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Worldwide Compilation of Young Igneous Rocks Ages Associated with High-Enthalpy Operating Geothermal Fields

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ABSTRACT

A database of the youngest dated igneous rocks found within the immediate area of 48 high-temperature geothermal fields has been compiled. Correlations are identified between the age of these igneous rocks, the volcanic environment and the power density (MW/km^2) that has been achieved with power development on the fields. All the developed fields in this data set have associated igneous rocks that are younger than 2.9 Ma, and 77% of them are Pleistocene (0.0117 Ma -2.58 Ma). Moreover, 83% are younger than 0.5 Ma and their average age is 0.36 Ma. This strong correlation of young igneous activity at the surface being associated with high temperature fields is interpreted as highlighting the importance of magmatic activity as a heat source for these systems. Only fields associated with igneous activity younger than 0.5 Ma have a power density $\geq$ 20 MW/km^2. The volcanic environment also seems to have an influence on the power density of the geothermal field, with the back-arc setting having the highest power density and youngest heat sources. These correlations may be useful to consider when evaluating the prospectivity of undrilled prospects where the age of volcanism has been assessed.

1. INTRODUCTION

This work considers 48 high-temperature geothermal fields that have been operating for more than 10 years and are part of the power density study of Wilmarth and Stimac (2015) and Grant (1996). Their studies relate the power density (MWe/km^2) to the temperature of the reservoir, additionally Wilmarth and Stimac (2015) associated these parameters to the field's tectonic setting – extensive or compressive - and its production history from selected proven areas constrained by deep drilling.

The results show two main temperature/power density relationships:

1. The first category is represented by fields showing a positive correlation between the power density and the temperature with a trend line of 2 MW/km^2 per 10°C of reservoir temperature (Figure 1). This group is defined by an extensional tectonic setting (e.g. Basin and Range, Rifts).
2. The second category is characterised by a negative correlation between the power density and the temperature and includes geothermal fields in compressive zones (e.g. Arc Volcanoes).

The interpretation of these correlations indicate that the volcanic setting also has control over power density, as in general permeability appears to decrease for Arcs when the temperature increases, but the opposite is true for fields in Rifts environment (Figure 1).

The objectives of the present work are:

- To collect dates on the youngest associated igneous rocks that may reflect the heat sources' ages for these operating geothermal fields and;
- To understand the ages distribution of the youngest known intrusion or volcanic deposits, which are interpreted as potential heat source for each geothermal field area. Some fields were identified with age ranges from several dating on a variety of rocks and are more likely to represent the longevity of the geothermal system.
- To identify correlations that can be used as guide for geothermal exploration rather than developing a rigorous method for estimating the age of geothermal system heat source.

All the data used in this work was collected from an existing rich literature on ages and sizes of heat sources and summaries of age ranges of active geothermal systems. The present study does not address the cooling rates of the heat sources and further research should be undertaken to determine the longevity aspect of the geothermal systems.

2. THE DATABASE

This work includes 48 exploited geothermal fields, of the 66 power plants listed in Wilmarth and Stimac (2015). Five of the fields do not have dated young igneous rocks. Dixie Valley and Beowawe are located within Basin and Range settings and Kizildere is in a similar tectonic setting to the Basin and Range. The heat in Dixie Valley, Beowawe and Kilzidere systems is thought to be derived from crustal thinning rather than specific intrusives. The heat sources' ages at Darajat and Tongonan have not been determined. Some attempts have been made to date rocks at Darajat, but most were basaltic andesites and andesites that were lacking in phenocrysts suitable for $^{40}Ar/^{39}Ar$ dating. The ages considered in this database are those with the highest reliability where surveys have defined the locations and the nature of the dated samples (e.g. intrusive bodies and complexes, lava domes and flows). If intrusive body dates are not available, the age of the youngest volcanic event is considered to be representative of the heat source's age.

Several dating methods have been used in the 48 fields. The most commonly used are the K/Ar, $^{40}Ar/^{39}Ar$, ^{14}C and Fission Track U^{238} methods, followed by thermoluminescence on zircons, U/Pb, Rb/Sr, and U/Th techniques. Therefore, the level of confidence is different for each heat source based on the dating method. For example, the $^{40}Ar/^{39}Ar$ method is more modern and accurate than the older K/Ar method. In some cases, the source does not describe the dates sufficiently to ascertain the methods or inherent uncertainties in the ages. Only 60.4% of the interpreted heat source ages in this database are identified in precise and available literature. The age of the last known eruption is taken as evidence that the heat source was at least partially active at the time of the event. Therefore, these ages are a lower end age estimate of the heat source, i.e., the heat source of the system may be younger than the estimated age but not older.

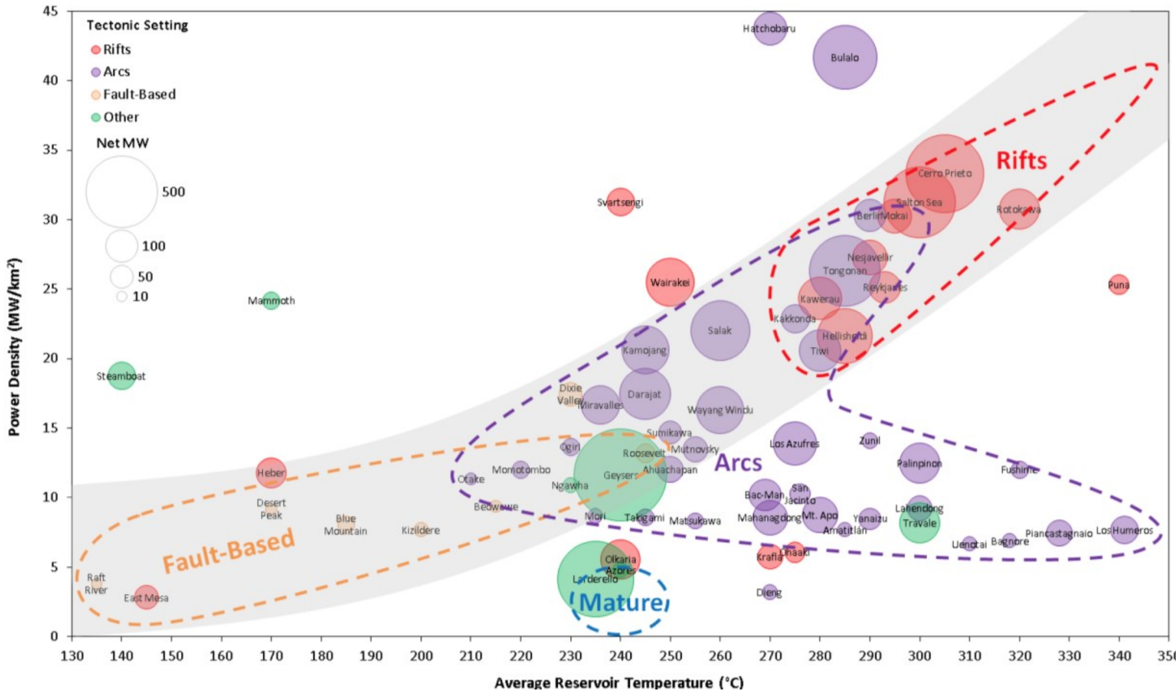


Figure 1: Power density vs Temperature for 66 high-temperature geothermal fields with interpreted affiliations; Wilmarth and Stimac (2015).

Table 1: Compilation of interpreted age dates and methods for different geothermal fields.

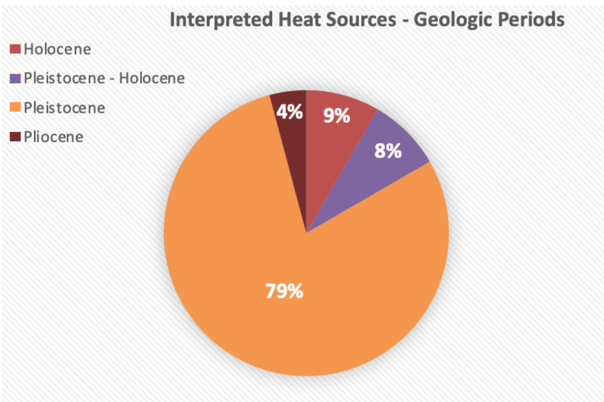
FIELD	AGE (Ma)	HEAT SOURCE	ROCK TYPE	TYPE OF DATING
Ahuachapan	< 0.1	Magma chamber under the Concepcion de Ataco caldera.	Dacitic and Andesitic	K-Ar on latest cinder cones (Gonzales et al., 1997)
Amatitlan	< 0.7	Dacitic domes and magma chamber of the Pacaya Volcano.	Dacitic	Not specified (Lima et al., 2000)
Azores	0.005	Magma chamber of the Agua de Pau Volcano.	Trachyte pumices	^{14}C (Moore, 1991)
Bac-Man	1.79	Camayan Intrusive Complex (CIC): basalt, microdiorite and plutonic dykes.	Dioritic	K-Ar (Ramos et al., 2012)
Bagnore	0.29	Basal Trachydacitic Complex of Mt Amiata.	Dacitic	$^{39}Ar/^{40}Ar$ on Sanidine (Ferrari et al. 1996)
Beowawe	Unknown	Granitic intrusion.	Granitic	No dating
Berlin	0.1	Active magma chamber of the Berlin Stratovolcano.	Andesitic	Not specified (D'Amore et al., 1999)
Bulalo	0.015	Dacitic domes (Bulalo Dome) to the SE of the Mt Makiling Stratovolcano.	Dacitic	$^{40}Ar/^{39}Ar$ on hornblende from Bulalo Dome (Vogel et al., 2006)
Cerro Prieto	0.05-0.04	Gabbroic intrusion (pluton) overlain by 4km-wide basaltic intrusions at 5-6 km depth.	Basaltic	Numerical modelling (Elders et al., 1984; Elders et al., 1997)
Darajat	Unknown	Magma chamber of the Gunung Kendang Stratovolcano.	Andesitic	No dating
Dixie Valley	Unknown		-	No dating
Fushime	0.026	Magma chamber of the Takeyama	Andesitic	Fission track ^{238}U (Okada et al., 2000)

		Volcano.		
Geysers	1.3 – 0.7	Pluton "The Felsite".	Granitic	$^{40}Ar/^{39}Ar$ and K-Ar (Hulen et al., 1996)
Hatchobaru	0.032	Andesitic lava domes and flows of the Kuyu Volcanic System.	Andesitic	Thermoluminescence (TL) on zircons (Hayashi et al., 2000)
Kakkonda	0.1	Neo-granitic pluton between Nyuto-san, Iwate-san, Hachimantai and Yakeyama Quaternary volcanoes.	Granitic	U-Pb (Ito et al., 2013)
Kamojang	1.2-0.45	Magma chambers of G. Rakutak, G. Gandapura, G. Guntur and G. Masigit stratovolcanoes.	Andesitic	K-Ar (Suparka et al., 2013)
Kawerau	0.3-0.0024	Magma body under the Putauaki Volcano.	Rhyolitic	^{14}C (Milicich et al., 2014)
Kizildere	Unknown	Deep fault affecting metamorphic basement under a graben (high burying).	-	No dating
Krafla	0.1	Magma chamber of the Krafla Volcano (Dolerite).	Dolerite	Not specified (Gunnarsson et al., 2015)
Lahendong	0.45	Dioritic intrusion beneath Mt Lengkoan and Mt Kasuratan.	Dioritic	Not specified (Brehme et al., 2014)
Larderello	3.8-2.9	Montieri Monzogranite Pluton (Granitic intrusions).	Granitic	K-Ar and Rb-Sr (Villa et al., 2006)
Los Azufres	0.36	Magma chamber under Los Azufres caldera.	Rhyolitic	Numerical modelling (Verma et al., 1995)
Los Humeros	0.24	Magma chamber under Los Humeros caldera.	Rhyolitic	Numerical modelling (Verma et al., 1995)
Mahanagdong	0.51-0.017	Magma chambers of Mt Cantodoc and Mt Cabalian.	Dacitic	Thermoluminescence (TL) zircons (Ramos, 1998)
Matsukawa	1.1	Dioritic intrusion (at 8 km depth) and/or Mt Iwate.	Dioritic	U-Pb and U-Th (Ito et al., 2013)
Miravalles	0.05	Magma chamber of the Miravalles Volcano	Andesitic	Not specified (Zuniga et al., 2005)
Mokai	0.026	Pukemoremore rhyolite dome (Maroa Volcanic Centre).	Rhyolitic	Not specified (Bignall et al., 2010)
Momotombo	0.0045	Magma chamber of the Momotombo stratovolcano.	Andesitic	Not specified (Hynek et al., 2013)
Mori	0.012	Andesitic intrusions and solidified magma of the Nigorikawa caldera.	Andesitic	^{14}C (Ide et al., 1982)
Mt. Apo	0.62	Magma chamber of Mt Apo.	Andesitic	K-Ar (Sajona et al., 1994)
Nesjavellir	1-0.1	Solidified dykes, magmatic intrusions and magma chamber of the Hengill Volcano.	Basaltic	Not specified (Zakharova et al., 2012)
Ngawha	0.5-0.0112	Putahi rhyolite bodies.	Rhyolitic	Not specified (Aggarwal et al., 2003)
Ogiri	0.33	Magma chamber of the Kirishimo Volcano.	Andesitic	Not specified (Nagaoka et al., 2011)
Ohaaki	0.34-0	Rhyolitic intrusions.	Rhyolitic	This age range was interpreted from the most recent activity of the Taupo Volcanic Zone (Wilson et al., 2011)
Olkaria East	0.25	Intrusions	Rhyolitic	^{14}C (Omenda, 1998)
Palinpinon	0.81	Andesitic bodies of Cuernos de Negros Volcano.	Andesitic	$^{40}Ar/^{39}Ar$ (Rae et al., 2004)
Piancastagnaio	0.29	Basal Trachydacitic Complex of Mt Amiata.	Granitic	$^{40}Ar/^{39}Ar$ on Sanidine (Ferrari and al., 1996)
Puna	0.4	Dacitic magma of the Kilauea Volcano.	Dacitic	K-Ar (Wright et al., 2006)
Roosevelt	0.5	Mineral Mountains Intrusive Complex: magma chamber and related rhyolitic intrusions.	Rhyolitic	Fission track ^{238}U and K-Ar on the rhyolitic intrusions (Evans et al., 1982)
Rotokawa	0.34-0	Rhyolitic domes (Haparangi).	Rhyolitic	This age range was interpreted from the most recent activity of the Taupo Volcanic Zone (Wilson et al., 2011)
Salak	0.12-0.04	Magma chamber of the Gunung Salak Volcano.	Rhyolitic	$^{40}Ar/^{39}Ar$, K-Ar and ^{14}C (Stimac et al., 2008)
Salton Sea	0.02-0.003	Basaltic and rhyolitic intrusions.	Basaltic and rhyolitic	Analytical model (Kasameyer et al., 1985)
Sumikawa	0.3	Magmas from Mt Hachimantai and Mt Yake.	Dioritic	Not specified (Tamanyu, 1991)
Svartsengi	1-0.1	Dolerite intrusions and dykes (mantle	Dolerite	Not specified (Arnorsson, 1995)

		magma reservoir).		
Takigami	0.018	Andesitic and dacitic lavas from the Kuyu Volcanic System.	Andesitic and dacitic	Fission track ^{238}U (Hayash et al., 2000)
Tongonan	Unknown	Magma chamber and granitic intrusions of Mahiao Plutonic Complex	-	No dating
Travale	3.8-2.9	Montieri Monzogranite Pluton (granitic intrusions).	Granitic	K-Ar and Rb-Sr (Villa et al., 2006)
Uenotai	0.2	Andesitic and dacitic lavas from the Kurikoma Volcano.	Andesitic and dacitic	Fission Track ^{238}U (Takeno, 2000)
Wairakei	0.01	Karapiti rhyolite.	Rhyolitic	^{14}C (Froggatt, 1981)
Wayang Windu	0.49	Magma chambers of the stratovolcanoes G. Malabar, G. Windu and G. Wayang.	Andesitic	K-Ar (Bogie et al., 1998)
West Tiwi	0.5-0.06	Magma chamber of the Mt Malinao Stratovolcano.	Andesitic	Not specified (Stimac et al., 2004)
Yanaizu	0.3-0.2	Magma chamber of the Sunagohara Volcano.	Rhyolitic	K-Ar and fission track ^{238}U (Mizugaki, 2000)
Zunil	0.3-0.1	Zunil-I: Paxmux Domes. Zunil II: Magma chamber of the Zunil Volcano and Paxmux Domes.	Dacitic and rhyolitic	Not specified (Lima-Lobato et al., 2000)
TOTAL DATED FIELDS	**32/53 (60.4%)**			

3. INTERPRETED HEAT SOURCE AGES

The database shows that the range of ages of the heat sources is limited between 2.9 Ma and a few thousands of years ago. More than 77% of the heat sources are Pleistocene (2.58 Ma to 0.0117 Ma, Figure 2). Thirteen percent (13%) can be classified in "Pleistocene - Holocene" because these have not a well-defined age. Therefore, the epoch is not identified, and a range of dates is provided. Six percent (6 %) of the ages are Holocene (0.0117 Ma – Present), however this number could be greater or fewer considering that some dates are not precise. For example, Momotombo sits on a very active volcano and the rock dating might be representative of the latest volcanic deposits and/or intrusions instead of the actual underlying heat source. The same consideration applies to Miravalles and Olkaria East fields, which have Pleistocene dates. The dates from Larderello and Travale give Pliocene ages (2.9 Ma) but as they were identified at two separate developments in the same field, they are only indicating one Pliocene heat source.



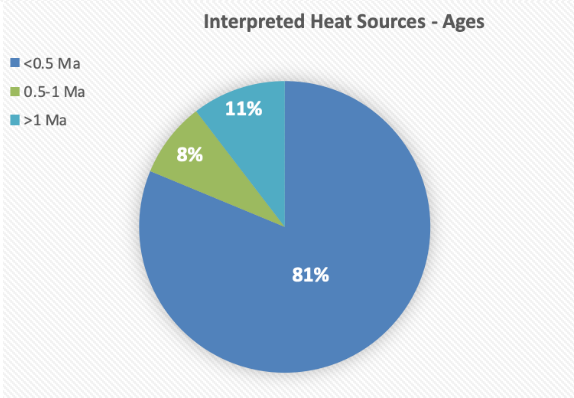
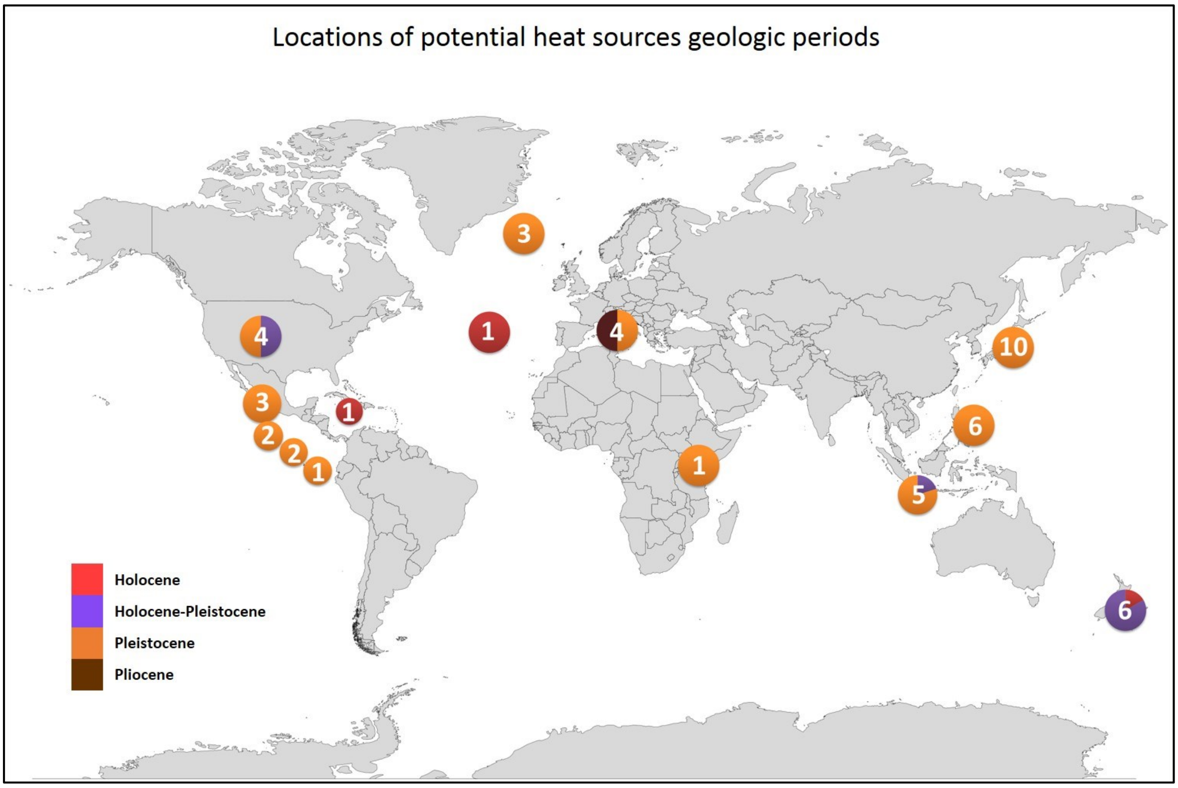


Figure 2: (a) Distribution of potential heat source ages, classified by geological time periods for 48 producing geothermal fields. (b) Distribution of potential heat source ages by attributed age ranges.

Further discussion could be undertaken about the distribution of the heat sources' ages by country or by tectonic plate if we had more fields, thus constituting a representative statistical sample. Having only 48 fields does not allow us to get a representative statistical interpretation of these ages in the world. Although Figures 3a and 3b illustrate the locations of the dated heat sources that are included in this work, this should not be taken as a statistical representation. For example, 100% of the fields in Nicaragua (e.g. Momotombo) and in Portugal (e.g. Azores) are Holocene, but this is not representative as there is only one field in each country. The main pattern seen in Figures 3a and 3b is the uneven distribution of the operating high-enthalpy geothermal fields in the world and the predominance of Pleistocene heat sources (e.g. Japan and Philippines).



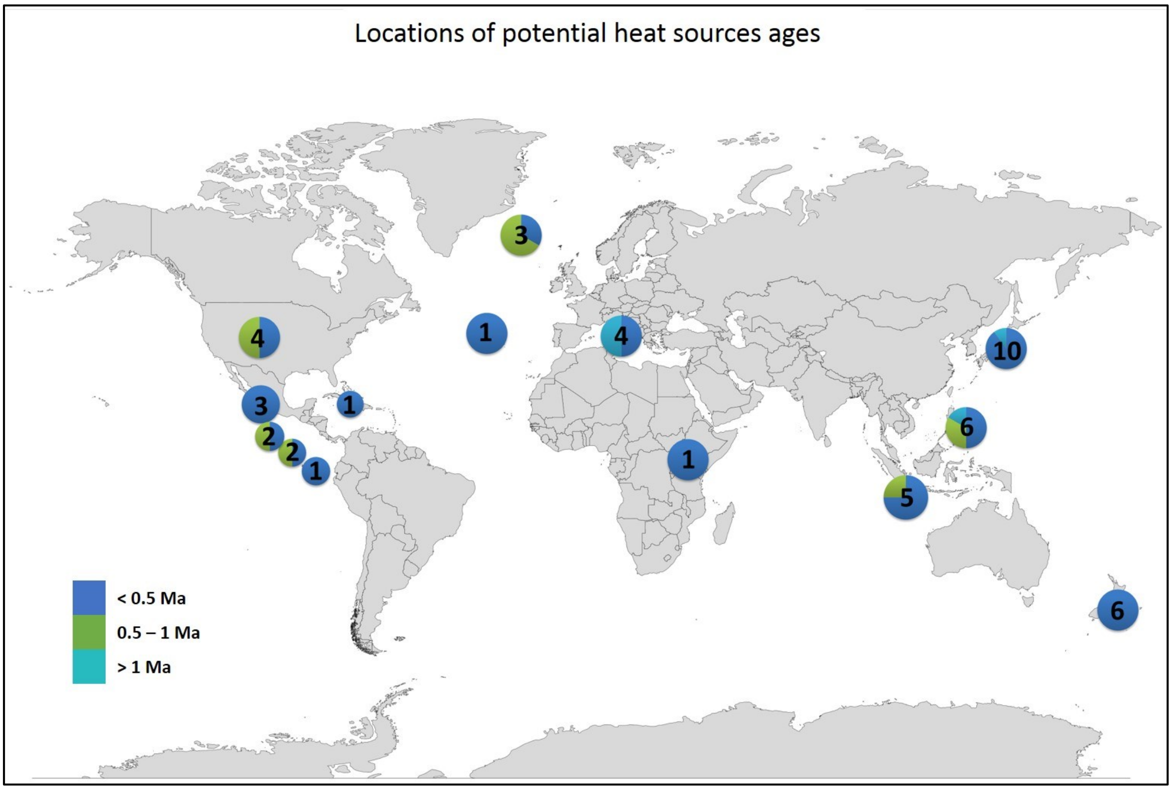


Figure 3: Distribution of the potential heat sources ages (a: geologic periods; b: age ranges) of 48 high-enthalpy geothermal fields in the world. The numbers represent the total number of fields included in this work for each country.

Figure 5 plots all the ages in a single diagram and shows that the mean age of the interpreted heat sources is 0.36 Ma, with 83% of the interpreted heat sources being younger than 0.5 Ma. The fields sitting within the Taupo Volcanic Zone (TVZ) in New Zealand are among those with the youngest igneous rocks associated with a heat source. Kawerau seems to be the youngest field with an age of 2400y before present. So far, there is no accurate rock dates of Rotokawa and Ohaaki hence we cannot assess whether the heat source is younger or older than the interpreted Kawerau heat source.

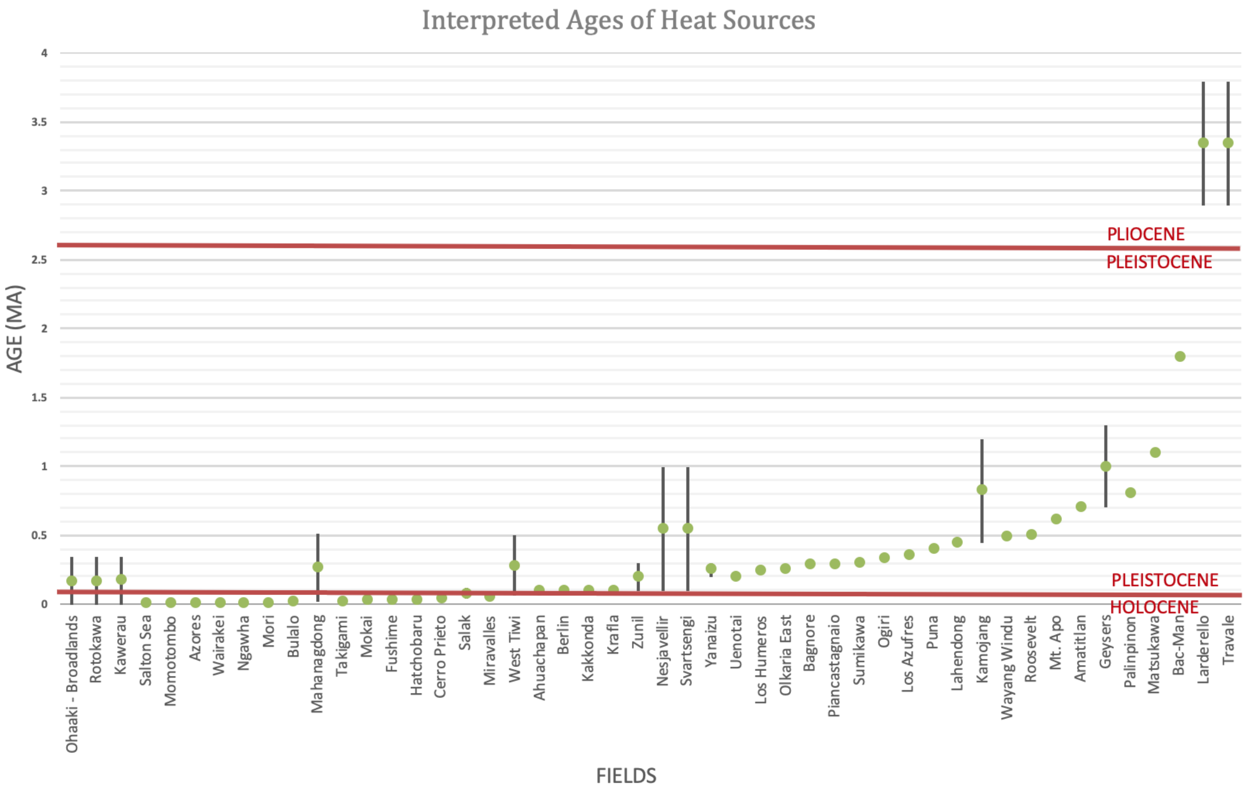


Figure 4: Interpreted ages of 48 heat sources. Some heat sources are represented by intervals as their exact age has not been determined yet.

4. INTERPRETED AGE VS VOLCANIC ENVIRONMENT

An alternative geological classification for the temperature versus power density diagram has been considered (Figure 5). This classification includes seven categories (e.g. Arc Volcanoes, Back-Arc, Basin and Range, Extensional Basin, Rift, Hot Spot, Ridge), which are only related to the geological settings. This was intended to visualise potential correlations between the volcanic environments and the interpreted ages. Wilmarth and Stimac (2015) include Italian fields in the categories Arc and Other (Figure 1), but according to the literature they do not fit these profiles because they are in extensional tectonic settings, thus we classified them in the Extensional Basin category. The Rifts and the upper part of the Arcs categories were replaced by Back-Arc, which includes all the fields in extensional settings related to subduction (e.g. back-arc basin, strike-slip fault). Although Ohaaki is located in an environment of Back-Arc, its power plant is plotted within the Arc Volcanoes category and we consider this as an anomaly. The lower part of the Wilmarth's "Arcs" group was replaced by "Arc Volcanoes". The "Fault-Based" group was also divided into the new groups "Rift" and "Basin and Range". The Islandic operating fields sit on a ridge, which is a very particular environment, therefore we separated them in a specific category even though they do not show the same patterns on the plot.

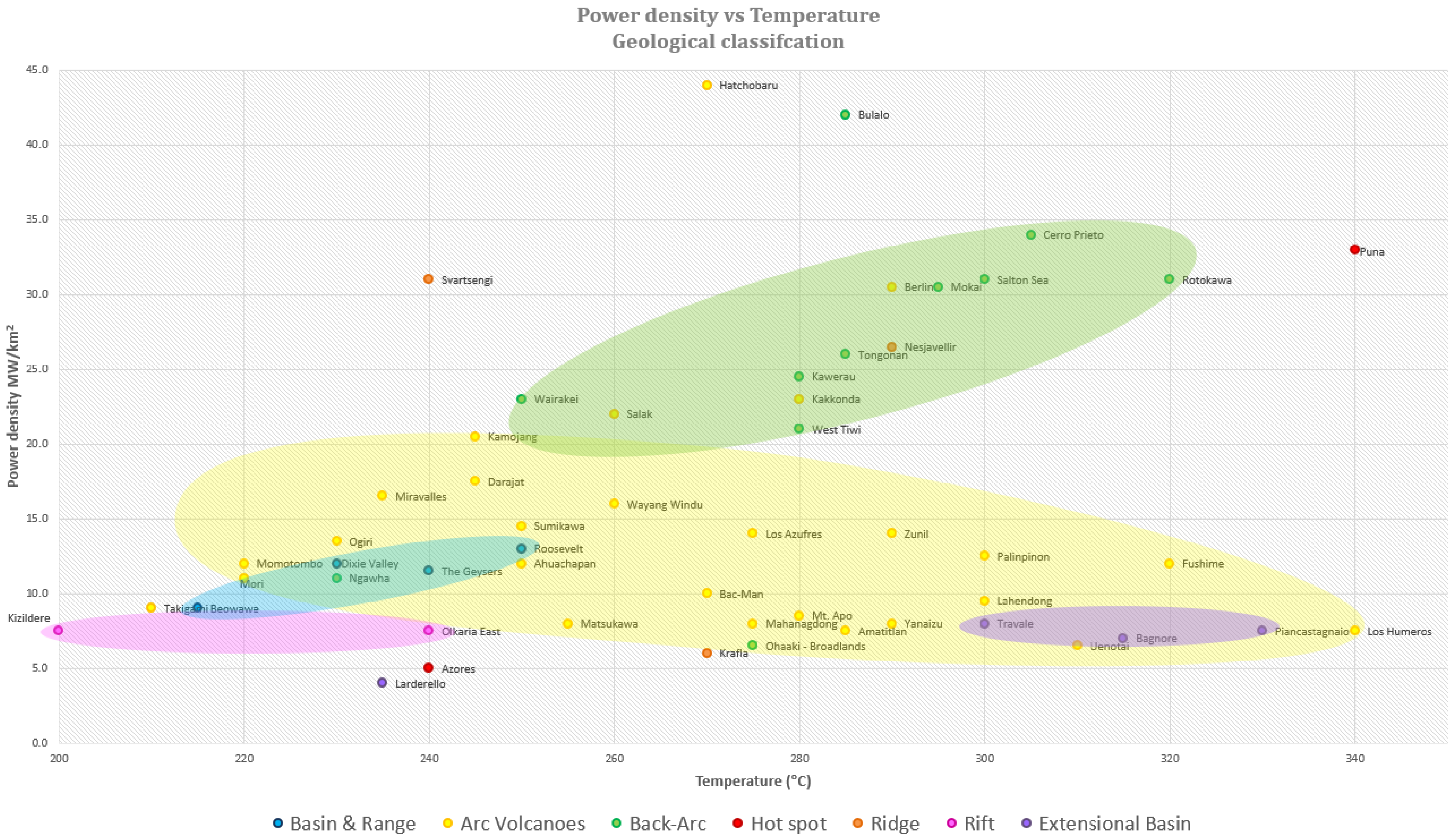


Figure 5: Power density versus temperature diagram with a revised geological classification.

Overall, there are still two main groups of geothermal fields, characterised by extensional or compressive tectonic settings, which follow the main power density versus average reservoir temperature trend lines, except for the Italian fields. The fact that the Italian fields are standing out of the trends might be explained by the complex European and Mediterranean tectonic phases such as the Pyrenean compression, the Alpine compression and several extensional episodes.
Figure 6 shows a plot of the interpreted ages for each volcano-tectonic setting. The interpreted ages of the heat sources in a Back-Arc environment are the youngest with 12 operating fields that are dated from 0.34 Ma to present. This is considered representative because of the large number of fields in this category. In addition, these operating fields are characterised by a high temperature and a high-power density (Figure 5).

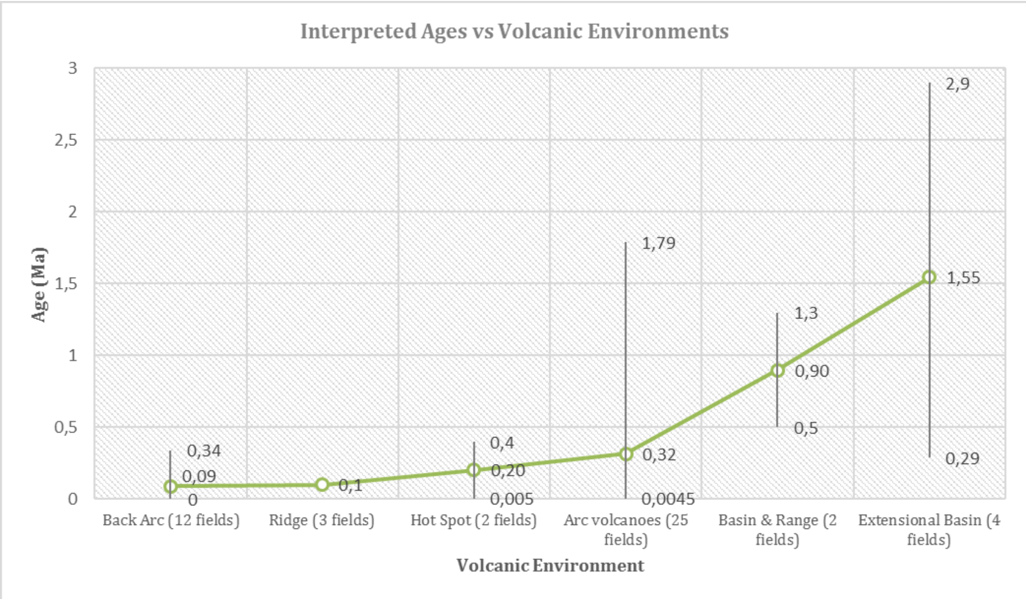


Figure 6: Interpreted ages versus volcanic environments diagram.

5. INTERPRETED AGE VS POWER DENSITY

When the geothermal fields are plotted in a diagram with the power density versus the interpreted age of the heat sources, a clear correlation emerges (Figure 7). Fields with a power density ≥20 MW/km^2 have got an interpreted heat source younger than 0.5 Ma. On the other hand, fields dated between 2.9 Ma and 0.5 Ma have a power density ≤20 MW/km^2. Therefore, the heat sources younger than 0.5 Ma would present a higher probability of a high-power density ≥20 MW/km^2.

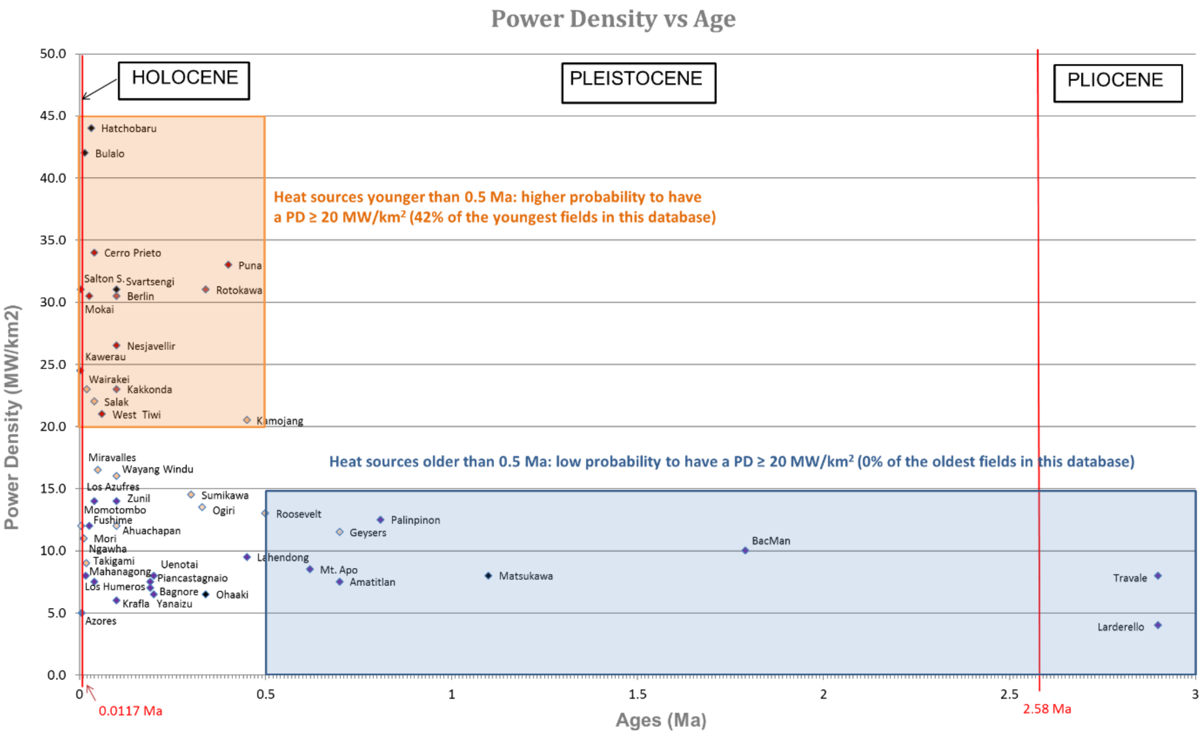


Figure 7: Interpreted ages versus power density diagram.

6. DISCUSSION AND CONCLUSION

The results of the database show that 83% of the interpreted ages of the heat sources are younger than 0.5 Ma and more than 77% are Pleistocene with an average age of 0.36 Ma. Therefore, the age range is restricted and can be considered as young.

The oldest fields (2.9 – 0.5 Ma) have a power density ≤20 MW/km². On the other hand, the fields with a power density ≥20 MW/km² have a heat source younger than 0.5 Ma. Hence, in this database, 42% of the heat sources younger than 0.5 Ma have a power density ≥20 MW/km² but none of the oldest heat sources shows a power density ≥20 MW/km².

Temperature plots do not show an obvious correlation between the interpreted ages of the heat sources and the average temperature of the geothermal reservoir. The same is applicable for the exploited areas of the geothermal fields and the interpreted age of the heat source.

Wilmarth and Stimac (2015) mention uncertainties regarding the power density values. These could vary in case that the fields are further developed (e.g. currently underdeveloped well-fields, environmental limitations, access issues, reduction of the production area). Nevertheless, the power density values seem to be correlated with the age of the heat source with the Back-Arc's heat sources as the youngest. In addition, the power densities seem to be related to the volcanic environment, with Back-Arc fields having the highest power density values while Arc-Volcanoes and Basins present the lowest power densities.

The results of this work have their own limitations related to the reliability of the age data. Firstly, the results are heavily dependent on the type of data and on data accessibility. This study rely on information in the literature and further analysis should be made from first-hand data or including the field operators reviews to mitigate unknown biases and errors. Secondly, the number of developed geothermal systems worldwide is still small from a statistical point of view, which decrease the statistical significance. Finally, each geothermal system shows a different longevity of hydrothermal circulation and including dates of hydrothermal alterations and reservoir host rocks might be useful to understand the link between the power density of a field and the age of its heat source. Further study could also consider the cooling rates of the different heat sources petrologies that can be inferred by combing age estimate, assessment of magma chamber volume and thermal decline using thermal modelling.

These additional studies are recommended to obtain more reliable results that would help in the evaluation of undrilled prospects where the age of the heat source has been assessed.

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