New Classification of High Temperature Geothermal Systems Based on 110 Geothermal Fields Worldwide

Bastien Hermant[1], Elisa Colas[1], Delphine Patriarche[2], Jean-Luc Auxiètre[1], Mathieu Bellanger[1].

[1] TLS Geothermics, 92 Chemin de Gabardie, 31200 Toulouse

[2] Storengy, 12 Rue Raoul Nordling, Bâtiment Djinn 92270 Bois-Colombes

bastien.hermant@tls-geothermics.fr

Keywords: geothermal fields, classification, worldwide database, geodynamical context, stress field.

ABSTRACT

Based on a database of 110 geothermal fields worldwide, we propose a new classification including scale complexity of geological parameters which define the geothermal resource. This new classification is more flexible than the existing ones and is based on three orders of parameters: mega-regional ones, regional ones around the geothermal field and local ones. With the database and the classification, we have studied the distribution of total worldwide installed electricity production in comparison to mega-regional and regional parameters. This study allows for defining favourable geological context for geothermal resource location such as convergent plate boundary contexts, extensive and/or strike-slip stress fields and thinning of crust and lithosphere. The unexpected importance of major strike-slip fault zones has also been highlighted. Therefore, this classification and the associated analysis will help to define new potential geothermal areas through analogies with existing geothermal fields.

1. INTRODUCTION

Several classifications of high temperature geothermal fields exploited for power generation already exist. They are built on production data (Bertani, 2005; Bertani, 2016) that can be combined with tectonic settings (Wilmarth and Stimac, 2015). The most advanced classification is built according to geological characteristics to create geothermal plays (Moeck, 2014). Classify geothermal fields is an important challenge. Indeed, an efficient classification allows for making analogies to assess new potential areas for geothermal or to define similarities between new exploration areas and existing fields. Therefore, we propose a new classification including scales complexity between geological parameters which define geothermal resource presence. This classification is less absolute than the one of Moeck (2014) but it is more flexible. Indeed, play types described by Moeck (2014) are based on a conceptual model built from cross-checked analysis of parameter of various scales. These parameters are not typical of one particular type of resource. For example, volcanism is a common parameter of geothermal systems of very different nature. To avoid this complexity, the new classification uses only observation data and do not try to build conceptual models.

The new classification is built in light of the study of a worldwide database of geothermal fields producing electricity. This one is based on the bibliographic review of more than 1300 articles about 110 geothermal field in 24 countries throughout the world (Figure 1). More than 120 parameters of various types are referenced (power plant, geology, production, geochemistry, petrophysics,…) and new parameters can eventually be added.

We define three orders of magnitude of studied parameters: the first order is composed of mega-regional parameters (geodynamical context, stress field); the second order is composed of regional data around the geothermal system (magmatism, major fault zones,…); the local order is composed of specific data of the geothermal system in relation to its exploitation (liquid/gas/vapor geochemistry, temperature, fluid flow,…). For each categorical parameter, the classification is unique. For example, a geothermal field classified in a rift context cannot be classified in a volcanic arc context at the same time. Furthermore, inferior orders parameters can be common to several superior orders. Indeed, volcanism can be present in both rift context and back-arc context. Therefore, this kind of classification is efficient to independently study the possible correlation between parameters.

2. GEODYNAMICAL CONTEXT CLASSIFICATION

Tectonic plate borders and tectonic plates themselves have very different geodynamical activity. A first order parameter of the classification is about location of geothermal system in relation to tectonic plate

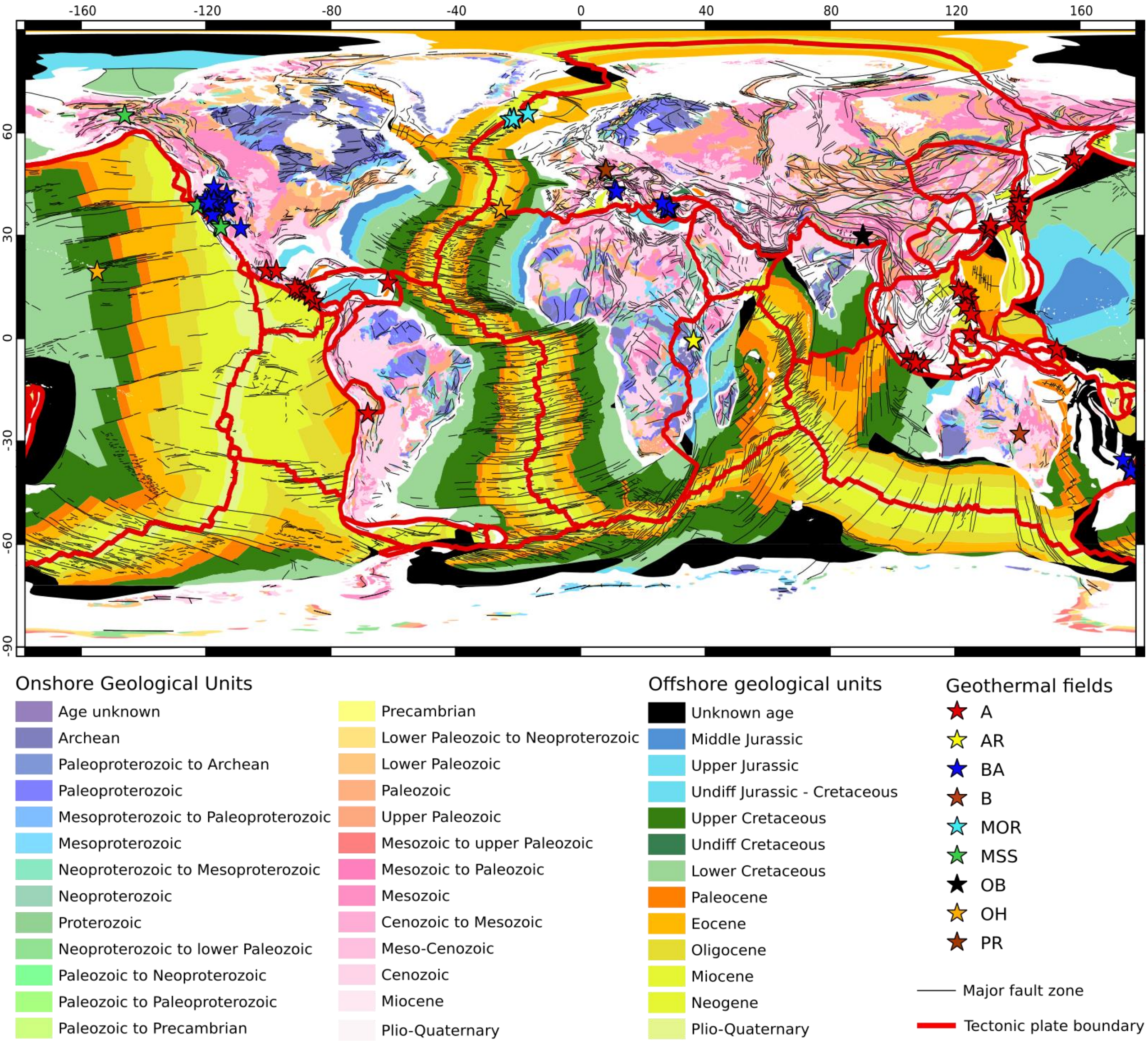

Figure 1: Geological world map with location of high temperature geothermal fields of the database (WGS84, EPSG : 4326) (A = Arc, BA = Back-Arc, MSS = Major Strike-Slip, OBe = Orogenic Belt, B = Basement, MOR = Mid-Ocean Ridge, AR = Active Rift, PR = Passive Rift, OH = Oceanic Hotspot)

boundaries and associated geodynamical context. All geodynamical contexts should be taken into account, even if they are not currently exploited for geothermal electricity production (Figure 2). Indeed, they could reveal an economical geothermal potential in the future.

2.1 Intraplate

Intraplate contexts have a tectonic activity relatively quiet. However, hotspots can be areas with particular activity (volcanic and tectonic). Indeed, they results from deep mantle plume rising generating remarkable magma production expressed on surface by volcanic activity. Nowadays, hotspots are not very well understood because they can be located in both continental and oceanic plates. They can also be located on a plate boundary like Iceland (example explained later). Therefore, in the new classification for intraplate contexts, hotspots are distinguished from cratons and they are shared between oceanic hotspot (Puna – Hawaii) and continental hotspot.

Cratons are areas tectonically relatively quiet and stable. They are divided in two categories: basement (Habanero – Australia) and intracratonic basin (Paris basin). This context is typical of conductive geothermal play describe by Moeck (2014).

2.2 Plate border

There are three types of plate boundary (converging, transforming and diverging) with different geodynamical characteristics and various implications for geothermal energy production.

Convergent

Convergent plate boundaries show contact between two lithospheric plates which converge toward each other. The lower plate plunges under the second tectonic plate (oceanic or continental) and sinks into the mantle. When the lower plate plunges into subduction zone, the characteristics of this subduction and the induced asthenospheric motions generate various geodynamical objects, which define subcategories of the classification: (1) volcanic arc (Darajat – Indonesia) is volcanic alignment, parallel to the subduction zone, resulting from the partial melting of the mantle corner located above the plunging plate (Stelling et al., 2016; Perrin et al., 2018); (2) Back-arc area (Dixie Valley – USA) is an extensional domain due to the combination between the plunging plate dynamics (rollback, slab tears) and the associated asthenospheric flows (Parson & Wright, 1996; Roche et al., 2018); (3) Major strike-slip (Cerro Prieto – Mexico) is a sliding area, often linked to converging angle between plates, which accommodate the movement speed gradient between different parts of converging tectonic plates (Storti et al., 2003; Cao and Neubauer, 2016; Nukman and Hochstein, 2018).

Convergence between lithospheric plates can involve collision. One plate can slip under the other but the induced geodynamical processes differ from those resulting from the subduction ones: (1) orogenic belt is caused by crustal thickening of the upper plate during collision (Yangyi – China); (2) orogenic foreland basins fill subsidence resulting from the flexure of the lithosphere due to overload of the upper plate (Molasse basin – Germany).

Transforming

Transform plate borders are sliding boundaries between two lithospheric plates without vertical movement. This type of boundary is relatively under-represented on the Earth surface but one example is the boundary between Caribbean and North American plates (Jordan, 1975; Boschman et al., 2014; Wessels, 2019). None of these transforming plate boundaries are currently exploited for geothermal energy production.

Divergent

Divergent plate boundary is an extensional domain where two tectonic plates moving away from each other. When this plate boundary is located within a continent, it initially forms a rift that can lead, for very active dynamic, to the opening of an ocean and the formation of a mid-ocean ridge.

Rifts are separated into active and passive rifts. This categorisation is still discussed because natural objects often result from complex processes. Passive rifts resulting from lithosphere horizontal stretching lead to thinning of the lithosphere and formation of grabens. Active rifts are the result of a mantle plume rising, causing lithospheric bulge and thinning: they are often combined with active volcanism (Koptev et al., 2015). The extension is then a result of this process.

The new classification then differentiates three types of divergent tectonic plate boundaries: (1) mid-ocean ridge (Reykjanes – Iceland); (2) active rift (Olkaria – Kenya); (3) passive rift. Iceland is the only irregularity of the classification uniqueness because it is a hotspot located beneath a mid-ocean ridge. We made the choice to consider the major Icelandic geodynamical context as being a mid-ocean ridge with enough volcanic emission to rise the surface and being exploited by humans.

3. FIRST ORDER PARAMETERS

Plate border	Convergent (C)	Arc (A)
		Back Arc (BA)
		Major Strike Slip (MSS)
		Orogenic Belt (OBe)
		Orogenic Basin (OBa)
	Transform (T)	-
	Divergent (D)	Mid Oceanic Ridge (MOR)
		Active Rift (AR)
		Passive Rift (PR)
Intraplate	Intraplate hotspot (P)	Continental Hotspot (CH)
		Oceanic Hotspot (OH)
	Craton (Cr)	Basement (B)
		Intracratonic Basin (IB)

Figure 2: Geodynamical order for the new classification of high temperature geothermal fields

The majority of geothermal fields (69/110) in the database have an installed capacity between 20 and 200 MWe (Figure 5). Only few geothermal fields have an installed capacity larger than 500 MWe (5/110). Fields with installed capacity lower than 10 MWe are under-represented, because the database is focused on geothermal fields with installed capacity larger than 10 MWe. However, some of these small fields are recorded because of their particular geodynamical context of location (Chena, Habanero, Soultz-sous-Forêt).

We do not use the number of fields to study installed capacity distribution according to the different parameters. Instead of it, we define the Total Worldwide Installed Electrical Power. The TWIEP value was 13.2 GWe in 2016 (World Energy Council), 14 GWe in 2017 (International Energy Agency) and 14.37 GWe in 2018 (ThinkGeoEnergy). According to the database, the TWIEP is 12.973 GWe. That respectively represents 98.3%, 92.6% and 90.3% of the TWIEP value of 2016, 2017 and 2018. Knowing that the database is based on articles essentially published before 2017, we can consider that most of the installed capacity is recorded. Therefore, the bias due to under-representation of small fields is acceptable. Nevertheless, this bias could be corrected with the addition of small geothermal fields and recent geothermal fields (after 2017) in the database.

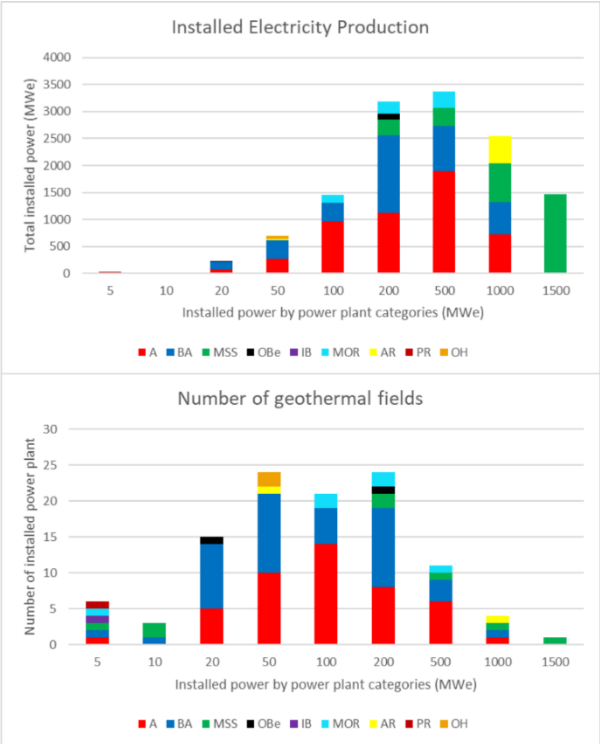

Figure 3: Distribution of number of geothermal fields and TWIEP according to geodynamical context and the installed capacity (A = Arc, BA = Back-Arc, MSS = Major Strike-Slip, OBe = Orogenic Belt, IB = Intracratonic Basement, MOR = Mid-Ocean Ridge AR = Active Rift, PR = Passive Rift, OH = Oceanic Hotspot).

3.1 Geodynamical context

The main part of the TWIEP is installed on a plate boundary. Only Habanero (craton – 1 MWe) and Puna (oceanic hotspot – 38 MWe) are located intraplate. Among geothermal fields located on a plate boundary, convergent and divergent plate boundaries represent respectively 91% and 9% of TWIEP (Figure 4). Divergent plate boundaries TWIEP is divided into 55% for mid-ocean ridge (Iceland) and 45% for active rift. Convergent plate boundaries TWIEP distribution are 44% for volcanic arc, 30% for back-arc domain, 25% for major strike-slip and 1% for orogenic belt (Figure 4).

Volcanic arc context is typical of the convective geothermal play (Moeck, 2014). TWIEP distribution shows that it represents the most important context for geothermal electricity production, particularly in Central America and in the Pacific Ring of Fire. Back-arc context is often difficult to define because of the subduction processes complexity. But this context represents a large part of the TWIEP, especially in the Basin and Range (USA). Unexpectedly, the significance of major strike-slips has been under-estimated. It may be because this context is rarely defined as a true context and often connected to another context. However, major strike-slip seems to be particularly favourable for geothermal energy. There are a limited number of geothermal fields in this context (Geysers, Cerro Prieto, Salton Sea, East Mesa, Heber, Chena, Tuzla) but their installed capacity are usually very large (> 100 MWe). Note that the distribution of installed capacity (Figure 3) highlight the importance of major strike-slip context. It also confirms the domination of volcanic arc and back-arc contexts, as much for the number of fields as for TWIEP.

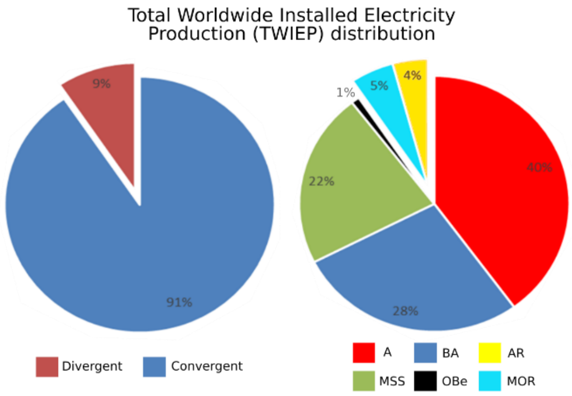

Figure 4: TWIEP distribution according to the type of tectonic plate border and the associated geodynamical context (A = Arc, BA = Back-Arc, AR = Active Rift, MSS = Major Strike-Slip, OBe = Orogenic Belt, MOR = Mid-Ocean Ridge). Context representing less than 1% of the TWIEP are not represented.

3.2 Stress field

This geodynamical classification is a conceptual point of view of geothermal field context but stress field analysis for each geothermal field can provide hard data to have an analytical point of view. Stress field data comes from the worldwide database World Stress Map 2016 (Heidbach et al., 2016). It includes data measured into holes and data calculated from seismic focal mechanisms. The nature of stress field associated to each geothermal system is defined according to available data in its surroundings. If data are too distant to the geothermal field or if they are too variable, the stress field would be defined as probable. If there is no data or if they do not allow for clearly describing the stress field, the stress field would be defined as unknown.

Stress field has been defined for 85% of the TWIEP and it has been safely defined for 52% of the TWIEP (Figure 5). A large majority of TWIEP (70%) is consistent with an extensive and/or strike-slip stress field. Compressive stress field represents 15% of TWIEP whose only 2% are safely defined. The stress field for geothermal fields located on a divergent plate boundary has not been defined or has been defined with not enough certainty. However, for geothermal fields located in a convergent plate boundary, stress field has been defined for 94% or the TWIEP and is predominantly extensive and/or strike-slip (78% of the convergent TWIEP) (Figure 5). Surprisingly, it is not consistent with the expected stress field for a

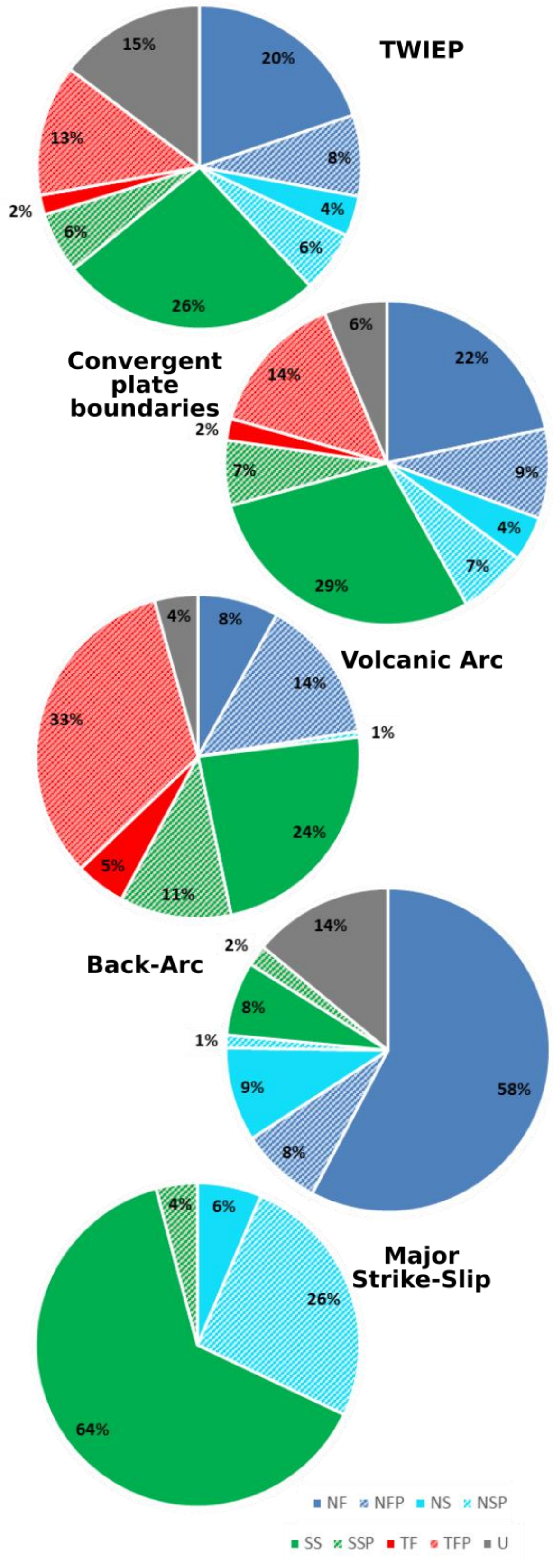

Figure 5: TWIEP distribution according to the stress field context (NF = Normal Fault, NS = Normal/Strike-Slip, SS = Strike-Slip, TF = Thrust Fault, U = Unknown, if P the stress field is considered as probable)

convergent context (more or less compressive). Focusing on the major geodynamical contexts, the volcanic arc context is the only one where compressive stress field is recorded (38% of volcanic arc TWIEP). Back-arc and major strike-slip recorded stress fields are consistent with the expected ones (72% extensive for back-arc TWIEP and 68% strike-slip for major strike-slip) (Figure 5).

But one of the main observations is the large weight of strike-slip stress field in the TWIEP. Strike-slip stress field represents 32% of the TWIEP and respectively 36%, 35% and 10% of convergent plate boundaries, volcanic arc and back-arc TWIEP (Figure 5). As expected, geothermal fields in a major strike-slip context are often in a strike-slip stress field (68% of the major strike-slip TWIEP). The importance of strike-slip stress fields is unexpected but could be explained by the permeability favourability of relay zone in large structures. Moreover, strike-slip structures are often sub-vertical. This geometry allows for a deep rooting and an important gradient into the structure which are favourable for fluid circulations into a possible geothermal system.

4. 2nd ORDER GEOLOGICAL PARAMETERS

4.1 Local geological factors

The three main economical parameters for geothermal energy are temperature, fluid flow and depth. Fluid flow is very complex to study and compare between geothermal fields because it depends on many parameters (the number of wells, the type of fluid,…). Therefore, we focus our study on temperature and depth of the reservoir. Based on the new classification, there is no particular behaviour of temperature and depth of the resource depending on the stress field and the geodynamical context. However, geothermal fields in a back-arc context have often an exploited resource temperature under 200°C. Therefore, these parameters strongly determine the location of geothermal resources but they do not constrain the local economic parameters like the geothermal gradient.

The stress field and the geodynamical context do not determine local economical parameter. But some local geological factors such as volcanism, plutonism and sedimentary basin may have impacts on the economy of geothermal projects. Indeed, the analysis of these parameters shows interesting results (Figure 6). Where there is volcanism (for 83% of the TWIEP), reservoir temperature is significantly higher (240-320°C with volcanism and 150-270°C without volcanism). Average geothermal gradients can be calculated with recorded reservoir temperature and depth. Their values are equivalent with or without volcanism and the maximum values is calculated for a geothermal system without volcanism (Yangyi – China). Volcanism can provide higher temperature but not necessary at lower depths. It probably depends on the depth of the magmatic chamber and its possible connection to fault zones into the geothermal system.

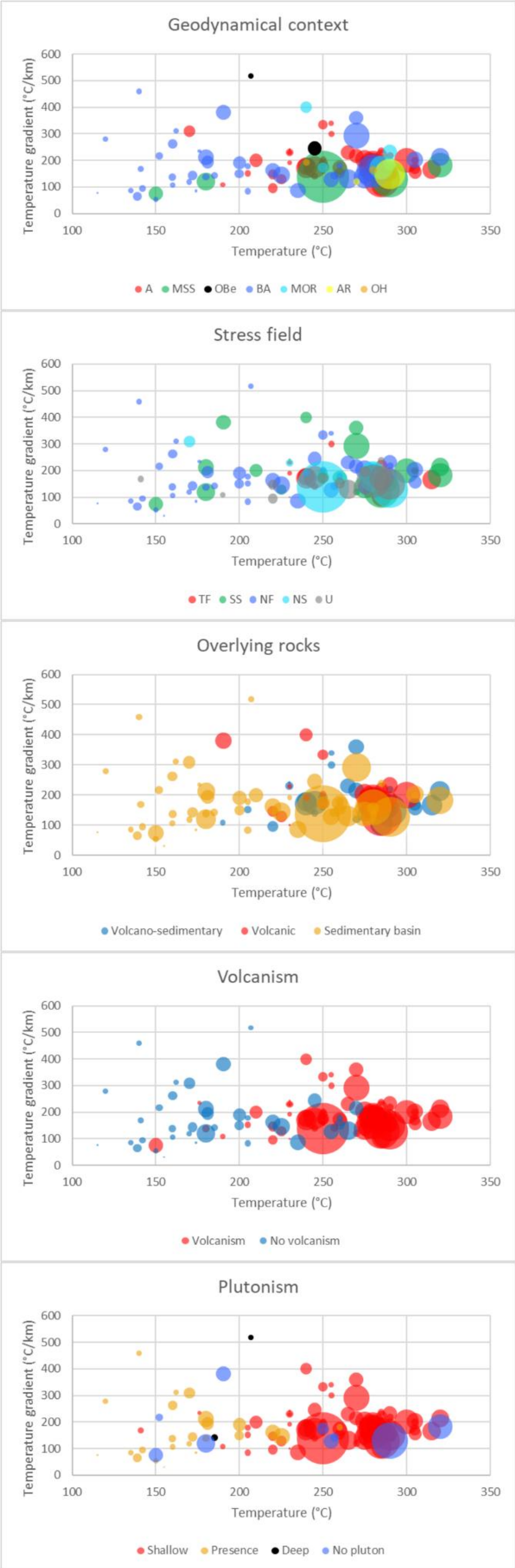

Figure 6: Influence of 2nd order geological parameters on temperature gradient and temperature for 110 geothermal fields

The sedimentary or volcano-sedimentary cover (for 75% of TWIEP) seems to be too common to observe a distinctive behaviour of temperature and depth distribution. No geothermal system is located directly into basement and almost all geothermal systems without volcanism include a sedimentary basin. The only observable trend is that geothermal systems with resource temperature lower than 200°C are often located in or under a sedimentary basin (Figure 6). Therefore, is the presence of overlying rocks necessary to the existence of a geothermal resource where reservoir is into the basement ? It is difficult to answer because there is no existing field in this case. But theoretically, the conductivity contrast between the basement (essentially quartz and feldspar) and the overlying rocks is favourable to an important temperature gradient in the overlying rocks and a heat concentration at the top of the basement. Thus, it is favourable but not necessary and there could be geothermal resources directly into the basement, especially thanks to major crustal faults zones (Bellanger et al., 2019).

The presence of a pluton (for 78% of the TWIEP) strongly affects the heat content of the geothermal system. If the pluton is located at shallow depth, the resource temperature is always higher than 200°C but not particularly shallower (Figure 6). Once again, it depends on the possible connection for subvertical fluid circulations between pluton formations and reservoir layers.

4.2 Lithospheric horizons

Geodynamical context generally involves a specific geometry of lithospheric horizons (Moho and Lithosphere-Asthenosphere Boundary). There are different models of Moho and LAB depths. We use several of them: LITHO1 (Pasyanos et al., 2014) for Moho and LAB, CRUST1 (Laske et al., 2013) for Moho, and Koptev et al. (2011) model for LAB. To evaluate the average depth of these horizons for each model, we randomly sample depth on 10000 points over the continental crust areas with a minimum distance of 100 km using the world Mollweide projected coordinate system (Figure 7). We choose the pseudo-cylindrical Mollweide projection because it is equal-area (Grafarend and Heidenreich, 1995) and it allows for keeping the same sampling density over the entire surface of the globe.

The results of this study show that the crust thickness under geothermal fields is lower than the average continental crust thickness. Moho is shallower of 3 km on average under geothermal fields for both models. Major strike-slip is the context where the Moho rising is the most expressed with an almost 8 km difference with a standard deviation σ_{MSS} = 4-5 km. However, geothermal fields in strike-slip context are almost all

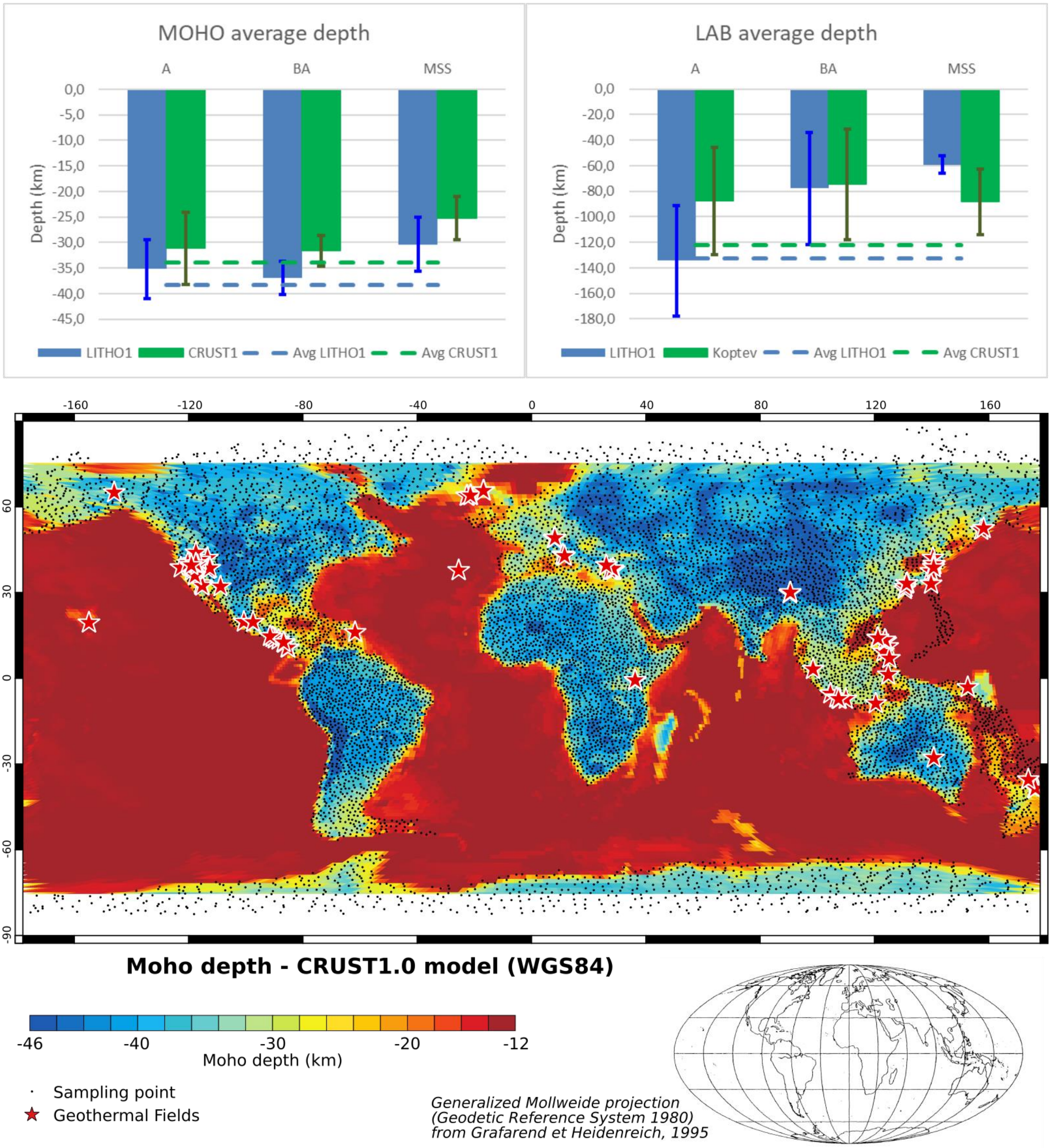

Figure 7: Average Moho and LAB depths under geothermal fields and under continental crust for CRUST1.0 and LITHO1.0 models ; CRUST1.0 Moho depth model (WGS84) with sampling points for average depth assessment ; Example of tue used Mollweide equal-area projection.

located in the same area (California and Imperial Valley). That prevents a global overview for this context. Moho depth is also lower in arc and back-arc contexts. But the difference with the average value for continental crust is lower than for major strike-slip context (arc = 2.8 to 3.0 km, back-arc = 1.3 to 2.3 km).

Even if standard deviation is large (σ up to 44 km), data expresses a large average rising of the LAB depth for the three main contexts. The average rising of the LAB is 44 km in the Koptev model and 31 km in the LITHO1 model. This rising is particularly well expressed for the back-arc context where both models give analogous results (LAB depth = 75-78km with σ = 43km). The LAB rising is also noticeable in major strike-slip context and arc context. However, the standard deviation of LAB depth for arc context is large (σ = 43 km) and the LITHO1 model shows a LAB depth under geothermal fields analogous to the average one under the continental lithosphere (133km). Thus, there could be an overestimation of LAB depth for arc context in the LITHO1 model, probably due to some difficulties with the plunging plate. Average value for geothermal fields in a strike-slip context have to be studied carefully because of the gathered locations of these fields.

5. DISCUSSION

The database needs to be completed to improve and extend the analysis. Geothermal fields with installed capacity less than 10 MWe should be taken into account to increase the number of geothermal fields in the database and improve the representativity of the study. Some parameters are not precisely filled out for all geothermal fields because of the lack of bibliographic data. It is an obstacle to the full use of the database potential. Another obstacle is the possible shift between bibliographic data and real data of the geothermal field but we consider that it essentially impact production data (power, fluid flow, number of wells,…) that we do not consider in this study. Therefore, the database also needs to be frequently updated with data from newly published articles.

However, the current database is a powerful tool to define a first order behaviour. The paradox between the similar prevalences of convergent plate boundaries and extensive/strike-slip stress fields in the TWIEP distribution (Figure 4; Figure 5) is very important. It is coupled with a rising of the Moho and the LAB under the geothermal fields. Therefore, the role of the geodynamical overview is critical to determine geothermal resource occurrence. The slab rollback (and tears) induces asthenospheric flows and lithospheric extension in the overriding plate where large faults control both exhumation of metamorphic core complexes (MCCs) and the magma ascent and/or fluid circulation (Reynolds and Lister, 1987; Huet et al., 2011). In this context, detachment faults and major strike-slip faults represent possible permeable structures deeply rooted down to the brittle-ductile transition (Famin et al., 2004; Mezri et al., 2015, Cao and Neubauer, 2016, Bellanger et al. 2019). These structures and the lithosphere thinning are particularly favourable for geothermal systems.

6. CONCLUSION

There are many ways to classify high temperature geothermal fields to evaluate trends and correlations between fields characteristics. Our classification does not intend to assign geothermal fields into closed categories to avoid the mixing of different scale geological elements which may not be linked. This choice allows for exploring possible correlations between parameters on an independent basis. The study of the worldwide database highlights favourable (but not necessary) geological conditions for geothermal resource existence. Thus, temperatures are positively influenced by volcanism and plutonism. The worldwide analysis also highlights the paradox between the equal importance of convergent plate borders and extensive to strike-slip stress fields in the current TWIEP. Our study also highlights importance of major strike-slip fault zones which are able to adjust speed gradient between different blocks in extension or compression. The deep rooting of these extensive and strike-slip structures and their permeability is a key parameter for geothermal systems. The currently exploited geothermal areas show a rising of Moho and LAB that could help to define new potential geothermal systems.

Indeed, high temperature geothermal development is closely linked to project economy and country ambition to massively develop this renewable energy. Some countries potential could have been under-estimated or overlooked because of the lack of surface manifestations (volcanism, hot springs,…) indicating an active geothermal system. With our database, it is possible to make a new assessment of geothermal potential not only based on surface manifestations. In this assessment, first order geodynamical parameters will play a preponderant role and could be coupled with other favourable criteria such as volcanism, magmatism or major fault zones. Other geological parameters of the database which are not exploited yet could be used to constrain the geothermal potential assessment.

7. REFERENCES

Bellanger, B., Auxiètre, J-L., Ars, J-M., Hautot, S. and Tarits, P.: The Key role of first-order geological paradigm in deep geothermal exploration, *Proceedings of European Geothermal Congress 2016*, Strasbourg, France, (2016).

Bellanger, B., Hermant, B., Galibert, S., Auxiètre, J-L.: A deep drilling in the French Massif Central to assess the potential of crustal fault zones for power geothermal purpose – The Sioule license project, *Proceedings of European Geothermal Congress 2019*, Den Haag, Netherland, (2019).

Bertani, R.: World geothermal generation 2001-2005: State of the art, *Proceedings World Geothermal Congress*, Antalya, Turkey, (2005).

Bertani, R.: Geothermal power generation in the world 2010–2014 update report. *Geothermics*, 60, (2016), 31-43.

Boschman, L. M., van Hinsbergen, D. J., Torsvik, T. H., Spakman, W., and Pindell, J. L.: Kinematic reconstruction of the Caribbean region since the Early Jurassic. *Earth-Science Reviews*, 138, (2014), 102-136.

Cao, S., and Neubauer, F.: Deep crustal expressions of exhumed strike-slip fault systems: Shear zone initiation on rheological boundaries. *Earth-Science Reviews*, *162*, (2016), 155-176.

Famin, V., Hébert, R., Philippot, P., and Jolivet, L.: Ion probe and fluid inclusion evidence for co-seismic fluid infiltration in a crustal detachment, *Contributions to Mineralogy and Petrology*, 150(3), (2005), 354-367.

Grafarend, E., and Heidenreich, A.: The generalized Mollweide projection of the biaxial ellipsoid, *Bulletin géodésique*, 69(3), (1995), 164.

Heidbach, O., Rajabi, M., Reiter, K., and Ziegler, M.: World stress map 2016, *Science*, 277, (2016), 1956-1962.

Huet, B., Le Pourhiet, L., Labrousse, L., Burov, E., and Jolivet, L.: Post-orogenic extension and metamorphic core complexes in a heterogeneous crust: the role of crustal layering inherited from collision. Application to the Cyclades (Aegean domain), *Geophysical Journal International*, 184(2), (2011), 611-625.

Jordan, T. H.: The present-day motions of the Caribbean plate. *Journal of Geophysical Research*, 80(32), (1975), 4433-4439.

Koptev, A. I., & Ershov, A. V.: Thermal thickness of the Earth's lithosphere: a numerical model, *Moscow University Geology Bulletin*, 66(5), (2011), 323-330.

Koptev, A., Calais, E., Burov, E., Leroy, S., and Gerya, T.: Dual continental rift systems generated by plume–lithosphere interaction, *Nature Geoscience*, 8(5), (2015), 388.

Laske, G., Masters, G., Ma, Z., Pasyanos, M.: CRUST1.0: An updated global model of Earth's crust, *Geophys Res Abs 14*, EGU2012-3743-1, EGU General Assembly, Vienna, Austria (2012)

Mezri, L., Le Pourhiet, L., Wolf, S., & Burov, E.: New parametric implementation of metamorphic reactions limited by water content, impact on exhumation along detachment faults. *Lithos*, 236, (2015), 287-298.

Moeck, I. S.: Catalog of geothermal play types based on geologic controls. *Renewable and Sustainable Energy Reviews*, *37*, (2014), 867-882.

Negretti, M., Reguzzoni, M., & Sampietro, D.: A web processing service for GOCE data exploitation. In *First International GOCE Solid Earth Workshop*, Enschede, The Netherlands, (2012), 16-17.

Nukman, M., and Hochstein, M. P.: The Sipoholon Geothermal Field and adjacent geothermal systems along the North-Central Sumatra Fault Belt, Indonesia: reviews on geochemistry, tectonics, and natural heat loss. *Journal of Asian Earth Sciences,* (2018).

Parson, L. M., and Wright, I. C.: The Lau-Havre-Taupo back-arc basin: A southward-propagating, multi-stage evolution from rifting to spreading, *Tectonophysics*, 263(1-4), (1996), 1-22.

Pasyanos, M. E., Masters, T. G., Laske, G., and Ma, Z.: LITHO1. 0: An updated crust and lithospheric model of the Earth, *Journal of Geophysical Research: Solid Earth*, 119(3), (2014), 2153-2173.

Perrin, A., Goes, S., Prytulak, J., Rondenay, S., and Davies, D. R.: Mantle wedge temperatures and their potential relation to volcanic arc location, *Earth and Planetary Science Letters*, 501, (2018), 67-77.

Reguzzoni, M., and Sampietro, D.: GEMMA: An Earth crustal model based on GOCE satellite data, *International Journal of Applied Earth Observation and Geoinformation*, 35, (2015) 31-43.

Reynolds, S. J., and Lister, G. S.: Structural aspects of fluid-rock interactions in detachment zones, *Geology*, 15(4), (1987), 362-366.

Roche, V., Sternai, P., Guillou-Frottier, L., Menant, A., Jolivet, L., Bouchot, V., and Gerya, T.: Emplacement of metamorphic core complexes and associated geothermal systems controlled by slab dynamics, *Earth and Planetary Science Letters*, 498, (2018), 322-333.

Stelling, P., Shevenell, L., Hinz, N., Coolbaugh, M., Melosh, G., & Cumming, W.: Geothermal systems in volcanic arcs: Volcanic characteristics and surface manifestations as indicators of geothermal potential and favorability worldwide, *Journal of Volcanology and Geothermal Research*, 324, (2016), 57-72.

Storti, F., Holdsworth, R. E., & Salvini, F.: Intraplate strike-slip deformation belts, *Geological Society, London, Special Publications*, 210(1), (2003), 1-14.

Wessels, R. J. (2019).: Strike-Slip Fault Systems Along the Northern Caribbean Plate Boundary., in: Transform Plate Boundaries and Fracture Zones, Joao Duarte, 375-395, *Elsevier*, (2019).

Wilmarth, M. and Stimac, J.: Power Density in Geothermal Fields, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia (2015).