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The Study of Supercritical Geothermal Potential in Indonesia from Geoscience Perspective

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ABSTRACT

Indonesia has set the target by 2060 anticipate the geothermal energy able to supply approximately 22 GW of the country energy demand. Realizing the ambitious goal through the nowadays geothermal extraction method appears challenging. The nation's favourable geological positioning within a subduction zone has elevated temperature conditions and shallow intrusions, indicative of potential supercritical geothermal reservoirs. Supercritical geothermal systems, characterized by exceedingly high enthalpy and located near or below the brittle-ductile transition zone, offer notable promise, marked by distinct temperature, pressure, and fluid attributes. Due to their exceptional power output per well, supercritical geothermal systems exhibit enhanced economic competitiveness for geothermal power plant initiatives. Moreover, they hold potential as efficient sources for green hydrogen production. This study aims to explore the opportunities for developing supercritical geothermal systems in Indonesia from geoscience perspective. Several developed geothermal fields which show signs of high temperature will be investigated to seek possibilities for further development. The study will involve discussions with geothermal developers, capture signals and clues for supercritical geothermal systems, and identify the geological settings and magmatic environments of developed geothermal fields in Indonesia. Challenges, benefits, and business opportunities of supercritical geothermal projects will then be examined, from the technical aspects. The main results will present considerations in developing supercritical geothermal projects along with the candidates for pilot projects in Indonesia.

1. INTRODUCTION

Today's geothermal systems, which are known to be conventional geothermal systems, only constitute a small portion (around 2%) of the total geothermal potential in the world at 15 Gigawatts of power globally and are largely confined to regions where concentrated heat is located near the surface due to the tectonic setting of the region that causes a shallow intrusion zone. Regretfully, the existence of conventional geothermal systems is very limited due to the complexity of the geological condition of the region. To reach geothermal energy's global target, unconventional geothermal systems seek to emulate the current geothermal system production through some pilot projects, such as supercritical geothermal systems, hot dry rock, and hot sedimentary aquifer. Although the unconventional system will require another method of extraction, more advanced exploration technology, and deep research, it is worth considering to be an option. This study zooms in on the opportunities for developing supercritical geothermal systems in Indonesia by comparing the global data to the current geothermal development status in Indonesia.

Supercritical geothermal systems are very high-temperature geothermal systems located at depths near or below the brittle–ductile transition zone in the crust where the reservoir fluid is assumed to be in the supercritical state (Reinsch, et al., 2017). The critical point for pure water occurs at 374˚C and 22.2 MPa but is higher for solutions containing dissolved salts 405˚C and 30.2 MPa. Aqueous hydrothermal fluid in supercritical conditions with a temperature of 400˚C and a pressure of 25 MPa has more than five times the power-producing potential of liquid water at a temperature of 225˚C (Elders, et al., 2014; Stimac, et al., 2015).

Located in convergent subduction geological setting which leads to intense volcanism activities, Indonesia has a good chance to discover supercritical geothermal system. Several developed geothermal fields have showed high-temperature sign that possibly hold the potential for further development. The subsurface data from existing wells and fields will give more confident to explore the supercritical geothermal system. Furthermore, the existing geothermal license holders have obligation to conduct research, development, and innovation on their projects. Hence, supercritical system investigation on existing field will have more legal support compared to the greenfield areas.

2. GEOTHERMAL RESOURCES IN INDONESIA

Indonesia is located in a subduction zone that is known to have great potential for geothermal energy resources. The geological settings of Indonesia cause the occurrence of magmatism activities that generate shallow intrusion in the subsurface so that the volcanic arcs were formed, namely Sunda Arc, Banda Arc, and Sangihe Arc. Those volcanic arcs result in a high enthalpy geothermal system, which is commonly associated with and has been proven to generate electric power generation (Hochstein & Sudarman, 2008).

To avoid confusion between supercritical and superheated resources, no distinction is made in this study. In this regard, a supercritical geothermal system is defined as a very high-temperature (superheated) and very high-pressure (supercritical) geothermal system located somewhere deep in the subsurface, way deeper than the conventional resource (Scott, et al., 2015; Reinsch, et al., 2017). The fluid is expected to reach above the critical point of temperature and pressure. As a comparison, the critical point for pure water is around 374°C and 221 bars, while seawater is around 407°C and 298 bars (Procesi, 2015; Scott, et al., 2015).

The deep occurrence of this supercritical condition pertains to brittle-ductile transition (BDT) zone occurrence. In the model by Scott et al. (2015), supercritical water resource is predicted to be extensively developed if the brittle-ductile transition temperature (T_{BDT}) reaches at least 450°C and larger if the temperature is higher. Aside from T_{BDT} influence, host rock permeability and intrusion depth influence the resource. The convective flow of the fluid should be confined for the intrusion to heat the fluid sufficiently to reach a supercritical condition; in other words, a high permeability of host rock is not favorable. Additionally, the depth of intrusion could have an effect on the fluid pressure above the intrusion, and shallower intrusion could lead to a lower pressure of the fluid. Thus, the better resources are those that lie in the vicinity of deeper magmatic intrusion nearer to BDT with a low permeability of host rock.

A supercritical resource is considered to be rather beneficial if it is developed, given its enormous power-producing capability. Considering the very high temperature and pressure of the resource, the fluid viscosity will be decreased, and compressibility will increase, instead, making the fluid mobility to be more intense and causing higher mass flow rates (Jolie, et al., 2021). Thus, the produced enthalpy would be higher than conventional resources and be expected to reach even more than 5 times the conventional high-temperature resources (Procesi, 2015). Therefore, it can improve the ratio of drilling costs to a power output per well, making the resource economically competitive. Some comparisons between conventional resources and supercritical resources are listed in the following table.

Table 1. Comparison between conventional geothermal systems and supercritical geothermal systems

	Conventional	**Supercritical**
Exploration and extraction method	Exploration method includes remote sensing, field mapping of structural and alteration features, fluid chemistry, gravity, magnetics, electrical survey, and deep exploration drilling (3G Survey).	Supercritical temperature conditions are often found at the roots of high-temperature geothermal system (Reinsch, et al., 2017). If sufficient permeability and recharge are not present then hydrofracturing and injection could be viable options (Elders, et al., 2014).
Average drilling depth and technology	The average drilling depth is typically ~500-2000m for slim holes or ~2000-3000m for standard holes and big holes (Mackenzie, et al., 2017).	It needs adapted drilling and completion technologies for extreme reservoir conditions (Muraoka, et al., 1998; Reinsch, et al., 2017; Jolie, et al., 2021).
Heat source, fluid, and permeability	Thermal fluids, heat source, and permeability occur naturally.	Heat source might occur naturally and need artificial fluids and enhanced permeability.
Enthalpy	Commonly, a high-temperature system reaching at least 200°C is preferred in reservoir shallower than 3,000 m (Moeck, et al., 2015).	To reach supercritical hydrous fluid conditions in natural geothermal systems requires deep drilling to a minimum depth of some 3.5–5 km where temperature conditions can be expected to range between 400 and 600°C (Friðleifsson & Elders, 2017).

3. OPPORTUNITY OF SUPERCRITICAL GEOTHERMAL SYSTEM IN INDONESIA

Indonesia, constructed by the convergence of several tectonic plates that lead to intense volcanism along the islands, is known to have considerably high geothermal potential with pretty much high-temperature resources. Several high-temperature fields in Indonesia are identified to exhibit the probable existence of even higher temperature resources if not as well as high pressure, possibly holding the potential of more critical resources that can be developed in the future. In Sumatra, many developed geothermal fields are located in the vicinity of the Great Sumatra Fault (GSF) zone. Silangkitang field is located in the margin of Sarulla graben with a high influence of GSF on the permeability and hydrology condition of the field. The heat source is associated with Quaternary Sarulla rhyolite dome (Gunderson, et al., 2000; Simatupang, et al., 2021). It is known that two of Silangkitang wells that were targeted directionally into the GSF found a very strong upflow in the vicinity of the fault. It is significantly overpressured with respect to a normal hydrostatic gradient with fluid temperature excess 310°C (Gunderson, et al., 2000). While Silangkitang field condition is highly affected by GSF, Sorik Marapi field which is also located adjacent to GSF is more controlled by the Quaternary stratovolcano of Mt. Sorik Marapi that acts as the heat source. The permeable zones are mostly associated with fractures from GSF zone and/or sedimentary rock units. Drilling result of T-05 and T-09 with total depth of about 2100 mMD shows discovery of ~320°C temperature at -600 to -900 masl with pressure 80-90 barg, with drilling directed to the upflow zone. The wells encountered typical benign reservoir liquid originated from meteoric water with low concentration of NCG content (Hidayat, et al., 2021).

In Java, the presence of deep well and/or high-temperature resources is identified in some fields i.e., Awibengkok field and Karaha-Bodas field. Awibengkok field is located on the southwestern side of Mt. Salak that acts as the main heat source of the system. The reservoir is liquid-dominated, having benign chemistry and low-moderate NCG content (Stimac, et al., 2008). Indication of deep permeability is detected at the southwestern portion of Awibengkok reservoir, confirmed in AWI 9.9 well at 3058 mMD. This corresponds to a reservoir pressure of 185 barg and a temperature of 321°C with upflowing conditions from the bottom feedzone. The well is one of the successfully drilled deepest well in Indonesia that encountered the resource. Micro-seismicity events suggests that permeability could extend to as deep as ~4000 m, in which the pressure can be expected to reach 257 barg, thus has a possibility of higher temperature and supercritical fluid (Libert, 2017). In Karaha-Bodas field which is located in the northern side of Galunggung volcano, the heat source comes from the Quarternary volcanic complex elongated from Karaha to Galunggung. Yet, the main source is the magmatic vapor plume beneath Talaga Bodas area. This field is partially vapor-dominated with steam zone formed above locally boiling fluid. About 350°C temperatures reaching ~140 bar pressure were measured at the bottom of TLG2-1 suggesting possible superheated conditions in the passively magmatic degassing area which is presumably a cooling intrusion (Allis, et al., 2000).

Aside from AWI 9.9 well, HLS-E1 well in Hululais field is also one of the deepest well drilled in Indonesia. The field is located near Barisan Range and GSF area, making the volcanism and structural permeability highly influenced by the GSF regime. The permeability comes from two dextral strike-slip faults which are also part of GSF segments. The heat source is associated with Suban Agung volcanism (Nurseto, et al., 2021). The deep well in this field reached the total of 3203 mMD and has been confirmed by pressure-temperature injection survey. The permeable zone is detected to be started from around 1900 mMD to the well bottom, identified from total loss circulation of 20 BPM with no gains of returns. Aerated drilling is successfully utilized in overcoming these challenges and possibly can also be applied for similar problem in the future (Toni, et al., 2016). Other well from the same wellpad, noted as HLS-EX reached total depth of 3280 mMD at -1355 masl. The reservoir temperature measured from this well is 258°C in the convective zone and reaching about 120 bar pressure with liquid phase (PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)

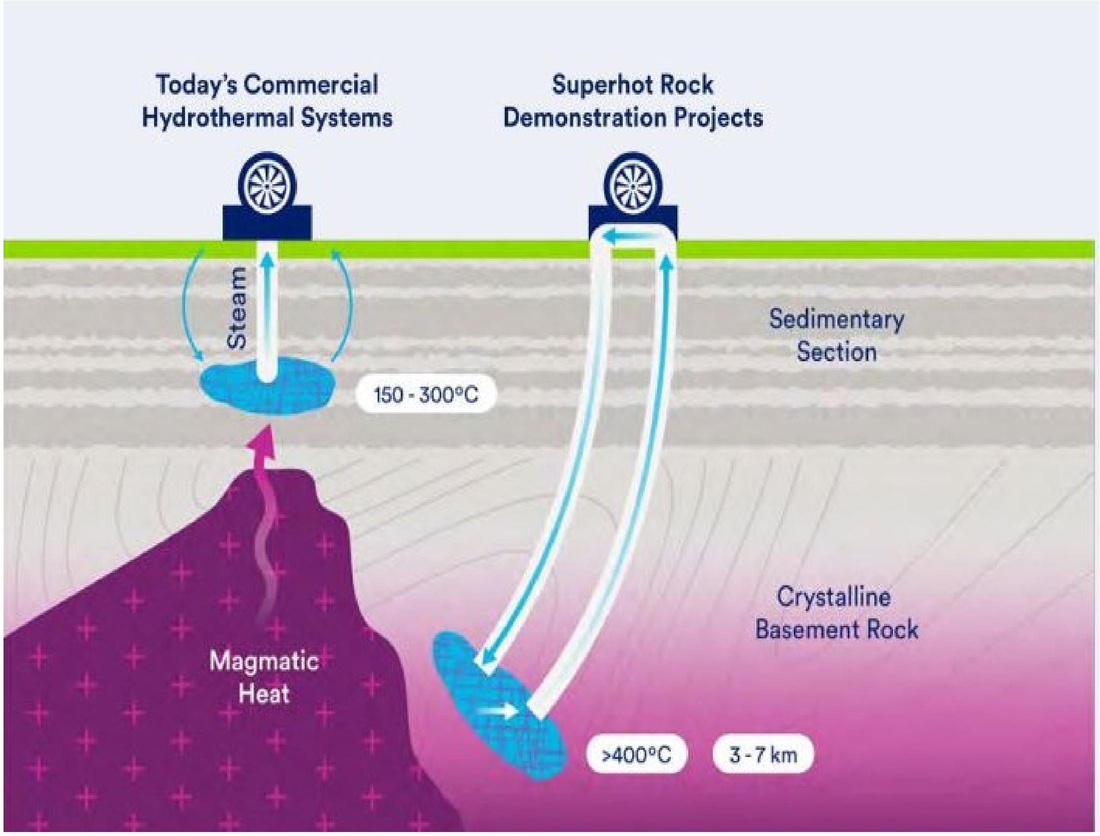

Figure 1: According to Hill (2022) the ideal pilot project to utilize the deep geothermal system is in volcanic region nearby the hydrothermal system that already proven due to the Currently available mechanical drilling methods can and are being used to drill to depths of 3-7 km to access relatively shallow superhot rock

4. COMPARISON OF SUPERCRITICAL GEOTHERMAL POTENTIAL IN INDONESIA, NEW ZEALAND, ICELAND, AND JAPAN

Several countries have already started to show interest in supercritical resource. In Iceland, the Iceland Deep Drilling Project (IDDP) is meant to be a pilot project for exploring the deep unconventional supercritical resource after the discovery of >380°C temperature with very high pressure and inflow rates in Nesjavellir geothermal field (Steingrimsson, et al., 1990; Reinsch, et al., 2017). Up until today, there are three IDDP projects with one concluded project located in Krafla geothermal field, one on-progress completion project in Reykjanes geothermal field, and one planned project in Hengill (Friðleifsson, et al., 2019).

Research was also conducted in New Zealand, focusing on Taupo Volcanic Zone (TVZ) area. Deeper untapped resource is under study to be developed to meet the future electricity demand. Regional geophysical study had been conducted to understand the regional subsurface condition of the field, including the brittle-ductile transition zone and connection between shallow and deep resources (Bannister, et al., 2015; Newman, et al., 2015). There has been no attempt to drill the supercritical resource yet.

Japan also participated in the exploration of deeper geothermal reservoir, knowing the drilling in Kakkonda Geothermal Field resulting in a very high temperature fluid with probable BDT encountered. Japan Beyond Brittle Project (JBBP) is designed to explore the deep enhanced geothermal system (EGS) reaching almost the ductile zone. The considered extraction would be near the top of BDT or beyond BDT depending on the study result (Muraoka, et al., 2014). As the geological setting of Japan is similar to Indonesia, the study result is most likely closely relatable to the resource condition in Indonesia, thus some lessons should be noted. In Table 3, comparison between geological condition and probable and proven supercritical resources in the mentioned countries before is outlined.

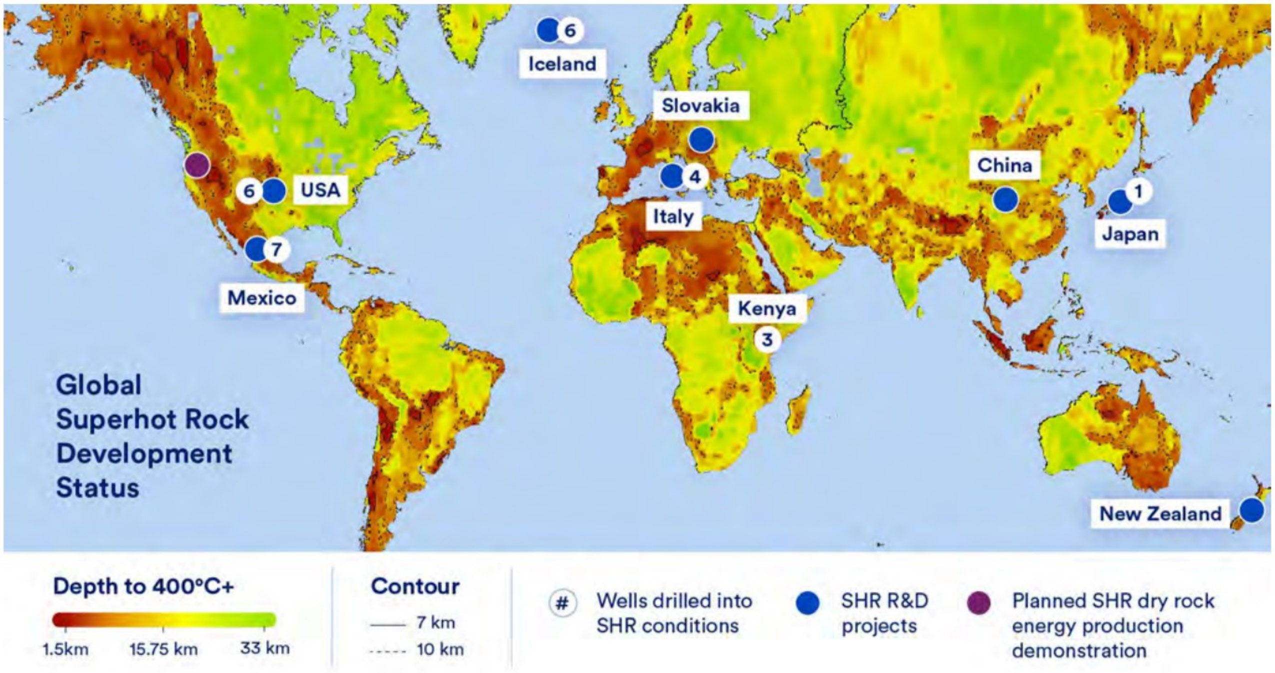

Figure 2: Superhot potential project location with the development status (Hill, 2022)

Table 3. Comparison between regional conditions, resource characteristics, and development method of proven supercritical resources in Iceland and probable supercritical resources in New Zealand and Japan with conditions in Indonesia.

	IDDP Project, Iceland*	Taupo, New Zealand**	Kakkonda, Japan**	Indonesia**
Geology setting	Both Krafla field and Reykjanes field are located in magmatic rift setting. Shallow magmatic intrusion is present in this field with system hosted in basaltic rock (Elders, et al., 2014; Scott, et al., 2015; Friðleifsson & Elders, 2017). IDDP-1 project encountered magma at 2096 m depth (Pálsson, et al., 2014).	Located in continental volcanic arc/extensional back-arc basin. Heat source is associated with volcanism (Bignall & Carey, 2011)	The field is located in the southern part of Hachimantai volcanic field. Kakkonda granite acts as the heat source of this field in which the drilling reached the granitic basement. Fractures abruptly decrease below 2860 m in the Kakkonda granite (Muraoka, et al., 1998)	Convergent subduction setting generates intense volcanism that usually became the heat source of the geothermal system (Hall, 2009). Intense structural influence is also notable in some fields i.e., Silangkitang, Sorik Marapi and Hululais (Hidayat, et al., 2021; Nurseto, et al., 2021; Simatupang, et al., 2021)

	IDDP Project, Iceland[*]	**Taupo, New Zealand**[**]	**Kakkonda, Japan****	**Indonesia****
Well depth	Final vertical depth of IDDP-1 is 2077 m. The well started as vertical well, but side tracking was made later on (Pálsson, et al., 2014) IDDP-2 well was drilled vertically down to 2750 m then directionally to the SW. The bottom of the well has a vertical depth of about 4500 m depth (Friðleifsson & Elders, 2017)	In Ngatamariki field, current deepest well depth reached 3398 mRF depth at NM6 vertical well and encountered greywacke basement (Bignall, 2009; Simpson & Bignall, 2016)	WD-1a's final depth reached 3729 m. The well is vertical to 800 m and drifted in various directions with a total of about 11 trajectory correction was made (Muraoka, et al., 1998)	Depth range of geothermal wells in Indonesia is 1200-2800 m depth (Purwanto, et al., 2021). The deepest well in Indonesia reached ~3000 m, i.e., AWI 9.9 in Awibengkok field and HLS-E1 and HLS-EX in Hululais field (Libert, 2017; Nurseto, et al., 2021; Nusantara, 2022)
Pressure and Temperature	IDDP-1 produced superheated steam at 452°C (Friðleifsson & Elders, 2017) IDDP-2 bottom of well reached ~426°C with 34 MPa pressure and good permeability (Friðleifsson & Elders, 2017)	Research efforts in New Zealand have included study of the deep (5-7 km) geothermal resource potential for the Taupo Volcanic Zone (Figure 3), which is estimated to have temperatures >400°C (Dobson et al, 2017). Deepest well (NM6) has ~260°C temperature (Bignall, 2009).	WD-1a exploration well encountered BHT of 500°C at 3729 m total vertical depth. Fluid pressure near the bottom of well is unknown in a natural state. Pressure reached 24 MPa at a depth of 3100 m with 380°C temperatures. Kakkonda conduction-dominated temperature gradient reached 32°C/100 m (Muraoka, et al., 1998; Muraoka, et al., 2014)	Temperature range in geothermal well is 200-300°C (Purwanto, et al., 2021) with some potential supercritical fields encountered temperature as high as 350°C, i.e., Karaha Bodas (Allis, et al., 2000)
Fluid characteristics	IDDP-1: acidic fluid is formed by condensation of sulphuric gas. The gas content is relatively low (Ármannsson, et al., 2014) IDDP-2: oceanic origin, a saline fluid system. The project affects the surrounding shallow geothermal reservoir fluid where the salinity decreased temporarily, and influx of atmospheric gas increased (Friðleifsson, et al., 2019)	Ngatamariki field has neutral chloride water condition (Boseley, et al., 2010). All fields in TVZ have neutral pH alkali chloride water (Simpson & Bignall, 2016).	The well did not produce supercritical fluid and the bottom hole was dry (Elders, et al., 2014; Dobson, et al., 2017) The fluid at 3708 depth was hypersaline and contain high concentration of heavy metals (Muraoka, et al., 1998)	Some fields (i.e., Sorik Marapi) shows benign fluid condition (Hidayat, et al., 2021), though it is a bit far from the heat source. Meanwhile, some well in several fields (i.e., Karaha) that tend to be closer to the upflow exhibits magmatic input with acidic fluid and high gas content encountered (Allis, et al., 2000)
Permeability	IDDP-1: transition from upper to lower reservoir has decreasing porosity and permeability. Main feed zone occurs at 2035 m depth (Mortensen, et al., 2014) IDDP-2: indications of good permeability at depth (Friðleifsson & Elders, 2017). Total loss circulation is encountered below 3.2 km to the bottom of well (Friðleifsson, et al., 2019)	Shallow-sourced EQ loci in southern TVZ show apparent cessation inferring 6-7 km depth BDT zone (Bibby, et al., 1995; Heise, et al., 2007). Total loss circulation was encountered from 2575 mrF down to the deepest depth of NM6 well. The greywacke basement	Brittle-ductile boundary is indicated at about 3100 m depth with temperature reached 380°C as farther depth shows lower fracture density (Muraoka, et al., 1998)	Some drilled wells that reached ~3000 m shows indicated permeability at depth, i.e., Awibengkok and Hululais (Libert, 2017; PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)

	IDDP Project, Iceland*	**Taupo, New Zealand****	**Kakkonda, Japan****	**Indonesia****
		has low matrix porosity (Bignall, 2009)		
Method	IDDP-1: The acid gas in the steam is proven can be scrubbed off with alkaline water in an experiment (Hauksson, et al., 2014). The pre-drilling used 36”/26” underreamer. The cement is also slurry and fiberglass drill pipes was used to place cement plugs (Pálsson, et al., 2014) IDDP-2: cement plugging was unsuccessful to handle the loss zone, thus drilling was continued blindly (Friðleifsson, et al., 2019)	Conducting survey geophysics method: 3D MT modeling to provide evidence down to 10 km depth, a passive-seismic broadband survey of the region to elucidate changes in crustal velocity structure between 3 and 8 km depth with the goal to get an integrated image of the brittle-ductile transition zone and identify potential deep drilling targets (Dobson, et al., 2017)	Efficient borehole cooling technique was implemented by using top-drive system which allows mud to be continuously pumped while running the BHA with additional mud-cooler system (Muraoka, et al., 1998)	Total loss circulation of 20 BPM is detected in HLS-E1 and solved with aerated drilling (PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)

*) Drilling Project/Proven

**)Non-drilling Project/Not Proven

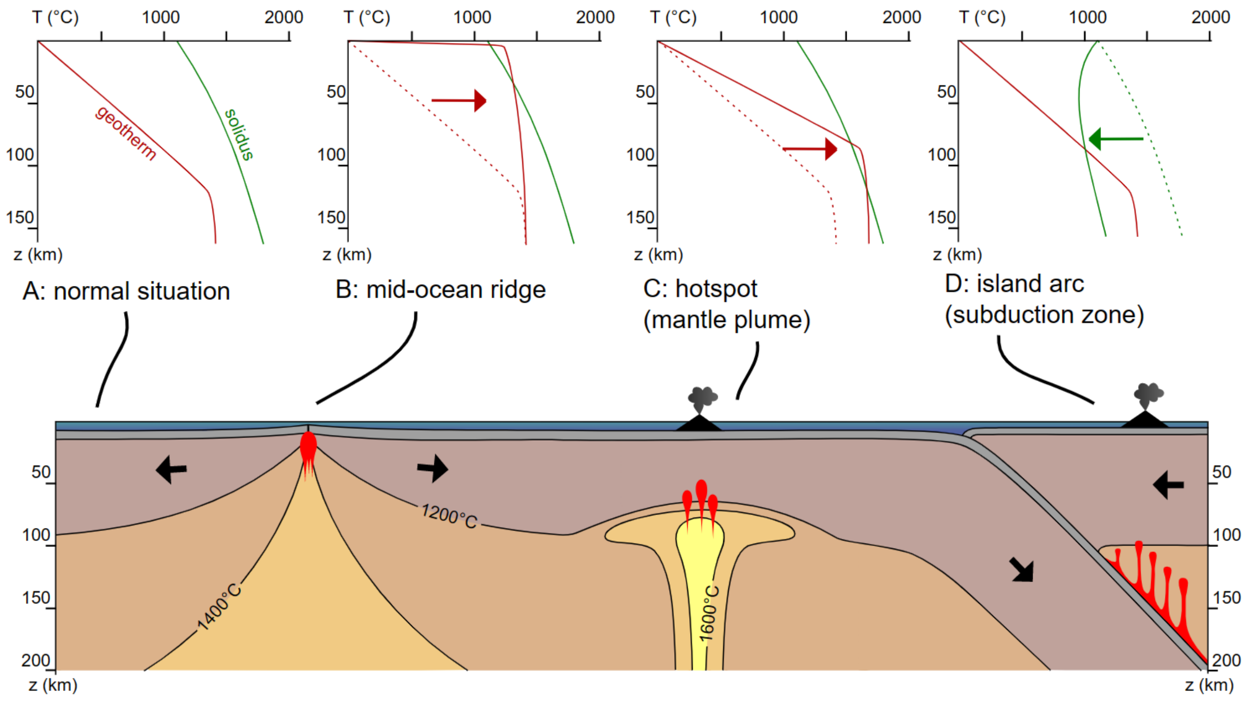

Figure 3: Diagram of physical processes in Earth’s upper mantle that lead to magma generation. A-D are different plate tectonic settings. The graphs show the geotherm in red (temperature curve inside the Earth) and the solidus in green (temperature where rock starts to melt). When the curves cross each other, partial melting of mantle rocks occurs Niu (2021) modified by Wouldper

5. SURVEY AND EXPLORATION

Figure 4 shows the distribution map of unconventional geothermal system in Indonesia according to exploration report by geological agency some area showed the potential geothermal field that could be fit as supercritical pilot project. This information that provided by Geological Agency of Indonesia is the good start of initiation study even so the detailed and more comprehensive research should be conducted to get more information regarding the distribution (Mustika, et al., 2022).

Several specific challenges should also be considered since the geological setting of Indonesia is very different than the pilot projects (high relief might cause deeper heat source, magmatic input of different tectonic settings might influence the heat source, etc). According to Dobson, et al. (2017) that already summarized several challenges in the supercritical pilot project such as Iceland and Japan, a number of serious issues were encountered while trying to successfully handle and utilize fluids from geothermal reservoirs at temperature and pressure conditions exceeding supercritical conditions of water. These issues need further in-depth investigation to get the lesson learned from previous projects.

Supercritical temperature conditions are often found at the roots of high-temperature geothermal system (Reinsch, et al., 2017) since this system is deeper than current commercial geothermal system that already produce, the approach and method in exploration to located the brittle-ductile transition whereas the supercritical condition will be found. Exploration method for better resource assessment such as advance geophysical exploration method to produce the integrated deeper image to find the brittle-ductile transition zone and identify potential deep drilling targets. Dobson, et al. (2007) mentioned that the integrated 3D MT modelling in New Zealand is possible to do modeling provide evidence down to 10 km depth, combine with passive-seismic survey to detect the changes in crustal velocity structure between 3-8 km depth.

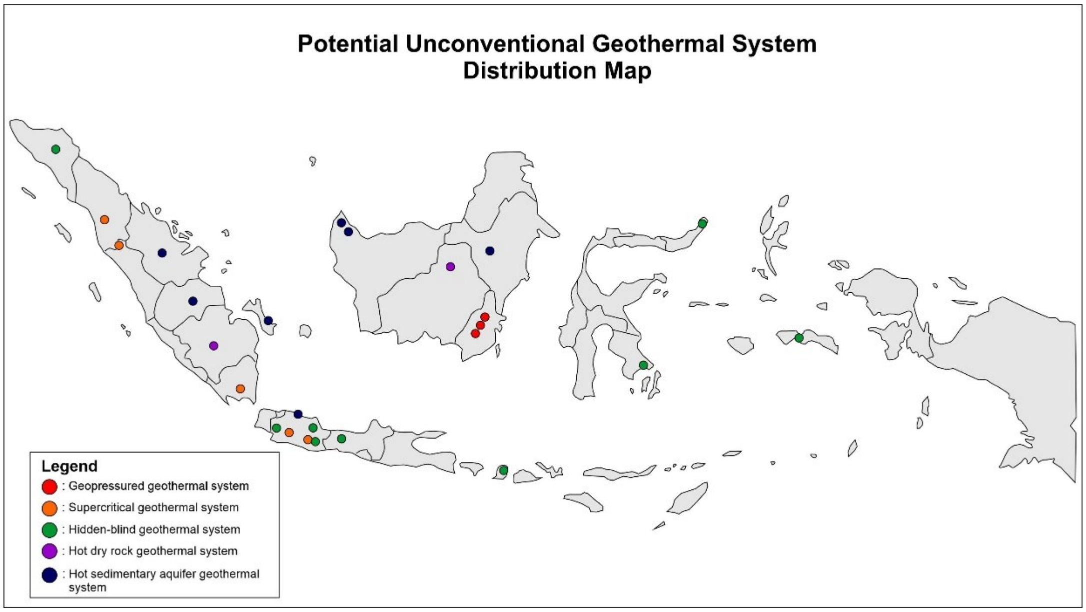

Figure 4: Potential Unconventional Geothermal System Distribution Map

Laboratory simulation and modelling also needed for supercritical systems, this is also including geologic and geophysical modeling of the brittle–ductile transition zone. The laboratory measurement of rock and fluid properties work is needed as the calibration since the system will be dealing with very high temperature, pressure and commonly with magmatic fluid. Since the acid magmatic dominated fluids are found in the hotter plastic rock and hydrothermal fluids circulate through the overlying cooler brittle rock.

The other important thing also to identify the economically feasible resource such as the source of the funding the project and the continuity of the pilot project. This could also relate to geohazard prevention due to the system commonly associated with active volcanoes since most of volcanic area in Indonesia is a densely populated area. Therefore, the surface facility and strategy should be prepared since the beginning, due to dealing with supercritical fluids and corrosive gases could be endanger the populated area. Despite the fact that the map based on the initial data and to be further investigation, but it showed that the highest possibility to start the pilot project on the exist field has more chance than the green field. Based on that fact, it should be considered some of the challenge in development phase from existence field.

The supercritical fluid located in brittle-ductile transition that mean the permeability is considered low comparing to the commercial geothermal field nowadays, if sufficient permeability and recharge are not present then hydrofracturing and injection could be viable options (Elders, et al., 2014). The hydraulic fracturing and injection could be a challenge especially for the system above that already running. The risk of both methods could affect the reservoir temperature above more over creation of heat reservoirs in fracture systems in dry superhot rock while avoiding seismic risk (Hill, 2022).

Besides that, on the drilling process in supercritical condition, we need to adapt some deep drilling and completion technologies in supercritical condition (high T and P). Casing cementing methodology for the hot rock environment is needed to be learned. Stage cementing tools using rubber packers are not advisable in formation hotter than 300°C and reversed circulation should be considered to secure good cementing over long sections (Pálsson, et al., 2014).

Furthermore, to reach supercritical conditions in natural geothermal systems requires temperature range between 400◦C and 600 ◦C (Friðleifsson & Elders, 2017) to keep the sustainability of the supercritical condition should be considered. The idea to create more permeability in brittle-ductile condition may lead into creating the supercritical system promising yet the fact that supercritical condition need in low permeability environment to keep the condition sustain.

6. CONCLUSION

Supercritical geothermal systems have opened up new opportunities in utilization of geothermal energy. Due to its fluid characteristic and enthalpy, a supercritical system may produce energy output of more than five times the conventional hydrothermal system. Although its development is promising, the investigation of supercritical systems in Indonesia remains to be limited mostly because it is considered very expensive and high-risk. However, the opportunity to discover a supercritical geothermal system can lay beneath the existing conventional hydrothermal system. Thus, further research and investigation can be conducted on Sarulla, Sorik Marapi, Awibengkok, Karaha Bodas, and Hululais fields as they have indication for higher temperature systems and higher pressure.

It is imperative for the Indonesian to meticulously consider the potential of supercritical geothermal systems, taking into account their existence and associated opportunities. This entails the establishment of comprehensive safety protocols and methodologies for estimating resources specific to this unconventional geothermal approach. Furthermore, it is recommended that Indonesia embark on a pilot initiative for drilling a supercritical geothermal system, drawing valuable insights from the experiences of other nations. After all, more advanced development of geothermal energy will help reduce the energy sector’s dependency on the fossil source of energy that dominated nowadays.

REFERENCES

Allis, R. et al.: Karaha-Telaga Bodas, Indonesia: A Partially Vapor-Dominated Geothermal System, *Geothermal Resources Council Transactions,* Volume 24, (2000)

Ármannsson, H. et al.: IDDP—The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system. *Geothermics,* Volume 49, (2014), pp. 66-75

Bannister, S., Bourguignon, S., Sherburn, S. & Bertrand, T.: 3-D seismic velocity and attenuation in the Central Taupo Volcanic Zone, New Zealand: imaging the roots of geothermal systems, *Proceedings World Geothermal Congress 2015,* (2015)

Bibby, H. M., Caldwell, T. G., Davey, F. J. & Webb, T. H.: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation, *Journal of Volcanology and Geothermal Research,* Volume 68, (1995), pp. 29-58.

Bignall, G.: *Ngatamariki Geothermal Field Geoscience Overview,* s.l.: GNS Science, (2009)

Bignall, G. & Carey, B.: A DEEP (5 km?) GEOTHERMAL SCIENCE DRILLING PROJECT FOR THE TAUPO VOLCANIC ZONE - WHO WANTS IN?. *Proceedings New Zealand Geothermal Workshop 2011*, (2011)

Boseley, C. et al.: A Resource Conceptual Model for the Ngatamariki Geothermal Field Based on Recent Exploration Well Drilling and 3D MT Resistivity Imaging, *Proceedings World Geothermal Congress 2010,* (2010)

Dobson, P. et al.: Supercritical Geothermal System - A Review of Past Studies and Ongoing Research Activities, *Proceedings 41st Workshop on Geothermal Reservoir Engineering*, (2017)

Elders, W. A., Friðleifssonb, G. Ó. & Albertsson, A.: Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide, *Geothermics,* Volume 49, (2014), pp. 111-118

Friðleifsson, G. Ó. et al.: The Reykjanes DEEPEGS Demonstration Well – IDDP-2, *European Geothermal Congress 2019,* (2019)

Friðleifsson, G. Ó. & Elders, W. A.: Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland, *GRC Transactions,* Volume 41, (2017)

Geological Agency: *Indonesia Geothermal Resource Map,* s.l.: s.n. (2021)

Gunderson, R. et al.: Exploration results in the Sarulla block, North Sumatra, Indonesia, *Proceedings World Geothermal Congress 2000*, (2000)

Hall, R.: Indonesia, Geology, In: *Encyclopedia of Islands.* s.l.:University of California Press, (2009), pp. 454-460

Hauksson, T. et al.: Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland, *Geothermics,* Volume 49, (2014), pp. 76-82

Heise, W. et al., 2007. Melt distribution beneath a young continental rift: The Taupo Volcanic Zone, New Zealand. *Geophysical Research Letters,* Volume 34.

Hidayat, R. et al.: The Characteristics of 320°C Geothermal Wells at Sorik Marapi Geothermal Field, *Proceedings The 2nd Digital Indonesia International Geothermal Convention (DIIGC),* (2021)

Hill, L. B.: *Superhot Rock Energy,* s.l.: Clean Air Task Force, (2022)

Hochstein, M. P. & Sudarman, S.: History of geothermal exploration in Indonesia from 1970 to 2000, *Geothermics,* Volume 37, (2008), pp. 220-266

Jolie, E. et al.: Geological controls on geothermal resources for power generation, *Nature Reviews,* Volume 2, (2021), pp. 324-339

Libert, F. T.: Evaluation of the Deepest Production Well in Salak Geothermal Field, Indonesia, *5th Indonesia International Geothermal Convention & Exhibition*, (2017)

Mackenzie, K. M. et al.: Use of Deep Slimhole Drilling for Geothermal Exploration, *Proceedings The 5th Indonesia International Geothermal Convention & Exhibition*, (2017)

MEMR: *Net Zero Emission Road Map - Energy Sector,* s.l.: s.n, (2022)

Moeck, I. S., Beardsmore, G., Harvey, C.: Cataloging Worldwide Developed Geothermal Systems by Geothermal Play Type, *Proceedings World Geothermal Congress*, (2015)

MoEF: *Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050,* s.l.: s.n, (2021)

MoEF: *Enhanced Nationally Determined Contribution, Republic of Indonesia,* s.l.: s.n, (2022)

Mortensen, A. K. et al.: Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE-Iceland, *Geothermics,* Volume 49, (2014), pp. 31-41

Muraoka, H. et al.: The Japan Beyond-Brittle Project, *Scientific Drilling,* Volume 17, (2014), pp. 51-59

Muraoka, H. et al.: DEEP GEOTHERMAL RESOURCES SURVEY PROGRAM: IGNEOUS, METAMORPHIC AND HYDROTHERMAL PROCESSES IN A WELL ENCOUNTERING 499DEGC AT 2618 m DEPTH, KAKKONDA, JAPAN, *Geothermics,* 27(5/6), (1998), pp. 507-534

Mustika, A. I. et al.: Discovering The Potential of Unconventional Geothermal Systems in Indonesia. *The 8th Indonesia International Geothermal Convention & Exhibition*, (2022)

Newman, G. et al.: The importance of full impedance tensor analysis for 3D magnetotelluric imaging the roots of high temperature geothermal systems: application to the Taupo Volcanic Zone, New Zealand, *Proceedings World Geothermal Congress 2015*, (2015)

Niu, Y.: Lithosphere thickness controls the extent of mantle melting, depth of melt extraction and basalt compositions in all tectonic settings on Earth – A review and new perspectives, *Earth-Science Reviews,* Volume 217, (2021)

Nurseto, S. T. et al.: Structural Geology and Volcanism in Hululais Geothermal Area, Bengkulu, Indonesia, *ITB International Geothermal Workshop 2020*, (2021)

Nusantara, V. D. M.: *Borehole geology of Well HLS-EX Hululais geothermal field, Sumatra Island, Indonesia,* s.l.: University of Iceland, (2022)

Pálsson, B. et al.: Drilling of the well IDDP-1, *Geothermics,* Volume 49, (2014), pp. 23-30

Procesi, M.: The Unconventional Geothermal Resources : Features and Current Uses, *Energy Science and Technology,* Volume 9, (2015)

Purwanto, E. H. et al.: An Updated Statistic Evaluation of Drilling Performance, Drilling Cost and Well Capacity of Geothermal FIelds in Indonesia, *Proceedings World Geothermal Congress 2021*, (2021)

Reinsch, T. et al.: Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities., *Geothermal Energy* 5(16), (2017)

Scott, S., Driesner, T. & Weis, P.: Geologic controls on supercritical geothermal resources above magmatic intrusions, *Nature Communications,* Volume 6:7873, (2015)

Simatupang, C., Matsuda, K. & Astra, D.: The Initial State Geochemical Model and Reservoir Response of 2 Years Production at Silangkitang, a Fault-Controlled Geothermal System along the Great Sumatera Fault. *Proceedings World Geothermal Congress 2021*, (2021)

Simpson, M. P. & Bignall, G.: Undeveloped high-enthalpy geothermal fields of the Taupo Volcanic Zone, New Zealand, *Geothermics,* Volume 59, (2016), pp. 325-346

Steingrimsson, B., Gudmundsson, A., Franzson, H. & Gunnlaugsson, E.: EVIDENCE OF A SUPERCRITICAL FLUID AT DEPTH IN THE NESJAVELLIR FIELD, *15th Workshop on Geothermal Reservoir Engineering,* (1990), pp. 81-88

Stimac, J., Goff, F. & Goff, C. J.: Intrusion-related geothermal systems, In: *Encyclopedia of Volcanoes.* s.l.:Academic Press, (2015), pp. 799-822

Stimac, J., Nordquist, G., Aquardi, S. & Lutfhie, S.-A.: An Overview of the Awibengkok Geothermal System, Indonesia, *Geothermics,* Volume 37, (2008), pp. 300-331

Sumardi, J. A. et al.: Indonesia Geothermal Drilling History: What We Can Learn From It?, *Proceedings 47th Workshop on Geothermal Reservoir Engineering*, (2022)

Toni, A., Pratama, R. A., Prasetyo, I. M. & Saputra, M. B.: The Deepest Geothermal Well in Indonesia: A Success Story of Aerated Drilling Utilization, *GRC Transactions,* Volume 40, (2016), pp. 263-270