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# Cataloging Worldwide Developed Geothermal Systems by Geothermal Play Type

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## ABSTRACT

The Play Type is a common concept in the exploration for subsurface natural commodities. A play type describes the generic geological environment that might host an economic accumulation of the commodity. The identification of a certain play type has implications for exploration and extraction strategies. In geothermal exploration, a systematic worldwide play type concept is presented which is based on geological controls on the accumulation of extractable subsurface heat. It groups geothermal systems according to geological setting rather than based on parameters such as temperature or thermodynamic properties, which are not known before exploration drilling and well testing is undertaken.

We have categorized over 90% of the World's developed geothermal resources into convective and conductive play types with further subdivision into their geothermal play types divided according to tectono-structural setting and the nature of the heat source (magmatic or non-magmatic).

Currently the World's geothermal developments are dominated by convective magmatic or plutonic play types but over recent years there has been increasing attention on exploiting the basin and range play (fault-controlled in extensional terrains) type, particularly in the Western United States and Western Turkey. Exploitation of conductive systems is at present restricted to small-scale developments in Germany and experimentation in Australia where unique situations have encouraged research and development of these systems. It is envisaged that the basin and range play type will receive increasing attention as we move forward into the 21st Century.

## 1. INTRODUCTION

After more than 100 years of history in geothermal energy extraction, the geothermal industry should have reached a sufficient maturity such that one would expect globally consistent terminology for describing geothermal systems. In particular, a consistent pathway through the commercial development of geothermal resources would be expected, beginning with a critical assessment of the characteristics of the geothermal system to efficiently guide the long development pathway from exploration through to production. In spite of this expectation, however, there remains no standardized global approach to the assessment of geothermal resources.

Given the fact that geothermal systems are components of geological systems, one might expect that some form of geological system analysis would be a fundamental step in geothermal resource assessments and that geological features would be used to distinguish between different types of geothermal systems. However, the focus to date has tended to remain firmly on the development phase of geothermal projects, such that temperature is the common metric for geothermal resources classification (Muffler, 1979; Hochstein, 1988; Benderitter and Cormy, 1990; Sanyal, 2005).

Instead, the development of an appropriate exploration strategy should be based on an understanding of the geological setting, and on this basis predicting the kind of geothermal reservoirs it is likely to host.

The geological controls on the distribution of porosity and permeability, the nature and extent of the heat source, and the distribution of temperature (vertical or horizontal) have varying importance depending on the nature of the reservoir hosting the heat resource. A logical way to approach a geothermal project at an early stage is through a globally consistent play type concept based on geological criteria as introduced by Moeck (2014) and Moeck and Beardsmore (2014). We re-iterate the geothermal play type catalog here, introduce in this context the term *geothermal geology* and provide examples of play type categorization of producing geothermal fields from selected countries. Eventually, we demonstrate that this play type catalog is applicable worldwide and identify the play type from this categorization that hosts the largest proportion of current installed electrical generating capacity (MWe).

## 2. GEOTHERMAL PLAY TYPES

At the scale of geothermal systems, geothermal plays can be most broadly separated into two types related to the mechanism by which heat is transported into the reservoir: either the heat transport is dominated by convection or conduction. Whether convection or conduction dominates depends primarily on the characteristics of the heat source and the distribution of permeability within the host rocks at the system scale (Bogie et al., 2005; Lawless et al., 1995). It is important to recognize that convection and conduction are end-members of a heat transfer continuum. Conductive intervals always exist in localized parts of a convective regime (frequently, for example, on the outer margins of convective systems) while minor convective intervals can sometimes exist within conductive systems. For example, gravity-driven convection might occur within a discrete aquifer within a conduction-dominated system in steep mountainous terrain where recharge zones are at a higher elevation than discharge sites. Alternatively, buoyancy variations due to different concentrations of fluid salinity can result in local convection within sedimentary aquifers.

Geothermal play types in convection-dominated systems can be grouped into ‘Magmatic’, ‘Plutonic’ and ‘Fault-controlled in Extensional Domains’ referring to the nature of the dominant heat source and tectonic setting (Moeck, in press). Geothermal play types in conduction-dominated systems can be grouped into ‘Intracratonic Basin plays’, ‘Orogenic Belts with Adjacent Foreland Basins’ and ‘Crystalline rock/Basement plays’. These have different characteristics of natural transmissivity (permeability-thickness), which may be formation (facies)-controlled, fracture controlled, or a combination of both. The new catalog of geothermal play types provides a range of generic conceptual models, each of which can serve as a basis for guiding the geothermal assessment process. Appropriate exploration methods can be chosen to delineate and quantify the important features of these generic conceptual models.

### 2.1 Convection dominated play system

Convection-dominated geothermal plays are subdivided primarily according to the nature of the heat source. The heat source is localized by either extrusive magmatic activity, or magmatic intrusion, by a young solidified pluton, or by uprising mantle such as at metamorphic core complexes (Moeck, in press). Convection-dominated geothermal play types often host what are referred to as ‘active’ geothermal systems (Gianelli and Grassi, 2001). They host all currently known ‘high temperature’ (>200°C) geothermal reservoirs shallower than 3,000 m. These invariably lie adjacent to plate tectonic margins; in regions of active tectonism (Nukman and Moeck, 2013); associated with active volcanism (Bogie et al., 2005) or young plutonism (< 3 Ma); and/or in regions with elevated heat flow due to crustal thinning during extensional tectonism (Faulds et al., 2009; Faulds et al., 2010).

#### 2.1.1 Magmatic plays

Relatively shallow, liquid magma activity is the dominant feature in all Magmatic Geothermal Plays (category CV1 in Fig. 1). The magma’s parental melts, recharge of magma and crystallized melts control fluid chemistry, fluid flow and the overall geothermal system. *Extrusive magmatic plays* can be found in regions with active basaltic volcanism at divergent plate margins (e.g. Iceland), basaltic to andesitic volcanism along island arcs (e.g. Java, Indonesia and some New Zealand systems), or recent andesitic to dacitic volcanism (e.g. South American Andes or Taiwan). *Intrusive magmatic plays* may have no recent associated extrusive volcanism, but be evident as intrusive bodies within volcanic piles or beneath flat terrain along pathways of active faulting. Both extrusive and intrusive magmatic plays can be associated with very high thermal gradients, while associated geothermal reservoirs may be vapor dominated or liquid dominated.

#### 2.1.2 Plutonic plays

A Plutonic Geothermal Play (category CV2 in Fig. 1) incorporates a heat source in the form of a young, crystallized but still cooling, intrusive igneous body. This play type can co-exist with magmatic play types, is associated with elevated thermal gradients and is typically located along continent-continent convergent margins with recent plutonism. *Plutonic plays without recent volcanism* are related to the emplacement of felsic plutons, and are characteristic of mature subduction zones and decaying volcanism in continental crust. This play type can be found in regions with declining volcanism and fore- or back-arc regions of fold-thrust belts along subduction zones (e.g. The Geysers, California). *Plutonic plays with recent volcanism* are illustrated by the example of the Larderello geothermal system (Italy), which is controlled by the interaction between igneous rocks and faults. Larderello is known for its recent volcanism (500-50,000 years old) and occasional phreatic eruptions. Geothermal reservoirs above the pluton may be vapor dominated or liquid dominated.

#### 2.1.3 Extensional Domain (fault-controlled) plays

In an Extensional Domain Geothermal Play (category CV3 in Fig. 1) the mantle is elevated due to crustal extension and thinning. The elevated mantle provides the principal source of heat for geothermal systems associated with this play type. The resulting high thermal gradients facilitate the heating of meteoric water circulating through deep faults or permeable formations. Examples of geological settings hosting Extensional Domain Geothermal Plays include the Great Basin (Western USA) and Western Turkey

#### 2.1.4 Hybrids

Some convective geothermal systems incorporate geological elements of more than one play type. Even after these systems have been extensively drilled to over 3 km depth, the geological evidence does not justify categorizing them into a single play type. Such systems are hybrids of the above categories. For example, the Taupo Volcanic Zone (TVZ) in New Zealand hosts over twenty identified convective geothermal systems within an extensional zone containing both magmatic and plutonic bodies. The zone includes several active volcanoes as well as historic volcanoes with ages ranging from a few thousand years to hundreds of thousands of years. Over 1000 geothermal drill holes have been drilled into at least fifteen of these active hydrothermal systems, with several drill holes exceeding 3 km in depth. Plutons have been encountered beneath one system, but the evidence from most others supports hybrid models with contributions from both magmatic and plutonic heat sources. In the TVZ, faults strongly influence the fluid flow and locations of geothermal reservoirs (Bignall, et al., 2010).

The Philippines provides others examples of hybrid play types. All currently developed geothermal fields are associated with convective magmatic or plutonic play types along the Philippine fault (or its branch faults). Extension influences the characteristics of geothermal systems on parts of this major fault.

There are hundreds of active and recently active volcanoes throughout the Indonesian archipelago. The many geothermal systems they host range from magmatic to plutonic play types. Insufficient field reconnaissance and exploration has been undertaken to characterize these systems and so the current developments are classified as magmatic or plutonic convective play types.

The geothermal fields in the East African Rift system are primarily fault controlled in an extensional domain with current and recent volcanism. Extension has proceeded in some locations, however, to a degree where magma has risen up and volcanic fields erupted. This hybrid play type is found in Kenya at the Olkaria (Axelsson et. al., 2013) and Eburru (Omenda, 2007) geothermal systems.

**2.2 Conduction dominated play systems**

Conduction-dominated Geothermal Play Types can be thought of as 'passive' geothermal systems. They are commonly located at greater depth than convection-dominated plays (Moeck, in press). Different geological settings tend to result in different natural porosity–permeability ratios within potential reservoir rocks, due to different diagenesis histories, lithology (deposition or petrogenesis), and faulting. The key impact from a geothermal exploration viewpoint is the absence or presence of producible natural reservoir fluids. Conductive play types dominate within intraplate, passive margin plate or orogenic belt settings where there has been no significant recent tectonism or volcanism. For example, hot sedimentary aquifers in basin environments may host natural producible reservoir fluids, while crystalline rocks might require development using engineered geothermal systems (EGS) techniques.

2.2.1 Intracratonic basin plays

An Intracratonic Basin Geothermal Play (category CD1 in Fig. 1) incorporates a reservoir within a sedimentary sequence laid down in an extensional or thermal sag basin. Intracratonic basins that originate from lithospheric thinning and subsidence are commonly divided into several troughs or sub-basins (Salley, 2000). Geothermal reservoirs are located in different basin portions depending on the internal present-day structure of the basin and diagenetic or lithofacies effects on porosity and permeability. Faults can play a role in defining the reservoir size and compartmentalization but are not the prime reservoir targets. Examples include developments within the North German Basin (Germany) and the Paris Basin (France).

2.2.2 Orogenic belt/foreland basin plays

An Orogenic Belt Geothermal Play (category CD2 in Fig. 1) incorporates a sedimentary reservoir within a foreland basin adjacent to an orogenic mountain belt. The wedge shape of the foreland basin results in a progressive deepening of potential aquifer rocks towards the orogen, with an associated increase in temperature. The downward bended formations are likely to host abundant natural geothermal fluids. Prime targets for production are faults that originate from local extension during the flexural bending process (Moeck et al., this volume). Examples include the Molasse basin extending through France, Switzerland, Germany and Austria, and the Alberta Deep basin in Canada. Within the orogenic mountain belts themselves, the great relief between mountains and steep-sided valleys can produce recharge-discharge systems resulting from the fault controlled flow of meteoric fluids, giving rise to hot springs suitable for direct heat use on the valley floors (Toth, 2009).

2.2.3 Basement (crystalline rock) plays

A Basement Geothermal Play (category CD3 in Fig. 1) is a faulted or fractured crystalline (usually granitic) rock with very low natural porosity and permeability but storing vast amounts of thermal energy. Such low porosity-low permeability rocks underlie large areas of continents but require reservoir development by EGS techniques to allow circulation between injector and producer wells using the hot rock mass as a heat exchanger (Cuenot et al., 2008). Brittle fault and fracture zones are prime exploration targets because they already contain some natural permeability, while mylonitic shear zones (i.e. ductile faults) have extremely low natural permeability and are less amenable to hydraulic stimulation. An example for granitic rock play type developed with EGS is the Habanero field in the Cooper Basin in Australia.

## 3. KEY GEOLOGICAL PARAMETERS TO CHARACTERIZE THE PLAY TYPES

A geothermal play consists of three main elements: (I) the heat source, (II) the heat transport mechanism, and (III) the storage unit including possibly a trap or cap to limit the escape of heat. These elements are analogous to the elements of a petroleum play, which consists of (I) a source rock, (II) a reservoir rock, and (III) a trap or cap (Fig. 2). The goal of play type analysis is to delineate and describe the geological controls on these elements (Fig. 2). This geological characterization of the main play elements is referred to as 'petroleum geology' for petroleum resources assessment, so we define the term 'geothermal geology' as the assessment of the geological controls on geothermal resources. The aim of geothermal geology is to identify and characterize the main elements of the geothermal system; heat source, heat transport mechanism, and heat storage. Simplified to generic play types, we can use the analogy between a petroleum play and a geothermal play to illustrate the main geological elements that need to be characterized through geothermal geology (Fig. 2).

The heat source for a geothermal play can be a recent magmatic intrusion; a cooling pluton or batholith; shallow mantle; or just a region of elevated thermal gradient heated conductively (such as a subducting slab). Heat transport pathways can follow advective fluid paths along faults or through stratigraphic layers (porous and permeable layers), or conductive pathways through solid rock. A geothermal reservoir can have high porosity, transmissivity storage capacity and thereby host a naturally producible fluid. These reservoirs may be dominantly formation-hosted or fracture-hosted. Such low transmissivity reservoirs might be considered appropriate for development using engineered geothermal system (EGS) techniques.

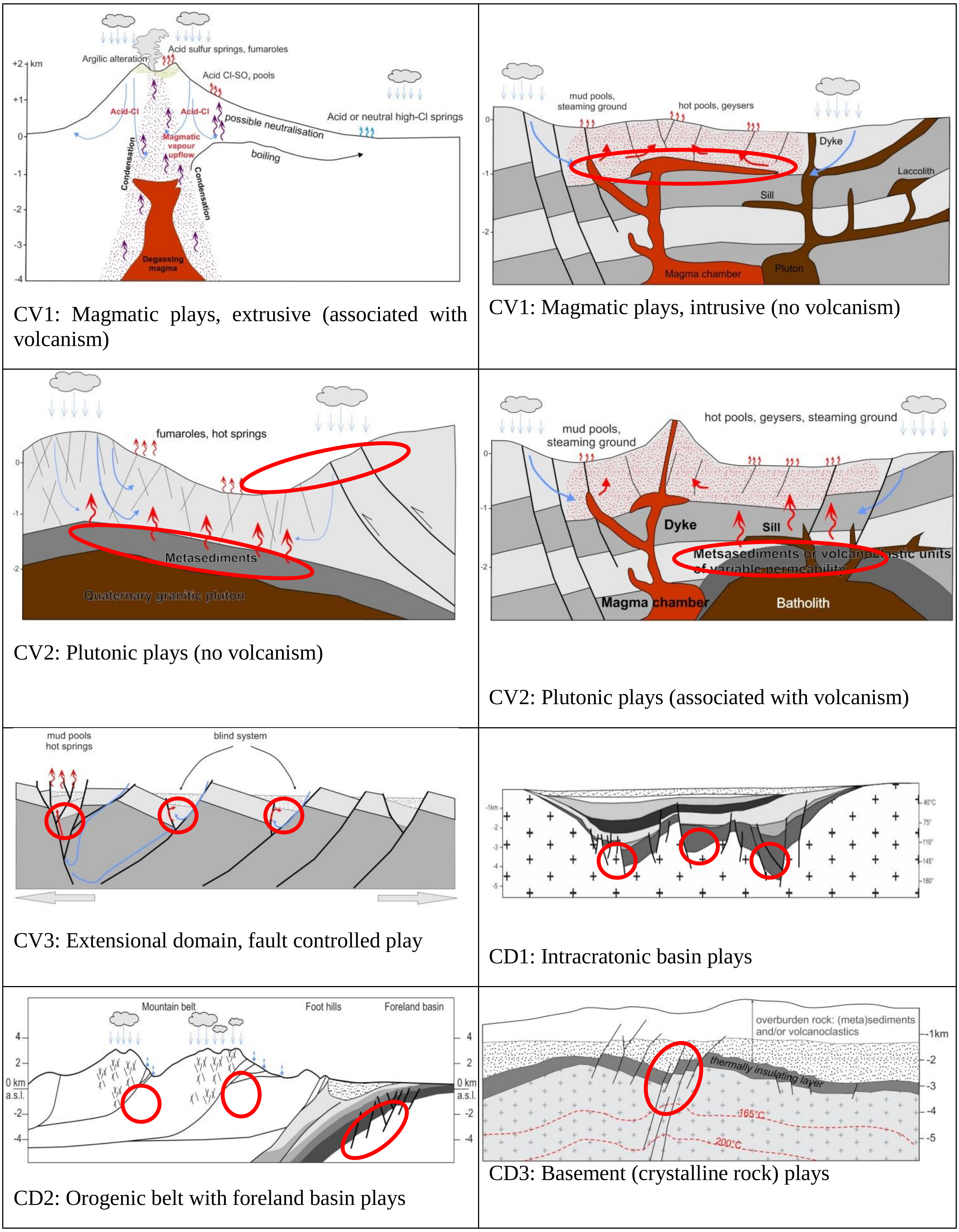


**Figure 1: Generic models of geothermal play types (modified from Moeck, in press). CV – convection dominated, CD – conduction dominated heat transport. Red marked areas indicate the region with the highest chance of production in each play type. Note the large areas for possible production in magmatic and plutonic systems, compared to the smaller areas in fault controlled play types.**

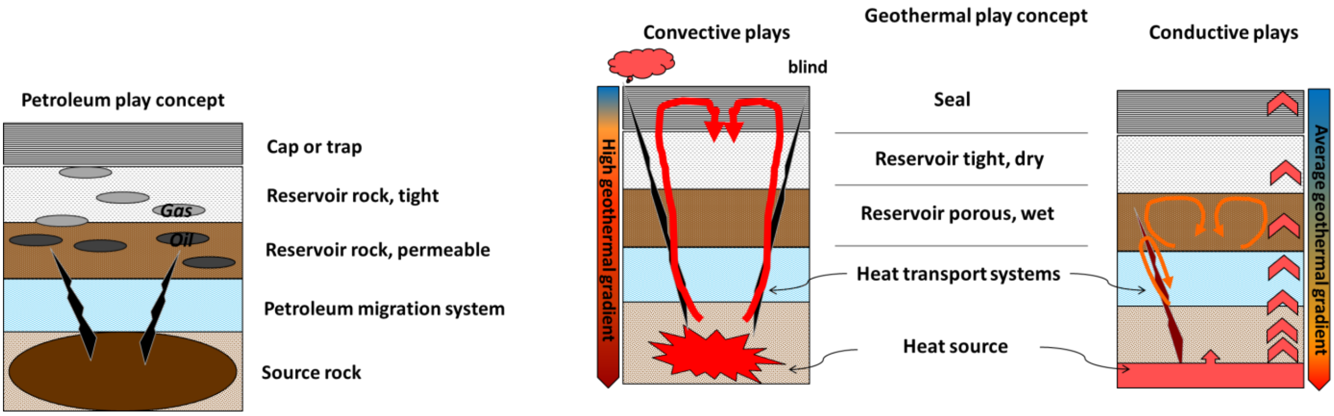


**Figure 2: Schematic illustration of geologic controls on elements of petroleum and geothermal plays. Porous reservoir rocks may host hydrothermal resources while tight reservoirs host petrothermal resources.**

## 4. CATALOGING WORLDWIDE PRODUCING GEOTHERMAL FIELDS INTO PLAY TYPES

In order to demonstrate the global application of the geothermal play type concept, we have categorized over 90% of the world's developed geothermal systems in Table 1, by focusing on the top ten countries based on installed geothermal generation capacity in 2013. The total installed capacity in Table 1 is just over 11,300 MWe. The current World generation (2014) is probably close to 12,000MWe.

Although many of the world's developed geothermal systems cannot be precisely categorized into a single play type, approximately 90% of the current world geothermal generating capacity can be categorized as plutonic or plutonic/magmatic play types. Less than 10% of the developments relate to convection-dominated extensional domain plays. Conductive play types currently host less than 1% of the world's geothermal generating capacity. Germany and Australia are the only two countries that have currently developed (Germany) or undertaken extensive experimentation (Australia) of conductive systems for geothermal power generation.

## 5. CONCLUSIONS

5.1 Currently developed geothermal systems globally are largely drawing from geothermal resources that can be grouped into just three of our six play types. Over 90% of the world's geothermal generation can be associated in some way with convection-dominated magmatic/plutonic plays.

5.2 Convection-dominated extensional domain plays host less than 10% of the world's geothermal generation.

5.3 The plutonic play type hosts several of the largest known geothermal resources based on current installed generation capacity. The heat source for this play type can extend over many square kilometers. Developments of plutonic plays at Larderello and The Geysers can be considered 'Giant' geothermal fields, analogous to the world's giant oil fields that are found rarely but have huge generation potential.

5.4 Magmatic plays host most of the World's'conventional' geothermal developments, being a of variable is size (capacity), occurring extensively along active margins and other active tectonic settings.

5.5 Geothermal developments in Extensional Domain plays are typically small, and lie within extensional or dilational active tectonic settings. Developments in the Basin-and-Range Province in the U.S.A. and in Western Turkey can be categorized as convection-dominated extensional domain plays. It is interesting to note that over the past five years (2010-2014) Turkey has installed over 200 MWe of new generation capacity in extensional grabens in the west of the country, while Nevada, New Mexico and Utah have harnessed well over 100 MWe of new generation in the Basin-and-Range province. We suggest that extensional domain plays represent a fertile target for potential developers to identify worldwide.

5.6 Europe (specifically Germany) has recently nurtured the development of geothermal systems within conduction-dominated orogenic plays. Conduction dominated play types can be considered 'longer-term future' development targets.

5.7 The advantage of the Play Type Catalog is that it allows the identification of common exploration and extraction strategies within similar play types around the world. This should accelerate progress along the learning curve for geothermal exploration in all geological settings, including for EGS developments. Further investigation and understanding of the geological controls on heat accumulation and extraction might result in additions or modifications to the Catalog.

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**Table 1 Producing geothermal fields from the Top Ten Geothermal Generating Countries USA, Philippines, Indonesia, New Zealand, Mexico, Italy, Japan, Iceland Turkey and El Salvador, grouped into play type. One play province can host more than one play type, e.g. the East African Graben system or the Taupo Volcanic Zone can be both magmatic/plutonic and fault controlled, however one mechanism dominated. The Chilean fields are in the process of exploration and exploration geochemistry indicates magmatic/plutonic hybrid plays (Dobson et al., 2013). Geothermal fields and installed capacity from www.thinkgeoenergy.com, www.tiefegeothermie.de and OpenEI (Young et al., 2014). Allocation of geothermal fields to play type by [(1)]Colwell et al. (2012), [(2)]Lienau et al. (1989), [(3)]Kolker, A.M. (2008), [(4)]Kolker et al., (2007), [(5)]Jones et al. (2011), [(6)]Blackett and Kolesar (1983), [(7)]Hulen and Norton (2000), [(8)]Geoproducts (1984), [(9)]Trexler et al., (2009), [(10)]Farrar et al (2003), [(11)]Hurwitz et al., (2010), [(12)]Adams et al. (2000), [(13)]Holland (2002), [(14)]Norton and Hulen (2006), [(15)]Hulen et al. (2003), [(16)]Smith (1978), [(17)]Blackett and Wakefield (2002), [(18)]Faulds et al. (2010), [(19)]Faulds et al. (2011), [(20)]Faulds et al. (2012), [(21)]Blackwell et al. (2009), [(22)]Caskey (2000), [(23)]Partida et al. (1995), [(24)]Monterrosa and Santos (2013), [(25)]Dobson et al. (2013), [(26)]Wolfgramm et al. (2009), [(27)]Moeck et al (2009), [(28)]www.tiefegeothermie.de, [(29)]King and Metcalfe (2013), [(30)]Rybach (2007), [(31)]Herzberger et al. (2010), [(32)]Moeck et al (this volume), [(33)]Bayerischer Geothermieatlas (2010), [(34)]Axelsson et al. (2013), [(35)]Omenda (2007), [(36)]Setjidji (2010), [(37)]Nasution and Supriyanto (2011), [(38)]Suryadarma et al. (2010), [(37)]Prijanto (1996), [(38)]Nukman (2014), [(39)]Raharjo (2012), [(40)]Brehme et al. (2014), [(41)]Habermehl and Pestov (2002), [(42)]Habermehl (2013), [(43)]Burns et al. (2000), [(44)]Meixner and Holgate(2008), [(45)]Cox and Brown (1992), [(46)]Soengkono (2000), [(47)]Bignall et al. (2010), [(48)]Bloomberg et al. (2012), [(49)]Boseley et al. (2010), [(50)]Arehart et al. (2002), [(51)]Christenson and Mroczek (2000), [(52)]Bignall and Milicich (2012).**

| Ranking by MWe | Country/State | Installed MWe | Geothermal fields | Installed MWe | magmatic or plutonic | extensional domain |
|---|---|---|---|---|---|---|
| 1 | **USA** | **3386** | | | | |
| | Alaska | | Chena | 0,73 | x | |
| | Oregon | | Neal Hot Spring & Klamath Falls | 33,3 | | x |
| | Hawaii | | Puna | 38 | x | |
| | Idaho | | Raft River | 15,8 | | x |
| | California | | Geysers Honey Lake, Mammoth, Coso, Salton See, Heber, East Mesa | 2732 | x | |
| | Nevada | | 29 Operating plants | 518 | | x |
| | Utah | | Thermo Hot Spring, Roosevelt | 48 | | x |
| 2 | **Philippines** | **1821** | Leyte, Negros, Luzon and Mindanao | 1821 | x | |
| 3 | **Indonesia** | **1267** | Java, Sumatra and Sulawesi | 1267 | x | |
| 4 | **New Zealand** | **1114** | Mokai,Wairakei,Rotokawa,Ngatamariki,Ohaaki, Kawerau, Ngawha | 1114 | x | |
| 5 | **Mexico** | **1017** | Cerro Prieto, Los Azufres, Los Humeros,Las Tres Virgenes, Cerritos Colorados | 1017 | x | |
| 6 | **Italy** | **874** | Larderello, Travelle-Radiocondoli and Mt Amiata | 874 | x | |
| 7 | **Iceland** | **694** | Bjarnaflag,Hellisheidi,Krafla, Nesjavellir,Reykjanes,Svartengi, Hasavik | 694 | x | |
| 8 | **Japan** | **515** | Honshu, Hachijojima, Kyushu, Hokaiido | 515 | x | |
| 9 | **Turkey** | **322** | Kizildere, Aydin/Germancik, Salavatli, Canakkale | 322 | | x |
| 10 | **El Salvador** | **204** | Ahuachapan and Berlin | 204 | x | |
| | **Total Mwe installed** | **11214** | | | 10276 | 937,1 |
| | **Proportion** | | | | 91,6% | 8,4% |

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