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A new 'geothermal play type' catalog: Streamlining exploration decision making

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ABSTRACT

Up to now there is no standardized global approach in the assessment of geothermal resources. In the standard assessment process for hydrocarbon resources, the lowest unit in a bottom up approach is the geologically based play type. This approach leads to prospects, recoverable or non-recoverable resources and ultimately to reserves and producing fields. A play type in petroleum geology represents a particular stratigraphic or structural geological setting, defined by source rock, reservoir rock and trap. Translated to geothermal systems, a play type might be defined by the heat source and the geological controls on heat transport and thermal energy storage capacity. Plays can best help if they comprise meaningful natural groups that can be used both for reliable field analog comparison and for exploration decision making in a specific geologic context. A logical and consistent framework for a geothermal play type catalog needs to be simple enough to communicate important aspects of geothermal energy potential to both non-experts and the general public. A play type catalog must also be comprehensive enough to provide a globally applicable geological framework to cover the whole range of possible geothermal systems. We therefore propose a catalog of geothermal play types based on geologic controls. Key defining elements of this catalog are whether heat transfer is dominated by conduction or convection, and the characteristics on a regional scale of the heat source, reservoir and host rock, porosity-permeability structure and fluid types. This new catalog is explicitly not based on temperature, depth or enthalpy, because these criteria cannot be reliably known prior to exploration. Although there might be future modifications and additions required the advantage of this new play type catalog is the facility to compare similar geothermal plays worldwide and their development to producing fields. Eventually this catalog may help to accelerate the learning curve in geothermal exploration and to a reliable assessment process towards commerciality of geothermal resources.

1. INTRODUCTION

'Resource assessment' is the process by which developers estimate the possible future energy production from a geothermal reservoir. It is an iterative process that continuously incorporates new information as it is gathered and interpreted throughout the various stages of the long development path from exploration to power generation. Resource assessment is integral to financing geothermal projects because the estimates of future energy production underpin financial models of investment returns. In spite of this critical function and the fact that geothermal energy extraction is a mature industry, however, to this date there is no universal or even widely agreed terminology and framework for reporting the outcomes of geothermal resource assessments.

To stimulate the financing of geothermal developments through stock markets or other commercial finance mechanisms, a globally applicable and consistent reporting framework is increasingly relevant. The 'Australian Code for Reporting Exploration Results, Geothermal Resources and Geothermal Reserves' (the Code) is a first attempt to design a globally applicable framework for the reporting the outcomes of geothermal resource assessments across all forms of geothermal energy generation. The Code defines three classes of Geothermal Resource based on increasing levels of geological knowledge and confidence, which reflect the increasing probability of an occurrence. The lowest level of the assessment process inferred by the Code is an 'Exploration Result', which is the outcome of any one activity in the resource assessment process. The Code also, however, introduces the term 'Geothermal Play' as an "informal qualitative descriptor for an accumulation of heat energy within the Earth's crust … in rock and/or fluid."

In the formalized reporting framework for hydrocarbon resources, the first step of the assessment does not start with exploration results but with the concept of a 'Play' that categorizes the geological setting and circumstances of the petroleum accumulation (SPE-PRSM, 2007). A petroleum play does not directly relate to the commerciality of a project, but is fundamental to the process of discovery and assessment (Fig. 1). The analysis and understanding of the relevant 'play type' is recognized as essential to strategically focused and successful petroleum exploration ventures. We would argue that the same is true for geothermal ventures, but the geothermal community currently lacks a formalized 'geothermal play' concept.

The utilization of geothermal heat and energy looks back to a much longer history than hydrocarbon production. The geothermal sector has exhaustingly tried to classify geothermal potential according to temperature (low-, medium-, high-temperature), to depth (shallow, medium-shallow, medium-deep and deep) or to hydrothermal versus petrothermal systems. For example, 'moderate temperature' has been described as between 90-150°C (Muffler, 1979), 125-225°C (Hochstein, 1988), 100-200°C (Benderitter and Cormy, 1990) and 180-230°C (Sanyal, 2005). Such classifications clearly prevent field analog comparisons at the early stages of resource assessment because a certain temperature can be found in all kinds of geological environments at various depths. In short, categorization by temperature or depth does not help in decision making for the appropriate exploration strategy. Temperature and depth are, virtually by definition, not known prior to exploration. Therefore, we cannot classify a geothermal resource based on temperature or depth before exploration, and we cannot use such a classification framework to estimate the probability of exploration success.

The ultimate question is: what are we actually looking for when we begin geothermal exploration? The answer is always “extractable thermal power”, but in different circumstances and locations the key risk might be reservoir temperature, production flow rate, or chemistry of fluids in place. The key risks dictate the most appropriate exploration strategy and these risks almost always relate to geology. What answers need to be provided by geothermal exploration, and how can we identify and learn from worldwide analogs? Factors such as porosity, permeability, nature and extent of heat source and distribution of temperature (vertical or horizontal) have varying importance depending on the nature of the reservoir hosting the heat resource. A logical way to categorize a geothermal project at an early stage is a globally applicable play type concept based on geological criteria that are generally known before exploration. We present such an exploration play type catalog in this article.

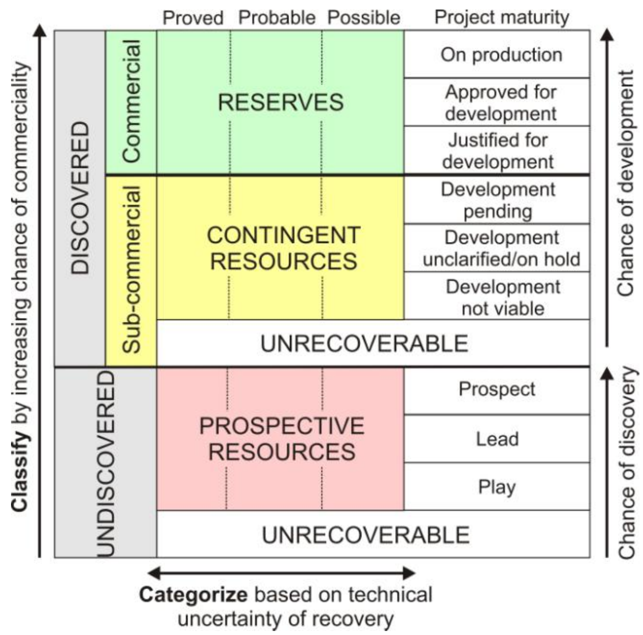

Figure 1: Classification of risk (vertical axis) and categorization of uncertainty (horizontal axis) for hydrocarbon systems according to the Petroleum Resources Management System (SPE – PRMS, 2007). The play is the lowest class in the scheme and therefore a fundamental part of the assessment process. Similar importance has geothermal exploration plays for the assessment process of geothermal resources.

2. PLAY TYPE CONCEPT

A play type in petroleum geology represents a particular stratigraphic or structural geological setting, defined by source rock, reservoir rock and trap. Translated to geothermal systems, a play type might be defined by the heat source and the geological controls on heat transport and thermal energy storage capacity. These criteria are related to the geological setting which controls the play type and has implications on the most appropriate exploration and heat recovery technologies. The requirement on a geothermal play type catalog are that it provides a logical and consistent framework that is simple enough to communicate important aspects of geothermal energy potential to both non-experts and the general public. Additionally, it must be comprehensive enough to provide a geological framework to cover the whole range of possible geothermal systems applicable for experts in industry and academia. Plays can best help if they comprise meaningful natural groups that can be used both for reliable analog comparison and for exploration decision making in a specific geologic context. In this lecture we will learn about a new catalog of geothermal play types based on geologic controls.

2.1 Play definition

A play may initially be defined as a model in the mind of a geologist of how a number of geological factors might generate a recoverable geothermal resource at a specific structural position in a certain geologic setting. Analog to the general play concepts described by Allan and Allan (2005) for hydrocarbon plays these geological factors must be capable of providing the essential ingredients of a geothermal play, namely:

- *The reservoir unit*, porous or fractured enough to store thermal fluids and yielding them to the well bore at commercial rates. Man-made reservoir units must be capable for stimulation treatments as fracturing or acidizing (often referred as to Enhanced Geothermal Systems-EGS). The more brittle the reservoir unit is the better the requisite for hydraulic stimulation and sustainable permeability enhancement. There are clearly physical limits to extract thermal fluids from any rock types. The main focus of play assessments is on the description of the reservoir unit to guide later exploration and recovery strategy.

- *The heat charge system*, comprising the type of heat source and the heat transport, expelling heat from deeper to shallower parts in the Earth's crust.
- *The regional topseal or caprock*, a low permeability unit or low thermal conductivity blanket or fault which traps the thermal fluids or heat at a (litho)stratigraphic level and concentrates steam, liquids or thermal fluids in specific locations, allowing commercial exploitation either without or with EGS treatments. Not all geothermal plays have a relevant topseal or caprock.
- *The timely relationship* of the above three ingredients, for example that a pluton intrudes into a porous rock formation, which is then covered by low-permeability rock as fine grained mélange at a forearc region of a subduction zones.
- *The play fairway*, the geographic area over which the play is believed to extend as for example the size of an intrusion in diameter and depth, or a fault zone hosting vast volumes of circulating fluids. The mapping-out of the play fairway belongs to the essential task in the early exploration phase and conceptual model building.

2.2 Criteria to categorize geothermal plays

Geothermal plays can be separated at the system scale into two large groups referring to heat transport: either the heat transport is dominated by convection leading to accumulated heat, or the heat transport is conduction dominated leading to distributed heat. 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, while 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.

Geothermal play types in convection-dominated systems are grouped into "Magmatic", "Plutonic" and "Fault-controlled in Extensional Domains" referring to the nature of the dominant heat source and tectonic setting (Moeck, submitted). Geothermal play types in conduction-dominated systems are grouped into "Intracratonic Basin plays", "Orogenic Belts with Adjacent Foreland Basins" and "Crystalline rock/Basement plays" divided according to the dominant permeability control; lithofacies, fractures, or a combination of both. In the next chapters the geologic controls on each play type are described and constrained by real-world case studies. This new catalog of geothermal play types provides a range of generic conceptual models that serve as basis for refinement through appropriate exploration methods.

3. CONVECTION DOMINATED GEOTHERMAL PLAY TYPES

Convection-dominated Geothermal Play Types include those often referred to as 'viable' or 'active' geothermal systems (Gianelli and Grassi, 2001). They include all known 'high temperature' (>200°C) geothermal reservoirs shallower than 3,000 m. These invariably lie adjacent to plate tectonic margins or in regions of active tectonism (Nukman and Moeck, 2013), active volcanism (Bogie et al., 2005), young plutonism (< 3 Ma), or regions with elevated heat flow due to crustal thinning during extensional tectonics (Faulds et al., 2009; Faulds et al.,2010). In convection-dominated geothermal plays, heat is transported efficiently from depth to shallower reservoirs or the surface by the upward movement of fluid along permeable pathways. Laterally extensive, porous high-permeability formations act as the primary reservoirs. Convection-dominated geothermal plays are grouped primarily according to the nature of the heat source. Favorable tectonic settings for convection-dominated Geothermal Play Types include (I) magmatic arcs above subduction zones in convergent plate margins (e.g. the Indonesian Sunda Arc or the Philippine-Japan Arc); (II) divergent margins located within oceanic (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 Fault in California or Alpine faults in New Zealand); and (IV) intraplate ocean islands formed by hot spot magmatism (e.g. Hawaii) (Fig. 2). It is possible for different types of convection-dominated plays to lie geographically close to each other where the structural setting varies over short distance scales.

3.1 Magmatic plays

A Magmatic Geothermal Play (category CV1 in Fig. 2) is distinguished by a shallow, intense heat source in the form of a young magma chamber. A relatively shallow magma chamber is the dominant feature in all Magmatic Geothermal Plays. The chamber's parental melts, recharge of basalt, and crystallized melts control fluid chemistry, fluid flow and the overall geothermal system. Ultimately, the placement of the magma chamber relative to the surrounding terrain controls the geometry of the geothermal system and affects the hydraulic head of steam and brine. Faults can act as seals or conduits, playing a role in the formation of reservoir compartments or hydrothermal convection, while accommodation zones of faults can sustain enhanced vertical permeability and channel hydrothermal plumes (Rowland and Sibson, 2004).

Extrusive magmatic plays can be identified in regions with active basaltic volcanism at divergent plate margins (e.g. Iceland), basaltic to andesitic volcanism along island arcs (e.g. Java), or recent andesitic to dacitic volcanism (e.g. South American Andes or Taiwan). This play type may include an upflow zone and an outflow zone, provided the topography of the volcano supports this zonation (Williams et al., 2011; Giggenbach, 1992; Hochstein, 1988). The outflow is generally modified from the original fluid, and has a lower temperature and higher pH than the upflow due to lateral migration (with associated heat loss) and loss of gases (during boiling) towards the flank of the volcano (Hochstein, 1988). Vertically extensive, low-permeability, clay-rich layers in steep terrain, such as andesitic strato-volcanoes, can cap high temperature reservoirs.

Intrusive magmatic plays are associated with an active magma chamber that does not lead to volcanism. Influenced by active faulting, deep rooted magmas can intrude beneath flat terrain with no volcanism, but with an upflow of liquids and the formation of hot springs, fumaroles, boiling mud pools and other geothermal surface manifestations. Hence, the Taupo Volcanic Zone (New Zealand) is an example of this sort of Geothermal Play (Bogie et al., 2005).

3.2 Plutonic plays

A Plutonic Geothermal Play (category CV2 in Fig. 2) incorporates a heat source in the form of a crystalline rock enriched in heat generating elements or a young, crystallized but still cooling, intrusive igneous body. Such Play Types are located where surrounding mountain ranges provide high recharge rates of circulating meteoric water, driving a hydrothermal system with possible vapor partition above the hot rock. This play type can co-exist with Magmatic play types and is typically located along continent-continent convergent margins with recent plutonism, such as the southern periphery of the Alpine Orogeny.

Plutonic plays without recent volcanism are related to the placement of felsic plutons is characteristic for mature subduction zones and decaying volcanism in continental crust. This play type can be found therefore in fields with declining volcanism and fore- or back-arc regions of fold-thrust belts along subduction zones. An example is The Geyers geothermal field in California where a long history of subduction during Mesozoic and early Cenozoic was followed by strike-slip offset along the San Andreas Fault during the late Cenozoic (Argus, 2001). This Andean-type continental margin produced forearc deposits, volcanism and accretion of terranes and mélange. A silicic pluton emplaced in early Quaternary representing the heat source. The 7 km deep and 14 km in diameter large pluton is overlain by porous greywacke sandstone representing the reservoir rock which is overlain by a low permeable caprock formation preventing the steam to percolate from the reservoir formation upwards. Since the recharge volume from meteoric water is not sufficient for steam production, sewage from adjacent communities is injected replenishing the geothermal system.

Plutonic play with recent volcanism is given by an example of the Lardarello geothermal system, which is controlled by the interaction between igneous rocks and faults. Lardarello is known for its recent volcanism (500-50,000 years old) with occasional phreatic eruptions. This play includes a vapor-dominated layer (H-horizon) above a fluid-dominated layer (K-horizon) (Bertini et al., 2006). The K-horizon sits above a granite intrusion emplaced during a Pliocene extensional event (1.3-3.8 Ma). Melts emplaced during a subsequent Pleistocene (0.3-0.2 Ma) magmatic event provide the primary heat source, while low-angle normal faults from the Pliocene event control the recharge of meteoric water into the system.

3.3 Extensional domain plays

In an Extensional Domain Geothermal Play (category CV3 in Fig. 2) 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), Western Turkey, pull-apart basins along the Sumatra Fault Zone, the Upper Rhine Graben, and the African Rift.

In general, segmented faults are more favorable for geothermal systems than large faults with large offsets. The local stress regime and its orientation relative to fault geometry has a controlling impact on permeability pathways, with faults oriented perpendicular to the minimum compressive stress direction more likely to be permeable (Barton et al., 1997). Belts of intermeshing, overlapping, or intersecting faults, such as step-over regions, fault terminations and accommodation zones, often provide high permeability pathways through closely spaced, breccia dominated fracture networks (Faulds et al., 2010). In the Western USA, for example, most known geothermal fields are located at step-over regions or relay ramps (Faulds et al., 2012), while geothermal systems are relatively rare along displacement maxima or on the mid-segments of faults.

4. CONDUCTION DOMINATED GEOTHERMAL PLAY TYPES

Conduction-dominated Geothermal Play Types (categories CD in Fig. 2) include all of what could be called ‘passive’ geothermal systems due to an absence of fast convective flow of fluids or short-term variations in fluid dynamics. These Play Types dominate within passive tectonic plate settings where there has been no significant recent tectonism or volcanism. In these settings, temperature increases steadily (although not necessarily linearly) with depth. Conductively heated geothermal reservoirs with potentially economic temperatures are located at greater depth than convectively heated geothermal reservoirs. Economic viability, therefore, is closely linked to the geothermal gradient. Gradients higher than the global average can be found in regions of high heat flow (for example, due to elevated concentrations of heat generating elements in the crust), or where overlying strata are thermally insulating (Beardsmore and Cull, 2001).

Conduction-dominated Geothermal Play Types can be sub-divided according to the natural porosity–permeability ratio within the potential reservoir rock, and the absence or presence of producible natural reservoir fluids. Conduction-dominated Play Types in this Guide are divided into Intracratonic Basin Type, Orogenic Belt with foreland basin Type, and Crystalline rock/Basement Type. Favorable tectonic settings for conduction-dominated Geothermal Play Types include (I) extensional, divergent margins and grabens, or lithospheric subsidence basins such as the North German Basin or the Otway Basin in Australia; (II) foreland basins within orogenic belts, such as the Molasse Basin north of the Alps, or the Western Canadian Sedimentary Basin east of the Rocky Mountains; (III) crystalline basement underlying thermally insulating sediments, such as the Big Lake Suite Granodiorite beneath the Cooper Basin in Australia.

Conduction-dominated Geothermal Play Types with low permeability potential reservoirs such as tight sandstones, carbonates or crystalline rock can only be developed using engineered geothermal systems (EGS) technology. Although EGS techniques might be applied to improve the productivity of any geothermal reservoir, development of many conduction-dominated geothermal systems depends strongly on them. Through the application of EGS techniques, non-commercial reservoir conditions (for example, rocks with naturally low transmissivity or storativity) might be improved. The in situ stress field is a critical parameter for EGS technology because the successful planning and management of large-scale injection and hydraulic stimulation requires knowledge of stress direction and magnitudes (e.g. Moeck, 2012; Moeck and Backers, 2011).

Faults do not naturally channel heat in their natural condition in conduction-dominated Play Types. However, faults can play an important role as a fluid conduit or barrier during production from these geothermal reservoirs, and may cause compartmentalization of the reservoir into separate fault blocks. Reservoirs can be either or a mix of depositional, diagenetic or fractured reservoirs depending on what mechanism influences most the present-day reservoir quality. Evaluation of fault pattern, (litho)facies, diagenesis including alteration characteristics should therefore be primary goals of exploration within these Geothermal Play Types.

4.1 Intracratonic Basin Plays

An Intracratonic Basin Geothermal Play (category CD1 in Fig. 2) incorporates a reservoir within a sedimentary sequence laid down in an extensional graben or thermal sag basin. Intracratonic basins that originate from lithospheric thinning and subsidence are commonly divided into several troughs or sub-basins (Salley, 2000). The long geological history of intracratonic basins usually produces a several kilometer thick sediment fill that spans a wide range of depositional environments that may include fluvial siliciclastics, marine carbonates, muds and evaporites. Lithology, faulting, and diagenesis control the pattern of high and low porosity domains (Wolfgramm et al., 2009; Hartmann and Beaumont, 2000), and are themselves strongly influenced by basin evolution and subsidence rates. Lithology, faults and the stress field control permeability and its anisotropy.

Geothermal plays are located in different basin portions depending on the internal present-day structure of the basin. Formations above salt diapirs might provide suitable geothermal reservoirs for district heating because high thermal conductivity of salt rock causes local positive thermal anomalies in the overburden (Norden and Förster, 2006). Formations in deeper parts of the basin might provide suitable reservoirs for power and heat production, provided they can produce at a flow rate of about 70 kg/s or more (Tester et al., 2007). In all potential sedimentary reservoirs, primary porosity (affected by deposition through lithofacies or biofacies) and secondary porosity (affected by diagenesis) have a major influence on the fluid storage capacity. Potential reservoir units are terrestrial sedimentary rocks, such as aeolian and fluvial siliciclastic sequences, and shallow to deep marine sediments from carbonate sequences to shale and pelagic clays. Typical fluids are high-Cl brines (referred as basinal fluids) or HCO3-rich fluids (referred as infiltration water).

4.2 Orogenic belt and foreland basin plays

An Orogenic Belt Geothermal Play (category CD2 in Fig. 2) incorporates a sedimentary reservoir within a foreland basin or orogenic mountain belt. 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 downward bending of the non-thickened lithosphere, forming areas of local extension and normal faulting in an overall compressional plate tectonic setting (Cacace et al., 2013). The wedge shape of foreland basins results in a progressive deepening of potential aquifer rocks towards the orogen, with an associated increase in temperature. Faults and reef complexes provide prime reservoir targets in carbonate rocks of the Bavarian Molasse Basin, Germany while highly permeable and porous sandstone in the Williston Basin in Saskatchewan, Canada, and North Dakota, U.S.A., also provide potential geothermal reservoir targets (Majorowicz et al., 1999).

Within the orogenic mountain belt itself, the conductive thermal regime can be locally disturbed where groundwater infiltration cools the rock mass. Groundwater flow and thermal gradient are both strongly influenced by extreme relief and resulting hydraulic head (Majorowicz et al., 1999; Toth, 2009). The great depth and small width of mountain belt valleys result in relatively shallow penetration of recharge water, discharging in valley floors or on shallow valley slopes (Toth, 2009). Conductive thermal gradients can vary from about 15-20°C/km beneath high mountains at to about 30-50°C/km beneath deep valleys (Craw et al., 2005; Grasby and Hutcheon, 2001).

4.3 Crystalline rock/Basement plays

The key feature of a Basement Geothermal Play (category CD3 in Fig. 2) 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). Fractured crystalline rocks attain potentially economic temperatures through elevated heat flow or thermal insulation in the overburden. Heat flow is likely to be elevated if underlying rocks have elevated radiogenic heat production from heat producing elements such as thorium or uranium.

Since crystalline rocks are generally not natural aquifers, fluids need to be injected both to improve the transmissivity of the rocks and to ‘charge’ the system with ‘geothermal fluid’. Mineralogy and crystal size may have major effects on the success of stimulation and the self-propping of induced fractures, critical to maintain fracture transmissivity after stimulation and shear-offset along a rough fracture surface.

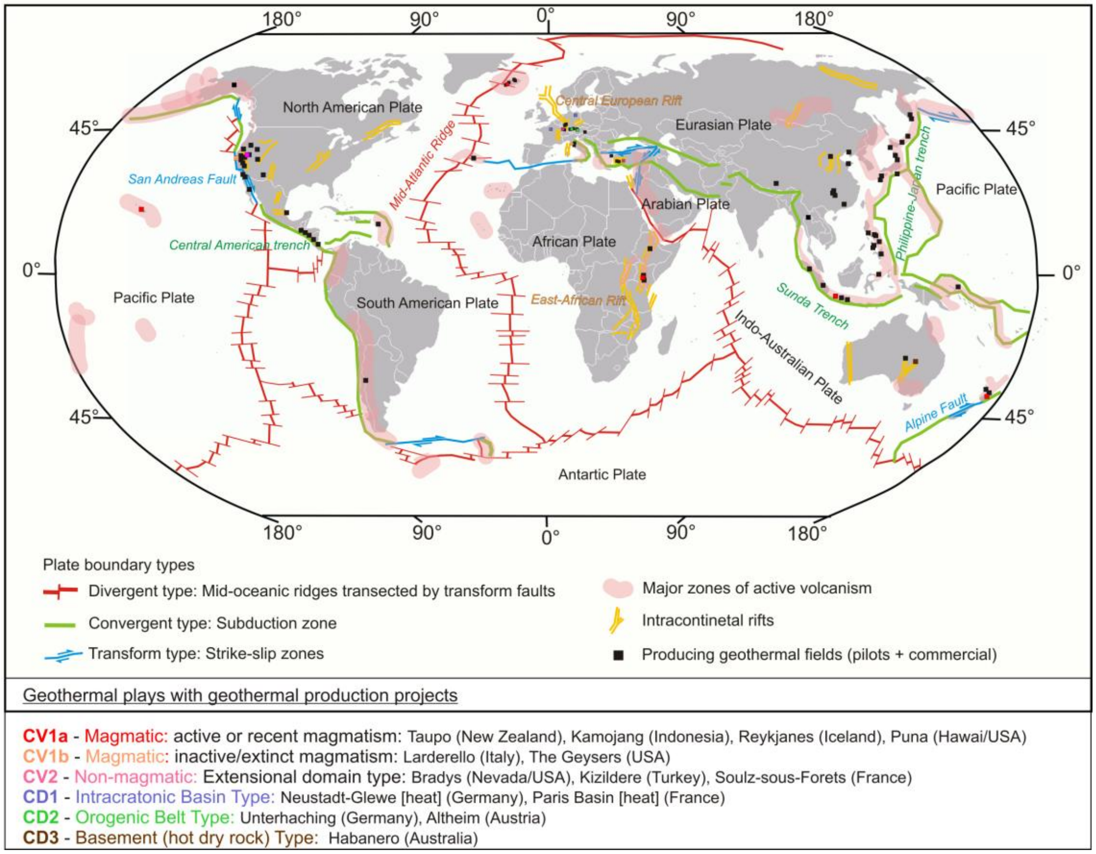

Figure 2: Worldwide producing geothermal fields related to the plate tectonic setting. Example fields a selected as play types upon which the new play type catalog is based. Modified from Moeck (submitted), installed geothermal fields compiled from http://geothermal-powerplant.blogspot.com; www.thinkgeoenergy.com; Zheng and Dong, 2008; Plate tectonic map based on Frisch and Löschke, 2003.

5. GEOTHERMAL PLAYS RELATED TO WORLDWIDE PRODUCING FIELDS

The main divisions for geothermal play types are 'conduction' and 'convection' dominated plays. This division goes back to the fundamental work of Rybach (1981). In contrast to Rybach (1981) we do not subgroup Convection Dominated Systems in *Hydrothermal* and *Circulation Systems* but in *Magmatic/Plutonic* and *Extensional Domain Plays* since our grouping concept is related to the geologic setting and controls. 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. Figure 3 shows all 187 producing geothermal fields from Figure 2, separated into regional triangles for the Americas, Asia/Pacific and Europe/Atlantic/Africa. It is obvious from these figures that most of the developed geothermal systems in the world represent convection-dominated magmatic play types (including plutonic plays). Developed extensional domain plays are mainly located in the Basin-and-Range in the U.S.A. and in Western Turkey.

The development of conduction-dominated geothermal plays has predominantly been restricted to Europe (specifically Germany) where the regulatory framework has nurtured their development. In contrast, not a single conduction dominated geothermal play has been developed in the Americas, and only two in the Asia/Pacific region (specifically Australia). Conduction dominated geothermal plays generally host 'tight' reservoirs that require engineering to enhance their productivity to an economic level. The developed conduction dominated geothermal plays in Germany are primarily in the Bavarian Molasse Basin, where the guaranteed German feed-in tariffs for geothermal power secure the juvenile but evolving geothermal technology development. The lessons learned from Germany show that geothermal developments are more cost-effective now compared to 10 years ago when geothermal field development began with exploration and drilling stimulated by Germany's 'Renewable Energy Act'. With progress down the learning curve for the specific geothermal play type within the Bavarian Molasse Basin, average drilling times have decreased and the overall costs for field development have significantly reduced (Lentsch and Schubert, 2013; Lentsch et al., 2012). This demonstrates the value of learning how to efficiently develop a geothermal project within a known geological setting.

The producing reservoir within the Bavarian Molasse Basin is an example of a previously non-economic play type (foreland basin, category CD2) with high recovery uncertainty that has evolved into a play type with greater probability of recovery and better economic outcomes. This provides a good example of the value of identifying specific play types and adopting exploration and development strategies for geological analogs.

Figure 3: The 187 developed geothermal systems worldwide, grouped into play types and into three regions. Geothermal systems are taken from the map in Figure 2. Notice the cluster on conduction dominated plays in the regional triangle of Europe/Atlantic/Africa representing the German developed systems in the Bavarian Molasse Basin.

REFERENCES

Argus, D.F.: Present tectonic motion across the Coast Ranges and San Andreas fault system in Central California. **GSA Bulletin**, **113/12**, (2001), 1580-1592.

Allen, P.A., and Allen, J.R.: The petroleum play. In: Allen, P.A. & Allen, J.R. (Eds.), Basin Analysis – Principles and Applications, 2nd edition. Wiley-Blackwell Science, Oxford, UK, (2005), 309–396.

Barton, C.A., Hickman, S., Morin, R.H., Zoback, M.D., Finkbeiner, T., et al.: Fracture permeability and its relationship to in-situ stress in the Dixie Valley, Nevada, geothermal reservoir. USGS Staff -- Published Research. Paper 359. http://digitalcommons.unl.edu/usgsstaffpub/359, (1997).

Beardsmore, G.R., and Cull, J.P.: Crustal Heat Flow: A Guide to Measurement and Modelling. Cambridge University Press, Cambridge, UK. 321pp., (2001).

Bertini, G., Casini, M., Gianelli, G., and Pandelli, E.: Geological structure of a long-living geothermal system, Larderello, Italy. *Terra Nova*, **18**, (2006), 163–169.

Benderitter, Y., and Cormy, G.: Possible approach to the geothermal research and relative cost estimate, in: M.H. Dickson, and M. Fanelli, eds., Small Geothermal Resources: UNITAR/UNDP Centre for Small Energy Resources, Rome, Italy, (1990), 61-71.

Bogie, I., Lawless, J.V., Rychagov, S., and Belousov, V.: Magmatic-related hydrothermal systems: Classification of the types of geothermal systems and their ore mineralization. In: Rychagov, S. (Ed.), Geothermal and Mineral Resources of Modern Volcanism Areas, Proceedings of the International Kuril-Kamchatka Field Workshop, July 16–August 6, 2005. http://web.ru/conf/kuril_kam2005/art3.pdf, (2005).

Cacace, M., Bloecher, G., Watanabe, N., Moeck, I., Boersing, N., et al..: Modelling of fractured carbonate reservoirs: outline of a novel technique via a case study from the Molasse Basin, southern Bavaria, Germany. *Environ Earth Sci*, Online first, doi: 10.1007/s12665.013.2402.3, 18 pp., (2013).

Craw, D., Koons, P.O., Zeitler, P.K., and Kidd, S.F.: Fluid evolution and thermal structure in the rapidly exhuming gneiss complex of Namche Barwa-Gyala Peri, eastern Himalayan syntaxis. *Journal of Metamorphic Geology*, **23**, (2005), 829–845.

Cuenot, N., Faucher, J.P., Fritsch, D., Genter, A., and Szablinski, D.: The European EGS project at Soultz-sous-Forets: from extensive exploration to power production. IEEE Power and Energy Society General Meeting. Pittsburg, 20-24 July 2008, paper 4596680, (2008).

Faulds, J.E., Hinz, N., and Kreemer, C.: Structural and tectonic controls of geothermal activity in the Basin and Range province, Western U.S.. Proceedings of New Zealand Geothermal Workshop, 19-21 November 2012, Auckland, NZ, (2012).

Faulds, J.E., Coolbaugh, M., Bouchot, V., Moeck, I., and Oguz, K.: Characterizing structural controls of geothermal reservoirs in the Basin and Range, USA, and western Turkey: Developing successful exploration strategies in extended terranes. Proceedings of World Geothermal Congress, Bali, Indonesia, 25-30 April 2010; paper 1163: 11 pp, (2010).

Faulds, J.E., Bouchot, V., Moeck, I. and Oguz, K.: Structural controls of geothermal systems in Western Turkey: A preliminary report. *GRC Transactions*, **33**, (2009), 375–383.

Frisch, W., and, Löschke, J. (Editors): Plattentektonik. Darmstadt: WissenschaftlicheBuchgesellschaft, (2003), pp. 190.

Gianelli, G., and Grassi, S.: Water-rock interaction in the active geothermal system of Panetelleria, Italy. *Chemical Geology*, **181(1/4)**, (2001), 113–130.

Giggenbach, W.F. (1992). Magma degassing and mineral deposition in hydrothermal systems along convergent plate boundaries. Economic Geology, Society of Exploration Geologists Bulletin, 97, 1927–1944.

Grasby, S.E., and Hutcheon, I.: Controls on the distribution of thermal springs in the southern Canadian Cordillera. *Canadian Journal of Earth Sciences*, **38**, (2001), 427–440.

Hartmann, D.J. and Beaumont, E.A.: Predicting reservoir system quality and performance. In: Beaumont E.A. and Foster, N.H. (Eds.), Exploring for Oil and Gas Traps. Treatise of Petroleum Geology Handbook Series. AAPG Publishing, Tusla (OK). 1146 pp., (2000).

Hochstein, M. P.: Assessment and modelling of geothermal reservoirs (small utilization schemes). *Geothermics*, **17-1**, (1988), 15-49.

Lawless, J.V., White, P.J., Bogie, I., and Andrews, M.J.: Tectonic features of Sumatra and New Zealand in relation to active and fossil hydrothermal systems: A comparison. Proceedings of the PACRIM '95 Congress, Publication Series—Australasian Institute of Mining and Metallurgy, **9/95**, (1995), 311–316.

Lentsch, D., and Schubert, A.: Risk assessment for geothermal wells – a probabilistic approach to time and cost estimation. GRC Transactions, 37, (2013), 971-977.

Lentsch, D., Savatis, A., Schubert, A., and Schoebel, W.: Overcoming drilling challenges with rotary steerable technology in deep geotehrmal wells in the Molasse Basin of Southern Germany. *GRC Transactions*, **36**, (2012), 165-169.

Majorowicz, J.A., Garven, G., Jessop, A., and Jessop, C.: Present heat flow along a profile across the Western Canada Sedimentary Basin: the extent of hydrodynamic influence. In: Förster, A., and Merriam, D.F (eds.), Geothermics in Basin Analysis; Springer, (1999), 61-79.

Moeck, I. (submitted): Catalog of geothermal play types based on geologic controls. Under Review *at Renewable & Sustainable Energy Reviews*.

Moeck, I., and Backers, T.: Fault reactivation potential as critical factor during reservoir stimulation. *First Break*, **29**, (2011), 67–74.

Moeck, I.: Iterative development of stress models for deep geothermal reservoirs. Proceedings of the 74th EAGE Conference and Exhibition, Copenhagen, Denmark, 4–7 June 2012. 5pp., (2012).

Muffler, L.P.J.: Assessment of geothermal resources of the United States – 1978. *USGS Circular*, **790**, (1979), 163 p.

Norden, B., and Förster, A.: Thermal conductivity and radiogenic heat production of sedimentary and magmatic rocks in the Northeast German Basin. *AAPG Bulletin*, **90/6**, (2006), 939–962.

Nukman, M., and Moeck, I.: Structural controls of a geothermal system in the Tarutung Basin, North Central Sumatra. Journal of Asian Earth Sciences, **74**, (2013), 86-96.

Roland, J.V., and Sibson, R.H.: Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand, Geofluids, **4(4)**, (2004), 259–283.

Rybach, L.: Geothermal systems, conductive heat flow, geothermal anomalies. In: Rybach, L. & Muffler, L.J.P. (Eds). Geothermal Systems: Principles and Case Histories. John Wiley & Sons; Chichester (UK), (1981), 3–31.

Salley, R.C.: Applied Sedimentology, 2nd Edition. Academic Press; San Diego (CA), London (UK), Burlington (MA). 523 pp., (2000).

Sanyal, S.K.: Classification of Geothermal systems – a possible scheme. Proceedings, 30th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan 31-Feb2, 2005, SGP-TR-176, (2005).

SPE-PRMS: Society of Petroleum Geologists, Petroleum Resources Management System Guide for non-technical users, (2007), 1-4, from: http://www.spe.org/industry/docs/PRMS_guide_non_tech.pdf, cited 13th June 2013.

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., et al.: Impact of enhanced geothermal systems on US energy supply in the twenty-first century. *Philosophical Transactions of the Royal Society A*, Mathematical, Physics & Enginerring Science, **365/1853**, (2007), 1057–1094.

Toth, J.: Gravitational Systems of Groundwater Flow—Theory, Evaluation, Utilization. Cambridge University Press, Cambridge, UK, pp 297, (2009).

Williams, C.F., Reed, M.J., and Anderson, A.F.: Updating the classification of geothermal resources. Proceedings, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan 31 - Feb 2, (2011).

Wolfgramm, M., Obst, K., Brandes, J., Koch, R., Raubbach, K., and Thorwart, K.: Produktivitaetsprognosen geothermischer Aquifere in Deutschland. In: Der Geothermiekongress. Bochum, Germany, Conference Proceedings, (2009).

Zheng, K., and Dong, Y.: The possible role of geothermal energy to the Chinese energy development. Proceedings, 8th Asian Geothermal Symposium, Dec 9-10, 2008, Vietnam Institute of Geosciences and Mineral Resources, Hanoi, Vietnam, (2008).