Augustine Volcano, Cook Inlet, Alaska has Magma Storage at Shallow Depth and Merits Geothermal Exploration

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ABSTRACT

South central Alaska, the state's population center, is facing a crisis caused by overwhelming dependence for electricity generated by natural gas from the aging Upper Cook Inlet field. Several options for diversification to green sources are being explored. Among them is Augustine Volcano, one of the hottest members of the Pacific Ring of Fire and only 100 km from the grid. A great deal is known about Augustine through efforts of the Alaska Volcano Observatory (AVO, a joint program of USGS, State of Alaska, and UAF). Augustine is one of the best monitored of US volcanoes and a rich, open data set has accumulated through this monitoring as well as geophysical and geochemical analyses of data and samples collected from eruptions, the most recent being in 2006. The volcano comprises most of an island owned by the State and lacks significant flora and fauna because of eruptive activity. Because virtually all work has been conducted with the intent of mitigating volcanic hazards, any effort motivated by geothermal development would have to fill in some gaps, particularly magnetotelluric and seismic surveys and slim-hole drilling. Nevertheless, there is strong evidence for a sustained magmatic heat source > 800°C at about 4 km depth. Analogy to similar circum-Pacific volcanoes that have been drilled in the near field suggests that temperatures > 200°C could be reached by 2 – 3 km of inward-directed drilling from a relatively safe location just beyond the flank of the cone. The eruption hazard can be mitigated by site selection, hardening and automating the power plant, and the months-long alert pre-eruption provided by monitoring. The cost of submarine cables, which could be run either to the east or west or both, could be mitigated by pairing the geothermal development with an offshore windfarm in the exceptionally favorable location adjacent to Augustine. A preliminary economic analysis suggests that such a development would produce green energy in 2030 at a cost comparable to todays' natural gas.

1. Introduction

Augustine Volcano is among the more active volcanoes of the Pacific Rim. Eruptions are fed from a dacitic magma chamber expected to be at 3.5 – 5 km, sustained and mixed with inputs of andesitic magma from below. If developed as a geothermal power source, it is well positioned to supply electric power to the Cook Inlet region (Fig. 1). Existing geothermal systems of this type produce 10^{1-3} MWe. However, volcanoes tend to each have unique attributes or personalities, making it difficult to arrive at meaningful estimates about their developable potential without robust geophysical surveys and complementary exploration drilling.

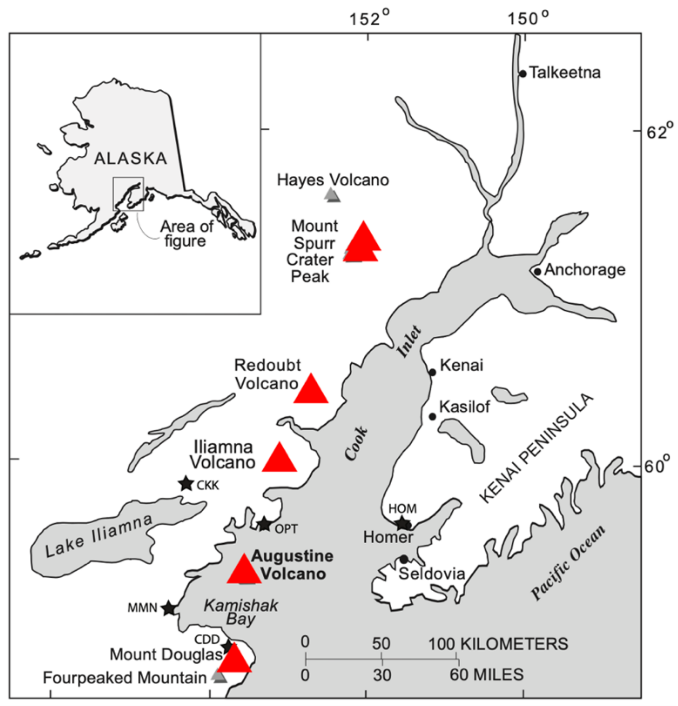

Figure 1: Map showing distribution of volcanoes on the west side of Cook Inlet. Note their fairly regular linear spacing. Augustine, Redoubt, and Spurr (specifically Crater Peak) have had multiple eruptions in historic time. Only Spurr and Augustine are located outside national parks.

No geothermal exploration has taken place at Augustine because of concerns about eruption hazards and the need for submarine power transmission. However, there are regions on Augustine Island that are protected from eruptions by topography and use of submarine transmission cables is now commonplace. Augustine provides an attractive opportunity to diversify power sources from the current heavy dependence on natural gas, with a source that is greenhouse gas free, continuous (baseload), and has minimal footprint.

The U.S. has not developed any power generation facilities in association with subduction zone volcanism, however there are numerous examples around the Pacific Rim that have been developed successfully. The fact that this is a new type of geothermal project for the U.S., but using an established technology, may make this project attractive for public as well as private sector funding.

Geothermal energy is arguably the only ecologically benign baseload source. It also has by far the smallest footprint of any energy source because the powerplant is collocated with its fuel source, which is also the site of waste (water from which energy has been extracted) disposal. As a green, renewable resource, geothermal energy is lagging development of other such sources, accounting for < 1% of global electricity production. The reasons include the long timeline and high financial risk (because drilling is expensive and finding a resource uncertain). In Alaska, all the most promising geothermal sites for electric power generation are associated with active volcanic activity and are remote, by Lower-48 standards.

2. The magma-hydrothermal relationship

All geothermal sites rely not only on a heat source, but also the ability to circulate fluid through rock to extract that heat and use it beneficially. Except for the interior western USA, known as the Basin and Range Province, all electric geothermal power generation in the US is associated with active or geologically recent (new or old heat, respectively) volcanism. In the Basin and Range, hot aqueous fluids transport energy upward through deep-rooted faults (White and Brannock, 1950). But most power production comes from volcanically active fields not associated with subduction (e.g., Salton Sea, CA; Geysers, CA) although with eruptions in the last 50,000 years. The reason for the association with magma is that the ultimate source of heat is Earth's mantle, too deep to drill to, but molten rock (magma) originating in the mantle buoyantly advects heat to the mid to shallow crust, generating hydrothermal systems comprising circulating water in porous rocks at drillable depths (Fig. 2). A reservoir temperature of about 200ºC or more is desirable, but cooler systems can be used as binary (two-fluid) geothermal power generation, with correspondingly lower thermal efficiencies. Geothermal fluid can also be valuable for space heating, but this requires loads to be proximal to the geothermal source. Only electrical transmission can transport geothermal energy over long distances, and for this purpose higher temperature systems are more desirable.

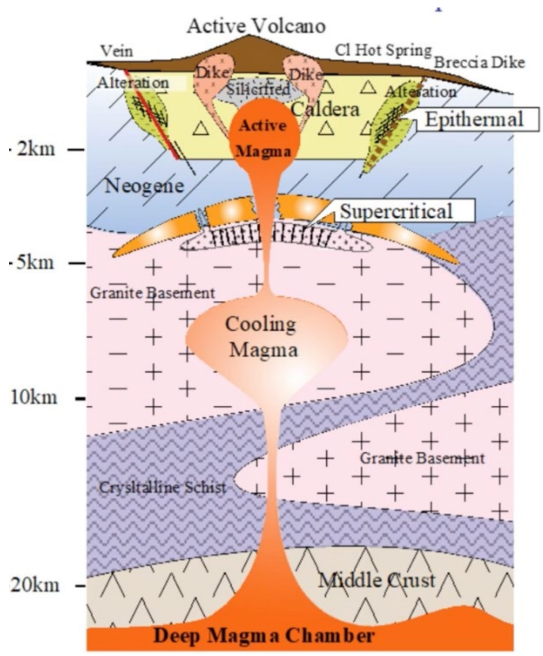

Figure 2: Idealized concept of Augustine-like magma-hydrothermal system in Japan (Tsuchiya, 2020).

Efficiency is a limitation of geothermal systems, constrained by the maximum temperature of the resource. Conventional geothermal power plants 200º – 300ºC are relatively inefficient (Fig. 3) compared to other steam turbine generating power plants that use fossil or nuclear fuel. Therefore, geothermal companies are pushing deeper to higher and higher temperatures, where the energy (more correctly, specific enthalpy of geothermal fluid) is as much as tripled and power plant efficiency is tripled as well, leading in theory to 10x productivity or 1/10 - fold decrease in drilling cost to get the same power. High temperature wells can energy discharge rates 10x conventional (> 100 MWt from one well). Thus, the potential to make geothermal a major player in green, renewable energy is strong. It is being pursued intensively in Japan and Iceland. However, engineering problems increase with temperature and have yet to be fully solved. As far as we know, these super-hot systems are all very close to magma under volcanoes and are the expected case for volcanoes in Alaska. This should be kept in mind for

Alaska's long-term future, because advances in long-distance power transmission, namely high voltage direct current (HVDC), have largely mitigated the problem of remoteness. But because realization of superhot geothermal may be as much as a decade in the future, this report will be confined to the prospects for development of conventional geothermal at Augustine Volcano. Nevertheless, we include consideration of magmatic conditions, because one cannot fully understand a hydrothermal system without considering its heat source, particularly with regard to renewability and the future potential noted above. It is important, but often neglected, to include the historic and geologic record of volcanic activity in considering the possibility of a volcano-hosted hydrothermal system.

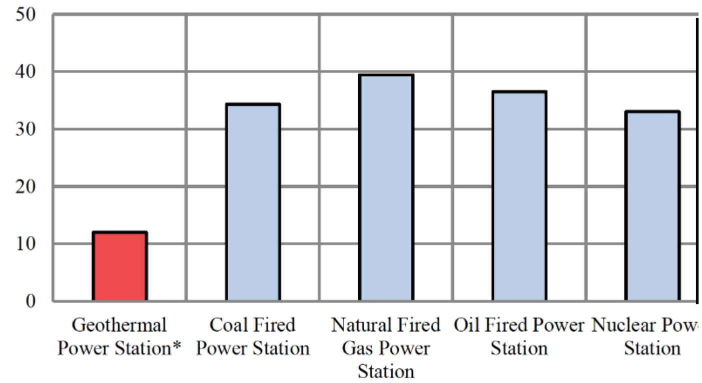

Figure 3: Efficiency (% of thermal energy converted to electrical energy) for various fuel sources (Moon and Zarrouk, 2012).

3. Why Augustine?

Augustine has much to recommend it for geothermal exploration:

1. It is close to the state's population center.

2. It represents a very large thermal energy source.

3. It is situated on state land.

4. It has an austere volcanic landscape that is unlikely to pose environmental concerns.

Despite this, very little has been done to date about geothermal at Augustine. The impediments are: 1) the perception of eruption risk, 2) plentiful natural gas in upper Cook Inlet, and 3) the need to run a submarine cable 100 km to the Kenai Peninsula (much less if to the west) would be prohibitively expensive. The first can be mitigated and is discussed below. The second perception has been dispelled, for example by the largest producer Hilcorp, which recently warned that adequate gas supply cannot be expected beyond 5 years from now (Alaska Beacon, 2022). The third perception can be dispelled by considering the improvements in submarine power transmission, led by transnational and international power transmission in China and Europe, and growth of offshore wind farms.

4. Augustine in context

Augustine is typical of many volcanoes that comprise the "Pacific Ring of Fire" (Fig. 4). The volcano is a complex of andesite to dacite domes, almost solidified magma thrust upward from the vent. Dome eruptions are preceded by eruptions of ash and accompanied by block and ash flows shed from growing, steep-sided domes. These are basically avalanches, somewhat like snow avalanches. They are seen as ash billowing from the flow and moving downhill at high speeds, concealing the movement of large blocks beneath them. They were well observed and described by the Alaska Volcano Observatory (USGS, UAF, ADGGS) during the most recent eruption of Augustine in 2006, and famously by Japanese scientists at Unzen Volcano, where some 10,000 such phenomena occurred during a four-year period, destroying much of the town of Shimabara at its base. This in large measure accounts for a lack of interest in the possibility of extracting geothermal energy from Augustine. However, such flows are constrained by topography. Recent eruptions products have been well mapped by Alaska Volcano Observatory scientists. Hence the high-risk areas are well known as are those that have not been impacted for millennia. Additionally, Augustine is one of the best monitored volcanoes globally.

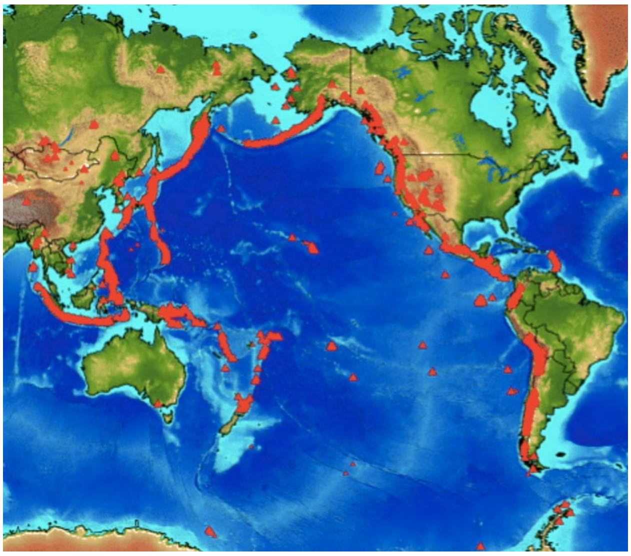

Figure 4: Active volcanoes of the Pacific Rim, the "Pacific Ring of Fire". Global Volcanism Program, Smithsonian NHM.

On the island, AVO operates 14 seismic stations, 9 GPS stations, 3 infrared sensors, and 2 webcams (J. Power, USGS, pers comm, 2023). The data are collected continuously and telemetered in real time to USGS in Anchorage. Frequent overflights for gas analysis and thermal analysis and photographic documentation are added during periods of unrest. Eruptive episodes are preceded by months to a year of elevated seismicity, providing ample warning. Flimsy structures on Augustine have survived block and ash avalanches. With robust structures, proper siting, and the ongoing monitoring it is possible to minimize the risk to geothermal operations and make it acceptable for humans, whose presence can be minimized, and they will have ample warning to evacuate, if necessary (Fig.5).

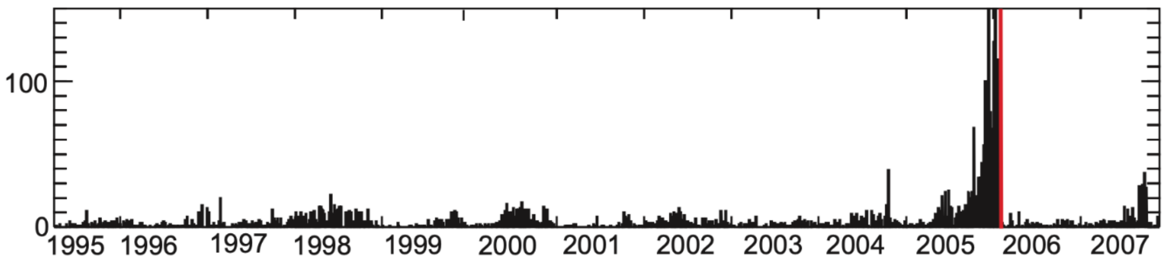

Figure 5: Seismic events per day during the decade leading up to the most recent eruption onset at Augustine (red line). Seismic activity begins to increase several months before eruptions start (Lalla and Power, 2010).

Most of the thermal power output from a volcano to the surface volcano is represented by volume of magma erupted per time. For Augustine, the magma discharge rate over the last two centuries has averaged about 2 x 10^6 m^3 per year (Beget and Kienle, 1992), representing a time-averaged thermal power of about 100 MWt (e.g., Eichelberger, 2020). This places Augustine well within the top 10% of active volcanoes in the circum-Pacific region. If that power seems strangely low by geothermal standards, it is because this is an average over time of extremely energetic short-term episodes, with power being energy per time. Furthermore, this is the heat that "got away" and is likely only a fraction of heat released from magma that remained below the volcano at shallow depth. The mean repose period (between eruptions) of Augustine is 36+/-10 years.

Despite its high rate of activity, Augustine is quite small, only about 15 km^3 (there is considerable uncertainty), with Jurassic basement exposed on the south side. This basement forms a prominence on the south side that is free of volcanic deposits, a safe location in almost any eruption. The volcano is sited in the expected place, midway between Iliamna and Douglas, for an Aleutian Range volcano, which except for some clusters (e.g., Katmai group) are semi-regularly spaced. The paradox of small total volume of Augustine despite high magma productivity could be due to massive removal of cone material by glacial ice flowing down Cook Inlet prior to 15,000 years ago or to a higher-than-normal proportion of magma crystallizing beneath the surface or to a higher-than-normal intensity of activity for the last several millennia. What is encouraging from a geothermal standpoint is that the shallow dacitic magma body beneath Augustine appears to be a long-lived feature that is sustained and caused to erupt by periodic injections of hotter, andesitic, or basaltic-andesitic magma from greater depth (Larsen et al, 2010). This is a familiar pattern in subduction zones, with examples like Redoubt (Wolf and Eichelberger, 1997) in Alaska, Unzen in Japan (Browne et al, 2006), Soufriere Hills on Montserrat, BWI (Murphy et al, 1998), and Pinatubo, Philippines (Pallister et al, 1992).

Table 1: Total geothermal power production from circum-Pacific subduction zone volcanoes

Country	MWe
Central America	862
Chile	48
Indonesia	2,289
Japan	532
Mexico	1105
New Zealand*	1064
Philippines	840
PNG	11
Russia	82
USA**	0
Total	6833

* atypical of subduction zones – rhyolite flareup with rifting.
** however, US leads the world in geothermal with extension localities (Salton Sea, Basin and Range, and a strike-slip window at Geysers), total 3,673.
Lund et al, 2022

In addition to extensive monitoring today, Augustine has been an object of intensive geological and geophysical studies during the last half century. The early work was quite general, but the more modern research is focused on Augustine as a volcanic hazard. As a consequence, much is known about the volcano's structure and stratigraphy and the physical and chemical characteristics of its eruptions. Little is known about its deeper structure and in particular electrical conductivity, the latter being an indication of the presence and distribution of hydrothermal systems and magma. Thus, the best that can be done is to review results of similar volcanoes where drilling data are available.

5. Geothermal development at subduction zone volcanoes

There is evidence that magma, the heat source of most electrical power generating geothermal systems, is deeper in subduction zones like those that surround the Pacific Ocean than for rift zones. The reasons are likely because the crust of rifts is thinner, bringing the mantle closer the surface, and the silicic magmas are drier, causing them to stall in their rise and accumulate at shallower depth. However, this is not a serious obstacle to geothermal development because hydrothermal systems in subduction zones appear to comprise hot plumes that rise from magma bodies. Hence 2-3 km of drilling should suffice. All volcanoes are different, but they have enough in common that Jolie et al (2021) could present a summary view of magma-hydrothermal systems in different tectonic settings (Fig. 6 for subduction). One might think of them as cones with a hot central chimney and wrapped in a wet blanket that hides the heat below. Rifts have a subaerial extent much smaller than subduction zones. Examples are Iceland; Salton Sea; and the East African Rift.

Geothermal power production by country from circum-Pacific subduction volcanoes is presented in Table 1. Japan, which had 19 such powerplants as of 2020, shows the typical spatial arrangement, with powerplants arrayed in a line, corresponding to the position of active volcanoes over the depth where the incoming subducting Pacific slab reaches about 100 – 120 km below sea level (Yasukawa et al, 2020). One could envision a similar arrangement for the Aleutian Range, except the more distant volcanoes would only be useful for manufacturing green fuels or ammonia, not for generating electricity without a massive cabling effort.

It is interesting to note that Indonesia has been very successful in developing its geothermal resources, both in terms of the total number of powerplants it has developed, and the average installed capacity for these plants. One reason is that Indonesia has more active volcanoes then the other countries. Government policy and how aggressive Indonesians are in drilling in difficult places may play a role too. At the other end of the spectrum, the US, which is still #1 in in total geothermal power generation (followed by Indonesia), has not made use of subduction zone volcanoes. Contributing factors are that US has easier places close to population centers to develop (e.g., Geysers, Salton Sea), most Lower-48 volcanoes are in protected federal lands and the remainder, while much more active, are in Alaska.

6. Some comparisons with Augustine Volcano

Subduction zone volcanoes that most resemble Augustine are those that erupt andesitic to dacitic magma triggered by injection from below by basaltic andesite or basalt. Two such volcanoes are discussed below: Pinatubo, Philippines, which erupted about 5 km^3 (DRE) of dacitic magma in 1991 (second largest eruption of the 20^{th} century after Katmai, Alaska in 1912) and Unzen Volcano, Japan, which erupted dacitic domes. A somewhat more chemically varied volcano, Mutnovsky, Kamchatka, Russia has been developed by drilling numerous geothermal boreholes on its flank and delivers about 60 MW of electricity to Petropavlovsk-

Kamchatsky. These volcanoes were selected because all were drilled on or close to the volcanic edifice itself (Fig. 6). Tongariro Volcano in New Zealand has recently been studied by 3-D magnetotellurics (Hill, 2021), and again conforms to the general concept of Jolie et al (2021). Finally, Crater Peak, Alaska, the only Cook Inlet volcano that has been investigated geothermally, at the time of this writing, is contrasted with Augustine.

6.1 Pinatubo Volcano, Philippines

A remarkable aspect of Mount Pinatubo, Philippines, is that it was drilled for geothermal development, with wells as hot as 350ºC (Delfin et al, 1996), shortly before the eruption of about 5 km^3 of magma. This volume is a lower limit for magma in the system because it is likely that the eruption did not nearly empty the magma chamber (Gerlach et al, 1996).

6.2 Unzen Volcano, Japan

In contrast to the Pinatubo eruption, for which the paroxysmal phase was short and entirely explosive, Unzen erupted only domes that shed block and ash flows, and over an extended period. The eruption lasted from 1989 to 1995, with most of the dome building occurring between 1990 and 1994. There was great interest in discovering what the inside of this volcano is like. The big question was how a magma originally with 6 wt% water could have peacefully released that volatile component as gas during ascent, keeping buuble pressure low so the magma did not fragment to ash. That amount of water could produce some 600x expansion upon decompression to one atmosphere, producing a mixture of tiny bubble walls (ash) entrained in superheated magmatic steam and exiting the vent at perhaps 300 m/s. Did the gas escape outward from the conduit into Unzen's cone, which would only be possible if rocks surrounding the conduit were permeable, or did it flow vertically upward through highly inflated and therefore permeable magma and/or along the conduit margins? Consequently, an International Continental Scientific Drilling Project was launched (Nakada et al, 1995). Given the long timespan required to raise money for a scientific borehole (ultimately costing about $20 M with major costs added to drilling by extensive road building and by use of huge amounts of cement during drilling through the outer fragmental portion of the cone), drilling did not penetrate the conduit until 2004, nine years after ascent of magma had ceased. The borehole design was novel. Drilling started vertically and then, using a downhole motor, deviated to a large angle from vertical to reach the conduit about one kilometer below the summit. Given that the conduit acted as a vertical pipe carrying 800ºC magma, the science team wa surprised to find a conduit temperature of only 160ºC. The wallrock was of very low permeability. The scientific answer to the degassing problem and hence effusive rather than explosive eruption was that the gas flowed up the conduit, escaping from inflated magma magma that subsequently collapsed to dense dome lava upon extrusion. Also, the cone itself was not hot, even after a major eruption. The lesson for geothermal development is that drilling production wells on the volcanic edifice should be avoided if possible. Less costly results may be obtained, if geometry permits, by spudding wells on bedrock, just outside the cone, and directionally drilling inward so as the access the region under the summit at 2 to 3 km. It should be noted that Augustine has an exceptionally favorable geometry for doing this.

6.3 Mutnovsky Volcano, Russia

A subduction zone volcano that has been extensively drilled and geothermally developed is Mutnovsky Volcano on the Kamchatka Peninsula of the Russian Far East. The main plant, 50 MWe (Fig. 6) and a smaller one, 6 MWe, supplies the main city on the peninsula, Petropavlovsk-Kamchatsky. In fact, Kamchatka has some parallels to Alaska in that it has limited access to the mainland of its country. During the winter of 1998, no oil or coal reached the peninsula by sea, the only route, and many people would have died in the bitter cold were it not for the continued operation of the geothermal power plant. This is a stark illustration of the benefit of diversity in energy sources.

Figure 6: The Mutnovsky 50 MWe powerplant located just beyond the flank of Mutnovsky Volcano. Photo by A. Kiryukhin.

The summit crater contains fumaroles that continuously emit steam and SO_2 at near magmatic temperatures, evidence for convection of magma at shallow depth within the conduit. The system has the general form of that suggested by Jolie et al (2021) but is much hotter, nearing supercritical. Magma may underlie the flank as well. Oxygen isotope data, which is sensitive to the elevation of the source water, shows that the hydrothermal system is recharged by the crater glacier. Thus it must be heated to high temperature under the volcano.

6.4 Combining cross sections of Augustine, Pinatubo, Unzen, and Mutnovsky

In Figure 7, relevant features of Unzen, Pinatubo, and Mutnovsky are superimposed on a cross section of Augustine from Waitt and Beget (2009). There is no vertical exaggeration so the elevation scale on the right is also valid for horizontal distance. Surface profiles were used to make vent position coincide. Subsurface features are all plotted according to the Augustine cross section base map. The implication of these analogues is that Augustine is a viable geothermal prospect. Discouraging results for Crater Peak on the flank of Mount Spurr should not cast doubt on this conclusion, because it is a very different type of volcano, with magma coming rapidly from a much deeper source and leaving little heat behind under the cone (Fig. 8).

6.5 Other volcanoes

Crater Peak is a flank vent on Mount Spurr and is the only geothermal prospect that has been explored in the Cook Inlet region. It is quite different from Augustine, or even Spurr itself as it erupts a fluid basaltic andesite whereas both Augustine and Spurr produce dacitic domes and tephra. Seismicity associated with eruption at Crater Peak extends to the lower crust at 40 km, the likely storage zone of the magma (Fig. 8). There is little or no warning of eruptive events, apparently because the magma ascends very rapidly through a well-established conduit. As such, deep heat is advected efficiently to the surface with little left behind to drive hydrothermal circulation. In contrast, seismicity under the summit region resembles that of Augustine, likely indicating shallow storage of silicic magma under the summit domes. However, the summit region would be very difficult to access due to glacial cover.

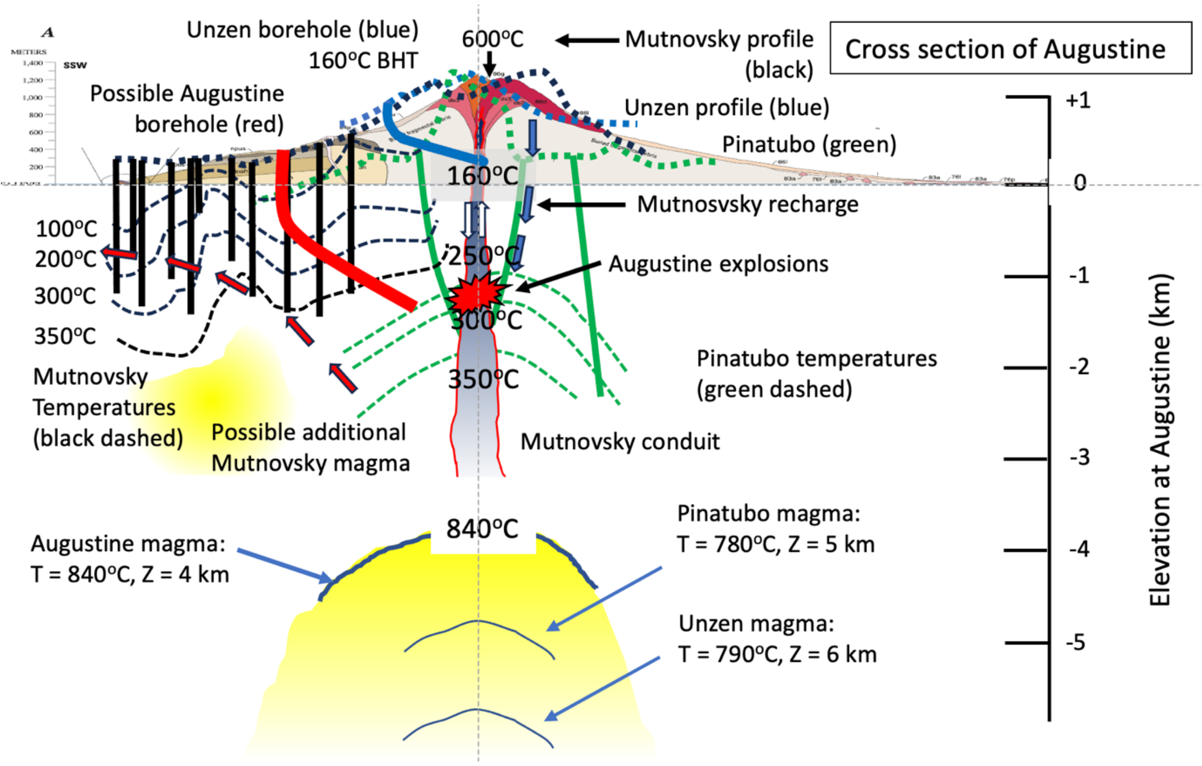

Figure 7: Geothermal features of Unzen, Pinatubo and Mutnovsky superimposed on a geologic cross section of Augustine (Waitt and Beget, 2009). All are at the same scale, with no vertical exaggeration. However, the overlaid features are aligned so that the summit vents of all three volcanoes coincide. Overlaid surface profiles are dotted lines, blue for Unzen, green for Pinatubo, and black for Mutnovsky. Boreholes are corresponding colors but solid lines. The temperature contours come from the Pinatubo boreholes prior to the eruption of 1996. Depths to the top of the magma bodies are from seismology, geodesy, and petrology (depth and temperature) for Augustine (Larsen et al, 2010; Cervelli et al, 2006; Power and Lalla, 2010) and from petrology for Pinatubo (Rutherford and Devine, 1996) and Unzen (Venezky and Rutherford, 1999). A scientific borehole (solid blue) reached the conduit of Unzen at a vertical depth of about 1 km below the summit (Nakada et a, 2005), 9 years after its 5-year eruption ended. The unexpectedly low temperature of 160oC probably results from the cone being a recharge area. Recharge at Mutnovsky is isotopically tagged as from the crater glacier. The water flows down (blue arrows) near the magma-filled, actively convecting (white arrows) conduit. The heated meteoric fluid than re-emerges in the geothermal system (Kiryukhin et al, 2018). A possible borehole sited on bedrock just outside the Augustine cone is shown as a solid red line to where it might reach temperatures >250oC beneath the volcano.

The use of magnetotelluric (MT) surveys to image the magma-hydrothermal systems of volcanoes has grown tremendously over the last decade. This is largely due to increased computer power that can now process the data in three dimensions. An array of stations is deployed to generate conductivity "soundings" of the crust beneath the array. This is useful in geothermal exploration because fluids, both aqueous and magmatic, are more conductive than solid rock. Of course, this is not without problems because some rock types such as carbon-rich and clay-rich layers can also be highly conductive. A particularly clear image of a typical, active subduction zone volcano is shown in Figure 9 of Tongariro, located on the North Island of New Zealand. The conductive zones displayed appear to be of a voluminous magma chamber (C1), a "conduit" (C2) which probably contains a high specific enthalpy aqueous fluid plume rising off the magma, broadening out into broad hydrothermal reservoir (C3) under the volcanic edifice.

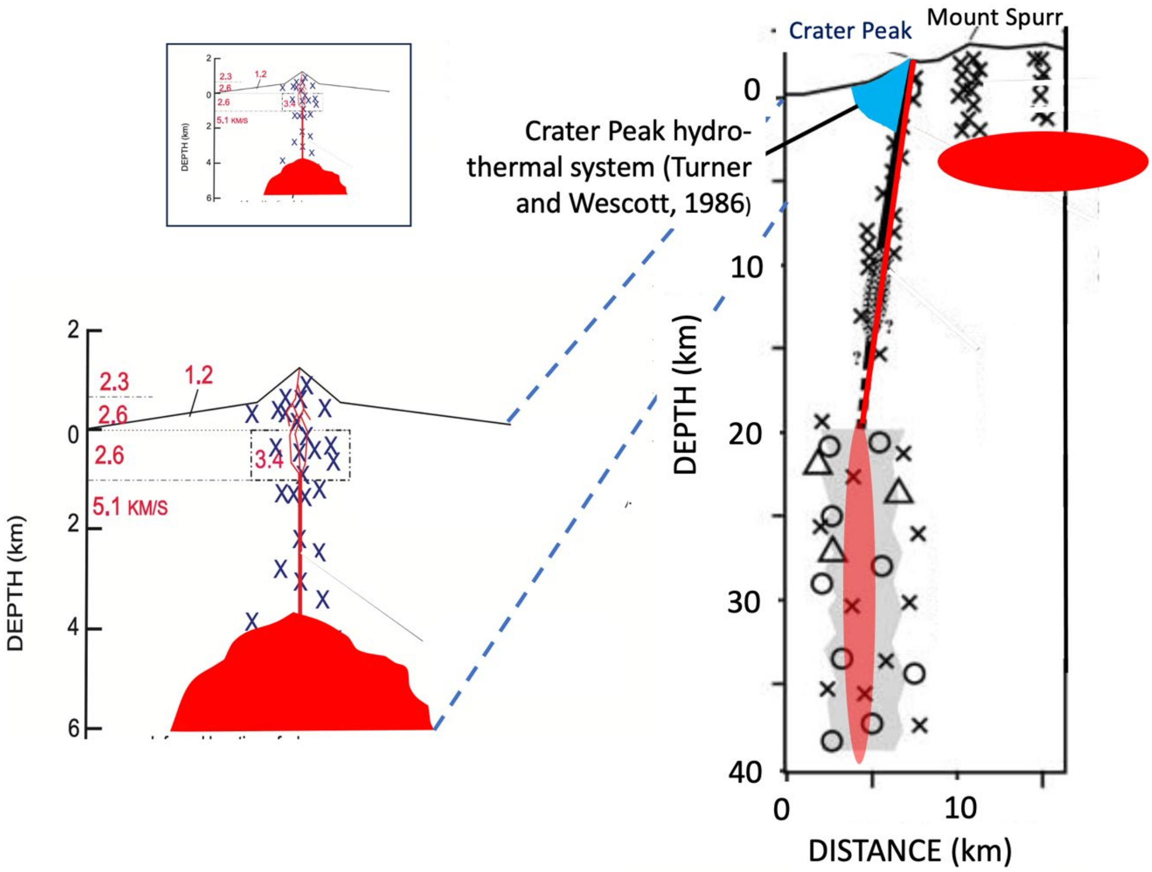

Figure 8: A comparison of seismicity under Augustine and Spurr/Crater Peak, modified from Lalla and Power (2010) and Power et al (2002). Mount Spurr may have shallow silicic magma beneath its summit. Width of magma bodies are unconstrained except for Crater Peak.

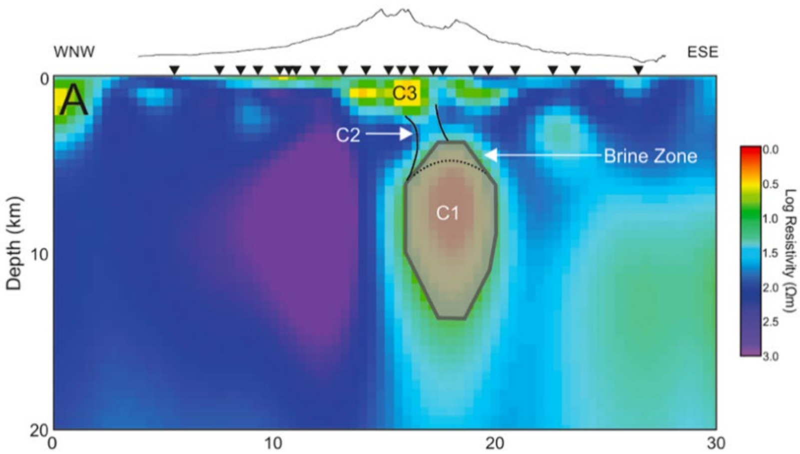

Figure 9: Cross section through 3-D magnetotelluric analysis of Tongariro Volcano, NZ (Hill et al, 2020). C1 is the magma chamber, C2 is the magma conduit, C3 is the hydrothermal system. Used by permission.

7. Economic Considerations

Black & Veatch (B&V) developed a regional integrated resource plan for the AEA/Railbelt electric utilities [Interior-Southcentral-Kenai Peninsula] that featured cost/performance estimates for a geothermal electric power plant in the region (B&V, 2010). All the scenarios developed in that regional plan indicated that geothermal power would become competitive in the 2030-time frame (B&V, 2010).

One of the authors of this paper (MW) updated the cost and performance estimates for a 50MWe geothermal power plant constructed at Augustine by: (1) applying local construction and operations cost multipliers to the Energy Information Administration's most recent detailed cost estimate studies for a generic geothermal power plant in the Contiguous U.S. (CONUS; Sargent & Lundy, 2019), (2) adjusted costs to reflect the trifurcation of the plant into a baseload generating unit, a modest peaking unit to serve emerging peaking capacity markets, and a heat recovery system to serve year-round green houses, and (3) escalating those costs to 2023$. Capital costs were annualized assuming a 4.44% real discount rate (State of Alaska opportunity cost of investment) and a 30-year plant life. Fixed and variable operating costs plus State of Alaska gross royalty payments were averaged over the plant life. The resulting levelized cost of electricity (LCOE) estimate is $108/MWh (10.8¢/kWh), "Augustine LCOE" in Figure 10 below. That cost was reduced to reflect a geothermal power plant's eligibility for federal investment tax credits under the Inflation Reduction Act (IRA, 2022) and associated net reduction in State gross royalty payments resulting in a net cost of $75/MWh (7.5¢/kWh). The net revenues from heat sales to local greenhouses and ancillary services sales to the Railbelt electric utility grid were estimated to total roughly $19/MWh (1.9c/kWh). The resulting net cost of electricity for the base load service is $56/kWh (5.6c/kWh) which is comparable to the current cost of power for Alaska's largest electric utility, which currently relies primarily on aging local natural gas fields for its electric generation.

Going forward, high quality offshore wind prospects adjacent to Augustine that span from Augustine down to the Barren Islands North of Kodiak Island present an opportunity to share the cost of transmission system interconnection and reduce total cost to well below the local utility outlook for 2030.

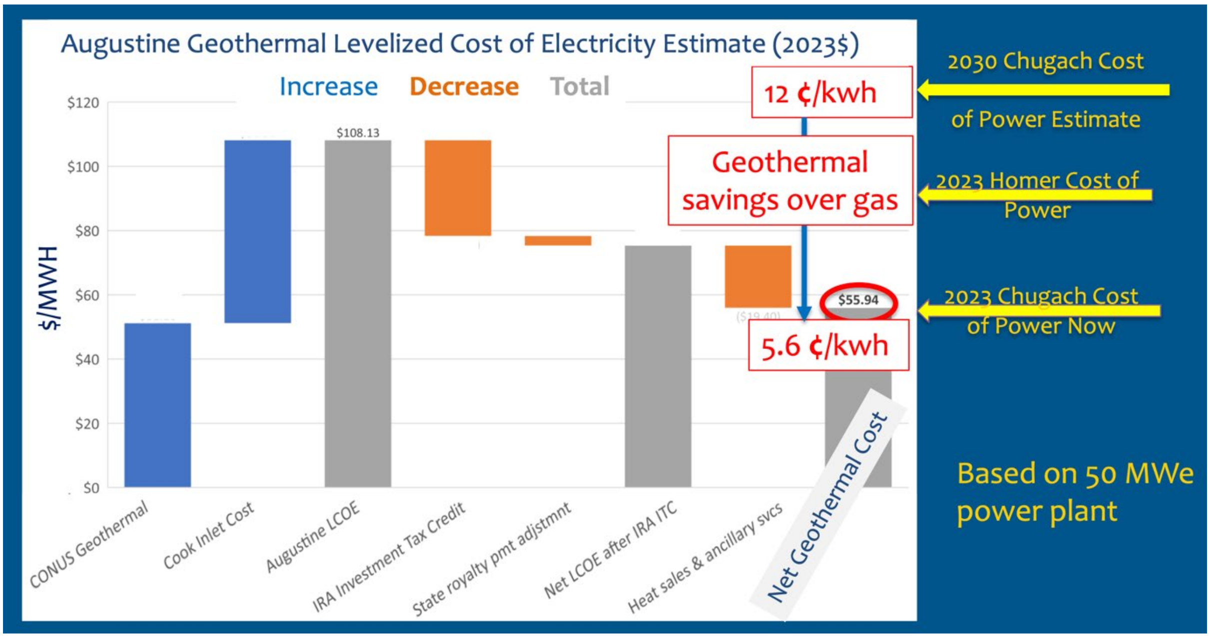

Figure 10: An estimate for electricity produced by geothermal energy at Augustine, after adjusted for various factors. See text for discussion. The analysis indicates that measured in 2023$, the project would match the current cost of natural gas-based electricity, whereas the cost from the present natural gas dominated generation mix is expected by the local electric utilities to more than double to roughly 12¢/kWh by2030.

8. Conclusions

There is little doubt that Augustine Volcano marks the position of accumulation of great deal of thermal energy at depths accessible by drilling, remarkable even by Circum-Pacific rim standards. Whether there is sufficient permeability near the magmatic heat source can only be determined by exploratory drilling. Much is known about Augustine and its magma reservoir, but nearly all these data were collected and analyzed for purposes of volcano hazard reduction. Nevertheless, the high level of monitoring the volcano and history of understanding its geophysical and geochemical signals precursory to eruption makes Augustine a safe place to work. The power plant and accompanying boreholes can be sited and hardened to minimize risk of property damage. The property is owned by the State of Alaska and its austere volcanic environment makes it immune to ecological damage from development. On the other hand, some geophysical studies pertinent to geothermal development have not been conducted, for example magnetotelluric surveys to produce a 3-D view of subsurface conductivity, seismic reflection, and LiDaR mapping to identify faults, and an aeromagnetic survey to elucidate subsurface structure. If these results are promising, then multiple slim holes should be drilled to directly reveal the distribution of permeability and heat at depth. The high cost of running a submarine cable(s) to the mainland sets a minimum level of electric power generation. This could be de-risked by pairing geothermal development with an offshore windfarm, for which the Augustine location is exceptionally favorable. The initial exploratory step to determine whether there is a geothermal resource worthy of development might cost of the order of $10,000,000.

There are a number of energy source options for this region, Alaska's most populous. However, given the ideal green and baseload characteristics of geothermal energy, we believe it would be prudent to take this exploratory step.

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REFERENCES

Black & Veatch 2010. Alaska Energy Authority Railbelt Integrated Resource Plan.

Browne, B.L., Eichelberger, J.C., Patino, L.C., Vogel, T.A., Uto, K. and Hoshizumi, H., 2006. Magma mingling as indicated by texture and Sr/Ba ratios of plagioclase phenocrysts from Unzen volcano, SW Japan. *Journal of volcanology and geothermal research*, *154*(1-2), pp.103-116.

Cervelli, P.F., Fournier, T., Freymueller, J. and Power, J.A., 2006. Ground deformation associated with the precursory unrest and early phases of the January 2006 eruption of Augustine Volcano, Alaska. *Geophysical Research Letters*, *33*(18).

Delfin Jr, F.G., Villarosa, H.G., Layugan, D.B., Clemente, V., Candelaria, M.R. and Ruaya, J.R., 1996. Geothermal exploration of the pre-1991 Mount Pinatubo hydrothermal system. *Fire and Mud (CG Newhall & S. Punongbayan, eds.)*, pp.197-212.

Eichelberger, J., 2020. Distribution and transport of thermal energy within magma–hydrothermal systems. *Geosciences*, *10*(6), p.212.

Gerlach, T.M., Westrich, H.R. and Symonds, R.B., 1996. Preeruption vapor in magma of the climactic Mount Pinatubo eruption: Source of the giant stratospheric sulfur dioxide cloud. *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines*, *415*, p.33.

Hill, G.J., Bibby, H.M., Peacock, J., Wallin, E.L., Ogawa, Y., Caricchi, L., Keys, H., Bennie, S.L. and Avram, Y., 2020. Temporal magnetotellurics reveals mechanics of the 2012 Mount Tongariro, NZ, Eruption. *Geophysical Research Letters*, *47*(8), p.e2019GL086429.

Jolie, E., Scott, S., Faulds, J., Chambefort, I., Axelsson, G., Gutiérrez-Negrín, L.C., Regenspurg, S., Ziegler, M., Ayling, B., Richter, A. and Zemedkun, M.T., 2021. Geological controls on geothermal resources for power generation. *Nature Reviews Earth & Environment*, *2*(5), pp.324-339.

Kiryukhin, A.V., Polyakov, A.Y., Usacheva, O.O. and Kiryukhin, P.A., 2018. Thermal-permeability structure and recharge conditions of the Mutnovsky high-temperature geothermal field (Kamchatka, Russia). *Journal of Volcanology and Geothermal Research*, *356*, pp.36-55.

Larsen, J.F., Nye, C.J., Coombs, M.L., Tilman, M., Izbekov, P. and Cameron, C., 2010. *Petrology and geochemistry of the 2006 eruption of Augustine Volcano: Chapter 15 in The 2006 eruption of Augustine Volcano, Alaska* (No. 1769-15, pp. 335-382). US Geological Survey.

Lalla, D.J. and Power, J.A., 2010. A two-step procedure for calculating earthquake hypocenters at Augustine Volcano: Chapter 7 in The 2006 Eruption of Augustine Volcano, Alaska (No. 1769-7, pp. 129-142). US Geological Survey.

Lund, J.W., Huttrer, G.W. and Toth, A.N., 2022. Characteristics and trends in geothermal development and use, 1995 to 2020. *Geothermics*, *105*, p.102522.

Moon, H. and Zarrouk, S.J., 2012, November. Efficiency of geothermal power plants: a worldwide review. In *New Zealand Geothermal Workshop* (pp. 19-21). Department of Engineering Science.

Murphy, M.D., Sparks, R.S.J., Barclay, J., Carroll, M.R., Lejeune, A.M., Brewer, T.S., MacDonald, R., Black, S. and Young, S., 1998. The role of magma mixing in triggering the current eruption at the Soufriere Hills volcano, Montserrat, West Indies. *Geophysical Research Letters*, *25*(18), pp.3433-3436.

Nakada, S., Uto, K., Sakuma, S., Eichelberger, J.C. and Shimizu, H., 2005. Scientific results of conduit drilling in the Unzen Scientific Drilling Project (USDP). *Scientific drilling*, *1*, pp.18-22.

Pallister, J.S., Hoblitt, R.P. and Reyes, A.G., 1992. A basalt trigger for the 1991 eruptions of Pinatubo volcano?. *Nature*, *356*(6368), pp.426-428.

Power, J., Jolly, A., Nye, C. and Harbin, M., 2002. A conceptual model of the Mount Spurr magmatic system from seismic and geochemical observations of the 1992 Crater Peak eruption sequence. *Bulletin of Volcanology*, *64*, pp.206-218.

Power, J.A. and Lalla, D.J., 2010. *Seismic observations of Augustine Volcano, 1970-2007: Chapter 1 in The 2006 eruption of Augustine Volcano, Alaska* (No. 1769-1, pp. 3-40). US Geological Survey.

Rutherford, M.J. and Devine, J.D., 1996. Preeruption pressure-temperature conditions and volatiles in the 1991 dacitic magma of Mount Pinatubo. *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines*, pp.751-766.

Sargent & Lundy, 2019. Energy Information Administration, Cost and Performance Estimates for New Utility-Scale Electric Power Generating Technologies.

Scott, S., Driesner, T. and Weis, P., 2018. A New Conceptual Framework for the Deep Roots of Magma-Driven Geothermal Systems. In *Proceedings of the Fourty-Second Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA.

Tsuchiya, N., 2020. Geological Model and Potential of Supercritical Geothermal Reservoir. In *Proceedings World Geothermal Congress* (Vol. 1).

Turner, D.L. and Wescott, E.M., 1986. *Geothermal energy resource investigations at Mt. Spurr, Alaska* (No. UAG-R-308). Alaska Univ., Fairbanks (USA). Geophysical Inst..

Venezky, D.Y. and Rutherford, M.J., 1999. Petrology and Fe–Ti oxide reequilibration of the 1991 Mount Unzen mixed magma. *Journal of Volcanology and Geothermal Research*, *89*(1-4), pp.213-230.

Waitt, R.B. and Begét, J.E., 2009. *Volcanic processes and geology of Augustine Volcano, Alaska* (p. 78). US Geological Survey.

White, D.E. and Brannock, W.W., 1950. The sources of heat and water supply of thermal springs, with particular reference to Steamboat Springs, Nevada. *Eos, Transactions American Geophysical Union*, *31*(4), pp.566-574.

Wolf, K.J. and Eichelberger, J.C., 1997. Syneruptive mixing, degassing, and crystallization at Redoubt Volcano, eruption of December, 1989 to May 1990. *Journal of Volcanology and geothermal Research*, *75*(1-2), pp.19-37.

Yasukawa, K., Nishikawa, N., Sasada, M. and Okumura, T., 2020. Country update of Japan. In *Proceedings World Geothermal Congress*.