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Catalog of geothermal play types based on geologic controls

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ABSTRACT

The key element in the characterization, assessment and development of geothermal energy systems is the resource type. Throughout the past 30 years many resource type schemes and definitions were published, based on temperature and thermodynamic properties. An alternative possibility to cataloging geothermal energy systems is by their geologic characteristics, referred to as geothermal plays. Applied to worldwide case studies, a new catalog is developed based on the effects of geological controls and structural plate tectonic positions on thermal regime and heat flow, hydrogeologic regime, fluid dynamics, fluid chemistry, faults and fractures, stress regime, and lithological sequence. Understanding geologic controls, especially of geothermal plays without surface expression, allows the comparison with hydrocarbon reservoirs through their ratio of porosity and permeability. This analog has implications on site-specific, first class exploration strategies and reservoir improvement through technologies specifically suitable for unconventional sustainable energy reservoirs. This article aims to introduce geothermal plays to a wide geoscientific community and to initiate a geologically based cataloging of geothermal resources. With this new catalog of geothermal plays, it will be ultimately possible to transfer lessons learned not only within one specific catalog type, but also technology from geothermal plays to unconventional hydrocarbon plays and vice versa.

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1. Introduction

Geothermal energy provides commercial base-load electricity from conventional hydrothermal resources for more than 100 years, with a global installed electricity generation of 10,751 MW_{el} [1] and direct use of 50,583 MW_{th} [2]. Whereas these prime geothermal systems are limited to tectonically active areas or regions with active

Abbreviations: MW_{el}, Megawatt electric; MW_{th}, Megawatt thermal; EGS, Enhanced Geothermal Systems; MPa, Megapascal; HDR, Hot Dry Rock; GHG, Greenhouse gas; CV, Convection dominated heat transfer regime; CD, Conduction dominated heat transfer regime

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volcanism, the concept of Enhanced or Engineered Geothermal Systems (EGS) has significantly increased the world-wide geothermal potential by technology reservoirs where the stored thermal energy can be extracted from subsurface even in areas of low or moderate heat flow. Tester et al. [3] claim that EGS resources could technically provide 100,000 MW_{el} cost-competitive electric energy in the USA by 2050. However, more effort in research and development is needed to realize this goal. Successful reservoir production from geothermal systems depends mainly on the appropriate selection of exploration methods. The decision for these appropriate exploration methods might depend on the type of geothermal energy system foreseen for heat and power production and necessitates a classification system for geothermal system types. A geothermal system is generally classified by its geological, hydrogeological and heat transfer characteristics, while a geothermal resource is formed by an economically sufficient amount of heat concentration in drillable depth of Earth's crust [4]. The term *sufficient* may dependent on technology development resulting in modern viable geothermal reserves that were not economic in the past. When it comes to geothermal prospects, resources and reserves, it is obvious that clear terms and definitions are required to provide reliable and comparable reserve estimation analogous to the classification schemes developed for petroleum resources. According to the Petroleum Resources Management System [5], reserves are classified as commercially recoverable resources and contingent resources are less certain because of some commercial or technical hurdle resulting in a lower confidence level for eventual production. The lowest level in this classification scheme is represented by prospective resources, which are estimated but undiscovered accumulation of potentially recoverable heat (i.e. prior to drilling). Unrecoverable resources are classified as not being commercially producible at the present point in time. While one portion the *unrecoverables* may become recoverable in the future with changing commercial and evolving technological circumstances, another portion may never be recovered due to physical or chemical constraints in the reservoir [5]. From this classification perspective, the lowest unit in a bottom up approach is the geologically based so-called "play type", which leads to prospects and ultimately to reserves. A play type in petroleum geology represents a particular stratigraphic or structural geological setting, defined by source rock, reservoir rock and trap [6]. Translated to geothermal systems, a play type might be defined by the heat source, the geological controls on the heat migration pathway, heat/fluid storage capacity and the potential for economic recovery of the heat. Ultimately the geological habitat does not only control the play type but also the decision for applied heat recovery technology.

The new interest in geothermal energy resources is tied to the question of economic risks and the production potential of individual geothermal resource types. Quantifying the chance of development and field production involves feasibility studies and utilization concepts for the economic development of specific geothermal systems. From this perspective, it is important to note that a geothermal resource is part of a geologic system where geologic factors such as lithology, faults, fractures, stress field, diagenesis, rock mechanics, fluid chemistry and geochemistry control key parameters, such as high porosity and high permeability domains, fluid flow, lateral and vertical temperature distribution and overall reservoir behavior during injection and production. A site specific appropriate field development should therefore be based on a profound understanding of the geologic controls of a geothermal play involving a suite of modern site specific exploration techniques. A clear and widely understandable new catalog of geothermal plays is required to fulfill the aims of exploration in reducing the risk of non-productive wells and guiding best choice reservoir technology to ultimately produce thermal energy on an economically sustainable level. The need for a new catalog may also emerge for two major reasons: (I) The recent development in Enhanced Geothermal System (EGS) technologies produces tangible pilot projects for heat and power generation from low-enthalpy resources, thereby extending the worldwide geothermal potential, and (II) the growing political-social request for renewable energy to reduce climate gas emission.

Throughout the past 30 years many catalog schemes and definitions for geothermal resources have been published, mainly based on temperature and thermodynamic properties. Temperature has been the essential measure of the quality of the resource, and geothermal play systems have been divided into three different temperature (or enthalpy) play types: low-temperature, moderate-temperature and high-temperature [7–13]. There are, however, no uniform temperature ranges for these types (Table 1).

Lee [14] pointed out that temperature and enthalpy alone are inconsistent and insufficient to catalog geothermal plays and suggests a catalog scheme by the specific exergy of a geothermal fluid as a measure of its ability to do a work. The term exergy is used in thermodynamics to define the amount of energy that is available to be used during a process that brings the system into equilibrium [15]. Lee [14] developed a specific exergy index as the ratio of the specific exergy of a given geothermal play to the specific exergy in the saturated steam at a pressure of 9 MPa. Lee's geothermal play catalog has some advantages, as it directly relates to relevant properties of the produced thermal fluid at the wellhead. However, it does not consider geological–hydrogeological aspects such as geological setting, controls on fluid flow, fluid chemistry and possible mineral precipitation in reservoir rock or in technical installations below and above the ground surface. All of these factors can impair the energy production and overall economic utilization of a geothermal resource. Moreover, Lee's [14] concept requires access to both temperature and pressure estimates for actual conditions at the wellhead; thus his catalog scheme can only be applied after drilling the first well. A geothermal play catalog and assessment scheme should, however, also be applicable before drilling for assessment and site specific field development.

Williams et al. [16] point out that it is still a substantial requirement that a resource assessment provides a logical and consistent framework that is simplified enough to communicate important aspects of geothermal energy potential to both non-experts and the general public. One possible solution may be to

Table 1
Catalog scheme of geothermal resources by temperature according to different authors (compilation modified from Lee [14]).

	Muffler [8] (°C)	Hochstein [9] (°C)	Benderitter and Cormy [12] (°C)	Haenel et al. [10] (°C)		
Low enthalpy	< 90	< 125	< 100	< 150		
Moderate enthalpy	90–150	125–225	100–200	–		
High enthalpy	> 150	> 225	> 200	> 150		
Sanyal [13]	Non-electrical (°C)	Very low (°C)	Low (°C)	Moderate (°C)	High (°C)	Ultra high (°C)
	< 50–100	100–150	150–180	180–230	230–300	> 300