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This paper describes an assessment of the enhanced geothermal system (EGS) resource base of the conterminous United States, using constructed temperature at depth maps. The temperature at depth maps were computed from 3 to 10 km, for every km. The methodology is described. Factors included are sediment thickness, thermal conductivity variations, distribution of the radioactive heat generation and surface temperature based on several geologic models of the upper 10 km of the crust. EGS systems are extended in this paper to include coproduced geothermal energy, and geopressured resources.

A table is provided that summarizes the resource base estimates for all components of the EGS geothermal resource. By far, the conduction-dominated components of EGS represent the largest component of the U.S. resource. Nonetheless, the coproduced resources and geopressured resources are large and significant targets for short and intermediate term development. There is a huge resource base between the depths of 3 and 8 km, where the temperature reaches 150–250°C. Even if only 2% of the conventional EGS resource is developed, the energy recovered would be equivalent to roughly 2,500 times the annual consumption of primary energy in the U.S. in 2006. Temperatures above 150°C at those depths are more common in the active tectonic regions of the western conterminous U.S., but are not confined to those areas. In the central and eastern U.S. there are identified areas of moderate size that are of reasonable grade and probably small areas of much higher grade than predicted by this analyses. However because of the regional (the grid size is 5′ × 5′) scale of this study such potentially promising sites remain to be identified.

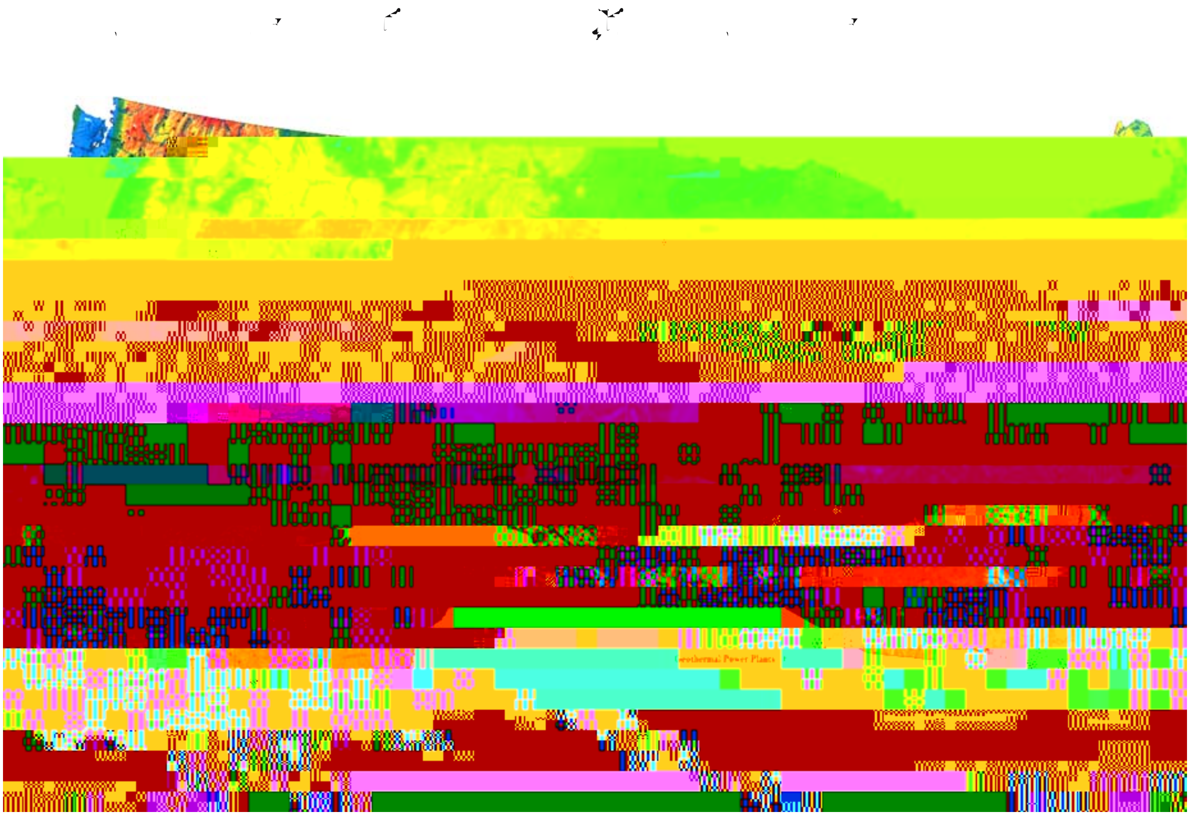
Several possible scenarios for EGS development are discussed. The most promising and least costly may to be developments in abandoned or shut-in oil and gas fields, where the temperatures are high enough. Because thousands of wells are already drilled in those locations, the cost of producing energy from such fields could be significantly lowered. In addition many hydrocarbon fields are producing large amounts of co-produced water, which is necessary for geothermal development. Although sustainability is not addressed in this study, the resource is so large that in at least some scenarios of development the geothermal resource is sustainable for long periods of time.

Geothermal, geothermal resource base, renewable energy, heat generation, U.S. heat flow, temperature-at-depth, coproduced fluids, enhanced geothermal systems (EGS).

Geothermal energy from areas with abundant hot water or steam has been developed extensively worldwide (Barbier, 2002). There is currently an installed capacity of more than 8,000 MW of hydrothermal geothermal energy with an average load factor exceeding 95%. Hydrothermal geothermal energy generally is considered to be developable if temperatures exceed 150°C and there is abundant producible water (or steam). It generally is assumed that such resources are exclusively related to areas

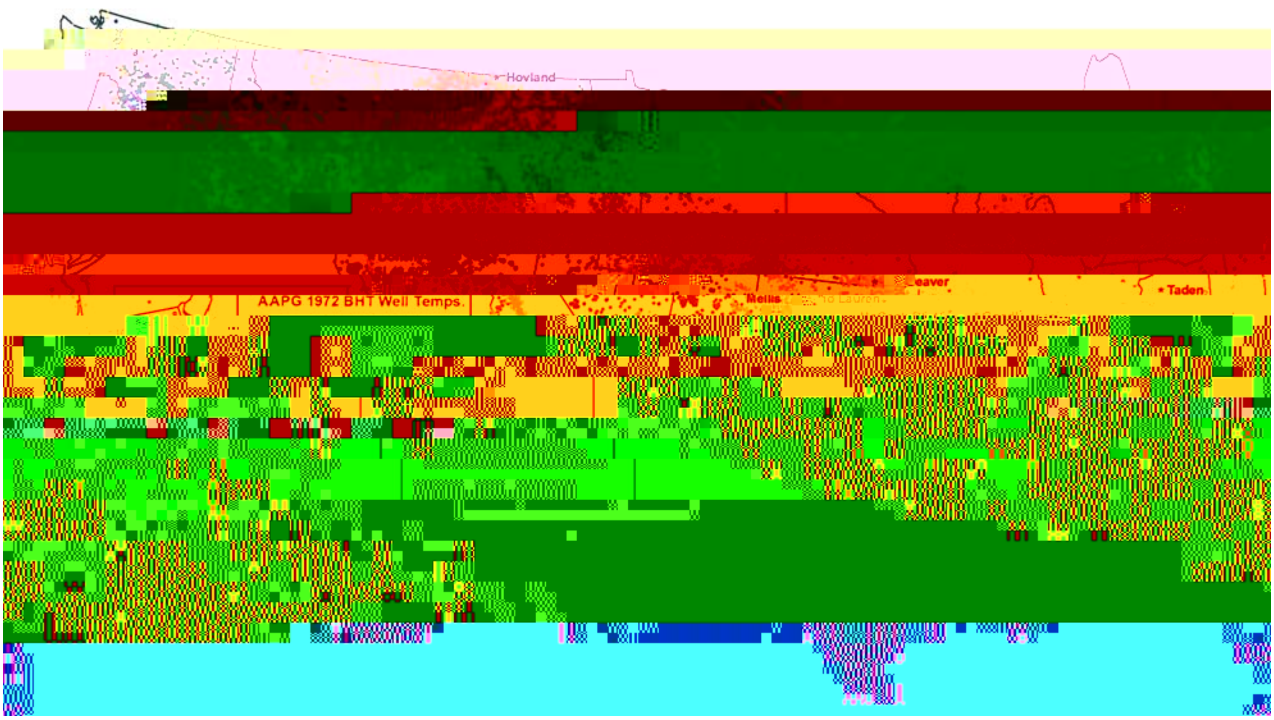
[1]Geothermal Lab, Department of Geological Sciences, Southern Methodist University, Dallas, TX 75275, USA.
[2]To whom correspondence should be addressed; e-mail: blackwel @smu.edu.

of young volcanic activity and or high heat flow associated with active tectonism and most of the developments so far conform to this hypothesis.



1. Heat Flow map of conterminous United States. Subset of Geothermal map of North America (Blackwell and Richards, 2004a).

data set used in developing this resource assessment. The conterminous U.S. portion of the map is shown in Figure 1. In order to expand coverage from the GSA-DNAG map (Blackwell and Steele,



2.

Quantitatively, the temperature T at depth X for a basement terrain (granite or metamorphic rocks at the surface) can be written as:

$$T(x) = T_0 + Q_0 x/K + A_0 b^2 (1 - e^{-x/b})/K$$

where $T(x$

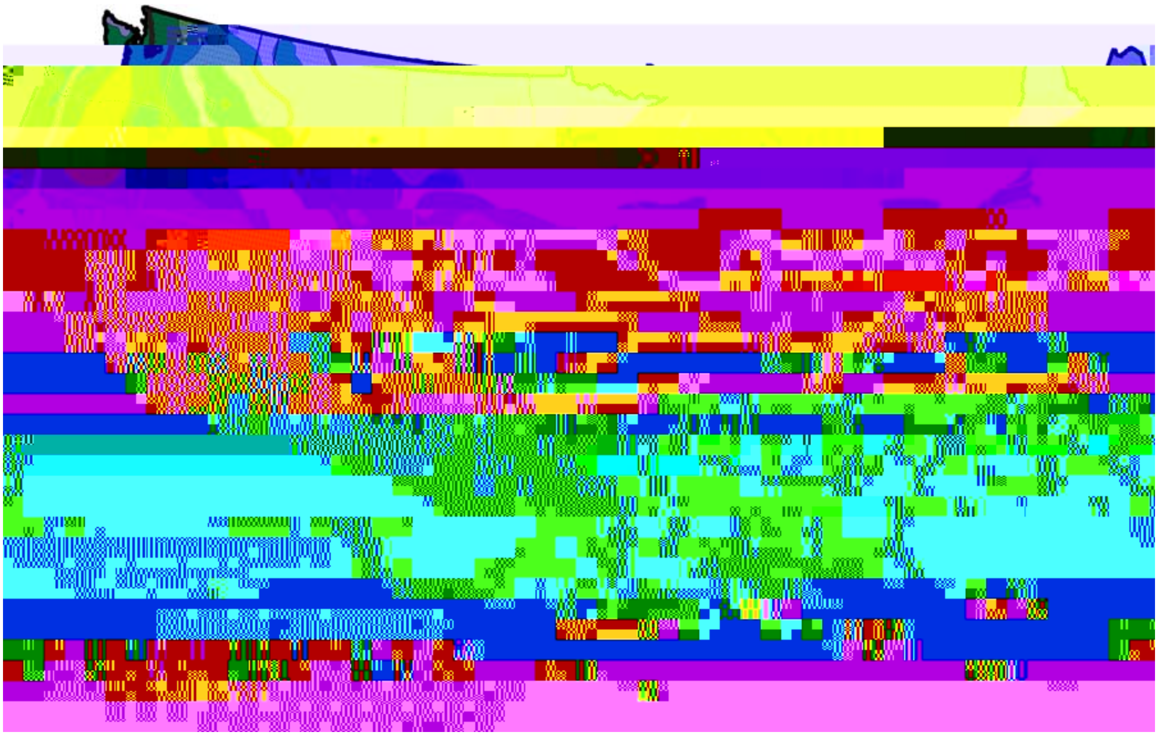
1

By dividing the thermal conductivity into the heat flow, mean gradients can be obtained. However, the approach used here to compute the specific depth temperatures does not require directly the use of geothermal gradients, although in some publications they are preferred because they are easier to understand than the heat flow. We start with the heat-flow value because in a single well the gradients can differ by as much as a factor of five or more depending on the thermal conductivity of the rocks, resulting in a lithologic (depth of measurement) bias. The gradients computed from the heat-flow map are smoother, appropriate with the scale of this study, and more regionally characteristic than some existing gradient compilations (Kron and Stix, 1982; Nathenson and Guffanti, 1980). On a regional basis those gradients can range from 15°C/km to more than 50°C/km, excluding of course the high gradients in hydrothermal areas.

A map of the thickness of sedimentary cover was prepared by digitizing the elevation of the basement map published by the AAPG (1978). The basement elevation was converted to thickness by subtracting its value from the digital topography. The resulting map is illustrated in Figure 5. Sediment thickness is highly variable from place to place in the tectonic regions in the Western U.S. and, for this reason, most of the areas of deformation in the Western U.S. do not have basement contours on the AAPG map. Because of the complexity and lack of data, the sediment/basement division in the Cordillera is not shown, with the exception of the Colorado Plateau (eastern Utah and western Colorado), the Middle Rocky Mountains (Wyoming), and the Great Valley of California. The area of most uncertainty is the Northern Rocky Mountain/Sevier thrust belt of the Cordillera. In that area basement thermal conductivity was assumed.

5.). The

In the Basin and Range and the Southern and Middle Rocky Mountains there are smaller, but locally deep basins filled with low thermal conductivity



6. Map of surface temperature (Gass, 1982) and generalized mantle heat flow for the conterminous United States.

basement rocks, consistent with a general trend from granitic rocks at the surface to mafic or high-grade metamorphic rocks at depths. For sedimentary basins the radioactive heat is primarily a function of the thickness of shale in the sedimentary column. However for sedimentary basins a constant heat generation value was used for the complete sedimentary section (1 W/m^3).

In the situation of thick sedimentary basins the radioactive scale constant in the underlying basement was assumed to be lowered in proportion to the thickness of the sedimentary section. If the sediment thickness exceeded 3 km, then the exponential factor of the layer with exponential distribution (b) was decreased below 10 km by 1 km for each km of sediment more than 3 km. More details are given in the Appendix.

The mean ground surface temperature is shown in Figure 6. This temperature represents the lowest value of the average heat rejection temperature for any energy conversion scheme and the starting point for the temperature depth calculation. The values are from measurements of temperature in shallow groundwater wells (Gass, 1982). The mean ground surface temperature varies from over 26°C in south Texas to less than 4°C in North Dakota. These temperatures can be used as shown in Figure 3 to calculate maximum attainable temperature differences which can then be used to calculate the thermal energy content of a rock volume for any U.S. region (difference of the rock temperature at depth and the average surface temperature).

To calculate the total resources, various geological factors are needed: the heat content, the stress regime, the geology of the basement, and the permeability. The heat content is the primary objective of this paper and will be discussed in more detail.

The results of the analysis are presented as temperature at depth and as thermal energy (or “heat”) in place for the conterminous U.S. The temperatures were calculated from the depths of 1 to 10 km at every km. Maps of the temperature at 4 km, 6 km, and 10 km depths are shown in Figure 7. Heat-in-place was calculated and is listed in the Table 3 for 1 km × 1 km × 1 km blocks centered at depths of 4.5, 6.5, and 9.5 km using the assumptions and equations shown in Figure 3. A more detailed calculation at depths of 3.5, 4.5, 5.5, 6.5, 7.5, 8.5 and 9.5 km is included in Tester and others (2006). The values listed in Table 3 and shown in histogram form in Figure 8 represent the geothermal resource base and not the amount of electrical power that can be generated. For demonstration purposes, the values are shown in terms of stored thermal energy, namely, exajoules (EJ = 10^{18} J). The only area excluded from the calculation is Yellowstone National Park (8980 km^2) for the depths of 3.5 to 6.5 km. The Yellowstone region represents a large area of high temperature and so its exclusion affects the resource base calculation of areas with high temperatures at shallow depths.

The histogram in Figure 8 shows that there is a tremendous resource base between the depths of 3.0 to 10 km in the temperature range of 150 to 250°C. Even if only 2 % of the resource were to be

7. Temperature at depth maps shown at 4 km (A), 6 km (B), and 10 km (C). Areas of high grade EGS resources (The Geysers/Clear Lake area, Oregon High Cascade Range, Basin and Range, Southern Rocky Mountains, and Salton Trough) are outlined in blue on 7A.

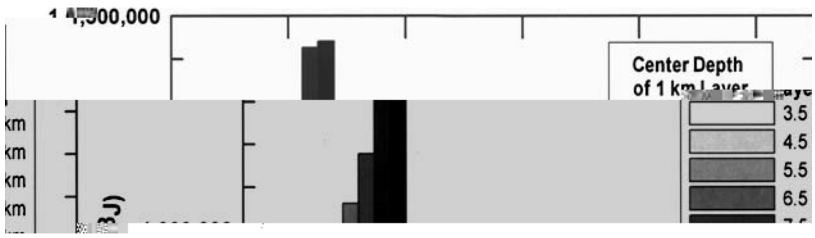
3. Heat in Place (Exajoules = 10^{18} J)

	AK[1]	AL	AR	AZ	CA[2]	CO	FL	GA	IA	ID	IL
4.5 km DEPTH											
Temp °C											
150	39,588	34	6,361	49,886	53,068	45,890	0	0	0	36,008	0
200		0	0	0	4,734	8,413	0	0	0	7,218	0
250		0	0	0	407		0	0	0	112	0
300		0	0	0	796		0	0	0	0	0
6.5 km DEPTH											
Temp °C											
150	361,688	9,148	20,725	52,335	54,243	54,667	4,339	95	10,729	35,257	2,005
200	187,722	60	6,373	74,305	70,941	51,170	2	0	0	53,875	
250		0	0	473	9,186	24,029	0	0	0	19,510	
300		0	0	0	176	1,077	0	0	0	359	
10 km DEPTH											
Temp °											

3. Continued

	ND	NE	NH	TX	UT	VA	WA	WI
4.5 km DEPTH								
Temp °C								
150	3,845	848	0	32,528	36,521	0	9,796	0
200	0	0		14	1,160	0		0
250	0	0			0	0		0
300	0	0			0	0		0
6.5 km DEPTH								
Temp °C								
150	36,938	60,446	1,050	117,096	50,085	991	44,388	1,733
200	2,534	1,018		21,659	44,178	0	13,290	0
250	0	0			8,626	0		0
300	0	0			0	0		0
10 km DEPTH								
Temp °C								
150	34,198	6,358	6,780	144,600	1,539	30,176	4,678	56,012
200	36,978	96,021	3,032	113,021	44,520	3,849	14,189	5,811
250	22,759	4,404		86,151	38,391	0	60,195	0
300	13	0		2,723	50,546	0	11,641	0
350	0	0			11,554	0		0
Totals	289,756	341,935	22,657	1,068,217	612,202	50,796	338,324	102,155

	WV	WY[3]	MA_CT_RI_VT	MD_NJ_DE	Continental U.S.A.[4]
4.5 km DEPTH					
Temp °C					
150		6,795	0	0	518,041
200		203		0	29,930
250		8		0	734
300		0		0	965
6.5 km DEPTH					
Temp °C					
150	3,367	68,411	183	468	1,062,065
200		7,132		0	641,638
250		334		0	94,405
300		177		0	2,268
10 km DEPTH					
Temp °C					
150	15,476	19,107	19,078	13,851	1,446,607
200	7,479	84,380	1,377	728	1,057,978
250	2,377	27,437		464	914,277
300		3,240		0	620,849
350		493		0	132,479



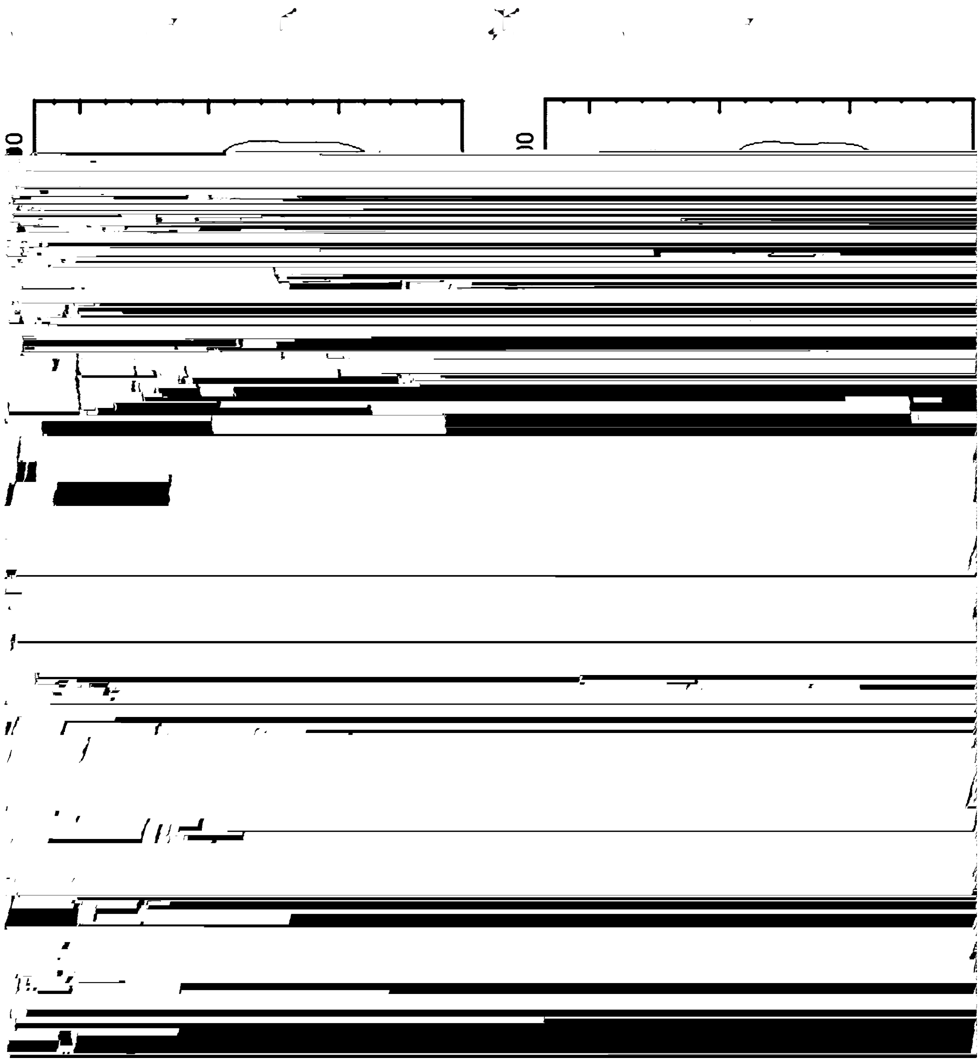
8. Histograms of heat content for conterminous U.S. as a function of depth for 1 km slices.

4. High-Grade EGS Areas (>200°C at Depths of About 4 km)

Region	Characteristics
Great Basin	30% of the 500 km × 500 km area is at temperatures >200°C. Highly variable geologic and thermal conditions with some drilling confirming deep conditions. Large-scale fluid flow both laterally and horizontally so extensive fracturing at depth in many areas. The stress regime is extensional. Rocks are highly variable with depths of 4–10 km mostly sedimentary with some granite and other basement rock types.
Snake River Plain and margins	75% of the 75 km × 500 km area is at temperatures >200°C. Details of the geology at depths of 3–10 km unknown, probably volcanics and sediments overlying granitic basement at 3–5 km, low permeability. The stress regime is unknown, existing fracturing may be limited.
Oregon Cascade Range	25% of the 50 km × 200 km area is at. High, uniform temps. & geology (volcanic and intrusive rocks dominate)-accessibility to the margins. The stratovolcanoes are excluded from the analysis. Conditions are more variable in California and Washington but some high-grade resources probably exist there as well.
Southern Rocky Mountains	25% of the 100 km × 300 km area is at temperatures >200°C. Geology is variable. Can have sediments over basement, generally thermal conditions in basement are unknown. Both high crustal radioactivity and high mantle heat flow contribute to surface heat flow. Probably highest basement EGS potential on a large scale.
Salton Sea	75% of the 25 km × 50 km area is at temperatures >200°C. Young sedimentary basin with very high heat flow, young metamorphosed sedimentary rocks at depth. There is extensive drilling in the existing geothermal systems and limited background data available from hydrocarbon exploration.
Clear Lake Volcanic Field	50% of the 30 × 30 km area is at temperatures >200°C (steam reservoir is 5 km × 10 km). Low permeability Franciscan sediments, may find granite at deeper depths. Possible access problems. Significant deep drilling with temperatures of 200°C at 2 km over a large area.

large, with temperatures more than 350°C at 5 km. In this area, supercritical geothermal conditions also might exist.

The island of Hawaii and the volcanoes of the Aleutian chain in Alaska have the best possibility



9. Temperatures in C° at depths of 2 to 5 km in The Geysers/Clear Lake thermal area (Erkan, Blackwell, and Leidig, 2005).

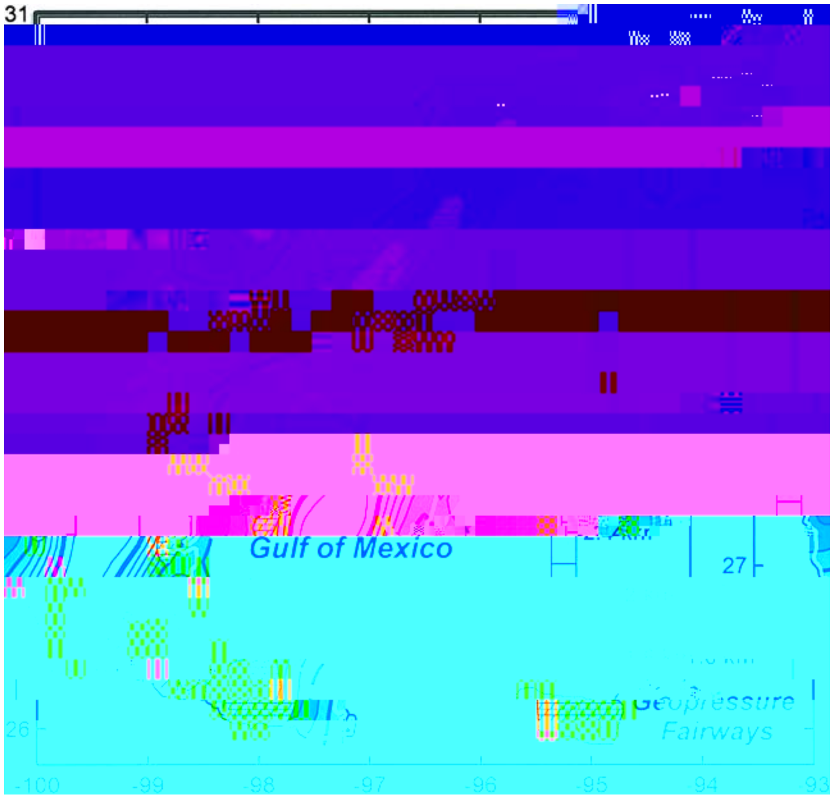
be developed in these types of areas before the transition is made to pure start-from-scratch EGS systems (McKenna and others, 2005). For the purpose of this report, these situations are divided into three categories, more or less in order of expense to develop: Co-produced Fluids, Geopressured Fluids, and Sedimentary EGS. In Table 5 coproduced hot water from oil and gas production has been included as an unconventional EGS resource type, because it could be developed in the short term and provide a first step to more classical EGS exploitation.

In addition to high temperature, a geothermal development requires large-volume flows of water, on the order of 500 to 1,000 gallons per minute (GPM) per MW (depending on the temperature). There are two typical types of existing situations associated with hydrocarbon development that are favorable for geothermal development. The first might be considered "conventional" hydrothermal development, in that high volumes of water are produced in some fields as a byproduct of hydrocarbon production. This situation exists, for example, in massive water-flood secondary recovery fields. Curtice and Dalrymple (2004) show that co-produced water in the conterminous United States amounts to at least 40 billion barrels per year, primarily concentrated in a handful of states (e.g. Texas, Oklahoma, California, Wyoming, Louisiana). In most mature hydrocarbon fields, the disposal of co-produced water is an expensive problem (Veil and others, 2004).

The factors required for successful geothermal electrical power generation are sufficiently high fluid flow rates for a well or a group of wells in relatively close proximity to each other, at temperatures in excess of about 100°C (212°F). Oklahoma and Texas alone produce more than 24 billion barrels

5. Equivalent Geothermal Power From Co-produced Hot Water Associated With Existing Hydrocarbon Production in Selected States (A complete listing is given in Tester and others, 2006; modified from McKenna and others, 2005.) (bbl = 42 gallon barrels per day, GPM = gallons per minute)

State	Total Water Produced Annually, in 47T250.4(476s99n)Tj /1.879.33m 001 TD 0.0001 Tc [(Total)-249.2(W)-0.4(ater)]TJ -1.711907m 05 TD -0.0002 Tc [(Produc



10. Location map showing the top of geopressured zones in km and geothermal "fairways" as defined by Gregory and others (1980).

under an area of more than 145,000 km^2 along the Texas and Louisiana Gulf Coast – this represents about half of the total area with geopressured conditions (see Fig. 10 where the depth to geopressure in the Texas Gulf Coast is contoured). The assessment included only the pore fluids of sediments in the interval between the top of the geopressured zones and the maximum depth of well control in 1975; that is, a depth of 6 km in Texas and 7 km in Louisiana. They did not include the resource potential of geopressured reservoirs within (i) onshore Tertiary sediments in the interval between the depth of maximum well control and 10 km, (ii) offshore Tertiary sediments, and (iii) Cretaceous sediments.

In contrast to geothermal areas of the western United States, subsurface information is abundant for the geopressured-geothermal area of the northern Gulf of Mexico basin. Hundreds of thousands of wells have been drilled in search of petroleum deposits in the Texas and Louisiana Gulf Coast. They stated that their information on geologic structure, sand thickness, temperature, and pressure were adequate for the purpose of their study. On the other hand, they noted a lack of sufficient data on porosity, permeability, and salinity.

The results of the assessment by Papadopulos and others (1975) were incorporated into the final conclusions of the overall geothermal resource assessment of Circular 726 (White and Williams, 1975). Based on their analysis, they assessed the thermal resource base to be 46,000 EJ and the methane volume to be 23,700 $\times$ 10^{12} SCF, with a thermal equivalent of 25,000 EJ. The resource base, according to their calculations, is then about 71,000 EJ.

The Wallace and others (1979) assessment extended the study to Cretaceous rocks north of, and beneath, the Tertiary sediments studied by the 1975 project for a total area of more than 278,500 km^2 (including offshore areas). The area they accessed extended from the Rio Grande in Texas northeastward to the vicinity of the mouth of the Pearl River in Louisiana; and from the landward boundary of Eocene growth faulting southeastward to the edge of the Continental Shelf, including unmapped

6. Summary of Nonhydrothermal U.S. Geothermal Resource Base Estimates

Source & Category	Thermal Energy, in 10^{18} J = EJ	Volume of Methane, × 10^{12} SCF	Total Gas + Thermal Energy, in 10^{18} J = EJ
Geopressured (Papadopulos and others, 1975)	46,000	23,700	71,000
Geopressured (Wallace and others, 1979)	110,000	59,000	170,000
Co-produced Resources	0.0944 – 0.451 (depends on water temperature)		
EGS			
Sedimentary EGS (lower 48 states)	100,000		
Basement EGS (lower 48 states)	13,300,000		
Volcanincs			
Hawaii	N/A		

Note. SCF: standard cubic feet of methane (ideal gas conditions) at 1 atm, 60°F.

Cretaceous sediments underlying the Tertiary sediments, extending farther inland. They assumed a depth limit of 6.86 km (22,500 ft) for development and a lower limit of temperature of 150°C (300°F). Wallace and others (1979) estimated a thermal energy of 110,000 EJ. The also estimated the accessible dissolved methane resource to be about 59,000 × 10^{12} SCF or 62,000 EJ (see Table 6).

Subsequent to these assessments, the resources and technologies for recovering geopressured geothermal energy were extensively studied by the U.S. DOE between 1979 and 1990 (Gregory and others, 1980; John, Maciasz, and Harder, 1998). Gregory and others (1980) identified a number of the most favorable areas in the Texas Gulf Coast for geopressure energy development and termed them "fairways." Locations of these fairways are shown on Figure 10. From late 1989 until early 1990, a 1 MWe plant was operated on the Pleasant Bayou well in the Texas Gulf Coast near Houston. The well produced hot water and dissolved natural gas. About half of the power was generated by a binary cycle plant running on the thermal energy of the water, and about half was generated by burning the gas in a reciprocating-engine-operated electric generator (Campbell and Hattar, 1990). The economics of the power generation at that time were not favorable, because of the low price of natural gas and oil, and the test was discontinued after the 6-month trial run. The well had been flow tested for a period of about 5 years with limited drawdown, so the geologic system seemed to be a success, and the reservoir sufficiently large to sustain production at about 3 MW for many years (Shook, 1992). With today's higher gas costs and increasing demand for natural gas, geopressured systems deserve to be reconsidered, because their economics in today's energy markets will be more favorable as pointed out in a recent study (Griggs, 2005).

Another scenario exists for geothermal development in many of the areas exploited for deep oil and gas production, especially in the Gulf Coast and in the mountain states region. In these areas, EGS development in the deep, high temperature part of the sedimentary section might be more cost-effective than basement EGS systems. Shown in Table 7 is a comparison of needs for EGS-type development costs versus reality in existing hydrocarbon fields. It is clear that many of the upfront reservoir costs have been reduced, and that the existing infrastructure can be adapted readily to geothermal electrical power production. As an indication of the possibilities, research into the suitability of such basin-hosted geothermal resources has begun in the north German Basin (Zimmermann and others, 2005). In this area, low-formation permeability requires stimulating potential sandstone reservoirs, and significant lateral drilling. But those conditions have not deterred activities.

Future research must be performed on the suitability of some of the wells/fields now being developed as deep, hot, tight, sandstone gas reservoirs; but, overall, it seems that large areas of the United States are suitable for future geothermal exploitation in the near term that have not been considered in the past. Many of these areas are hot, and most are being artificially stimulated (fractured), or horizontally drilled, or both, at the present time. These areas are clearly EGS types of systems but with known drilling and development costs and abundant water.

Furthermore theoretical modeling suggests that stimulations in sedimentary settings, where there is some intrinsic porosity and permeability, are more favorable than a fractured basement rock setting (Nalla and Shook, 2004).

The general size of this resource has been calculated separately from the general EGS resource, which is primarily in basement rocks. The areas that are considered to be in this EGS category are the areas of sedimentary section deeper than 4 km. The deep sections of sediments are present over many areas of the United States (see Figure 5). Especially promising large areas occur in the Gulf Coast, the Appalachian Basin, the southern Midcontinent, and the Rocky Mountains. Therefore, a conservative resource base figure of 100,000 EJ is listed in Table 6 for sedimentary EGS systems. Although this number may be a few percent of the total EGS value of 13,300,000 EJ (Table 6), the accessible fraction of the energy in a 10- to 25-year time frame may be equal to the accessible basement EGS value.

Table 6 provides a summary of resource base estimates for all components of the geothermal resource. By far, the conduction-dominated components of EGS represent the largest component of the U.S. resource. Nonetheless, the hydrothermal, coproduced resources, and geopressured resources are large and significant targets for short and intermediate term development.

The EGS resource base value for only the states of Louisiana, Mississippi, and Texas is 1.5×10^6 EJ. This number does not include the offshore areas of the Gulf of Mexico. In order to understand the magnitude of the thermal energy or heat content of the rock, it is useful to consider the following "thought experiment." Imagine a 14 km long $\times$14 km wide $\times$1 km thick slice of rock below the ground surface, which is at an initial temperature of 250°C. Reasonable average values are 2550 kg/m^3 and 1000 J/kg °C, for the density (ρ) and heat capacity (C_p) of the rock, respectively. If this mass of rock is cooled by 200°C, to 50°C, then the heat removed is given by

$$Q = \rho C$$

The Wallace and others (1979) value for the specific geopressure value could be considered to add to the baseline EGS figures from the analysis of stored thermal energy reported in Table 6. This is because of the characteristics of the sedimentary basin resource. Wallace and others (1979) used a value of approximately 20% for the porosity of the sediments. Because the heat capacity of water is about five times larger than that of rock, the stored thermal energy is approximately twice what would be present in the rock mass with zero porosity as as37eah3(gT85.4(ea)to92.2e53.6(the)-354.8(times)]TJ 0 -1-294.2(39295(ummariz.4(con81.

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Several models of thermal conductivity and radioactive heat generation of the upper 10 km were used for the temperature at depth calculations. Shown in Figure A.1 are the geologic distributions over depth scale over which the temperature at depth was calculated.

Case A

Case D is relatively similar to the Case C. In this case the geology is represented by a sedimentary layer of thickness 3 to 4 km, overlying basement rocks. Again the conductivity distribution in variable for the sedimentary section, while the basement rocks have a conductivity of 2.7 W/m/K. The only difference from Case C is the depth scale of the heat generation (the value of b), which is variable. The value of b is selected so that b = 13