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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

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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

avoid cataloging geothermal plays by temperature and simply state the range of temperatures at the individual site.

Due to technological development, in particular in EGS technology, currently there are more geothermal systems that are potentially economical than there were 30 years ago. Therefore, a new cataloging scheme for geothermal play systems should characterize geologic controls on geothermal resources, recognizing that future technological developments may alter quantitative boundaries and definitions based on temperature. A catalog of geothermal system plays should not be mistaken with a geothermal system classification, which is preferably used for financial reporting schemes aiming to distinguish between different degrees of certainty and project maturity (G. Beardsmore, 2013, personal communication).

2. Geologic perspective on geothermal play systems

In contrast to the straightforward definition of hydrocarbon play systems, which are clearly defined by their source rock, reservoir and trap, geothermal play systems are lacking such a clear set of geological features. Instead, geothermal play systems appear in diverse geologic environments and theoretically all over the world. For geothermal resource utilization, important factors are how much heat is stored at a drillable depth and if this heat is producible at an economic rate for a specific project. Pioneering work in describing and cataloging geothermal systems was done by Manfred Hochstein in the late 1980s. After 30 years of development in geothermal technology, however, it is time, to extend Hochstein's catalog to incorporate EGS.

The American Geosciences Institute defines a geothermal system generally as [17]:

“Any regionally localized geological settings where naturally occurring portions of the earth's internal heat flow are transported close enough to the earth's surface by circulating steam or hot water to be readily harnessed for use”.

Since this definition refers only to convective geothermal resources, Williams et al. [16] broadened this definition to include also conductive geothermal resources:

“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”.

This definition still excludes the concept of EGS, where the geothermal play system conditions are enhanced from previous non-economic to economic conditions. The key point for EGS is that the ratio of the temperature to the flow rate (or production and injection rate) must be given for an economic use. Although the quantitative meaning of *economic* might change through time, the terms flow rate, temperature and economics must be linked for a modern geothermal system definition. The definition of Williams et al. [16] should therefore be extended as follows:

“A geothermal system is any localized geologic setting where portions of the Earth's thermal energy may be extracted from natural or artificially induced circulating fluids transported to a point of use. Enhanced Geothermal Systems are portions of the Earth crust where the ratio of flow rate and fluid temperature is naturally too low for economic use, and therefore the flow rate must be increased to a sufficient flow rate/temperature ratio by enhancing the natural permeability through technological solutions”.

In EGS the circulating fluid can be the natural fluid if a hydrothermal system is hosted by a low permeability formation, or it can be an artificial (i.e. injected) fluid if the formation of the geothermal system does not contain enough fluid volume for heat extraction (referred to as Hot Dry Rock or petrothermal system).

Referring to the revised definition of a geothermal system above, an alternative possibility is classifying geothermal play systems by their geologic setting. Recent attempts in categorizing geothermal plays are the play fairway analyses of hydrothermal systems in the United States, where the geographic extent of favorable settings is defined [18], or the play concept of rift zones where repeating sets of prospects with common characteristics define a play group [19]. From a structural geology perspective, a catalog theme can be guided by the plate tectonic setting, for example, whether the play system is related to convection or conduction dominated heat transfer and if the geothermal play system is magmatic or non-magmatic. Understanding and characterizing the geologic controls on geothermal plays has been an ongoing focus on different scales, from plate tectonics (e.g. [20,21]) to local tectonics/structural geology [22]. In fact, the geologic setting has a fundamental influence on the potential temperature, on the fluid composition, the reservoir characteristics and whether the geothermal play is a convective or conductive system.

In particular, a structural geological understanding helps to better interpret geophysical data and to identify favorable settings for drilling [23]. Essential parameters are the stress field and reservoir geomechanics, since the orientation of the current stress field has an impact on fluid flow along faults and ultimately on the permeability anisotropy in fractured reservoirs [24]. The stress field is also crucial for EGS development because technology reservoirs, particularly the technology of reservoir stimulation, aim to increase the permeability by generating additional fractures [25]. Orientation and growth of these artificial fractures are strongly controlled by the stress field and geomechanical rock properties, which need to be understood prior to stimulation and defining injection rates. A more important factor than generating fractures through stimulation might be keeping the induced fractures open during production and subsequent formation pressure drop. The analysis of the fault reactivation potential by the slip and dilation tendency technique helps in risk assessment during injection in general, which also includes re-injection [26]. A quantitative structural geology evaluation involving 3D structural geological modeling, stress field analysis and fault stress modeling is therefore a fundamental part in geothermal field development from exploration to drilling to reservoir engineering [27].

This work will review these aspects along with a newly developed catalog scheme based on the author's work experience in different geologic-geothermal settings. This catalog involves both convective and conductive dominated geothermal plays. Special emphasis is given to geothermal exploration that provides site-specific guidelines for geothermal systems, especially EGS.

3. Geothermal plays in relation to plate tectonic setting

Plate tectonic settings have a fundamental influence on the characteristics of a geothermal play. The thermal regime and heat flow, hydrogeologic regime, fluid dynamics, fluid chemistry, faults and fractures, stress regime and lithological sequence are all controlled by the plate tectonic framework and are critical for understanding the geothermal play system. The thermal state of the crust at active plate boundaries is distinct from that in other large-scale geological provinces, such as tectonically quiescent settings (e.g. cratons), major fault zones (active or inactive), or deep, sedimentary basins (intracontinental or in front of orogenic zones).

In general, geothermal plays are dominated either by a convection or conduction heat transfer regime. Convection-dominated geothermal plays – often referred to as viable or active geothermal play systems due to their fluid dynamics [28] – host high enthalpy resources and occur at plate tectonic margins, or settings of active tectonism or volcanism (Fig. 1). Convection of thermal fluids induced by a heat source or elevated heat flow transports heat from deeper levels to the surface. Structural controls have a major effect on fluid flow pathways in convection-dominated systems. In high temperature play systems, fluid flow velocities are faster than in low temperature resources [29]. Several factors and processes influence convection within a geothermal play. Besides a high temperature gradient, high permeability ($>10^{-14}$ m^2; 10 mD) is necessary to allow significant convection, whereas in low permeability layers ($<10^{-15}$ m^2; 1 mD) only minor or no convection occurs [9]. Generally, a high geothermal gradient, natural fluid flow and fluid dynamics characterize convection-dominated geothermal plays.

In contrast, conduction-dominated geothermal plays host low to medium enthalpy resources, which can also be called passive geothermal play systems due to the absence of fast convective flow of fluids and less short-term fluid dynamics. These systems are located predominately at passive tectonic plate settings where no significant recent tectonism or volcanism occurs. Here, the geothermal gradient is average, thus this type of geothermal play is located at greater depth than convection-dominated geothermal systems. Conduction-dominated geothermal plays in low permeability domains such as tight sandstones, carbonates or crystalline rock require EGS technology to be utilized on an economic level. Faults can still play an important role in these systems as a fluid conduit or barrier during production and may induce compartmentalization of the system into separate fault blocks. Lithofacies, diagenesis, dissolution processes including karstification and fractures play a major role for reservoir quality evaluation comparable to oil and gas plays.

An important factor in understanding the occurrence of convection and conduction-dominated play systems is distinguishing between igneous and non-magmatic geothermal plays. These terms refer to the heat source and tectonic activity. Igneous play systems can induce both conduction and convection-dominated geothermal plays. The difference is that conduction-dominated systems in or close to igneous rocks are related to high radiogenic heat production (typically high heat producing element rich granites), but no active volcanism and minor or no active tectonism occurs. Alternatively, convection-dominated magmatic plays require a magma chamber as the heat source in volcanic and tectonically active areas. In conduction-dominated igneous plays, large volumes of natural fluids are absent. These "dry" systems require EGS technology for hydraulic fracturing and injection induced circulation of fluids to transfer heat from depth to surface.

Fluids play an important role in geothermal system utilization, since they are necessary for transporting heat from the reservoir to the surface. The volume of produced fluids determines whether a geothermal play system is economic. The appropriate balance between production and injection of thermal fluids influences the economic life-time of a geothermal reservoir. Moreover, the fluid chemistry has major effects on the efficiency and life-time of a reservoir and the material selection of technical installations to minimize phenamona such as corrosion and mineral precipitation (i.e. scaling). It is, therefore, important to understand the reservoir fluids' origin, chemistry, recharge characteristics, and meteoric water content. Hochstein [9] points to the influence of steep topography in geothermal play systems, which cause large volumes of meteoric water recharge into convective geothermal plays via high infiltration rates. The influence of steep terrain on the hydraulic head is not only significant in volcanic field settings as in Hochstein's concept but also in sedimentary basin settings

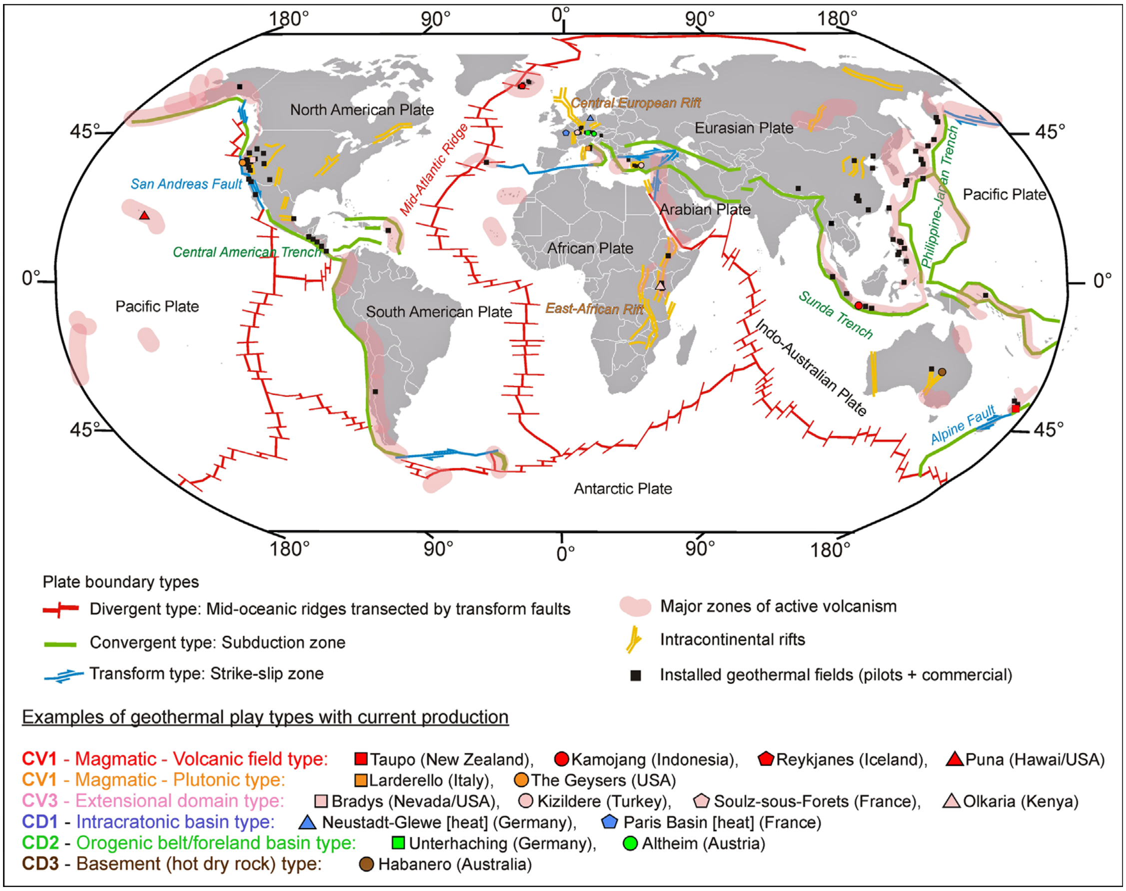

Fig. 1. Geothermal fields installed worldwide in a plate tectonic setting. Geothermal play types with example fields: CV – Convection dominated heat transfer, CD – conduction dominated heat transfer. (List of geothermal fields from http://geothermal-powerplant.blogspot.com; www.thinkgeoenergy.com; Zheng and Dong, 2008 [30]; plate tectonic map based on Frisch and Loschke, [31]).

adjacent to mountain belts. The hydrogeologic model for the Alberta Basin incorporates the effects of topographic relief on infiltration of fluids into the basin [32], that hosts low enthalpy conduction-dominated systems in different carbonates and tight (i.e. low permeability) sandstones [33]. Thus, the effects of steep terrain can be important for infiltration in both high and low enthalpy systems.

The majority of the world's operating geothermal power plants produce electricity in settings where faults transect much of the lithosphere, or where magma chambers occur (Fig. 1). Deep reaching faults and active volcanism characterize active plate tectonic margins. Understanding the processes of active tectonism at different scales may be crucial for characterizing convection-dominated, high enthalpy geothermal resources. In conduction-dominated, low enthalpy geothermal plays, it is crucial to understand the entire geodynamic evolution, particularly the role of faults and fractures in the present-day stress field. Therefore, it may be prudent to catalog geothermal play systems according to their plate tectonic setting, heat source (magmatic/intrusive or non-magmatic), and geologic controls on heat transport mechanism, storage system and permeability structure.

The following sections incorporate the existing catalog schemes for geothermal resources and place them into a plate tectonic and structural geological context. Each new catalog class of geothermal play is documented by a well-known or studied type locality.

4. Geologic controls on geothermal plays

4.1. Convection-dominated geothermal plays

Active plate tectonic processes are dominated by the dynamic interplay between lithosphere and asthenosphere, which is driven by mantle convection. Active tectonism and volcanism are predominantly found at active plate margins and represent favorable settings for high enthalpy, convection-dominated geothermal play systems. Favorable tectonic settings include: (I) magmatic arcs above subduction zones in convergent plate margins (e.g. the Sunda arc or the Philippine-Japan arc); (II) divergent margins located within oceanic settings (e.g. the mid-Atlantic ridge), or intracontinental settings (e.g. East African rift); (III) transform plate margins with strike-slip faults (e.g. the San Andreas or Alpine faults) and (IV) intraplate ocean islands formed by hot spot magmatism (e.g. Hawaii). Major fault zones can transect much of the lithosphere and can act as major fluid conduits that connect to crustal regions of elevated heat flow caused by upwelling asthenosphere (e.g. asthenospheric wedge at subduction zones, asthenospheric bulge beneath rifts) and tectonic denudation of warm middle to lower crust (metamorphic core complex in extensional terrains) [31].

In convection-dominated geothermal plays, upward circulation of fluids transports heat from depth to shallower reservoirs, or to the surface. These play systems occur in areas of active tectonism [34], active volcanism [35], young plutonism (<3 Ma) and elevated heat flow caused by extensional tectonics [36,22]. Hochstein et al. [37] use a similar catalog scheme for comparable geologic settings and describe advective geothermal systems in tectonically active regions. These authors emphasize the impact of the terrain topography, which they describe as a moderate to mountainous terrain combined with a hydrogeological setting that forces convection [37]. Convection-dominated plays are controlled by either an igneous activity like a magma chamber in volcanic areas, or faults in extensional terrains, or both, such as intrusive bodies at fault zones (Fig. 2). The fluids originate commonly from infiltration of meteoric water from high elevation and may also involve partial mixing with magmatic fluids [35]. A cataloging scheme for convection-dominated play systems is illustrated in Fig. 2 with magmatic play types in volcanic and plutonic fields on the one side and fault controlled geothermal plays in domains with extensional local or regional deformation on the other side.

4.1.1. Magmatic geothermal plays–volcanic field and plutonic type

Magmatic play systems can be found in regions with active basaltic volcanism at divergent plate margins as on Iceland, basaltic to andesitic volcanism along island arcs as on Java [35], recent andesitic to dacitic volcanism as along the south American Andeans or Taiwan and along continent-continent convergent margins with recent plutonism, as in the southern periphery of the Alpine orogeny [38]. Magma chambers in volcanic fields, with their parental melts, recharge of basalt and crystallized melts, control fluid chemistry, fluid flow and the overall geothermal play system. These systems can be separated into an upflow zone and an outflow zone [9] (Figs. 2 and 3). In contrast, a pluton crystallized from magma and slowly cooling below the surface, can be several hundreds of meters to some kilometers in dimension and include batholiths, stocks, dikes, sills, laccoliths and lopoliths. The presence and scale of a heat source in these play types may be controlled by the age of magmatism: Active and recent magmatism commonly indicates a viable underlying heat source [39], while inactive or extinct magmatism may be reflected by large-scale igneous intrusions at greater depth (>5 km depth), with remnant heat and heating by radioactive decay in granitic rock. The terms *active*, *recent* and *inactive* magmatism used in this article follow the definitions of McCoy-West et al. [39], with active magmatism related to volcanism <500 years old, recent magmatism related to volcanism 500–50,000 years old, and inactive or extinct magmatism related to volcanism $>50,000$ years old.

The primary reservoir and target for large-scale power production in a magmatic geothermal play along island arcs is the high temperature upflow zone. In contrast, the outflow zone is

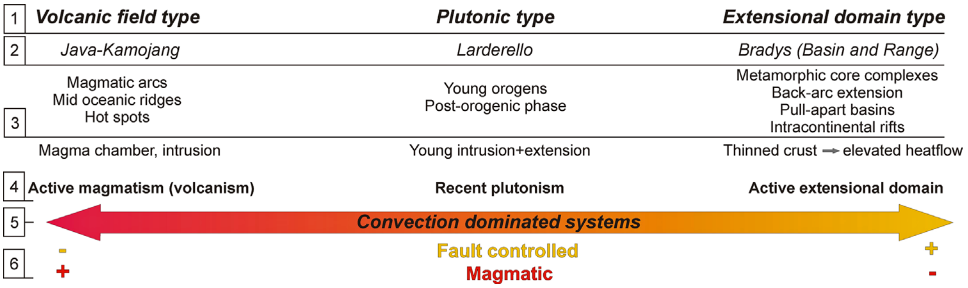

Fig. 2. Catalog scheme for convection dominated geothermal play systems based on the geologic controls of igneous activity as magmatism (volcanic type with typus locality Java, Indonesia), recent plutonism (intrusion type with typus locality Laderello Italy in the periphery of the Alpine orogeny), and absent igneous activity but significant active extension (extensional domain type with typus locality Basin and Range, western USA.). 1 – Play type, 2 – Typus locality, 3 – Plate tectonic setting, 4 – Geologic habitate of potential geothermal reservoirs, 5 – Heat transfer type, 6 – Geologic controls.

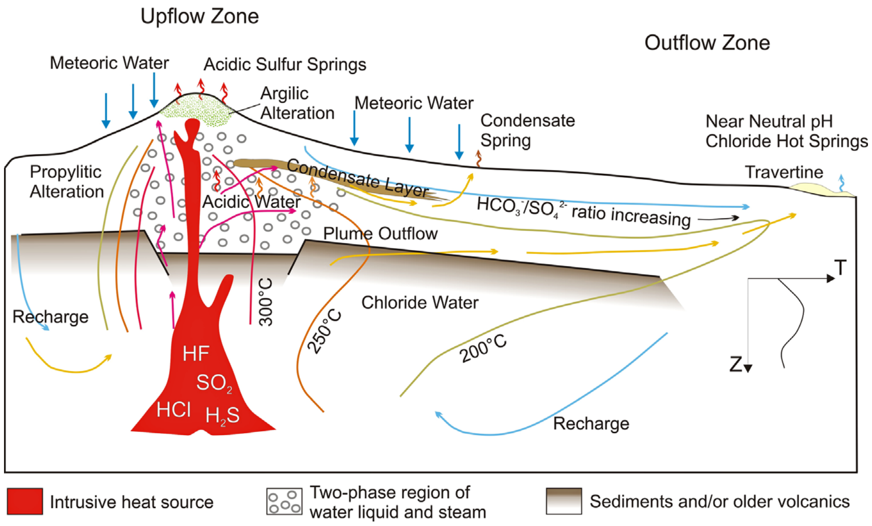

Fig. 3. Geothermal play type related to an active volcanic field typical for a magmatic arc setting above a subduction zone (compiled and modified from [9,16]).

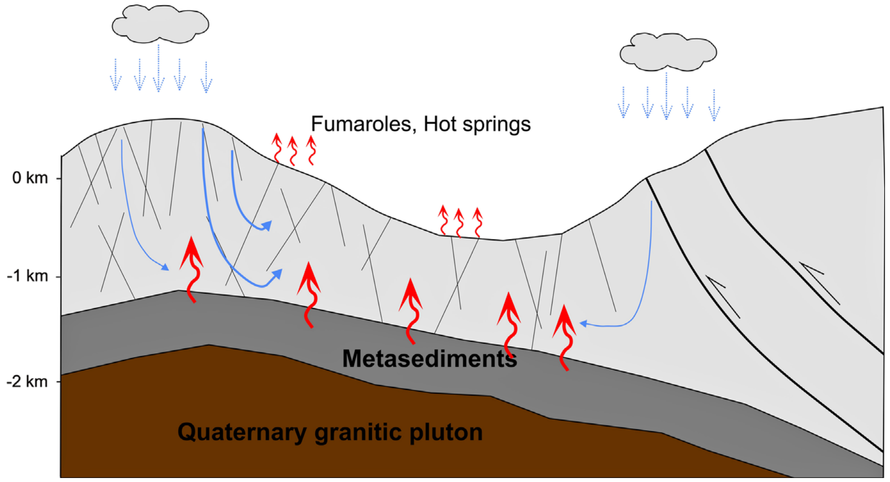

Fig. 4. Geothermal play type related to recent plutonic fields typically found at intrusions along continent-continent or continent-oceanic convergent or transform margins.

generally referred to as a secondary reservoir (of medium to low temperature) and can be utilized for small power plants if flow rate is sufficient [9]. The temperature gradient at the outflow zone typically increases at shallow depth and declines below the outflow layer (Fig. 3). Typical outflow springs spread out at the toe of the outflow are accompanied by travertine and temperatures between 40–100 °C [16]. However, outflow springs do not reflect a high temperature geothermal play system below the spring. Geothermal manifestations in the upflow zone are acidic springs associated with thermo-chemically altered rock forming alteration clays that indicate high temperature plays below the spring. The upflow zone commonly consists of a vapor-dominated part above a liquid-dominated part. Condensate layers in steep terrain, such as volcanoes, can conceal high temperature play systems. Condensate layers are generated by upwelling fluids condensed at a certain depth above heat source (Fig. 3). Such layers can neutralize initially acidic fluids [40]. The outflow from such condensate layers acquires the cation content of the condensate layer, and its geochemistry is modified from the original vapor in the geothermal system [9]. The necessary condition for the formation of condensate layers is a low permeability domain of < 0.04 mD at the depth of the steam-water boundary in vapor-dominated systems [40]. The most famous geothermal plays with condensate layers exist at Laderello (Italy), with other examples at Kamojang hot springs and Tangkubanprahu warm springs (both West Java/ Indonesia). Whereas island arc volcanism with associated basaltic to andesitic extrusions forms the typical upflow zone – outflow zone assembly, continental arc volcanism involves andesitic to dacitic magma. If the magma chamber is not recharged with basaltic melts, continental arc related geothermal plays may exhibit characteristics of outflow zones. Effectively, maximum temperatures of < 240 °C are lower [41,42] in continental than in island arc related geothermal play systems, which can have maximum temperatures of > 300 °C [43].

The difference between the Laderello-type (i.e. plutonic play type) and the Java-type (i.e. volcanic field play type) in this catalog scheme (Fig. 2) is that Laderello is associated with recent plutonism (Fig. 4) and extension [38], and Java is associated with active volcanism (Fig. 3) typical for magmatic arcs along convergent margins or mid-oceanic ridge settings. Other examples for the Java-type are geothermal play systems in Iceland, which are related to a mid-oceanic ridge environment at a divergent plate margin. Plutonism controlled geothermal systems are typically located along continent-continent convergent or transform margins with recent magmatism and with (e.g. Larderello) or without (e.g. the Geysers) recent recharge of meteoric water [44]. In Laderello, 1.3–3.8 Ma granite intrusions are associated with young (0.3–0.2 Ma) magmatism. This magmatism generates a fluid-dominated (K-horizon) layer above the granite and a vapor-dominated (H-horizon) layer above the fluid-dominated layer. Pliocene extension associated with the emplacement of magmatic rocks generates low-angle normal faults that control the recharge of meteoric water into the high temperature system [38]. The Geysers field is another example of this play type, where a large felsic pluton provides the heat source for a vapor dominated fluid in porous meta-sedimentary reservoir capped by a low permeability serpentinite, mélange and meta-greywacke [44] (Fig. 4). The lack of natural recharge requires injection of treated sewage to keep the recovery at a high level [45].

Indications and exploration methods for magmatic (both volcanic field and plutonic) geothermal play systems are the following:

4.1.1.1. Typical reservoir rock types. Various types of volcanic rocks (various types of basalt, intermediate to felsic lava flows, ash-flow tuffs) and sedimentary rock. Indicative rocks are travertine deposits at the end of outflow zones.

4.1.1.2. Typical fluid types. Upflow zone: acid sulfate waters, gas from magma chamber: SO_2, HCl, HF, CO_2, H_2S, low pH from 0–3 [9].

Outflow zone: Sodium chloride, neutral to alkaline pH, mixing with meteoric water, Ca-rich, low-Mg, Gas: CO_2 and H_2S.

4.1.1.3. Typical exploration methods

- Detailed study of geothermal surface manifestations, hydrogeological regimes and geological settings, as well as geochemical analysis of streams, diluted thermal fluids, hot springs and groundwater wells.
- Resistivity surveys (Magnetotelluric) to identify the high resistivity anomaly of upflow zone.
- The concept of minimum power potential is based on observed natural heat loss over a thermal reservoir [46], from which it is assumed that thermal fluids causing observed positive temperature anomalies at the surface can be produced by an unspecified number of wells. This method requires an extensive program of shallow temperature measurements. Assessments of heat loss in these systems are often underestimated and inaccurate. The method was developed 30 years ago when computer power and software was not available to calculate fluid volumes from 3D geological models at certain depths. Today, remote sensing and software solutions deliver much more accurate results.
- Only at upflow zones: empirical geothermometers (Na–K–Ca) [47].
- At upflow and outflow zones: thermodynamic geothermometers [48], if not contaminated with Mg-bearing surface water.

4.1.1.4. Typical targets. In magmatic settings, such as volcanic arc regions along convergent plate boundaries, the upflow region is typically the target, rather than the outflow region, because of higher temperatures.

4.1.2. Non-magmatic geothermal plays – extensional domains

Non-magmatic convection-dominated geothermal play systems are either fault controlled or fault-leakage controlled. In purely fault controlled play systems, convection occurs along the fault and is commonly combined with infiltration of meteoric water along the fault [49]. In fault-leakage controlled play systems, the fluid leaks from the fault into a permeable concealed layer. In turn, fluids can move from a permeable layer into the fault zone and from there to the surface (Fig. 5). As thermal fluids move away from the upwelling zone along a fault zone, they mix with cooler groundwater or meteoric water, as indicated by an increase of bicarbonate and magnesium and decrease of boron, sulfate and chloride [50,51].

The Great Basin in the western U.S. is an example of a region that hosts predominately fault controlled geothermal plays [22,52–54]. The Great Basin, as part of the northern Basin and Range Province, has experienced large-magnitude extension crustal thinning and emplacement of metamorphic core complexes throughout the Cenozoic [55]. All of these factors cause elevated heat flow. Late Cenozoic intrusions and volcanism coincided with extension, but generally ceased by the late Miocene. Although several small Cenozoic volcanic centers still exist in the Lake Lahontan Basin, most of the geothermal play systems appear to be associated with

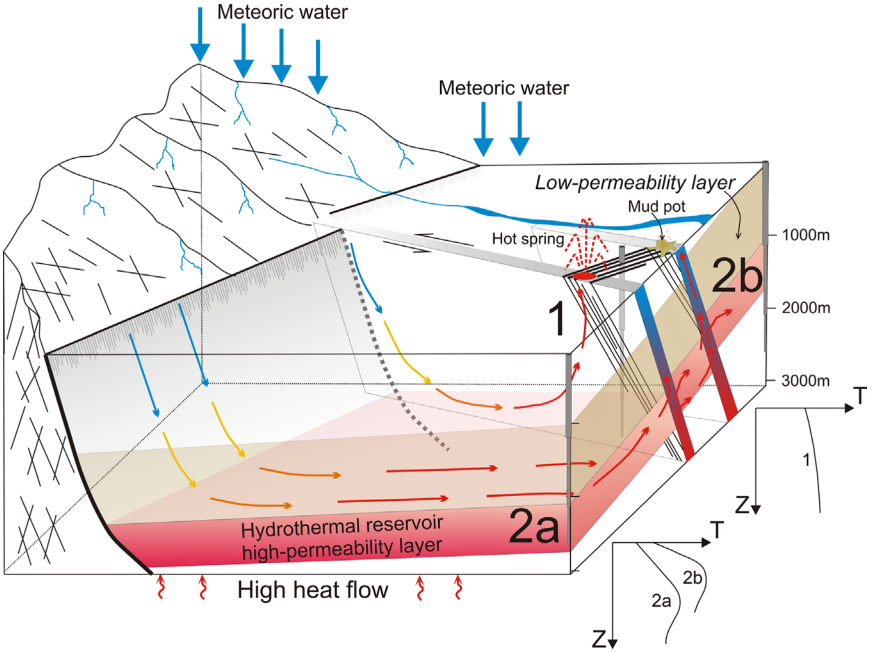

Fig. 5. Non-magmatic active geothermal play system in active extensional terrains with different types of reservoirs (1, 2a and 2b) (compiled from [9,16,22,49]). Type 1 is a convection cell from infiltration to discharge along one fault. Temperature gradient is gradually increasing at well site 1. Type 2a and 2B are fault leakage controlled plays. The temperature gradient of a well drilled into such an area rises up to the permeable layer and drops below the layer (well 2a and 2b).

Quaternary normal faulting and are clearly non-magmatic [56,57]. Ongoing geodetic measurements indicate continued trends of rapid extension, suggesting that the crust is even thinner beneath the Lake Lahontan Basin than in the surrounding areas [58].

New seismic data indicate that crustal thickness ranges between 24–44 km and even thinner crust along the NW-SE trending Walker Lane belt [59]. These zones of thinner crust correspond to regions of upwelling asthenosphere and higher heat flow where the Moho has moved closer to the surface. Fluids circulate deep within the crust and transport heat to near the surface along permeable faults [60]. The age and origin of thermal fluids is still controversial but seem to be of meteoric origin [61] and of Pleistocene age (10–30 ka), when the area was covered by the large Lahontan Lake system. Most of the data from Dixie Valley indicate ages of thermal fluids between 12–14 ka, whereas the recharge age is between 900a and 5 ka [62]. Only some of these geothermal plays have surface expression; most of the resources are concealed. Another example of extensional terrain geothermal plays is Western Turkey [36] or tectonically active intra-continental rift grabens, such as the East African rift or the Upper Rhine graben in Central Europe.

Fluid flow along faults is controlled by the state of stress in the crust. Fault stress modeling could help to identify favorable faults for geothermal energy production from a complex fault pattern [53,63]. Dilational or shear dilation faults seem to be most the favorable structures [54,64]. Due to the presence of fossil geothermal fluids, proper re-injection and maintenance of reservoir pressures are crucial to the management of reservoirs in the Great Basin. Re-injection into fault controlled geothermal plays requires a careful selection of well sites to avoid thermal breakthrough of injected cooled water along permeable faults to the production wells. Injection and production wells should not be placed along the same fault in the same fault block.

Characteristic for non-magmatic convection-dominated geothermal plays are as compiled in the following section:

4.1.2.1. Typical reservoir rock types. Various from volcanic, plutonic or to sedimentary rock; travertine and silica at hot springs are indicative for reservoirs at depth.

4.1.2.2. Typical fluid types. High-Cl and high-HCO_3, low-(Ca, Mg).

4.1.2.3. Typical exploration methods

- MT (magnetotelluric) is the standard method for reservoirs >500 m depth combined with surface mapping and shallow temperature drilling [65].
- Other resistivity methods are used, such as AMT (audiomagnetotellurics) and CSAMT (controlled source audiomagnetotellurics) for shallow reservoirs <500 m depth on a case-by-case basis [65].
- Density methods, such as gravity and recently microgravity, are used to identify lithology, dense alteration (silicification), and volcano or basin geometry. Active seismics are used to develop seismic velocity models.
- Reflection seismic in volcanic areas often gives poor results and cannot identify hot fluids, but in a graben and basin setting it is useful to define structural settings.
- (Airborne) magnetic surveys are employed to map near-surface alteration and iron-rich volcanic rocks.
- Geochemistry combined with geologic mapping and resistivity surveys to map clay cap alteration and leaking points.
- Self-potential methods (natural surface voltages) are used for mapping hydrology in areas of low relief.
- All methods combined with differential Global Positioning System contribute to geothermal potential maps [66], and regional geothermal Geographic Information System (GIS) can be developed [67].
- Satellite Interferometric Synthetic Aperture Radar (InSAR) has been recently applied to image structures with lateral outflow of thermal fluids by showing areas of subsidence associated with fluid production and areas of uplift related to injection [68].
- Analysis of fault evolution to identify the fault blocks and settings with higher fracture density [52].

4.1.2.4. Typical targets. Dilational and shear-dilational faulting regimes [22]; fault intersections; and extensional domains in convergent settings, especially when linked with high topographic relief. Mountain ranges nearby where meteoric water infiltrates to deep hot regions might represent favorable targets in fault controlled non-magmatic geothermal systems. Convergent settings contain a variety of extensional domains including back-arc basins, pull-apart basins or graben structures. Hydraulic gradients and potential fluid pathways along faults need to be identified to utilize the geothermal potential of these sites. Combined with new geothermal plant technologies, these fault controlled geothermal systems of medium temperature (150° ± 30 °C) could be developed to small-scale geothermal programs providing energy for small communities even in remote areas. Such concepts would increase the geothermal potential of convergent plate settings.

4.2. *Conduction dominated geothermal plays*

Geothermal plays in passive plate tectonic settings where no asthenospheric anomalies occur (e.g. passive continental margins and intracontinental tectonically inactive areas) are mainly conduction-dominated, as exemplified by the conductive settings of sedimentary basins. In conduction-dominated hydrothermal play systems, deep aquifers are heated by a near normal heat flow. In

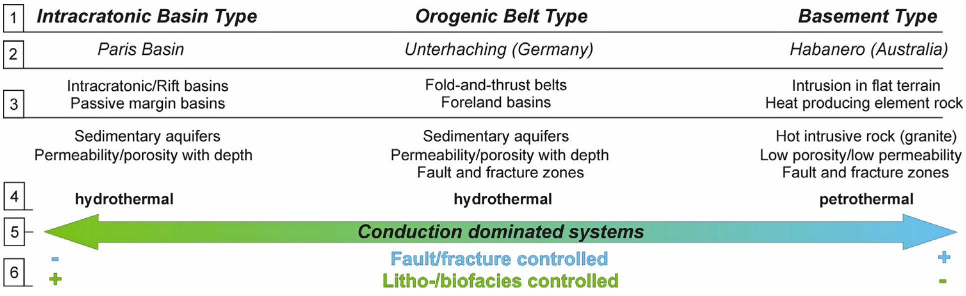

Fig. 6. Conduction dominated geothermal play types, ranging from intracratonic basins to foreland basins of orogenic belts with its characteristic foredeep to basement (igneous or metamorphic) provinces. Geologic controls in conduction dominated plays are either litho- or biofacies of sedimentary rock and faults and fractures. Typically these play types are lacking active faulting and seismicity. Labels are as in Fig. 2.

basement or crystalline igneous rocks, referred to as petrothermal systems, locally elevated heat production originates from granites and can lead to a significant positive temperature anomaly, such as at the EGS reservoir in granitic rock in Soultz-sous-Forêt [69]. Petrothermal EGS resources lack producible formation fluids and require that fluids are injected through an artificial fracture network.

Conduction-dominated geothermal play systems came into focus due to new developments in EGS technologies. The reason for this focus is that the naturally non-commercial conditions associated with conductive geothermal play systems can be improved by reservoir creation in crystalline rock or reservoir enhancement in tight i.e. low permeability aquifer rocks. These systems can be classified into hydrothermal and non-hydrothermal (or petrothermal, i.e. hot dry rock systems) with a permeability anisotropy predominantly being fault controlled and/or litho- or biofacies controlled (Fig. 6). Applying advanced reservoir technology and engineering to developing man-made geothermal technology reservoirs and improving their efficiency is more important in conduction dominated play systems than in convection-dominated play systems. Therefore, classifying and understanding potential EGS settings in conduction-dominated play systems is essential. This classification contains three different settings: (I) the intracratonic basin type, (II) the orogenic belt type and (III) the basement/crystalline rock type. These types are further considered with respect to the porosity-permeability ratio of the reservoir rock and the absence or presence of producible fluids in the reservoir (Fig. 6).

4.2.1. Igneous geothermal plays– basement type

Crystalline (e.g. granitic) rocks host vast resources of heat energy in igneous provinces, which often underlie large areas of continents. These low porosity-low permeability rocks require reservoir development by stimulation techniques to allow circulation between injector and producer wells, with the rock mass acting as the heat exchanger. This concept is referred to as Hot Dry Rock (HDR). The engineering of an augmented permeability structure between the wells constitutes a primary challenge of EGS development in crystalline rock. The most important factor for reservoir engineering in these plays is the stress field. The magnitude of the intermediate principal stress is of particular importance, because this controls the in situ stress regime. Geomechanical parameters and failure models of the reservoir rock under stimulation conditions need to be considered. To produce electricity reasonably efficiently requires water temperatures exceeding 180 °C [70]. The generally accepted performance target for a well doublet is a production rate of 50 l/s and minimum rock temperature of 200 °C (e.g. [71,3]). However, the specific end-user needs must be considered, and perhaps crystalline rocks can be used for direct heat as well as electricity in areas where there are low-temperatures. In Alberta, for example, lower temperature in the basement from the Alberta Basin would help to augment the efficiency of oil sand production by replacing volumes of natural gas with geothermal energy [72]. In Central Europe, the population density and infrastructure justify district heating as prime use of geothermal energy. In the following chapter, geological environments of EGS types are reviewed. The most important HDR sites are summarized in Table 2.

Characteristic for igneous basement geothermal plays are:

4.2.1.1. Typical rock types. Rocks with elevated heat production containing radiogenic heat producing elements as Thorium or Uranium as found crystalline rocks and intrusive rocks.

4.2.1.2. Typical fluid types. Need to be injected.

4.2.1.3. Typical exploration methods

- Depending on the temperature, depth and lithological sequence, several geophysical methods are used, such as magnetotelluric and gravity to detect the granitic body and reflection seismic to identify facture zones.
- Geosystem analysis is necessary to estimate stress field and hydromechanical conditions. Relatively early the first exploration well is drilled to obtain petrophysical and mineralogical parameters and to verify the stress field for stimulation concepts.

4.2.1.4. Typical targets. Crystalline rock and fracture zones therein.

4.2.2. Non-magmatic geothermal plays – intracratonic basins and orogenic belts

Conduction dominated geothermal play systems without active igneous activity cover the different types of geologic settings located within intracratonic basins (i.e. within the stable continental crust) and within orogenic belts and associated foreland basins. The tectonic activity in these settings is commonly low to absent. Advective heat transport may play a role in mountainous areas of the orogenic belt type, where high permeability domains and deep rooted faults allow deep circulation of meteoric water. This type of circulation is often associated with the subsequent formation of hot springs [77]. Geothermal play systems in mountain belts are rarely associated with hydrothermal reservoirs, but are rather the result of deep circulation systems associated with complex major crustal scale faults. These areas typically contain low to moderate heat flow [78]. In sedimentary basin settings, conduction-dominated hydrothermal plays are located in deep aquifers heated by a near normal heat flow. Effectively, sedimentary basins host prime aquifer systems from where the thermal water can be produced and utilized. The exploration target is to identify high porosity/high permeability or high porosity/low

Table 2
Selection of key sites for HDR activities in different tectonic regimes and with different major lessons learned during development or operation. HPHT-High Pressure High Temperature conditions.

Project	Activity time	Tectonic regime	Depth (km)	Temperature (°C)	Lessons learned
Fenton hill new Mexico/USA	1972–1996 (research)	Magma chamber under a young caldera normal faulting [73]	2.8 3.6 4.2	320	No significant temperature drop after 11 months water loop > 3 wells are necessary for efficiency
Rosemanowes/UK	1978–1991	Batholith normal faulting [74]	2.5	85	Stimulation and proppant techniques, multi-cell reservoir design [74]
Soultz/France	1987-present (research)	Horst at upper hine graben normal to strike-slip regime [75]	3.3 5	200	Stimulation techniques Induced seismicity
Cooper Basin/ Australia	2003-present (commercial)	Inverted basin reverse faulting regime [76]	4.2	240	Borehole and reservoir stability under HPHT conditions

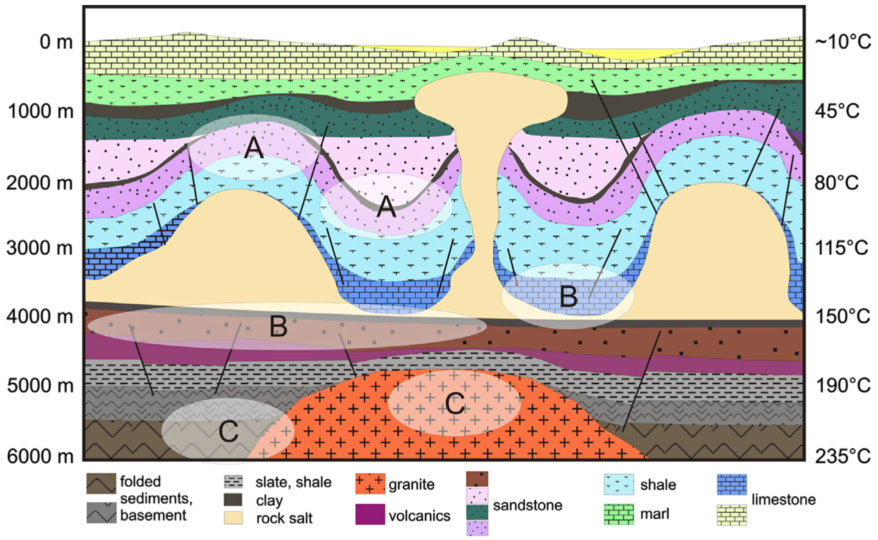

Fig. 7. Schematic cross section of an intracratonic sedimentary basin and various geothermal play types at different depth and temperature ranges. Temperature is an average assuming a geothermal gradient of 32 °C/km. A – Geothermal plays above 3 km depth with temperature suitable for district heating, B – Deep geothermal plays below 3 km depth suitable for heating and electricity, C – Very deep geothermal plays below 4 km depth as potential HDR systems.

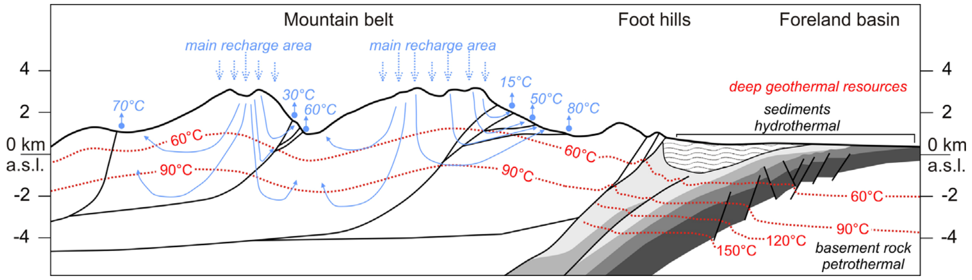

Fig. 8. Geothermal play types in orogenic belt and adjacent foreland basins. Red lines – Schematic isotherm distribution, recharge locations, fault geometry and basin geometry after Craw et al., [83]. Blue lines – Water flow lines result from heat advection and topography controlled hydraulic head, blue arrows – Discharge temperatures [86]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

permeability domains at different temperature levels. Commonly, these hydrothermal systems occur at great depth (> 3 km). Low permeability domains in sedimentary basins may represent EGS resources where the permeability (and hence the productivity) need to be enhanced by a variety of reservoir stimulation techniques [79,80]. However, it is debatable if reservoir stimulation in tight sedimentary rock provides sustainable and sufficient flow rates when substantial natural fracture permeability is lacking [3]. The success of EGS in tight, hot sedimentary aquifers may be strongly affected by the storage capacity expressed by porosity of the host rock [4]. The heat content of the fluid in the porous layer setting is strongly affected by the basin geometry, an artifact of the basin type and evolution (Fig. 7).

Two different basin types have been distinguished for hydrothermal sedimentary energy systems: (I) Extensional or lithospheric subsidence basins, such as the Central European Basin System, and (II) foreland basins within orogenic belts, such as the Molasse Basin of the Alps or the Western Canada Sedimentary Basin associated with the Rocky Mountains. The sedimentary sequences in foreland basins are influenced by significant crustal subsidence (up to several kilometers) towards the orogen due to the weight of the thickened crust of the orogenic belt and loading of erosional products from the mountain belt on the non-thickened crust. The result of this process is lithospheric bending that forms areas of local extension and normal faulting in compressional plate tectonic settings (Fig. 8) [23]. The wedge shape of foreland basins with the down-bending of aquifer rock may cause local positive geothermal gradients, especially when faults or highly permeable layers allow advective heat transport from the deeper to the shallower parts of a foreland basin. Faults and reef complexes are prime reservoir targets in the carbonate rock of the Bavarian Molasse Basin, Germany [23]. Highly permeable, porous sandstone in the Williston Basin of Saskatchewan, Canada and North Dakota, U.S.A. host potential geothermal resources [81].

In the adjacent mountain belt, groundwater flow and thermal gradient are strongly influenced by large hydraulic heads resulting from the pronounced topographic relief [82,83]. The great depth and small width of mountain belt valleys result in relatively shallow penetration of recharged water, which then discharge on valley floors or shallow valley slopes [81]. Thermal highs occur underneath high mountains and thermal lows beneath the valleys (Fig. 8), resulting in varying local thermal gradients due to meteoric water circulation. Beneath high mountains at about 15–20 °C and beneath deep valleys 30–50 °C [83,77]. The near surface geothermal gradient can be disturbed in recharge areas of the mountain ranges where infiltrating water cools the rock mass. Similarly, the heat flow ranging from low to moderate to high in mountain belts [77] needs to be corrected by the amount of heat loss during the ice-age and other paleoclimatic effects [84]. The formation of geothermal plays in mountain chains is dominated by the bulk-rock permeability of the host rock. The permeability allows the infiltration of meteoric water, especially in the high relief areas. Highly permeable faults act as fluid flow pathways to discharge spring locations. Grasby and Hutcheon [77] point out that high permeability of fractured rock, groundwater flux and deep circulating fluids, combined with advective heat transport are most critical for the formation of hot springs in mountain belts. Hot springs temperatures depend on the transit time of the infiltration water, the circulation depth of the fluid, the rock permeability, geometry of major thrust faults, lateral ramps and bedding planes (Fig. 8). This type of geothermal play might be vulnerable to thermal water production if the production rate is not adjusted to the recharge volume over time. The transit time for meteoric water in mountainous areas ranges from several decades to over 5,000 years depending on the rock's effective porosity [62]. The transient time is the time that the fluid requires to migrate from the recharge area to the spring. Mountain belts and adjacent foreland basins are referred to as Cordillera-cum-foreland basins in the classification scheme for groundwater flow systems after Toth [82]. Mountain belts and their associated foreland basins are hydraulically disconnected by the frontal fault of the foothills due to the fact that most of the water recharged in the mountains discharge in valley floors at about the same elevation as the average foreland basin elevation. Effectively, circulating meteoric water in mountain belts has a shallow penetration depth, with not much water left for deeper circulation towards the foreland basin [82].

In contrast to foreland basins, intracratonic basins that originate from lithospheric subsidence are commonly divided into several sub-basins [85]. The long history of intracratonic basins produce several kilometer thick sediment fills that span a wide range of deposits, including fluvial siliciclastics, marine carbonates, muds and evaporites. Basin evolution and subsidence rates have a major effect on faulting and fault pattern characteristics, diagenetic processes and the resulting increase or decrease of porosity. High and low porosity domains are controlled by lithology, faulting, and diagenesis [86,87]. Permeability anisotropy is controlled by either lithology or faults or both. Recently, new concepts for complex coupled process modeling have been developed for geothermal systems. These models incorporate geomechanical facies at various scales [88], which require the examination of facies-dependent geomechanical parameters [88].

Application oriented basin analysis and sequence stratigraphy is the key to successfully developing conduction dominated geothermal plays in sedimentary basins. As schematically illustrated in Fig. 7, geothermal reservoirs are located in different basin portions depending on the internal present-day structure of the basin. Crustal regions above salt formations might be suitable geothermal reservoirs for district heating, because the high thermal conductivity of salt rock causes local positive thermal anomalies in the overburden of salt accumulations [89–91]. In deeper parts of the basin (below 3 km depth), geothermal systems might be suitable for power and heat production, provided EGS technology is applied to enhance productivity up to the required flow rate of 50–70 l/s [92,3,93]. A critical parameter for EGS technology is the in-situ stress field, because large scale injection and successful hydraulic stimulation require knowledge of stress direction and magnitudes (e.g. [94,26]). The slip tendency method is an appropriate technique for estimating the fault reactivation potential prior to stimulation. This is an essential measure for minimizing induced seismicity during large scale injection [25].

The geological environment of sedimentary basins is generally well studied through hydrocarbon exploration, and substantial databases from seismic surveys and drilling can be re-evaluated for geothermal assessment and field development [27]. Exploration methods for geothermal targets might differ slightly from hydrocarbon exploration, since temperature needs to be mapped in addition to reservoir quality. Recent advances in the combined use of neural networks and subsequent joint interpretation of magnetotelluric data, seismic tomography and lithostratigraphy might lead to new exploration strategies for these geothermal

Table 3

Catalog of geothermal play types applying the scheme from Figs. 2 and 5. Examples represent typical geologic systems in which geothermal reservoirs are already discovered and developed. These examples might act as typus localities for respective geothermal play types. Reservoir characteristics host rock, fluid type and temperature range refer to the examples and do not reflect necessarily general characteristics. Categories of fluid types: Basinal fluids are saline brines and NaCl-dominated, infiltration fluids are carbonate waters and HCO_3-dominated, crustal fluids are acidic and H_2S/HCl-dominated (modified from [80]).

Heat transfer	Geologic controls	Geologic system plate tectonic setting	Geothermal play type	Index	Examples	Characteristics		
						Host rock	Fluid	Temperature in (°C)
Convection Dominated (CV)	Magma chambers in active volcanic fields	Volcanic arc regions at subduction zone	Volcanic type	CV1	Java - Kamojang (Indonesia) [99] Taupo – NZ [100]	Andesites Rhyolithes	Crustal fluids mixed with infiltration fluids (meteoric, seawater)	70–320
		Mid oceanic Ridges (MOR) Mantle plumes (hot spots)			Reykjanes – Iceland [101] Hawai (USA) [102]	Basalt		
	Crystallizing magma, intrusions + active faulting	Decrescent volcanism in steep terrain at young orogenic belts	Plutonic type	CV2	Larderello (Italy) [103] The Geysers (USA)	Sediments Granite, Grabbo	Infiltration and crustal fluids	100–350
	Active faulting (natural seismicity)	Metamorphic core complexes Pull-apart basins Back-arc basins Intracontinental rifts (grabens)	Extensional domain type	CV3	Great Basin (Basin and Range) – USA [22] Western Turkey Soultz-sous-Forêt (France) [71]	Volcanic sedimentary rock	variable	150–240
Conduction Dominated (CD)	Lithofacies (grain size, mineralogy)	Intracontinental rift basins	Intracratonic Basin Type (hydrothermal)	CD1	North German Basin [27]	High–low permeability fluvial sediments	Basinal fluids	< 150
	Biofacies (fossil content)	Passive margin basins						
	Litho-/biofacies + faults/fractures	Fold-and-Thrust-belts Foreland basins	Orogenic belt type (hydrothermal)	CD2	Molasse Basin (South Germany) [23]	High–low permeability marine sediments	Infiltration fluids (basinal fluids possible)	< 160
	Faults/fractures	Intracontinental intrusion in flat terrain	Basement type (petrothermal hot dry rock)	CD3	Cooper Basin (Australia)	Granite rock with high radiogenic heat production	–	150–320

plays [95,96]. Target zones, their characteristics and exploration methods are:

4.2.2.1. Typical reservoir rock types. Terrestrial sedimentary rocks such as eolian and fluvial siliciclastic sequences and shallow to deep marine sediments from carbonates sequences to shale and pelagic clays; deltaic and pelagic sediments can be source rock for H_2S.

4.2.2.2. Typical fluid types. High-Cl brines.
Infiltration water, rich in HCO_3^-.

4.2.2.3. Typical exploration methods

- D/3D seismic surveys.
- Re-processing of existing seismic reflection as often available (but not always accessible) from hydrocarbon exploration.
- Reconnaissance from existing well and seismic data.
- Joint interpretation of magnetotelluric and reflection seismic data.
- Appraisal wells including well log and core data. Often, appraisal wells are planned as future operating well why it is drilled in larger diameters compared to gas exploration wells.

4.2.2.4. Typical targets. High porosity/high permeability domains or high porosity/low permeability domains in sedimentary rock; fault and fracture zones, damage zones of faults, and karst zones in carbonate rock.

5. Discussion

The new catalog for geothermal play types based on geological controls outlined here allows a better evaluation of site-specific exploration, field development and overall selection of geothermal applications. Table 3 demonstrates the application of the catalog to existing discovered geothermal fields worldwide by ordering geothermal play types according to their geologic habitat and dominant geologic controls. Moreover, the catalog allows comparison with hydrocarbon play systems, which, in turn, facilitates selection of appropriate technology transfer from hydrocarbon to geothermal reservoirs. The comparison with hydrocarbon reservoirs applies especially to conduction dominated geothermal play systems and the related basin types. Hitherto, only hydrothermal sedimentary play systems are developed for commercial use, with a focus on foreland basins. This fact is exemplified by the growing geothermal industry in the Molasse Basin in Germany, Switzerland and Austria (e.g. [87,97,98]).

One approach for evaluating conduction-dominated geothermal play systems is by their ratio of porosity to permeability. In Table 4, different discovered geothermal reservoirs of both basin and basement play type are compiled along with their depths and reservoir rock type. The depth of geothermal plays might be an important factor for successful long-term reservoir production. Typically, the depth of a reservoir correlates with a reduction in permeability and porosity due to high in situ stress and diagenetic effects, both of which promote cementation. As shown at the EGS research site Soultz-sous-Forêt, the most productive depth range is between 1.7 and 3.5 km. However fault and fracture zones can have positive effects on permeability at greater depths [104].

In Fig. 9, the geothermal play systems from Table 4 are illustrated in a porosity-versus-permeability diagram with regard to reservoir rock type. A similar reservoir classification scheme has been developed by Salley [85] for hydrocarbon resources.

Table 4
Compilation of different geothermal reservoirs, their host rock formation, depth, porosity and permeability. CD1-Intracratonic basin play type, CD2-Foreland basin play type, CD3-Basement play type. The type indices refer to indices in Table 3. Porosity and permeability data from: (1)Personal comment Blocher and Hassanzadegan (GFZ) and references indicated by square brackets.

Type	Geological system	Formation/rock type	Depth range	Porosity in %	Permeability in mD
CD1a	North German Basin	Lower permian Rotliegend formation/red bed sandstone [106,107]	4.0–4.2 km	⌀ 10 (8–12)	⌀ 1–10 (0.01–120)
CD1b	North German Basin	Upper Triassic stuttgart formation/fluvial weakly cemented sandstone [108]	630–710 m	⌀ 26 (5–35)	⌀ 100 (0.02–5000)
CD1c	North German Basin	Upper Triassic exter formation/fluvial sandstone [87]	0.8–2.6 km	17–31	500–1000
CD1d	Alberta Basin, central part	Cambrian Basal sandstone [33,105]	2.5–5 km	10–19	0.4; 20-500
CD2a	Bavarian Molasse Basin	Upper Jurassic Bankkalk formation/massive carbonate rock, partly dolomitized [23,98,109]	3.2–3.6 km	(1)18.1	(1)2.5–0.003
CD2b	Alberta Basin, central part	Devonian Wabamun; Nisku; Cooking Lake formations/carbonate rock [33]	1.2–1.7 km	5.2,10.4, 8.3	4.8; 21.4; 27.7;
CD2c	Bavarian Molasse Basin, Western Part	Upper Jurassic/Tuberoidic limestone [23,104]	3.2–3.6 km	(1) ⌀ 4.9	(1) 0.1–0.001
CD2d	Bavarian Molasse Basin	Upper Jurassic/Massenkalk facies, reef limestone [87,97,109,110]	3.2–3.6	2 to 2.5	2563; 6x10^3;
CD2e	Alberta Basin, central part	Devonian Leduc formation/reef complex [33]		7.3	141.7 (0.01–4700)
CD3	Basement rock Rhine graben shoulder (Soultz)	Crystalline rock/Granitic rock [104,111]	1–1.4 km 3.7–5 km	15 1	1–10 0.001

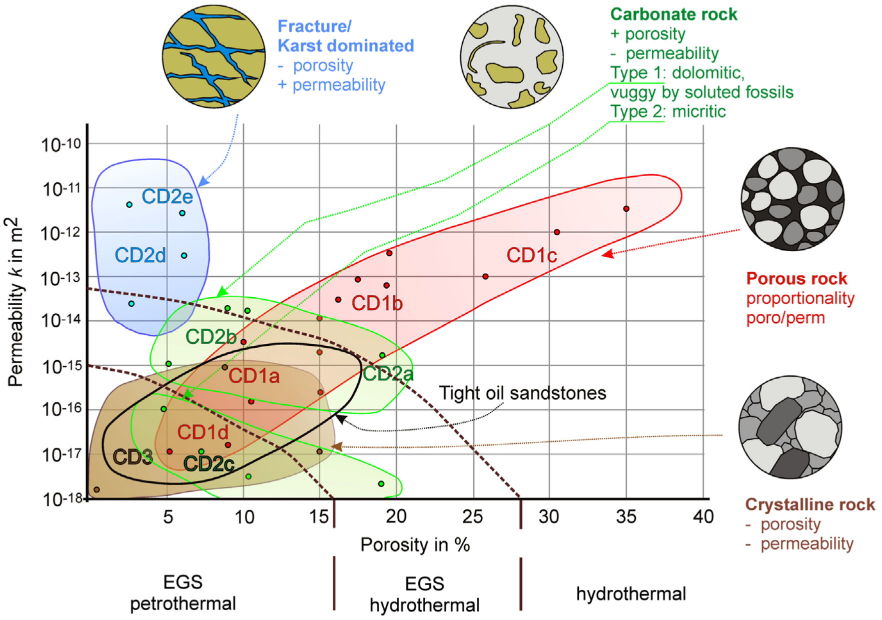

Fig. 9. Porosity and permeability relation of different geothermal reservoirs with data points from Table 4. Porosity/permeability domains are characteristic for different reservoir rock types. Numbers refer to type indices in Table 4. Reservoir performance as enhanced geothermal system (EGS) in petrothermal or hydrothermal setting is similar to tight oil reservoirs in the Alberta Basin. Data points from references in Table 4, tight oil reservoir ratio from Hartmann and Beaumont [86].

Carbonate rock with partly dissolved biogenic content and filled pore space due to secondary dolomitization has a high porosity versus a low permeability (type CD2a and b in Fig. 9), whereas karstic and highly fractured carbonate rock, such as reef formations, have a low porosity versus high permeability (type CD2e and 2d in Fig. 9). The commercial geothermal prospects in Germany are mostly in this latter reservoir type in a foreland basin play system and can be considered as hydrothermal systems that do not require EGS technology [87]. Sandstone formations are characterized by a proportional ratio of porosity to permeability, and this ratio is obviously controlled by depth (CD1a–d in Fig. 9). The deeper the sandstone formation, the less porosity and permeability, although subsidence of sandstone can have positive effects on porosity due to dissolved feldspar, carbonate and sulfate minerals in diagenetic zones at $>140\,^\circ\mathrm{C}$ [86]. However, quartz cement, illite and chlorite form as products from feldspar dissolution and can decrease porosity [105]. As a result, sandstones shallower than 1 km have a high porosity/permeability ratio and can be classified as hydrothermal systems, whereas deeper sandstone formations have a lower permeability and can be classified as EGS hydrothermal systems, which require technology to increase reservoir productivity. Crystalline rock, as found in Soultz-sous-Forêt, can be classified as an EGS hydrothermal play if porosity and permeability is high enough as in the upper portions of the Soultz-sous-Forêt geothermal field, or EGS petrothermal if porosity is so reduced that producible fluids are absent (CD3 in Fig. 9). In this latter case, fluids have to be added to the systems, as described above under the Hot Dry Rock site in Table 2.

Comparable with hydrocarbon reservoirs, most geothermal plays have a similar porosity/permeability ratio as tight sandstones (Fig. 9) [86]. This opens the possibility of technology transfer from unconventional hydrocarbon resources to geothermal resources. Experience from reservoir quality evaluation, stimulation, system optimization, risk management and induced seismicity can be adapted from unconventional hydrocarbon technology to EGS resources and vice versa. In contrast to unconventional hydrocarbon resources, the environmental benefits of geothermal resources are near zero greenhouse gas (GHG) emissions, along with renewable energy production. Consequently, the technology used in unconventional hydrocarbon resource development can be employed for green energy production. Considering the impact of GHG production on climate change and the growing public demand for sustainability and environmental protection, an increased use of geothermal energy can gradually lower GHG emissions. Depleted hydrocarbon brown fields could be re-used as geothermal resources and therefore renewable energy systems. Given the fact that geothermal energy will become increasingly economically competitive with oil and gas [2], geothermal energy systems as unconventional reservoirs are both environmentally and eventually economically attractive.

6. Conclusion

Research on the geological characteristics of natural geothermal resources is essential to adapting stimulation and drilling techniques that drives down the costs of EGS development. The ability to create man-made geothermal reservoirs consistently is mostly limited by a lack of understanding of how geothermal reservoir formation occurs in nature. A geological-based geothermal play type catalog helps in understanding the nature of a resource and defining appropriate exploration strategies, reservoir evaluation and quantification of the geothermal potential.

There are two primary geothermal play types, the convection-dominated play systems, which include the vast majority of operating geothermal power plants world-wide, and the conduction-dominated geothermal play systems, which include hydrothermal and petrothermal systems in sedimentary basins or crystalline rock. Conduction-dominated play systems can be described by the ratio of porosity versus permeability and with regards to the application as EGS petrothermal, EGS hydrothermal or pure hydrothermal.

The advantage of a geologically based catalog scheme is the adaptation of site-specific exploration and technology strategies for field development. This scheme is in contrast to catalog schemes based on temperature, which say nothing specific about the reservoir itself or best development practices. Targets for geothermal resources are often coincident with other energy resources including coal bed methane and unconventional gas and oil. The knowledge of other factors such as energy storage, groundwater systems, coal mining, and carbon geo-sequestration need to be considered in evaluating the geothermal potential of a region. The relationship between these competing geological resource potentials needs to be understood for the best decision at site and depth. Trans-national projects, such as the EU-funded GeoMol project, www.geomol.eu, which is aimed at collecting and evaluating data from the Alpine foreland basins in Europe, are a step in the right direction towards a sustainable utilization of limited subsurface geo-resources, especially in highly populated areas as Central Europe.

The geological system based catalog of geothermal reservoirs might also be important for optimal economic and environmental configurations of geothermal energy conversion. Understanding a geothermal reservoir as part of a geologic system helps to quantify the geological uncertainty that needs to be included into economic optimization concepts.

Geothermal energy from EGS and hydrothermal resources is still in the technology development stage. As a result, there is a high degree of uncertainty in cost estimates for producing heat and electricity from deep geothermal resources. Worldwide, though, there is a significant ramp up in research and development around these resources, so that their potential can be realized. It is likely that costs will reduce with more efforts on improving geothermal technology, along with the growing interest in geothermal energy utilization.

Remarkably, the technology used for unconventional oil production from sandstones and carbonates is similar to geothermal EGS technology. If reservoirs are categorized as a function of their porosity to permeability ratio, it becomes clear that most EGS geothermal resources and unconventional tight sandstones belong to one reservoir type. Cataloging geothermal resources by their geologic controls helps to adopt site-specific exploration, field development and energy production. Successfully developed methods in exploration and geothermal energy deployment can be adopted within one geothermal system type. Specifically, stress field analysis, quantitative structural geology, reservoir geomechanics and reservoir engineering are key topics in both geothermal and unconventional tight reservoirs. In contrast to unconventional hydrocarbon resources, geothermal energy production emits nearly no greenhouse gases (GHG). There is enormous potential for technology transfer; extraction technologies used for unconventional hydrocarbon reservoir extraction could be employed for a green energy resource. The classification scheme of petroleum resources may encourage the geothermal community to classify geothermal resources by their chance of commercialization, including categorization based on technological improvements. Recognition and understanding of a geologic environment, with its characteristic controls, are the fundamental first step towards a classification scheme for geothermal resources.

This introduction to a new catalog may not be a complete picture of geothermal play systems, but it might provide a logical framework for a new scheme for typifying geothermal plays. Hybrid play types may exist, for example in the East African rift system, where crustal extension causes thinning of the crust and the subsequent formation of magmatic intrusions and volcanism. Effectively volcanic (CV1 in Table 3) and fault-controlled extensional domain play types (CV3 in Table 3) may co-exist in the same geologic system. Generally spoken, each play type lies within a geological continuum, and it is possible for specific geothermal systems to have geological characteristics of more than one play type. This play type catalog, however, shall help to accelerate technology and knowledge transfer within one appropriate play type. As such, this new catalog is oriented towards successfully developing geothermal resources worldwide. It is now possible to better compare geothermal plays with hydrocarbon plays by contrasting their geological environment and geologic controls. It might be a feasible vision to transfer technology already developed for unconventional hydrocarbons to the green sustainable energy of geothermal resources.

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