An Opportunity of Geothermal Proportions in Sedimentary Basins

John Holbrook[1], Joseph N. Moore[2], Derek Elsworth[3], Karin A. Block[4], Rick Allis[5], Herbert Einstein[6]

[1] School of Geology, Energy, and the Environment, Texas Christian University, Fort Worth, TX 76129 John.Holbrook@tcu.edu

[2] Energy and Geoscience Institute, University of Utah, Salt Lake City, Utah, 84108 jmoore@egi.utah.edu

[3] Energy and Mineral Engineering, G3 Center and EMS Energy Institute, Pennsylvania State University, University Park, PA 16802 elsworth@psu.edu

[4] Department of Earth and Atmospheric Sciences, City College of New York. New York, NY 10031 kblock@ccny.cuny.edu

[5] Utah Geological Survey, Salt Lake City, Utah, 84105 rickallis@utah.gov

[6] Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 einstein@mit.edu

INTRODUCTION

The 7.2 billion people currently inhabiting the planet all need heat and light and those in the developing world each aspire to the many evolving necessities of the modern i-life. The net 10 people added in the last five seconds will likely seek the same (http://www.census.gov). Together they feed an ever-expanding thirst for energy. Finding new energy sources to meet these demands is a principle challenge of our time. However, energy tends to come with some environmental cost. Energy holds to the axiom that no given source pollutes at some smaller scale, but all sources pollute at some larger scale. Some methods of energy conversion have less impact than others, however, and some have the added attractive attribute of being renewable. Meeting the burgeoning national and global demand for energy is a grand challenge on its own merits. Added is the challenge of growing this capacity meaningfully with an energy mix that will have minimal negative environmental impact, have the potential to endure, and, oh yes, is cost effective.

Enter the NSF SEES Program (Science, Engineering, and Education for Sustainability). NSF SEES is a series of funding initiatives intended to promote research into sustainability. Sustainability clearly encompasses a broad landscape but some SEES subinitiatives (e.g., Stainable Energy Pathways, etc.) focus directly on energy conversion and utilization (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504707). Geothermal energy fits this mold well in that it taps a large and renewable energy source within the deep earth that is retrievable with little impact to the surficial environment. Sedimentary basins both host large reserves of geothermal heat and are broadly distributed geographically, with proximity to population centers (Tester, et al, 2006; Williams, 2007). They also have the native permeability that permits the flow of geothermal fluids, a must for extracting this heat. Sedimentary basins are thus natural targets for a new generation of geothermal pilot plants that generate power from deeply sourced heat.

The SedHeat initiative sprouted from these seeds. SedHeat is an NSF RCN (Research Coordination Network) with the stated goal *"To form a central point of unity, exchange, and education to exceed the science and engineering challenges of sedimentary-basin geothermal energy."* This effort began with a workshop in November 2011 in Salt Lake City, Utah that was supported by the NSF SEES initiative and convened to consider the question, *"What are the basic science and engineering questions that need to be addressed in order to make geothermal energy production from sedimentary basins practical?"* From this, SedHeat has continued as a research community focused on addressing these challenges. Large-scale geothermal energy from sedimentary basins has not yet seen its potential realized. Improved knowledge is needed before this can occur. SedHeat hosts workshops, supports student projects and travel, delivers short courses and provides education, and, overall, facilitates research on sedimentary-basin geothermal systems for a network of >300 researchers involved in the quest for sustainable and affordable geothermal energy. The group, both by necessity and by design, is highly diverse and includes a robust representation from Geology, Engineering, Geophysics, Education, and Social Sciences. All are unified by an interest in the prospects of recovering geothermal energy from deep sedimentary basins and in finding the breakthroughs in science and engineering needed to make this energy source bloom.

In the following we share our consensus views on research priorities in sedimentary-basin geothermal. In particular, we present some of the ongoing activities and the efforts of SedHeat to support future research.

THE PROMISE OF GEOTHERMAL ENERGY

The heat within the earth constitutes a vast store of energy that builds mountains and basins, but could also be providing electricity for our homes. But, how much of this energy can be realistically tapped? Geothermal energy banks a steady radiation of heat that raises the globe to the ~14.5^{O}C average temperature (IPCC, 2007) at the Earth's surface by a depth of ~580 m. The temperature increases to over 500-1000^{O}C at the base of the Earth's crust. The currently maintained global radiation of heat energy from the interior of the Earth is approximately 44 terawatts (KamLand Collaboration, 2011) and represents the sustained energy that is available and renewable without mining the heat accumulated over geologic time. Between stored and sustained heat, recovery of an estimated 1+ megawatt/km^2 is considered conservative and sustainable for net power generation (Tester, et al., 2006; Williams, 2007; DOE, 2008). Thus 1000 km^2 provides at least one gigawatt and the ~10 million km^2 land area of the United States could contribute 10TW, dwarfing of the roughly one terawatt (1000 gigawatts) of currently installed electric capacity within the U.S. (DOE/EIA, 2010).

Current geothermal technology depends on heat extraction from geothermal fluids at temperatures beginning between 100^{O}C and 150^{O}C, which typically occur at depths of 2-6 km (Tester, et al., 2006; Blackwell, et al., 2007; William, 2007; Esposito and Augustine, 2011; Figure 1). Around 500,000 km^2 of well-dispersed sedimentary-basin area exists below 4 km within the conterminous U.S., and these strata commonly host sufficient heat to reach these critical temperatures (e.g., Figure 2). The total heat within these sedimentary basins below 4 km that is available as a resource base is estimated to be 100,000 EJ (Tester, et al. 2006). For perspective, the U.S. utilizes approximately 100EJ/year (DOE/EIA, 2010). The current energy portfolio for electric power is rich in fossil fuels, and the geothermal contribution remains small (Figure 3). The negligible output of CO_2 inherent to geothermal power means that significant gains in capacity for this energy source could help mitigate the impact on climate change by replacing more carbon-rich energy sources.

Sedimentary basins are a prime target for a new generation of geothermal development because they host the three critical conditions needed to produce geothermal energy: 1) heat; 2) water; and 3) permeability. Hydrothermal/magmatic systems provide most of the three gigawatts of geothermal electric capacity currently available in the U.S.

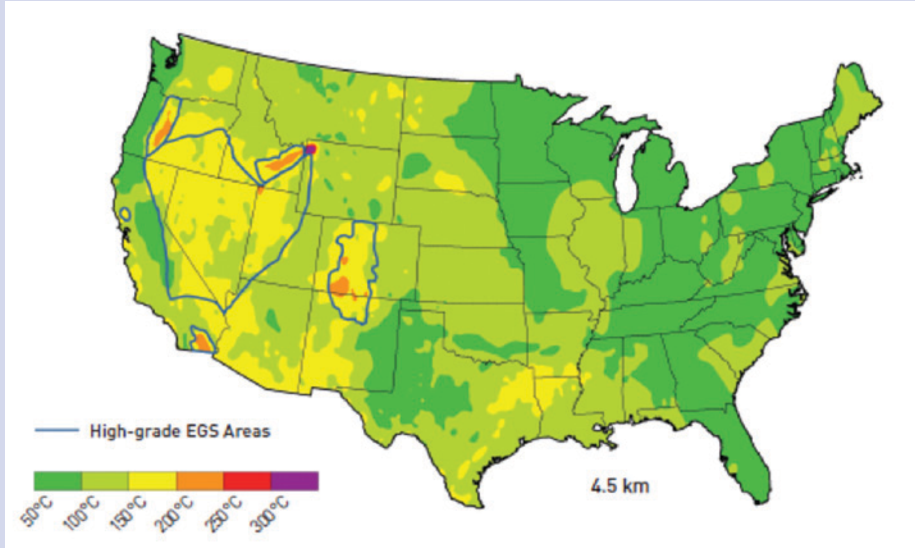

Figure 1: Average temperature at 4.5 km, conterminous United States. (Tester, et al., 2006, after Blackwell and Richards, 2004)

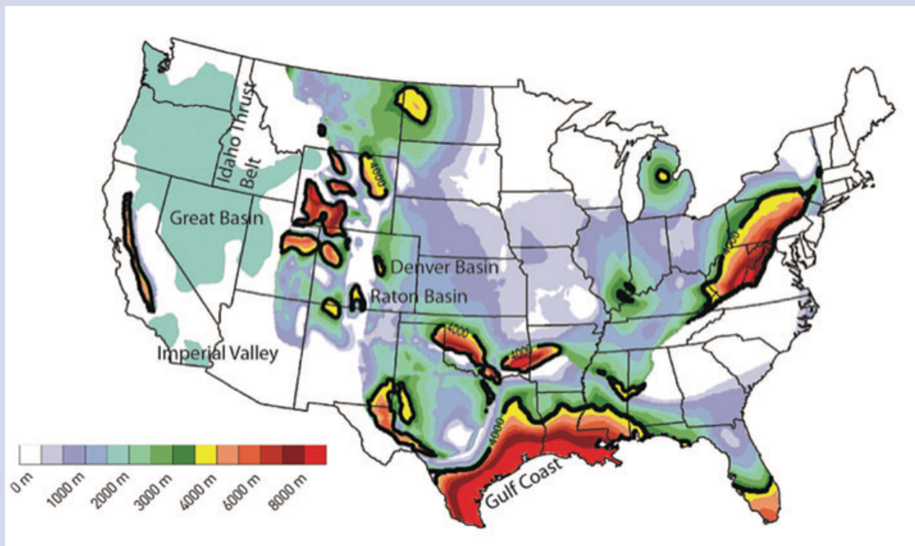

Figure 2: Distribution of sediment thickness in the conterminous U.S. 4 km isopach in black. Numerous basin-and-range basins over 4 km excluded for small resolution (Tester, et al., 2006)

and studies on Engineered Geothermal Systems (EGS) reservoirs have been the focus of added attention in recent years (Tester, et al., 2006; DOE, 2006; DOE, 2008). Hydrothermal/magmatic systems are local and well tapped. While vast areas of crystalline basement host ample heat at depth, the needed water and permeability are not native to these rocks. Furthermore, efforts to provide or develop these critical attributes through EGS have thus shown limited success. Conversely, sedimentary basins natively host large hot rock volumes with the two otherwise missing elements of water and permeability and offer a more forgiving environment for an initial run at large-scale geothermal power. They are also a potential stepping stone for EGS application in the more expansive heat resources hosted in crystalline rock. Sedimentary-basin geothermal resources can be classified as: 1) co-produced fluids from oil and gas fields; 2) geopressured regimes; and 3) deep sedimentary extraction with natural and enhanced (c.f., EGS) permeability. If the aggressive goals of 10% increase in capacity by 2014, doubling the geothermal capacity by 2020, and 100,000MW in 50 years (DOE, 2008; reaffirmed in DOE-GTP Mission and Goals: April 11, 2011) are to be realized, new technologies, including power from sedimentary basins and other novel resources must be added to the current geothermal mix (Shook, 2009).

With proper management, heat can be extracted from geothermal fluids sustainably, with negligible pollution to the surface and atmosphere (Duffied and Sass, 2003; Blodgett and Slack, 2009; Tester, et al., 2006) and with a significant positive impact on total carbon footprint and concomitant influence on climate. Our principle technical barriers are in learning how to harvest this energy with sufficient predictability and efficiency to make it economically viable. Given the complex architecture of basin fills, the loss of permeability with depth, the complicated

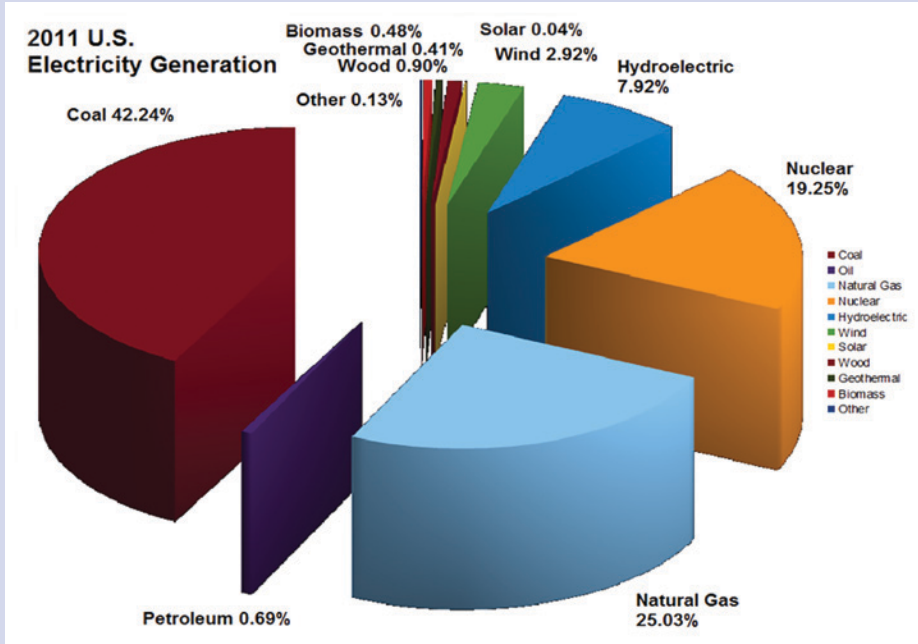

Figure 3: Distribution of electric generation by source in the U.S.for 2011. (Figure from http://earthdesk.blogs.pace.edu/tag/clean-water-act/; raw data available at http://www.eia.gov/totalenergy /data/monthly/#electricity)

fracture processes, and the briny diagenetic conditions inherent to sedimentary basins, this harvest will not come without its challenges.

SOME BASIC RESEARCH CHALLENGES

Geothermal energy has true advantages as a prospective energy source, but also faces some challenges. The magnitude and distribution of geothermal heat are generally known and sufficient for large-scale production. The technology to drill sedimentary basins and the thermal needs for energy production are also an area of extensive experience and established capability. So why is geothermal power not the norm? Like most such issues it boils down to the economics of benefit and risk. Consider this scenario. At the current consumer price of ~$0.10/kilowatt hour, a well producing at 100kg/s and yielding 10 Megawatts would gross $24k/day. A well drilled to the 3-6 km depth needed to attain >150^{O}C in most sedimentary basins would cost roughly $7-10 million to drill, then as much as $5 million in additional development costs (e.g., logging, completion and stimulation, etc.). It would thus take approximately two years to recover the investment of this well, not including the costs of the plant and infrastructure on the surface. Conversely, an oil well producing 5,000 bbl/day would gross $400k/day at $80/bbl and pay for itself at 17x this rate (based on calculations by Rick Allis in workshop keynote address; in Holbrook, et al., 2012). With this investment and return ratio, a geothermal prospector cannot afford too many misses before gaining a success and the risk/benefit ratio for petroleum looks much more appealing to the average investor, producer, and driller. Thus, the extraction of waste heat from petroleum wells and the recovery of heat from played fields thus offers promise as it seems cheaper than drilling new geothermal wells. Petroleum producers, however, do not drill deliberately for production of large volumes of water. The optimal point of success for a geothermal well is about 80kg/s (~0.5 barrels/s) of water at around 150^{O}C (after Tester, et al., 2006). This level of water production is not what you generally want in an oil well. The 150^{O}C temperatures where the preferred geothermal reservoirs begin to start are also the temperatures where the oil window begins to dwindle. While several companies are looking seriously at waste heat recovery as a geothermal source, they do so selectively and cautiously.

The challenges for bringing geothermal energy from the sedimentary basin to the home are in improving the ability to predict and manage the subsurface. With small profit margins and the need to accept long-term return on investment, the appetite for risky drilling programs is expectantly low. Producers need to be assured that payback is reasonably certain and the risk of a dry hole is minimal. This, of course, is a familiar problem to all those working resources in sedimentary basins. In this case, the low return-on-investment-per-well means that the need for precision and success is stepped-up a notch.

The first SedHeat workshop in Salt Lake City assembled a series of questions that define the core research challenges of sedimentary-basin geothermal energy (Figure 4). The needs and importance of each of these questions are elaborated more fully in our NSF-SEES flyer (Holbrook, et al., 2012), available at the SedHeat.org website. Many of these questions apply to gaining a better fundamental understanding of the native sedimentary basin, and address both the heat and fill factors. Critical is gaining an understanding of the distribution of geothermal heat and predicting how this heat system will respond to heat extraction. Field observation coupled with high-resolution modeling of basin fill processes and a more precise determining of the movement and chemistry of fluids through complex fill systems is a keystone in the success of sedimentary basin geothermal. Finding and tracking these fluid conduits in deep basins also demands a new generation of geophysical techniques with increased resolution. The need for coupling of engineering and science is also

Questions Pertaining to the Native Sedimentary Basin

- *How does heat move within sedimentary basins at large scales and how does this impact the renewability of the resource?*
- *How is heat stored and released on the local and micro scales and how does this impact efficiency of heat sweep?*
- *What are the fundamental sedimentary processes that control the filling of sedimentary basins across all scales, and how do they impact permeability, connectivity, and heterogeneity of deep-basin flow paths?*
- *What are the diagenetic processes that operate in deep sedimentary basins and how do they increase or reduce permeability as they evolve?*
- *What controls the natural processes whereby fractures form and evolve within basin sediments, and what is the impact of these fractures on the transmission of fluid flow?*

Geophysics

- *How can discrete geophysical methods be integrated to identify basin properties critical to geothermal development (e.g. permeability pipes, thermal distribution, etc.)?*
- *What are the critical advances needed to better predict and measure changes in thermal properties of fluids and solids in deep-Earth settings during development and production?*
- *How can geophysical aspects of deep-Earth settings be effectively simulated within the lab?*

Engineering of Geothermal Systems

- *What new or improved well technologies can make drilling and developing large boreholes possible and practical at very high temperatures?*
- *What new techniques can be defined that permit us to predict, control, and monitor stimulated fracture systems in deep, hot, and heterogeneous media?*
- *How can we effectively monitor the evolution of fractures, heat regime, and stress conditions induced by geothermal extraction?*
- *What are the relationships and thresholds between modified fluid pressures and induced seismicity?*
- *Can numerical decision models be generated that effectively predict geothermal operational risk?*

Education and Cyberinfrastructure

- *What short-term and long-term efforts will prove most effective toward tempering workforce shortages expected of an emerging geothermal industry?*
- *What efforts would prove most effective at raising the current low profile of geothermal energy in the mind of the public and policy makers?*
- *What are the positive and negative feedbacks tied to relationships between the geothermal and oil and gas industries as it relates to perceptions, workforce development, and educational infrastructure?*
- *What are the most effective forms of cyberinfrastructure that may be used to promote sharing of data and education materials to best aid the development of geothermal curricula?*
- *What are the best vehicles for fostering cross-disciplinary education and scholarship between engineering and science disciplines?*
- *What are the best processes for building an educational and workforce pipeline from K-12, though undergraduate, to graduate, to professional in the geothermal sciences, and how can we best assure that women and minorities are not leaked from this system?*
- *What can be done to retain underrepresented groups in the educational and career pipeline toward potential geothermal positions?*
- *What are the cyberinfrastructure platforms that will best facilitate effective exchange of ideas and data and foster greatest participation for the SedHeat community, and what is the best approach for constructing this platform?*

Figure 4: Some key questions defining the driving needs of sedimentary-basin geothermal research as assessed by the NSF SEES workshop Tracking an Energy Elephant (see Holbrook, et al., 2012 for more detail on these questions and research needs.)

acute. Improving our ability to predict and control fracture propagation through heterogeneous strata under high T/P conditions is mandatory to integrating of matrix permeability conduits with engineered fracture patterns, and requires an understanding of both engineered and native basin conditions. Engineering and geophysics merge particularly in the management of risk from induced seismicity. In addition, advances in drilling are required to sink the need large boreholes into basin media with highly elevated ambient heat. All of this will require information sharing and a new workforce generated through surmounting of numerous challenges in education and cyberinfrastructure.

Many of these questions are familiar and long-standing because of the commonality between extracting heat vs. petroleum from sedimentary basins. Some however are new, and all diverge because of the basic change in application and the low margins of error demanded by successful geothermal production. One familiar commonality is that geothermal energy from sedimentary basins requires a robust cooperation between geologists, engineers, geophysists, and educators if this endeavor is to meet with any success. Geothermal space heating in homes and commercial buildings expanded when the ratio between cost and eventual return became predictable and positive. Realizing geothermal electric energy from sedimentary basins is similar and requires that the risk threshold be lowered such that economic gain is more certain for the producer. Forward movement on a better understanding of the basic science and engineering of sedimentary basins remains the key to lowering this economic risk.

WAYS FORWARD

Presently, the most pressing need in establishing sedimentary-basin geothermal as a viable energy source is demonstrated success. These successes will come from two directions. First are breakthroughs in the fundamental science and engineering of sedimentary basins that improve the ability to predict fluid pathways passing through sufficiently large volumes of hot rock. Second are examples of actual economic successes in geothermal development of sedimentary-basins.

One key area for a fundamental breakthrough in basic science and engineering for geothermal energy is in gaining better constraints on basin-fill processes and properties that will aid in prediction of natural and engineered permeability pathways in deep sedimentary basins. This was the theme of a GSA Penrose conference convened by SedHeat in October of 2013. This meeting hosted a coordinated series of 52 presentations, gathered around principal themes. All presentations are available on the SedHeat.org website together with notes for the pre-meeting short course, attended by early-career and established professionals alike. In addition the conference is being followed by a series of "incubator" workshops that focus on actualizing ideas developed at the conference and are centered on the deep processes in the Raton Basin, co-production of energy and minerals from brines in the Idaho thrust belt, and improving constraints on the heat budgets of sedimentary basins (Figure 2). Furthermore, researchers in the group are already working on such issues as coupling CO_2 sequestration with geothermal energy by using waste CO_2 as a working fluid, directive fracture models for deep sedimentary basins, and induced seismicity from high-volume water injection.

Some basins are being actively examined for potential geothermal production. Recent investigations in the Great Basin indicate temperatures of 150 - 230^{O}C occur at depths of less than 4 km where heat flows exceed 80 mW/m^2 (Allis et al., 2011, 2012). Basins with more than 2 km of unconsolidated sediments are the most attractive because of the insulating effects of these sediments. The reservoirs targeted are primarily in Paleozoic carbonate rocks because of their high permeabilities, which commonly are in the range of 10 to 100 millidarcy, but siliciclastic rocks may also serve as thermal aquifers. Because of the lateral extent (>100 km^2) of these stratigraphic reservoirs, these individual basins have the potential to generate hundreds of MWe, based on reservoir modeling which suggests sustainable power densities of 2 - 5 MWe/km^2 are possible. Other regions of high potential include the Imperial Valley of California, where nearly a dozen geothermal systems are identified, the Rio Grande Rift of New Mexico and Colorado, the Denver Basin, and the Gulf Coast (Figure 2).

INTERESTED IN SEDHEAT?

SedHeat is an open network of researchers and welcomes new members. We will be hosting activities in the near future in support of geothermal research. These include large and small workshops, short courses, and student opportunities. If you would like to be looped into upcoming events, just send us an e-mail at John.holbrook@tcu.edu, or check out our web page at Sedheat.org. Feel free to join SedHeat and take part in the fun.

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