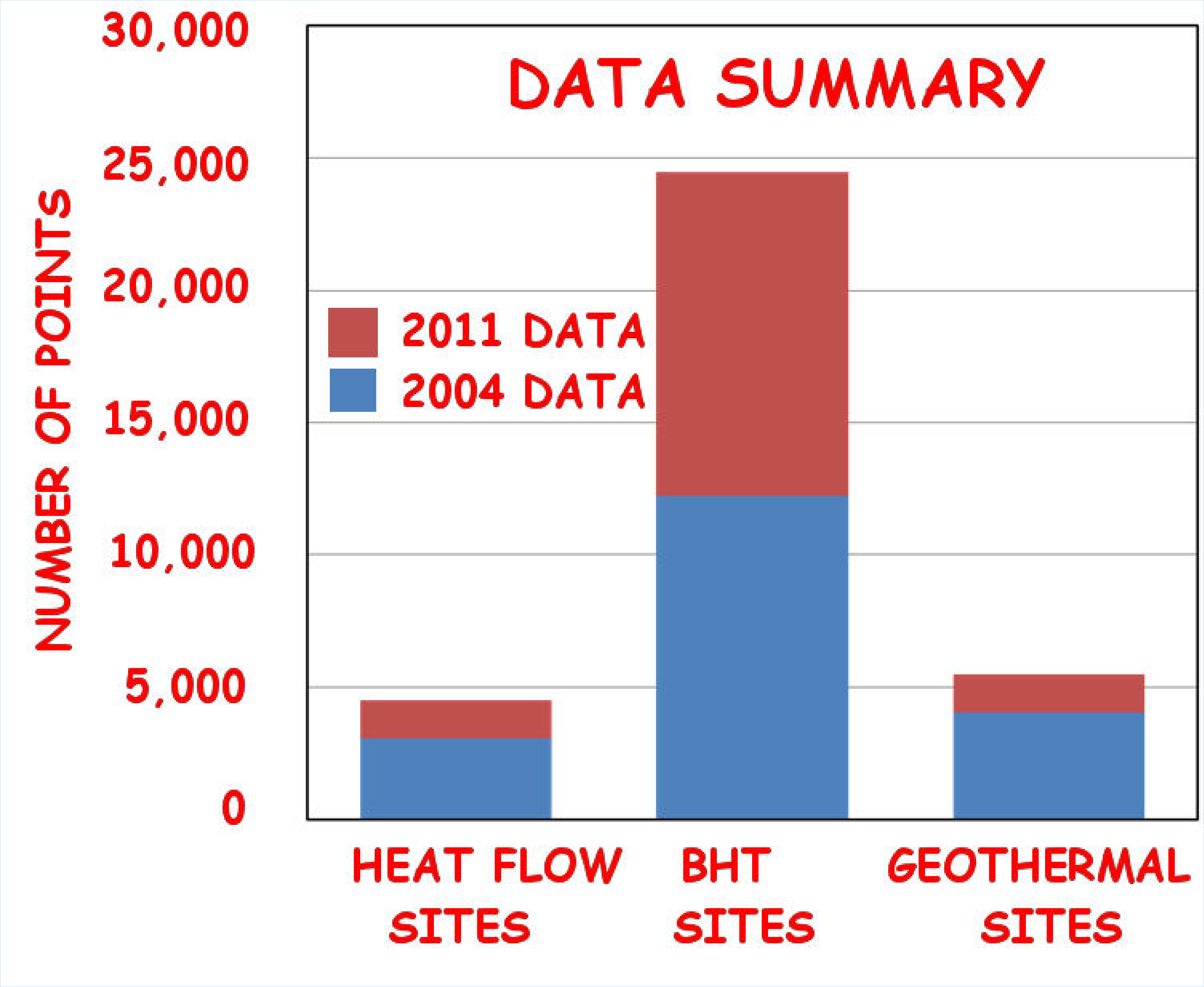

2011 Google US Heat Flow Map

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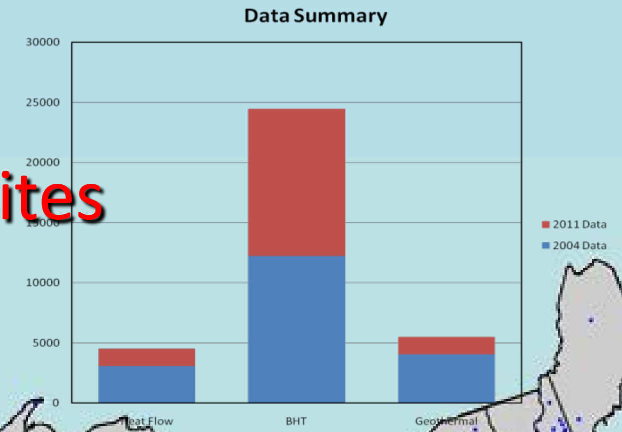
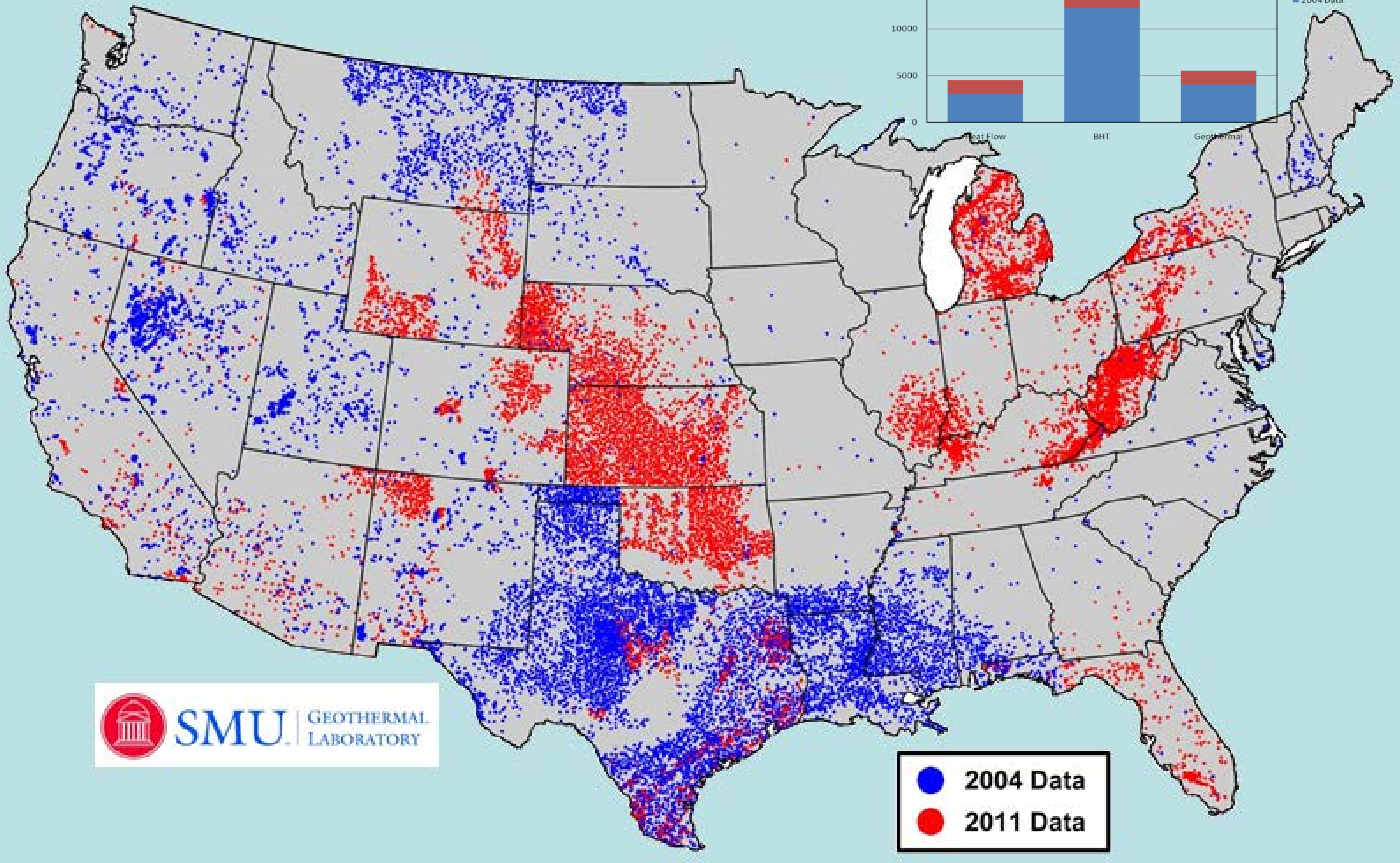
2011 Google Heat Flow Map Data Sites





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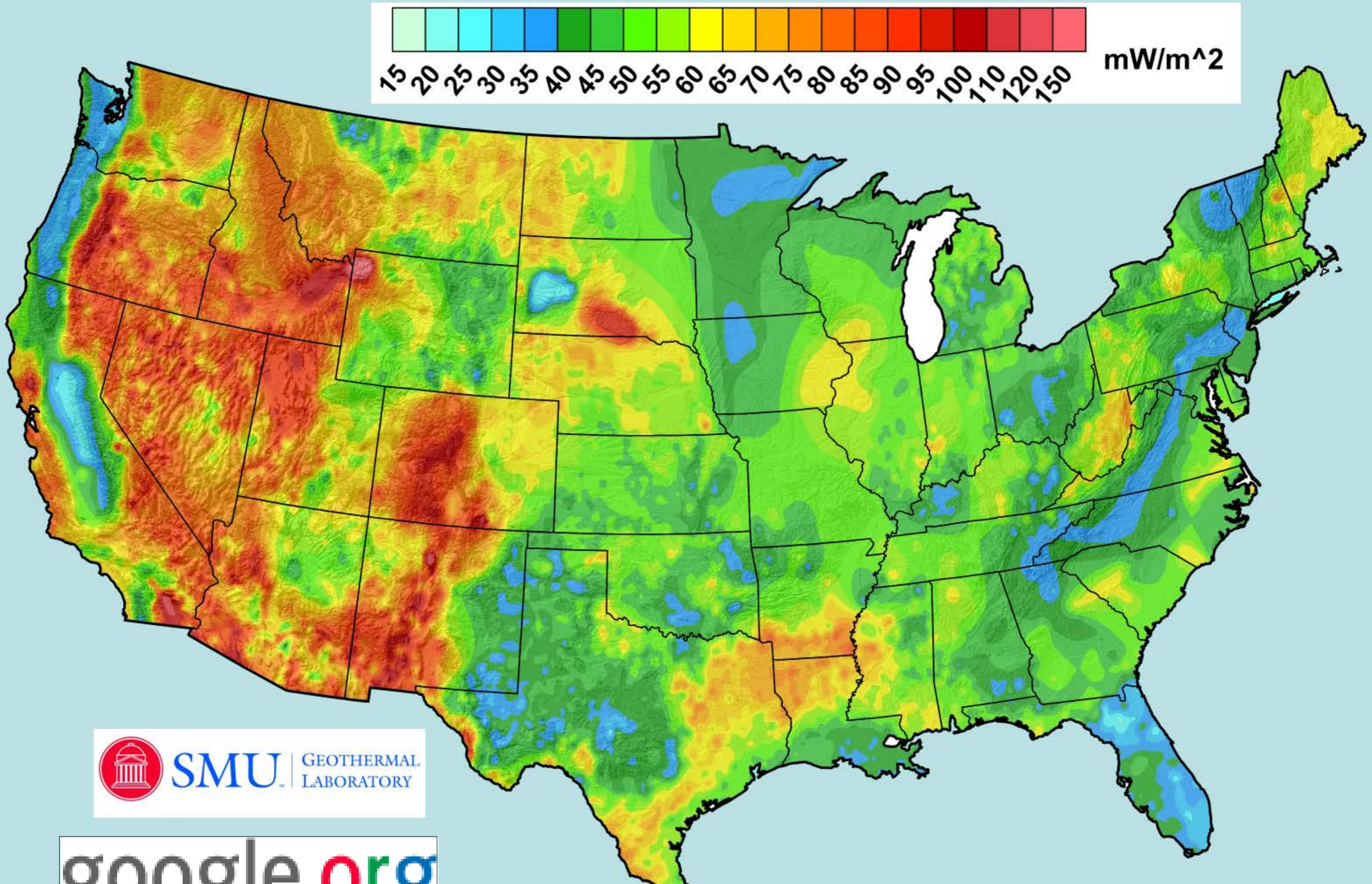
2011 US Heat Flow Map



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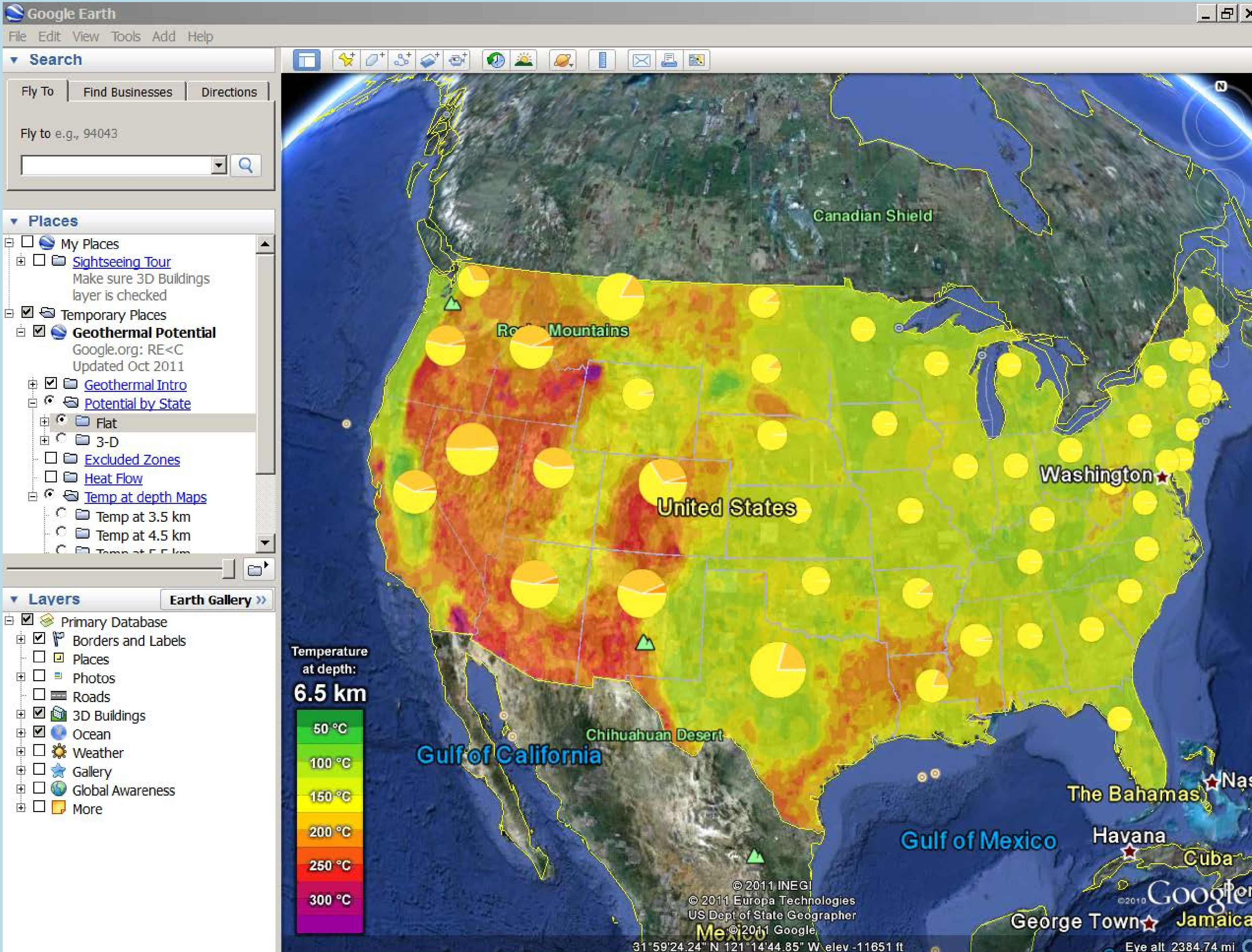
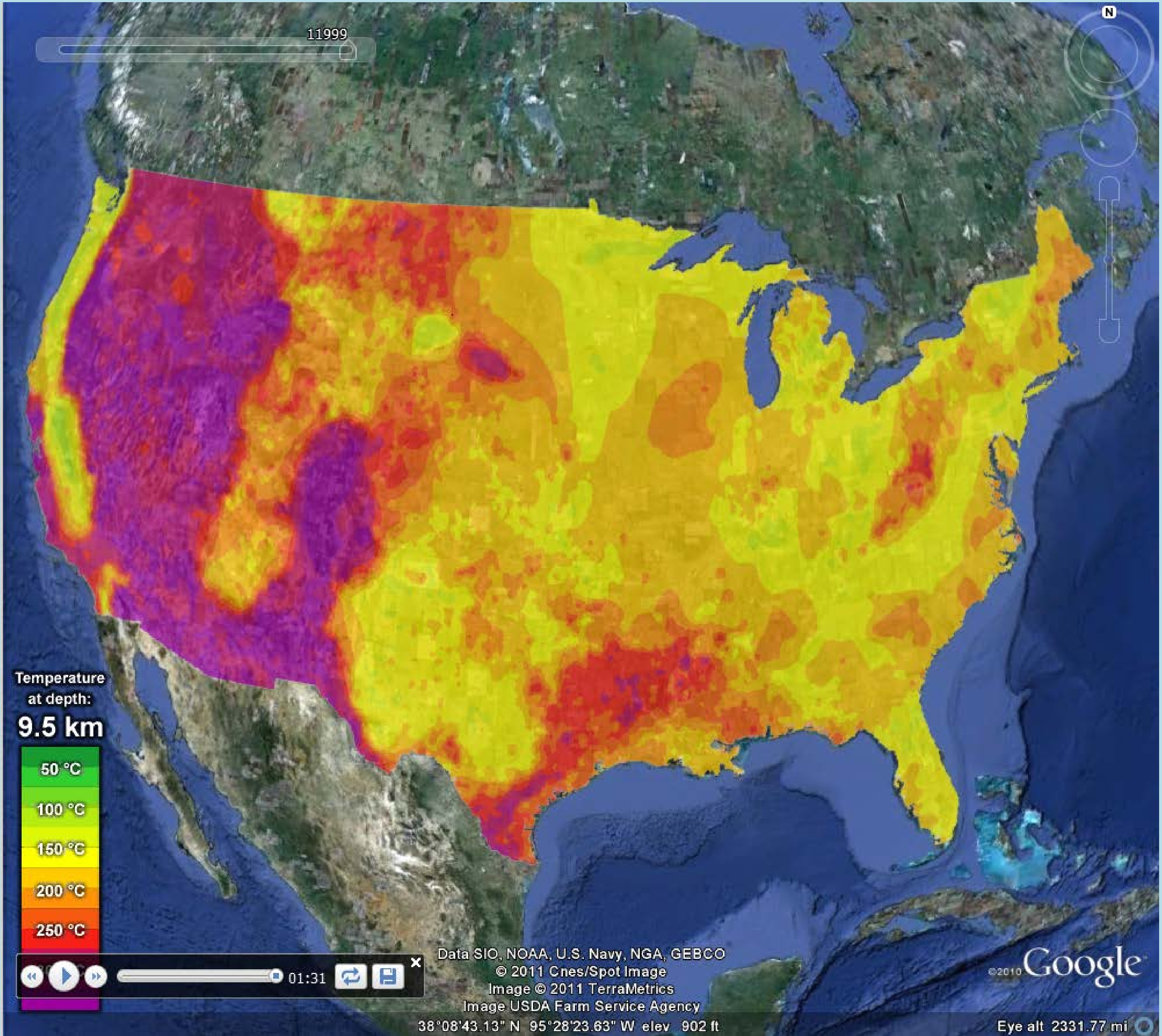
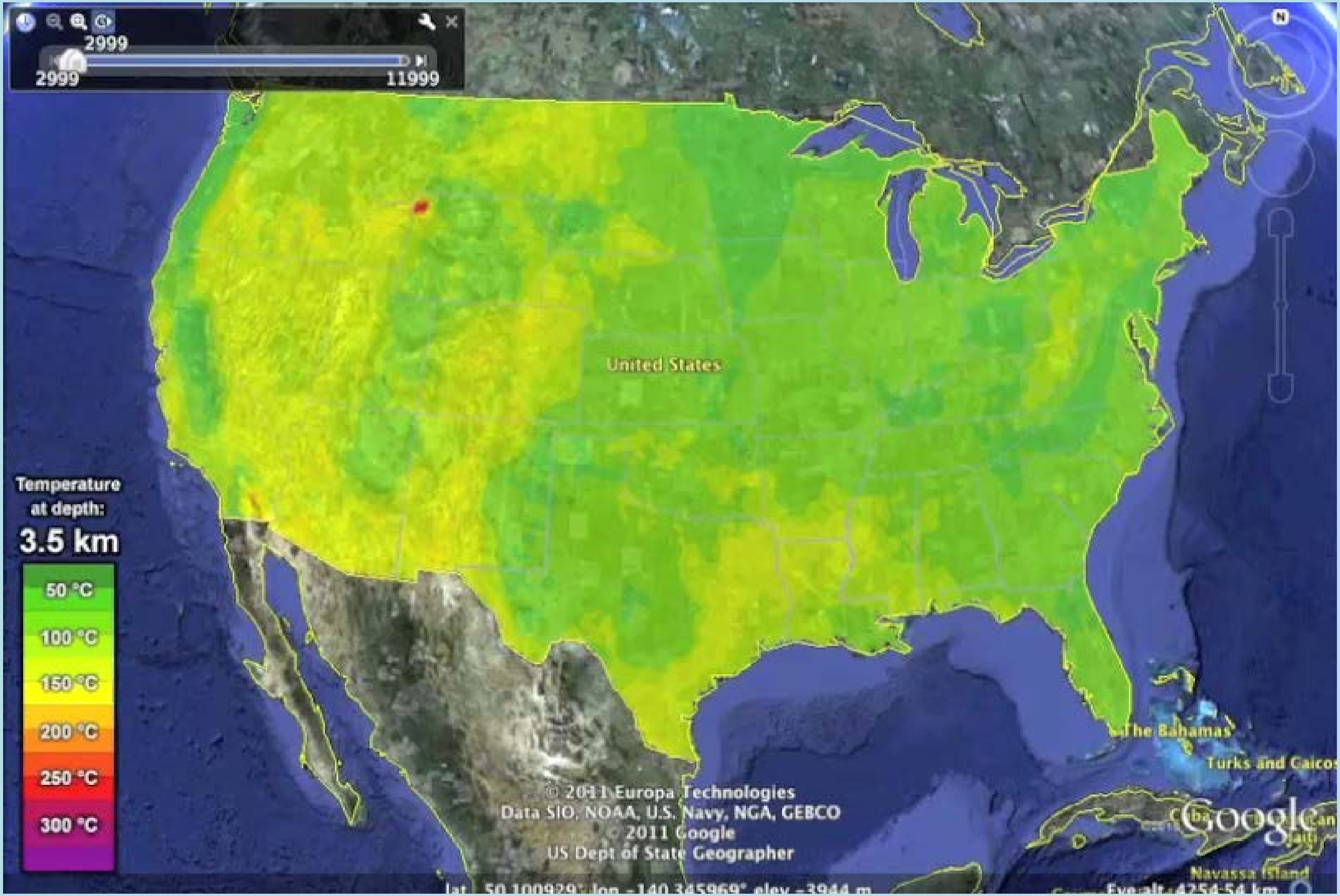

Google Earth
File Edit View Tools Add Help
Search
Fly To
Find Businesses
Directions
Fly to e.g., 94043
Places
My Places
Sightseeing Tour
Make sure 3D Buildings layer is checked
Temporary Places
Geothermal Potential
Google.org: RE<C
Updated Oct 2011
Geothermal Intro
Potential by State
Flat
3-D
Excluded Zones
Heat Flow
Temp at depth Maps
Temp at 3.5 km
Temp at 4.5 km
Layers
Earth Gallery »
Primary Database
Borders and Labels
Places
Photos
Roads
3D Buildings
Ocean
Weather
Gallery
Global Awareness
More
Canadian Shield
Rocky Mountains
United States
Washington
Gulf of California
Chihuahuan Desert
Gulf of Mexico
The Bahamas
Havana
Cuba
George Town
Jamaica
Temperature at depth:
6.5 km
50 °C
100 °C
150 °C
200 °C
250 °C
300 °C
© 2011 INEGI
© 2011 Europa Technologies
US Dept of State Geographer
© 2011 Google
Google
31°59'24.24" N 121°14'44.85" W elev -11651 ft
Eye alt 2384.74 mi


11999
Temperature at depth:
9.5 km
50 °C
100 °C
150 °C
200 °C
250 °C
01:31
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Cnes/Spot Image
Image © 2011 TerraMetrics
Image USDA Farm Service Agency
38°08'43.13" N 95°28'23.63" W elev 902 ft
©2010 Google
Eye alt 2331.77 mi



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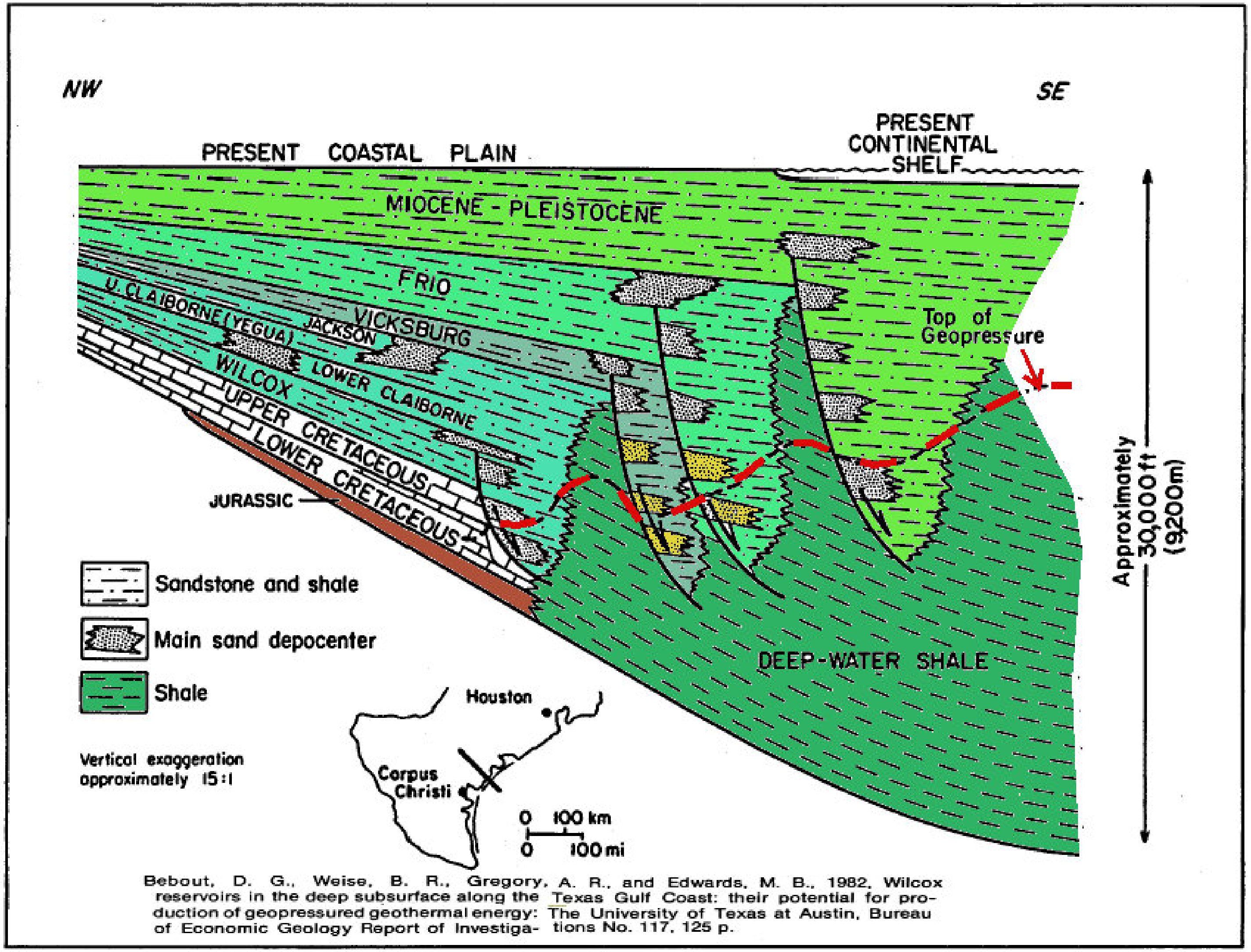
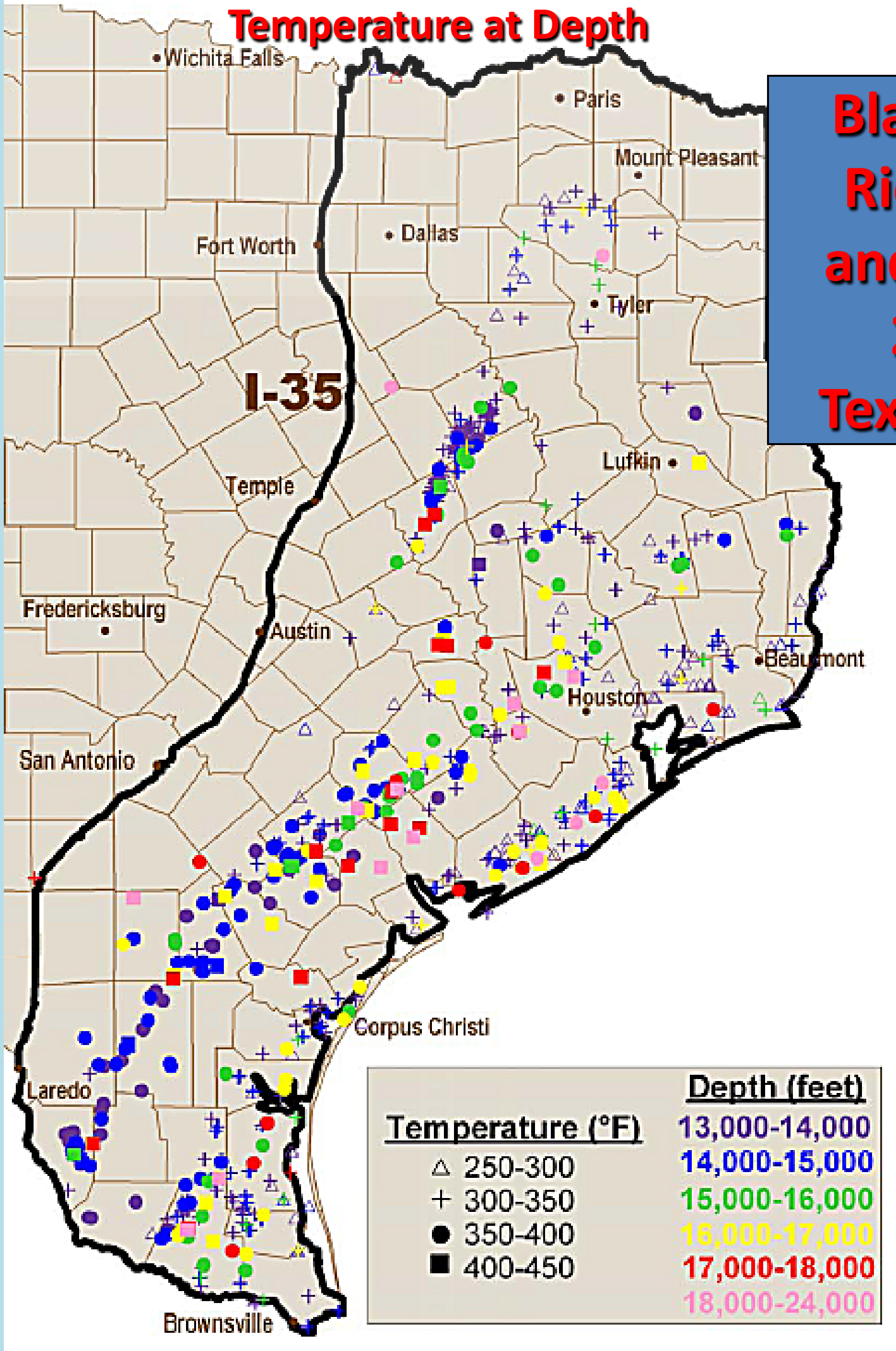
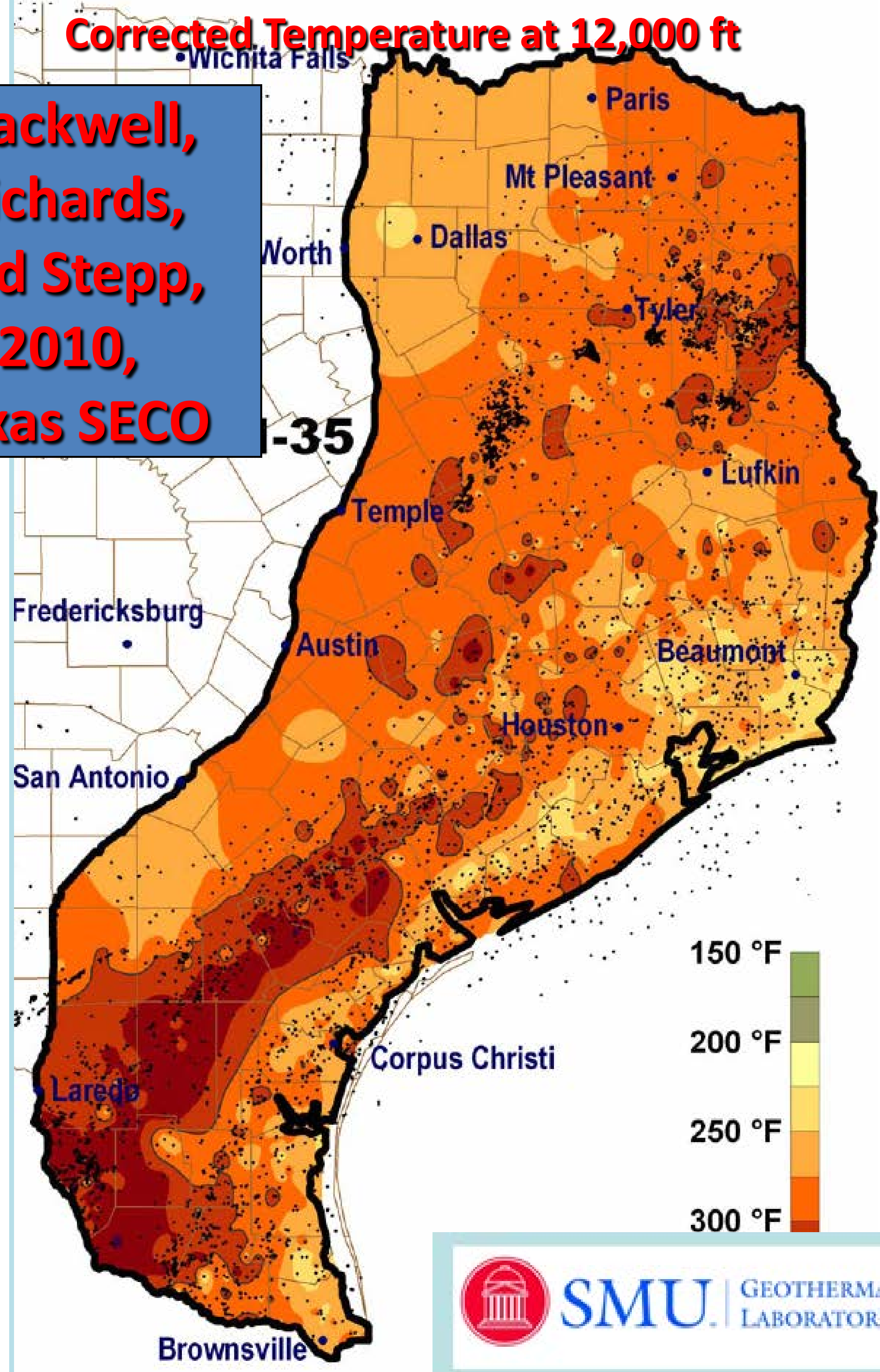


Schematic cross section, central Texas Gulf Coast, showing relationship among major growth faults, expansion of section, sand depocenters, and top of geopressure (after Bebout and others, 1982).

Gulf Coast Geology and Geopressure Geothermal Resource Setting: USGS (1979) estimates 70 to 170 MW resource potential (gas & heat)



Blackwell, Richards, and Stepp, 2010, Texas SECO



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Chena Mobile Power System

Denbury Resources – Gulf Coast Green Energy

RPSEA.org Demonstration Project

Mississippi Summerland Field

190°F current surface temperature

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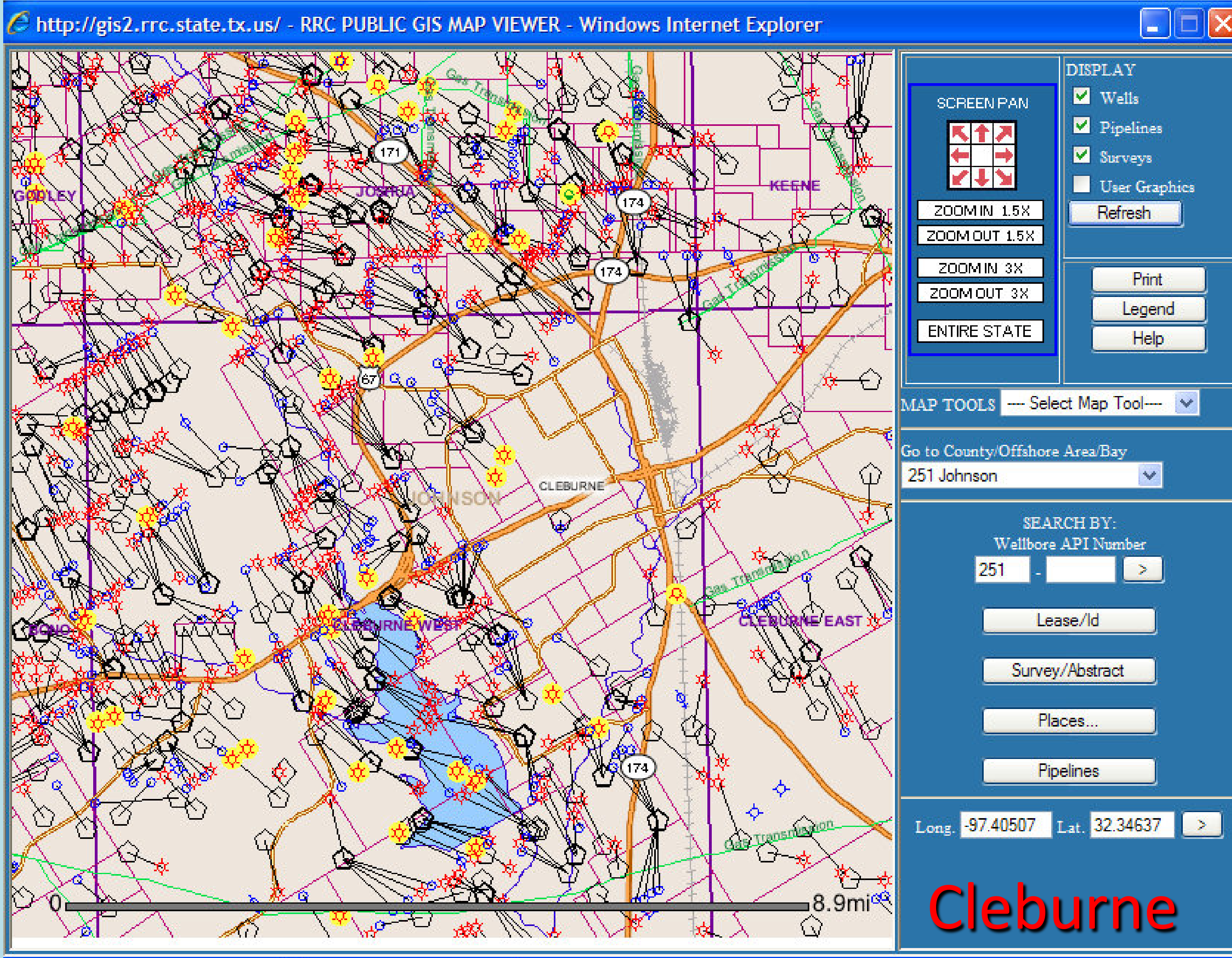

Horizontal Wells as EGS Heat Exchangers

Giddings Austin Chalk Play, Haynesville Shale Play, etc

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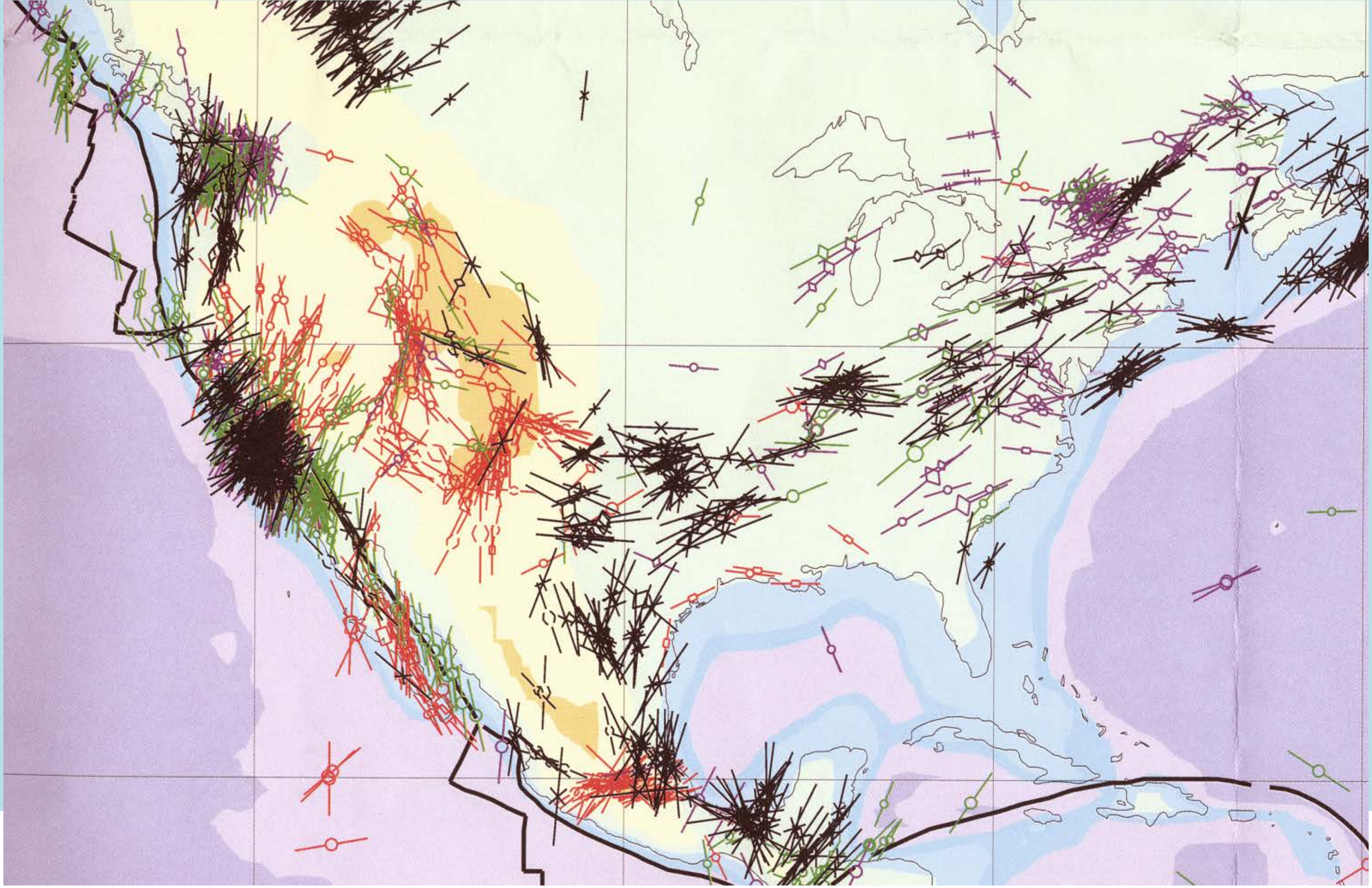


Inferred from:

- Focal mechanism
- Wellbore breakouts
- Fault slip data
- Volcanic alignments
- Hydraulic fracturing
- Overcoring

Red data—Normal faulting stress regime: $S_v > S_{Hmax} > S_{hmin}$

Green data—Strike-slip faulting stress regime: $S_{Hmax} > S_v > S_{hmin}$

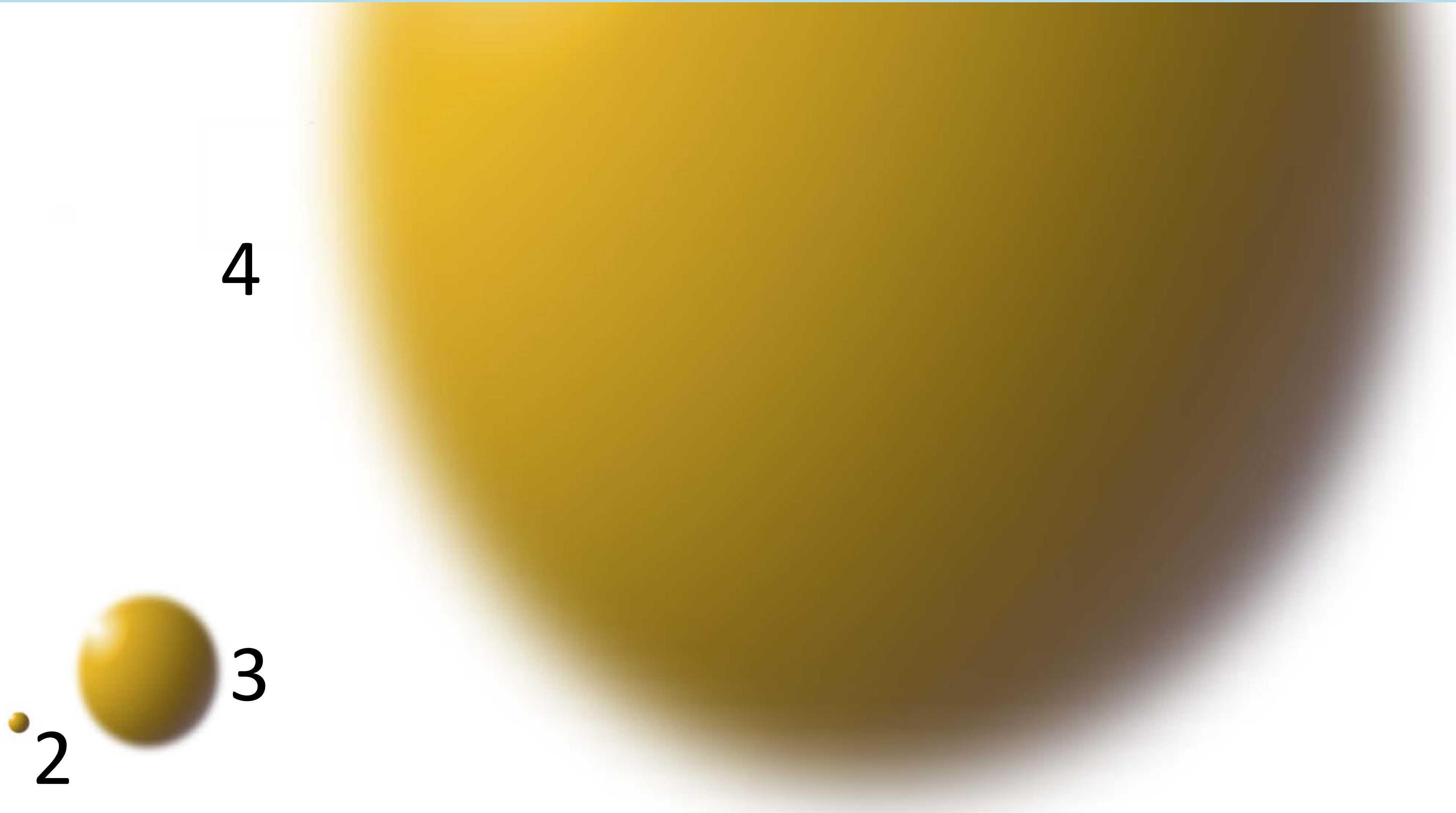
Purple data—Thrust faulting stress regime: $S_{Hmax} > S_{hmin} > S_v$

Black data—Stress regime unknown

MAXIMUM HORIZONTAL STRESS ORIENTATION

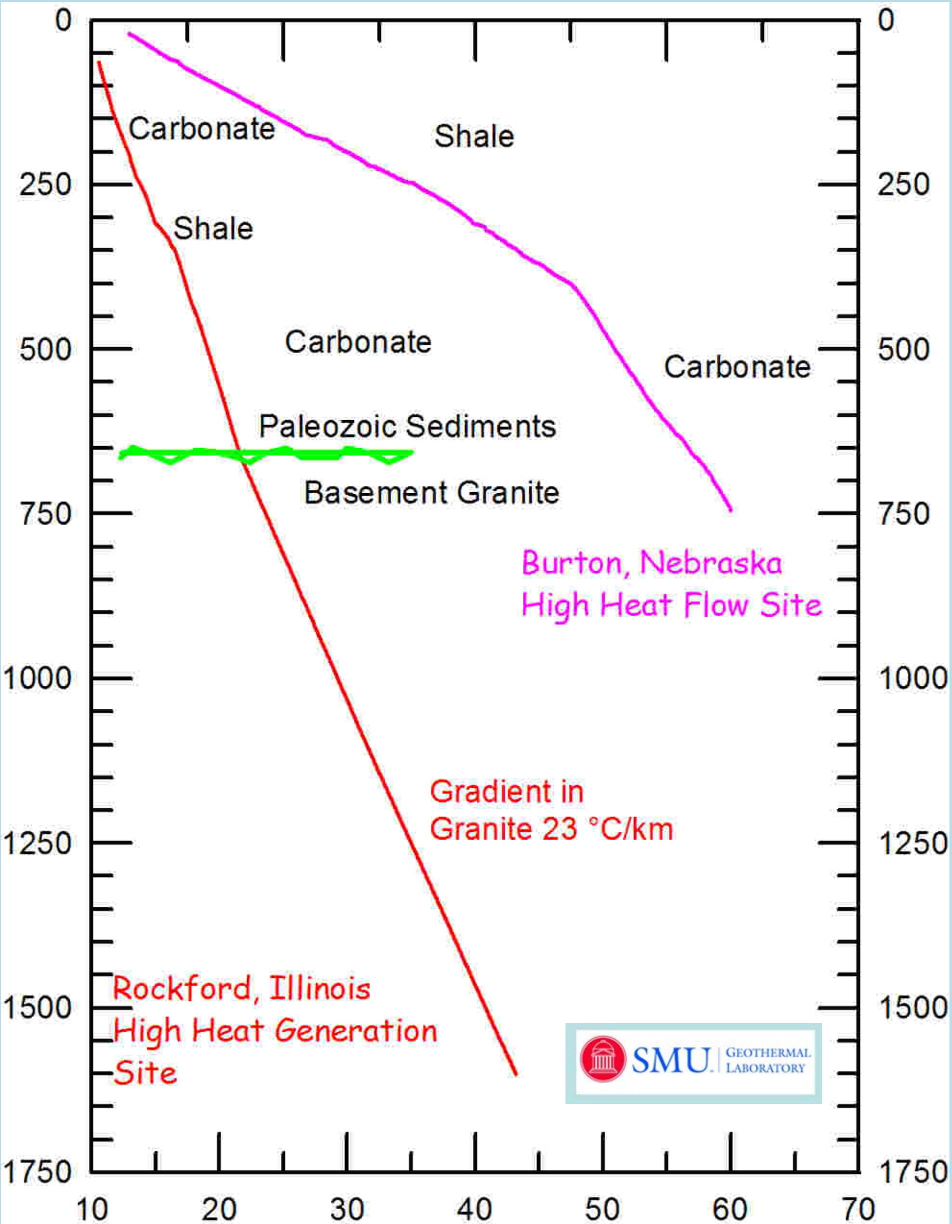
Temperature Calibration
Thermal Conductivity Determination
Permeability and Porosity
Reservoir Models
Stress Regime/Fracture Characteristics
Basement Character
Aquifer Characteristics
Fill-in Data In some Places (Site Specific)
Economic Modeling

Reality of Earthquake Risk is that it is small!
Energy Scales as 30 Times Magnitude!

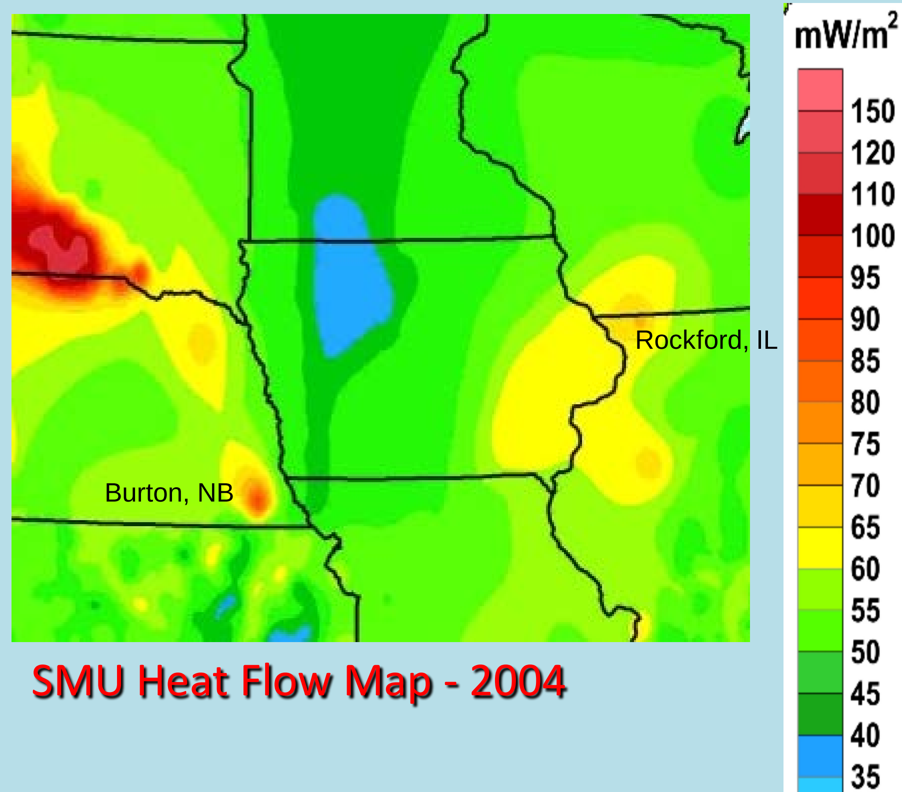


If Life Gives You Hot Water

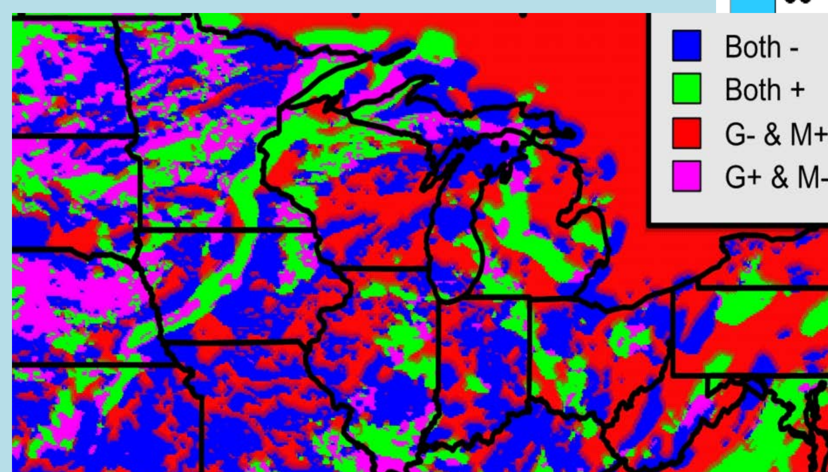
Make Ice!



Deg C and Meters



SMU Heat Flow Map - 2004



Energy Forms

- Gas-variable cost-Peaking (Baselaod)
- Coal-"cheapest" –Baseload, carbon source
- Nuclear-expensive, most dangerous-Baseload
- Wind-not base load, >30% typical
- Solar-solar-thermal, not baseload
- Geothermal-Baseload
  – Hydrothermal (conventional, > 150°C, 300°F)
  – Enhanced (Engineered) Geothermal Systems
  – Geopressure (> 125°C, 250°F dissolved methane)
  – Coproduced (> 125°C, 250°F)

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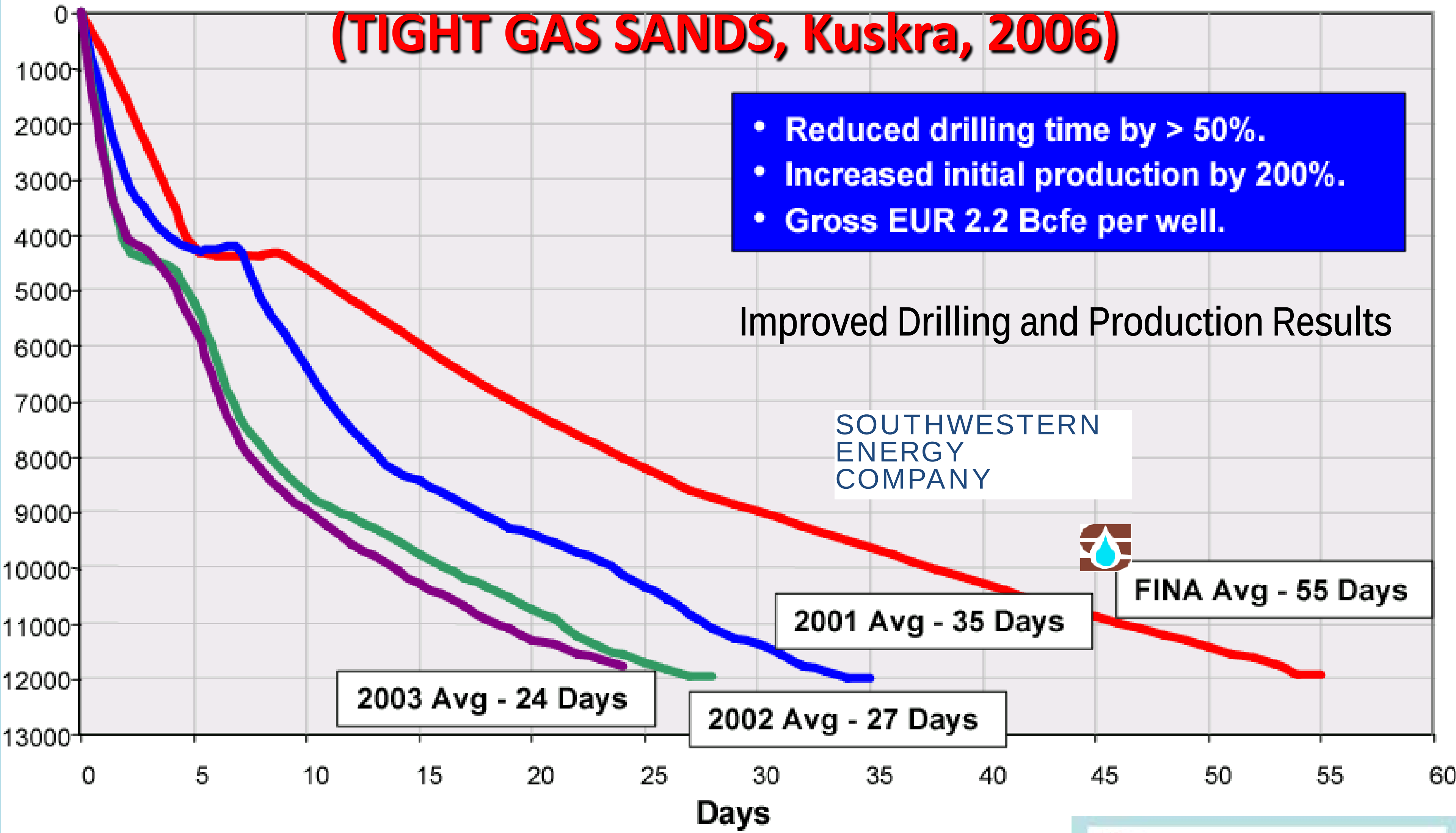
The Effect of Experience
OVERTON FIELD, EAST TEXAS
(TIGHT GAS SANDS, Kuskra, 2006)



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