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UPDATING THE CLASSIFICATION OF GEOTHERMAL RESOURCES

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ABSTRACT

Resource classification is a key element in the characterization, assessment and development of energy resources, including geothermal energy. Stakeholders at all levels of government, within the geothermal industry, and among the general public need to be able to use and understand consistent terminology when addressing geothermal resource issues such as location, quality, feasibility of development, and potential impacts. This terminology must encompass both the fundamentally geological nature of geothermal resources and the practical technological and economic aspects of resource exploitation while remaining understandable to the broad community of non-specialists. In the United States, the classifications applied to geothermal resources are primarily the legacy of resource assessment and characterization studies conducted in the 1970s during a time of rapid development and new interest in geothermal energy. That many of the standards developed during that time are still in use today is a testament to the quality of the original work. However, developments over the past 30 years, especially advances in geothermal technology, have expanded the scope of exploitable geothermal resources beyond the earlier classifications. As part of its ongoing work to assess geothermal energy resources in the United States, the U.S. Geological Survey (USGS) is working with the Department of Energy (DOE), the geothermal industry, and academic partners to develop a new geothermal resource classification system that will reflect the current state of knowledge regarding geothermal technology and serve as a effective means of characterizing, quantifying, assessing and communicating important aspects of geothermal energy potential. This paper describes the scope of the effort as well as initial progress in establishing the new classification terms.

BACKGROUND

Geothermal energy resources are characterized by geologic settings, intrinsic properties, and viability for commercial utilization. Coherent frameworks for classifying these resources are necessary for a number of purposes, including resource assessment, exploration, development, and reporting (e.g., AGCC, 2008). The diversity of both the nature of the geothermal resource and its exploitation presents a challenge in the context of resource classification, as definitions and concepts that serve one purpose may be inadequate for or even counterproductive when used for other purposes. Classification has been a feature of geothermal investigations from an early date, with large numbers of publications either devoted to or touching on the topic during the 1960s and 1970s (e.g., White, 1965; White et al., 1971; Kruger and Otte, 1973). Some approaches have continued in use until the present. For example, the basic framework for geothermal resource characterization and assessment developed by Muffler and Cataldi (1978) is foundational to recent resource assessments by the USGS and other organizations (Williams et al., 2008a, b). However, with technological changes, the international growth of the geothermal industry, a more detailed understanding of geologic and tectonic processes, and the potential development of new types of resources, it is timely to revisit and potentially revise these earlier approaches to geothermal resource classification. Within the international geothermal community, the varied needs and classification systems developed to meet those needs make it unlikely that any one system will meet all potential requirements, let alone be adopted uniformly by all concerned.

In the United States, the Geothermal Steam Act of 1970 gave responsibility for assessing geothermal resources to the USGS, with DOE (and its predecessor ERDA) collaborating and providing significant financial support. The USGS-DOE classification effort outlined here is part of those ongoing assessment efforts and has two primary objectives. First is to develop a revised and updated classification system that meets the needs of current USGS and DOE resource characterization and assessment activities. Second is to provide tools for translating among the terms and definitions used by different systems so there can be clear and consistent communication of both qualitative and quantitative resource assessment results.

Within this context, we propose the following guidelines for developing geothermal resource classifications. Specifically, a geothermal resource classification system should

1. be simple and logical for effective communication with and understanding by both experts and non-experts,
2. be valid from scientific and technical perspectives,
3. meet clearly identified needs for categorized resource information,
4. be easily translated into other classification systems,
5. avoid misconceptions that may unintentionally adversely affect commercial activities,
6. eliminate gaps or overlaps between categories, and
7. avoid unnecessary (and potentially incorrect) predictions by focusing on fundamental physical and chemical properties of resources rather than on aspects of utilization that can be altered by evolving technological, regulatory and economic factors.

CURRENT GEOTHERMAL RESOURCE ASSESSMENT TERMINOLOGY

In this paper we follow earlier USGS geothermal resource studies in using the terminology adopted by Muffler and Cataldi (1978) for the subdivision of the geothermal resource base. These subdivisions are easily illustrated through a modified McKelvey diagram (Figure 1), in which the degree of geologic assurance regarding resources is set along the horizontal axis and the economic/technological feasibility (often equivalent to depth) is set along the vertical axis (Muffler and Cataldi, 1978). USGS geothermal assessments consider both identified and undiscovered systems and utilize the following definitions. The geothermal resource base is all of the thermal energy in the Earth's crust beneath a specific area, measured from the local mean annual temperature. The geothermal resource is that fraction of the resource base at depths shallow enough to be tapped by drilling in the foreseeable future that can be recovered as useful heat economically and legally at some reasonable future time. Similarly, the geothermal reserve is the identified portion of the resource that can be recovered economically and legally at the present time using existing technology (Muffler and Cataldi, 1978).

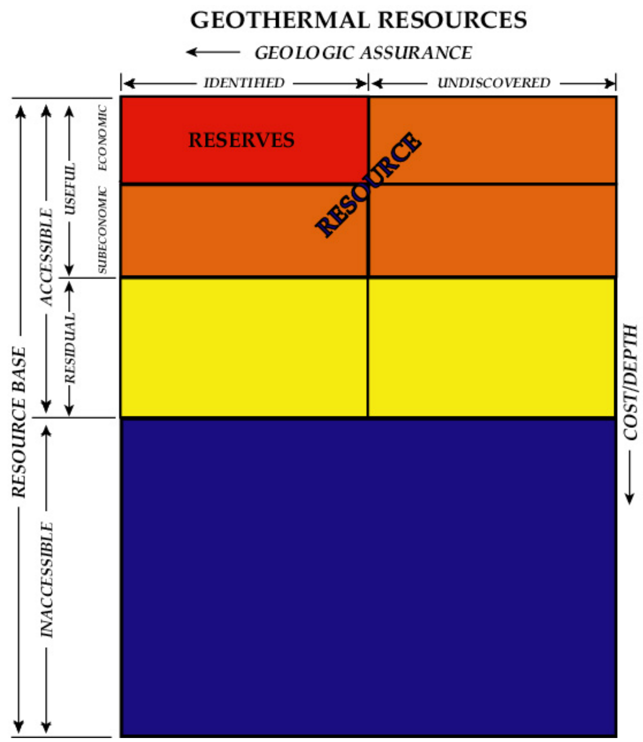


Figure 1: McKelvey diagram representing geothermal resource and reserve terminology in the context of geologic assurance and economic viability. Modified from Muffler and Cataldi (1978).

One fundamental aspect of geothermal resource classification that has not been consistently addressed is the development of a clear and concise definition of a geothermal system. In oil and gas assessments, conceptual definitions of petroleum systems have expanded to encompass "the natural hydrocarbon-fluid system in the lithosphere that can be mapped and includes the essential elements and processes needed for oil and gas accumulations to exist" (Magoon and Schmoker, 2000). Similarly, an important goal in geothermal resource assessments is to understand the process by which an exploitable, or potentially exploitable, geothermal reservoir forms and evolves over time. The AGI Glossary of Geology (Neuendorf et al., 2010) includes an earlier USGS definition of a geothermal system as "any regionally localized geological setting where naturally occurring portions of the Earth's thermal energy are transported close enough to the Earth's surface by circulating steam or hot water to be readily harnessed for use." This definition covers natural hydrothermal systems but is not applicable to conductive geothermal resources or Enhanced Geothermal Systems. To broaden this definition, we propose a provisional alteration of this definition as follows. A geothermal system is any localized geologic setting where portions of the Earth's thermal energy may be extracted from a circulating fluid and transported to a point of use. A geothermal system includes fundamental elements and processes, such as fluid and heat sources, fluid flow pathways, and a caprock or seal, which are necessary for the formation of a geothermal resource.

A key requirement of geothermal classification for resource assessments is to provide a logical and consistent framework for quantifying the geothermal resource in the context of the general definitions given above. The following examples highlight issues in the classification of natural convective geothermal systems formed through the free convection or forced convection/advection of water in the subsurface, natural conductive geothermal systems, which are based on the exploitation of temperatures at depth developed through the conductive geothermal gradient, and Enhanced or Engineered Geothermal Systems (EGS), which can be developed in both convective and conductive environments.

EXAMPLES OF GEOTHERMAL RESOURCE CLASSIFICATION

Temperature and Thermodynamic Properties

As the means by which geothermal energy is identified and utilized, temperature is a fundamental measure of the quality of the resource and consequently is the primary element of most classification systems. For USGS assessments, geothermal systems have been divided into three temperature classes: low-temperature (<90^{o}C), moderate-temperature (90 to 150^{o}C), and high-temperature (>150^{o}C) (White and Williams, 1975; Muffler, 1979; Williams et al., 2008b). High-temperature systems include both liquid- and vapor-dominated resources. Moderate-temperature systems are almost exclusively liquid-dominated, and all low-temperature systems are liquid-dominated. All three temperature classes are suitable for direct use applications, but in general moderate- and high-temperature systems are viable for electric power generation. Systems at the upper end of the low-temperature range can be exploited for electric power generation if sufficiently low temperatures are available for cooling the working fluid in a binary power plant.

Other thermal classification systems have been proposed, with most focusing on dividing geothermal resources into a similar set of three or, more simply, two classes that define a progression from low to high temperature (or enthalpy) geothermal resources (Figure 2). In each case the temperature/enthalpy boundaries are set at temperatures thought to be significant in either a thermodynamic or an economic utilization context. This approach has been refined to the greatest degree by Sanyal (2005), who proposed a series of divisions focused on thermal boundaries of significance to the geothermal developer. For example, the boundary at 100 °C is tied to the boiling point of water, whereas that at 190 °C is related to the ability of geothermal wells to self-flow (as opposed to requiring pumping of reservoir fluids).

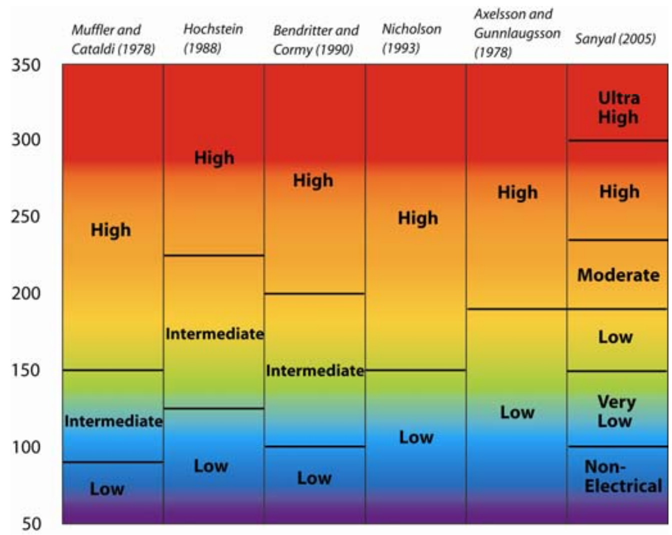


Figure 2: Example classifications of geothermal resources by temperature.

Lee (2001) recognized the apparently irreducible diversity of approaches to temperature/enthalpy classification and proposed a system of classification in terms of specific exergy (or available work), which has been used in calculations of electric power generating potential in geothermal resource assessments (e.g., Brook et al., 1979; DiPippo, 2005; Williams and Reed, 2008) and is defined as

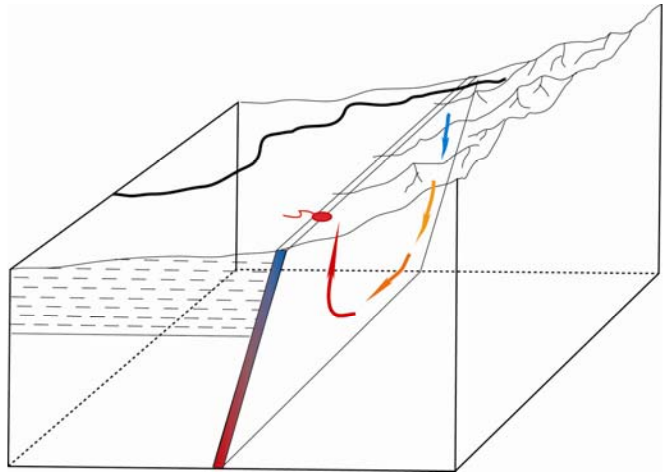
$$E = m_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)] \qquad (1)$$

where s_{WH} is the entropy of the produced fluid and s_0 is the entropy at the reference temperature (the triple point of water in Lee's analysis). The use of specific exergy has an advantage in relating directly to the relevant properties of the produced geothermal fluid at the wellhead. Lee (2001) developed a specific exergy index as the ratio of the specific exergy of a given geothermal system to the specific exergy in saturated steam at a pressure of 9 MPa. The resulting low, medium and high quality classes provided by Lee (2001) are logical in the context of utilization as well as fundamental properties of steam, but the communication of those classes to the non-specialist is complicated by the requirement to refer to thermodynamic properties such as enthalpy and entropy, as well as the need to have access to both temperature and pressure estimates for actual or potential conditions at the wellhead.

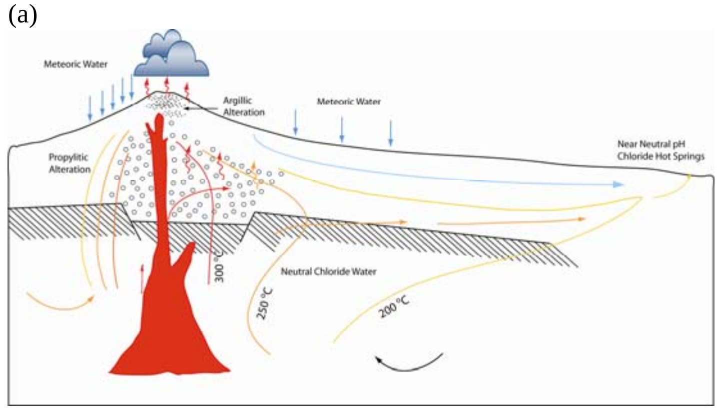
Consequently, although there are solid reasons for varied divisions in terms of temperature or other thermodynamic properties, there is no compelling reason for one set of divisions to be chosen over another. The fundamental requirement of simplicity is still valid, as is the need to avoid imbedding any set of classes with assumptions about utilization that may be contradicted by changes in the technology of exploitation. One possible solution may be to avoid classifying geothermal resources by temperature altogether and simply state the range of temperatures or other thermodynamic properties used in the particular assessment application while recognizing that future technological developments may alter boundaries and definitions. Resolving this issue requires further work and discussion within the geothermal community.

Geologic Setting and Fluid Chemistry

Understanding and characterizing the geologic controls on geothermal resources, has been an ongoing focus of investigations, whether in the context of plate tectonics (e.g., Muffler, 1976; Heiken, 1982) or specific processes, such as volcanism (e.g., Henley and Ellis, 1983; Wohletz and Heiken, 1992). Renewed interest in geothermal energy exploration and development has led to updated efforts to characterize resources in a geologic/tectonic context (e.g., Walker et al., 2008; Erdlac et al., 2008; Brophy, 2008). A key element in these studies is the recognition that the geologic setting of a geothermal system has a fundamental influence on the potential temperature, fluid composition, and reservoir characteristics. Examples of this influence are shown in Figures 3a and 3b. Figure 3a shows an example fault-hosted deep circulation (or amagmatic) geothermal system, in which the geothermal fluid originates as meteoric water that gains heat through circulation to depth within a fault zone (Reed, 1983). Figure 3b shows the scope of geothermal manifestations within an island-arc volcano (Henley and Ellis, 1983) with varied temperatures and fluid chemistries occurring within different parts of the volcanic edifice. Each model incorporates the essential elements of the geothermal system as defined above and provides a context for interpreting field observations. For example, in the volcanic context (Figure 3b), chemical analyses can identify geothermal waters as dominantly acid (SO_4), neutral chloride (Cl), or soda springs (HCO_3) (Giggenbach, 1988), and these water types, as well as other chemical characteristics, can be related to different processes in the geothermal system (Henley and Ellis, 1983).



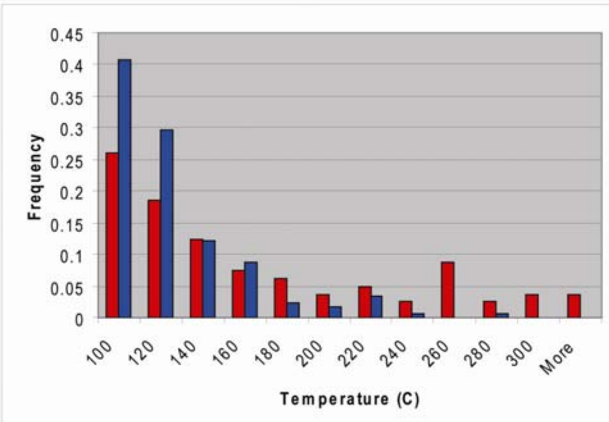
(a)



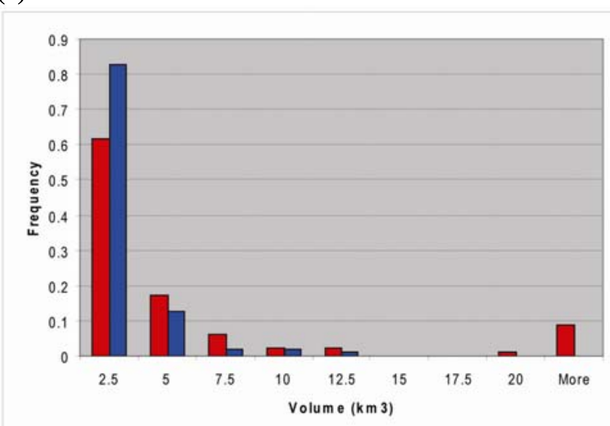
(b)

Figure 3: (a) Schematic representation of a normal fault-hosted geothermal circulation system. Modified from Reed (1983). (b) Schematic representation of geothermal systems formed within a volcanic arc environment. Modified from Henley and Ellis (1983).

Properly defined, geologic conceptual models such as these have significant value for geothermal assessment, exploration and development by providing quantitative constraints on characteristics of the resource. Even relatively simple classifications, such as whether geothermal systems are related to magmatic activity or not, highlight important differences in resource potential. Figure 4 shows the distribution of estimated and measured reservoir temperatures and volumes for identified geothermal systems in the United States (Williams et al., 2008a,c), divided into those associated with active or recent magmatism and those deriving heat solely from deep circulation in regions of elevated heat flow. As expected given the high temperature, shallow heat sources and the potentially large volumes of permeable, young extrusive rocks, the “magmatic” geothermal systems are, on average, higher in temperature and larger in volume than the deep circulation or “amagmatic” systems.



(a)



(b)

Figure 4: (a) Histogram showing the temperature distribution of identified geothermal systems in the United States differentiated as either magmatic (red) or amagmatic (blue). (b) Histogram of estimated reservoir volume for the same geothermal systems. (Williams et al., 2008a, b)

Conductive Geothermal Resources and Enhanced Geothermal Systems

As noted by Hochstein (1988), classification systems developed to provide a framework for assessing convective geothermal resources are not necessarily applicable to conductive resources in sedimentary formations. Most resource classifications developed for sedimentary geothermal resources to date have been focused on the method of exploitation, such as dedicated pumping from sedimentary aquifers (Reed, 1983), coproduction with oil and gas (McKenna et al., 2005), self-flow from geopressured formations (Muffler, 1979), and even geothermal production coordinated with CO_2 sequestration (Pruess, 2006). Although the utilization scenarios for these sedimentary resources are diverse, there is consistency in the geologic and thermal environment, as the resources are associated with the predominantly conductive setting of sedimentary basins. Consequently, in ongoing assessment and classification work, we will consider these as a single broad class of geothermal resources.

By contrast, EGS cover essentially the entire range of geothermal environments from reservoir creation in low permeability and porosity crystalline rock at depth through high porosity, low permeability sedimentary formations to augmented production in a producing convective geothermal reservoir. In order to provide a consistent framework for assessing EGS resources as distinct from naturally-occurring geothermal resources, we propose the following provisional definition. Enhanced Geothermal Systems comprise the portion of a geothermal resource for which a measureable increase in production over its natural state is or can be attained through mechanical, thermal, and/or chemical stimulation of the reservoir rock. In this definition there are no restrictions on temperature, rock type, or pre-existing geothermal exploitation. (In order to avoid confusion with abbreviations, Enhanced Geothermal Systems and Engineered Geothermal Systems are considered synonymous.)

SUMMARY AND FUTURE PLANS

The above discussion lays out proposed definitions and applications for certain aspects of geothermal resource classification, such as the definitions for geothermal systems and Enhanced Geothermal Systems. In addition, as part of ongoing work in this area we will build on existing schemes to propose a single comprehensive geologic/tectonic framework for geothermal resources. We will also continue to evaluate revisions to classifying geothermal resources from a thermodynamic perspective, but the diverse approaches taken to date indicate that there are potentially irreducible differences in classifying on the basis of temperature/enthalpy. Anticipating that different classification approaches will remain in use within the international geothermal community, we will produce a set of spreadsheet-based tools for translating among various classification systems for potential use by those utilizing geothermal data repositories. Incorporating public domain software for calculating thermodynamic properties, these tools will provide users with the ability to enter basic data from field sites, such as temperature, pressure, and fluid chemistry and then obtain information on classification of the system according to existing schemes. We expect the new classification information and the associated tools to be publicly available by the end of 2011.

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