The occurrence, size and geometry of geothermal resources in volcanic terrains

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Abstract. Volcanic terrains in general, and arc volcanic belts in particular, have been prime geothermal exploration targets as far back as the first geothermal power generation at Larderello, Italy, in 1904. The popularity of this terrain for geothermal exploration and development is based on the concept of young shallow magma bodies providing an abundance of shallow crustal heat and also on the presence of hot springs and fumaroles observed within these terrains. The success in developing these geothermal resources ranges from spectacular (e.g. Japan, Philippines, Indonesia, New Zealand, Italy, Iceland) to disappointing (e.g. Cascade Range of northwestern North America). The types, shapes and geometries of geothermal resources in volcanic terrain range in size from large broad three-dimensional fractured stockwork systems to narrow geothermal cell conduits. Effective and economic exploration and development of these resources is greatly improved by understanding the varying sizes and geometries of these resources and matching the exploration strategy design specifically for each exploration target rather than applying a single exploration formula and data interpretation model to all settings. Information from the mining industry provides valuable insight into the range in geometry and size of these resources. This body of knowledge should be used by the geothermal community: (1) for more effectively designing exploration programs specific to each prospect to interpret the body of exploration data in terms of site-specific geology and tectonics; (3) to integrate basic risk management best practices into exploration and development programs.

1. Introduction
Surface expressions of high temperature geothermal resources in volcanic terrain attracted early attention and development of geothermal energy for electrical power (e.g. Larderello, Italy; Wairakei, New Zealand and The Geysers, U.S.A.), and continue to attract exploration and development (e.g. Indonesia, Chile). Surface expressions of the geothermal potential in volcanic terrains include hot springs, geysers, fumaroles, and the physically dominating presence of the volcanoes themselves. Occasionally the striking volcanic edifice and the concept of an underlying magma chamber can belie the actual geometry of the dynamics of geothermal resources that form within this terrain. Geothermal
resources in volcanic terrain can range in size from multiple square km to conduits of a few hundred meters across. A large body of knowledge describing the size and geometry of geothermal systems in volcanic terrain has been assembled for decades by the mining industry. Base and precious metals ore bodies formed by now-fossil equivalents of geothermal systems have been documented in great detail. A review of some of these data (e.g. [1-8]) provide valuable insight into the wide range of geothermal exploration targets.

Data from the mining industry identifies four general site associations for the occurrence of geothermal activity in volcanic terrain: (1) large-scale fracture networks associated with plutons (porphyry style mineralization); (2) fractured subvolcanic rock; (3) skarns and related pluton-contact zones; and (4) regional structural dilation conduits. The types of exploration tools, and the interpretation of data provided by these tools should change markedly for a kilometer-scale stockwork-type target from that of a dilation upflow conduit of only a few hundreds of meters across. These data also demonstrate that hydrothermal fluid within active volcanic terranes show changing ratios over time between magmatic fluids, formation water and meteoric water [9], [10]. The knowledge of the various geometries and sizes of geothermal resources in volcanic terrain can provide a much better understanding as to how exploration programs can be most effectively designed and data interpreted for each exploration site. These data can be used effectively to reduce risk, both in time and budget, when applied to exploration and development of geothermal resources.

2. Igneous-Hosted Fractured Pluton, Breccia Pipe, Skarn and Subvolcanic Hydrothermal Affiliations

Plutons and subvolcanic dykes have the potential for hosting hydrothermal fluid flow through fracture permeability. Large-scale fractured plutons, analogous to porphyry mineral deposits, can be one or more kilometer across, presenting a large 3-D exploration target. Breccia pipes are vertical breccia fluid flow conduits usually ranging from a few meters to a few to tens of meters across. Rarely breccia pipes can form with a diameter of hundreds of meters. The breccia pipes can form from mechanical or phreatic processes and although commonly narrow structures, they can have high transmissivity. Contact skarn structures can occur when magma intrudes calcareous sediments. The metasomatic chemical reactions replace carbonate minerals with calc-silicate minerals and can form open permeability for fluid flow. Their geometry varies greatly, influenced by the mechanics and geometry of the pluton and tectonic strain associated with the intrusion. Subvolcanic permeability can form in vertical subvolcanic features when fractures develop, either cooling fractures and/or stress dilation fractures. The geometry of these vertical conduits varies markedly, thus their permeability can change along all three axes. These flow structures are generally limited to a maximum of a few hundreds of meters across.

The pluton stockwork fracture systems occur within highly fractured portions of some felsic plutons and extending into overlying fractured, thermally metamorphosed, rock (figures 1, 2 and 3). Examples of these types of geothermal systems include Darajat and Dieng, Indonesia and The Geysers, California, U.S.A. At depth these systems typically have planar sections measuring in square kilometers, can occur in multiple intrusive cycles, have a hydrothermal life of up to a few hundreds of thousands of years, and have hydrothermal fluid sources ranging from magmatic to meteoric over the duration of activity [11]. Effective fluid flow within a fractured stock can be supported by a fracture density of 10 to 2 percent, as observed in the Bingham Canyon porphyry (figure 3 [7]). The expansive geometry and temperature within these stockwork systems can support larger-scale power generating facilities. The fluid sources supporting a stockwork fracture network system commonly changes over the duration of hydrothermal activity. The initial fluid typically has a magmatic component. Other fluid sources may also include connate and metamorphic water from adjacent rock. Meteoric water commonly plays a progressively greater role within these hydrothermal systems, typically becoming the dominant fluid source [11].
Figure 1. An expansive stockwork-style fracturing associated with a silicic pluton is capable of hosting a broad geothermal resource (adapted from Burnham [12]). The image shows three potential fracture sites for geothermal resources: (1) expansive fractured plutonic rock (black fracture lines); (2) fractured intrusive dikes (D1 and D2, purple) and (3) breccia pipes (BP, red).

Figure 2. Map showing the broad 3-dimension Dieng, Indonesia, pluton-hosted stockwork geothermal resource and isotherms at sea level (from Layman et al. [13]).
Skarn and related calcareous rock-hosted hydrothermal processes within volcanic terrains are associated with the replacement of carbonate minerals with calc-silicate minerals. This very dynamic process is caused by reactions resulting from the chemical and thermal disequilibrium between the calcareous formations, the hydrothermal fluid and the intruding igneous magma, often facilitated by the mechanical stresses associated with the intruding magma (figure 4) [14]. The mechanical trauma to the host formations and the metasomatic silicate mineral alteration can result in the development of permeability at and near the contact boundaries, allowing hydrothermal fluid to ascend along these structures. Similar mechanical processes can also occur with shallow magmatic intrusions into igneous and other non-calcareous formations. However expansive permeability would be dependent solely on mechanical stress fractures without the additional calc-silicate chemical replacement permeability.

Figure 3. Stockwork vein density as percent of rock in the Bingham Canyon porphyry deposit, Utah, U.S.A. Stipple-pattered areas identify overlapping intrusive bodies. Light gray shaded areas identify low- and high-grade pre-mineralization (from Gruen et al. [7]).

Figure 4. The history of hydrothermal activity along the boundary zone of a granodiorite intrusive and the host calcareous country rock. Changes in fluid chemistry over time produced variations in precious and base metal mineral deposition. Drill hole and sample locations are also identified (from Xei et al. [14]).
Fractured subvolcanic rock, particularly dikes (Figures 5 and 6), can host geothermal cells which are measured in hundreds of meters rather than kilometers across (e.g. [4] and [15]). Hydrothermal cells can develop within fractured subvolcanic rock where the fractures within the brittle dikes and stocks provide a continuity of vertical permeability, allowing geothermal fluid to ascend. These fracture systems are typically associated with localized strain. This combination of fractured subvolcanic bodies and strain restrict the fracture permeability to confined sections of the subvolcanic structures. The up-flow area of these systems is defined by the geometry of the local strain area creating a fracture network within the subvolcanic rock. Hydrothermal cells in this setting have resulted in the formation of epithermal mineral deposits. While subvolcanic structures are common, only a small percentage of subvolcanic rock is subject to the tension dilation strain required for supporting fracture-hosted upflow of geothermal fluid. Figure 5 is a diagram from Boyle [3] showing the distribution of hydrothermal veins developed within fractures of a diabase dike that intruded volcaniclastic sediments. The fractures did not propagate into the less brittle host rock, confining fluid flow to fractures in the brittle diabase. Figure 6 shows an outcrop of a section of andesite dike in the Bend Highlands, Oregon (U.S.A.), area of the Cascade Range. This 150 m long section of dike shows strong low-pH alteration, the result of subsurface boiling of geothermal fluid within the local fractured dike. Outcrops of other similar dikes in this area show no evidence of geothermal fluid flow.

Figure 5. A line drawing of hydrothermal veins in a subvolcanic diabase dike intruding volcaniclastic sediments (from Boyle [3]). The fractures hosting hydrothermal fluid flow were extensive enough to host the formation of economic mineral deposits.

Details of hydrothermal fluid flowing through dilated fractures within and adjacent to dikes are available from slices of excavations within mines. Figure 7 shows a planar view at the 1400 m level in the El Bronce epithermal vein system, Petorca, central Chile [4]. This study examined dextral fault shearing that formed within jogs of more regional strike-slip faults. The jog-related dilation created fracture flow paths within both andesite dikes and adjacent formations. The dilated fracture network hosting hydrothermal fluid flow and related ore deposition (green in figure 7) is confined to an area less than 800 m long, a restricted section of the total andesite dike array (red in figure 7).
**Figure 6.** An eroded segment of a dike in the Bend highlands area of the central Oregon Cascade Range. This fractured 200 m long section of the dike hosted extensive hydrothermal fluid up-flow. Acid-sulfate alteration dominates the secondary mineralogy in this outcrop, indicating late-stage subsurface boiling of the hydrothermal fluid.

**Figure 7.** Camus et.al. [4] present a planar view of the 1400m level of a dyke- and dilated fracture-hosted hydrothermal deposit. Note the fracture relationship between the andesite dikes (red), major fluid flow veins (green) and disseminated smaller fractures (blue). The green zones would have been the geothermal production target when this system was active.

### 3. Dilation Structures within Volcanic Terrain

Not all active geothermal resources in volcanic terrain have a direct affiliation with volcanic or magmatic occurrences. Structural dynamics share localized stress field shifts with some tectonic structures common to transcurrent faults zones, orogenic terrain and extensional terrain. Regional
Tectonic structures within or juxtaposed to volcanism provide the opportunity for fault jogs, dextral and sinistral shearing and pull-apart grabens with localized high-angle dilation structures. These points of tension are observed to be potential hosts for hydrothermal cells. This occurrence of geothermal cells has been studied in great detail by the mining industry. Active and fossil geothermal cells of this type are long recognized exploration targets for epithermal mineral deposits (e.g. [4], [16] and [17]). Rowland and Simmons [18] describe these structures as high-flux hydrothermal conduits made up of three zones, feed zone (> 2,000 m depth), an epithermal zone (<200-2,000 m depth), and a discharge zone (0-200 m depth). The temperature of the geothermal fluid is determined largely by local heat flow and depth of the base of the feeder stem. The higher heat flow of the volcanic terrain does contribute to a higher local thermal gradient. The source of fluid for these geothermal cells is predominantly meteoric water, though occasionally metamorphic water from greenschist-grade metamorphism is observed.

![Figure 8](image.jpg)

**Figure 8.** Geometry of a dilated fracture-hosted epithermal deposit in volcanic terrain at Waihi, New Zealand (from Simpson and Mauk [21]). Geothermal cells are developed in dilated structures within strike-slip jog zones or within differential offset. The near-surface splay converges with depth to a narrowing structural up-flow stem.

Excavations of epithermal ore deposits provide detailed structural and hydrothermal fluid flow information of the shallow crustal sections of geothermal cells. Figures 8 and 9 show near-surface cross-sections of the geometry of geothermal cells in pull-apart basins, jogs and step-over structures. The widening upper zone reflects changes in the degree of compression in the lithologies at near-surface conditions. The deeper stem conduit extends downward, intersecting deep fluid collector structures. The size of the structures or “feed zone” stems or conduits of these cells are laterally constrained, usually measuring in hundreds of meters. While occurring in volcanic terrain, these dilated structures are akin to geothermal cells in non-volcanic extensional terrain and transcurrent fault zones [19], [20]. Mining of epithermal ore bodies on the flank of the Morro Hediondo caldera (figure 10) has excavated epithermal ore deposits within up-flow zones along vertical dilated structures [4]. These individual dilation structures are the result of breakage and local rotation of blocks between regional strike-slip faults cutting through the flank of the caldera.
Figure 9. A structural cross section of the Rodnikovoe epithermal gold deposit located in a currently active geothermal system in the Mutnovsko-Asachinskaya area of southern Kamchatka, far eastern Russia (from Takashi et al. [15]).

Figure 10. Distribution of epithermal ore deposits formed by fossil geothermal cells controlled by structural dilation zones on the flank of Morro Hediondo caldera, Chile (adapted from Camus, et al. [4]). The caldera rim is shown in green. The 6 km wide offset zone between two NNW-striking right-lateral strike-slip faults, identified by orange arrows, contains rotational compensation fault blocks. Dilation structures between rotating block fragments within this jog zone hosted up-flowing hydrothermal fluid. Structural dilation points containing epithermal ore bodies are marked in red.
Transcurrent fault systems passing through volcanic terrain create the opportunity for the development of structures capable of hosting geothermal cells. The transcurrent Sumatra Fault Zone overlies and is coeval with the volcanism associated with the Indian plate subducting beneath Sumatra. The Sumatra Fault Zone is a composite of right-lateral faults located in the Barisan Range, extending the length of the island. The transcurrent movement is a tectonic accommodation formed by the oblique subduction of the Indian plate beneath Sumatra (figure 11). The Sumatra Fault Zone contains highly variable stress conditions at a local scale. Tectonically confined points of tension provide the potential for vertical dilation conduits to form, host structures for geothermal cell conduits. The macro- and micro-tectonics of this fault zone (figures 11, 12, and 13) present good examples of how fault jogs, fault spays and stepover offsets result in pull-apart grabens and both broad and localized high-angle dilation structures form within a transcurrent fault zone.

Figure 11. Sumatra transcurrent fault zone located in the Barisan Range, extending the full length of Sumatra. Red circles identify dilation, step-over and pull-apart zones and related grabens. The Java Trench is the leading edge of the subduction zone. The Sumatran sliver plate is moving north-westward relative to the main body of the island, an artifact of the northward oblique subduction of the Indo-Australian plate. The transcurrent Sumatra Fault Zone accommodates the boundary between the Sumatran sliver plate and the main body of the island (from Muraoka et al. [22]).
Weller et al. [23] provide data on the seismic characteristics of structures along a section of the Sumatra Fault Zone (figure 12). The map provides a planar view of the distribution of earthquake epicenters. Also shown are focal mechanisms for ten of the epicenters with high data quality, and cross sections showing the vertical distribution of epicenters. Cross sections A and C depict the vertical distribution of earthquake epicenters at locations where the faulting is converging to a single strike-slip fault plane. The epicenter distribution shows the fault movement to be vertical and extending downward in excess of 12 km, through the brittle portion of the crust. Cross sections B and D identify a bimodal vertical distribution of epicenters at locations were the strike-slip faulting has bifurcated, forming step-over structures hosting pull-apart grabens. The ten focal mechanism spheres all show near-vertical strike-slip motion.

Figure 12. The figure shows a planar view along the Sumatra Fault Zone. Earthquake epicenters are identified as circles. Focal mechanisms are identified to the left of the planer view for ten events. Cross sections A, B, C and D display the vertical distribution of epicenters at four locations crossing the fault zone (from Weller et al. [23]).
A detailed view of the seismic activity associated with a single pull-apart graben in the Sumatra Fault Zone (figure 13) is provided by Muksin [24]. These pull-apart grabens contain complex strain and stress zones which form very localized points of both dilation and compression. The changes in stress within these structures are shown by the focal mechanisms identified at select earthquake epicenter events in figure 13. The red stars in this figure show that the dilated geothermal fluid conduits are limited in location within the pull-apart structure.

Figure 13. The Tarutung Basin is an example of a pull-apart basin in the Sumatra Fault Zone (from Muksin [24]). The red stars identify hot spring locations, the white circles identify earthquake epicenters. The blue-shaded ellipses identify surface hot spring deposits. The focal mechanism spheres identify the range of strike-slip to low-angle fault motion.

The data from the Sumatra Fault Zone demonstrate how the structural complexity of transcurrent fault systems are able to produce localized dilation structures capable of hosting geothermal cells within volcanic terrain that are not directly associated with magmatic activity. The vertical strike-slip faults extend through the brittle crust, providing deep conduits at points of extension for water to ascend. The geometry of these cells has a narrow up-flow stem usually on the order of a few hundred meters, expanding outward near the surface.

3.1 A real-world example: Applying insight from mining industry data to identify drill targets

Newberry Volcano (figures 14, 15 and 16) is a Pleistocene to Holocene large bimodal volcano with a central nested caldera structure. The most recent eruption occurred within the caldera 1,350 years ago. Holocene silicic and basaltic volcanism attracted geothermal interest to the volcano by the early
1970s. High temperature gradients were observed in temperature gradient holes drilled on the upper west flank of the volcano. This west flank thermal anomaly has no expression at the surface, either active or fossil. It is a true “blind” prospect. Exploration for geothermal drilling targets in a true “blind” geothermal area has its challenges. Two deep exploration wells were drilled in the 1990's, both sited to intersect ring fractures, with the conceptual model that caldera ring fractures were structures with high vertical permeability. The wells encountered bottom-hole temperatures of 289 and 315 °C respectively, and both were dry, with no sustained fluid flow. About ten years later another company (Davenport Newberry) conducted a geophysical exploration program and drilled two deep exploration wells (Davenport wells NWG 55-29 and NWG 46-16, figures 14 and 15). Both of these wells encountered bottom-hole temperatures of approximately 315 °C. The first well encountered multiple fractures that were isolated, no interconnectivity to a larger fracture network, and was not able to produce. The second well (NWG 46-16) encountered deep sets of fractures that were capable of sustained flow tests. The exploration methodology and interpretation of geophysical data used to identify the specific volcanic drill targets in this absolutely blind prospect did not follow the popular published geothermal recipes. The success in identifying deep drill targets was based on mining industry data which showed the various geometries of convective cooling in shallow hot plutons. The site of the discovery well 46-16 would have been eliminated as a possible resource target by the standard popular geothermal MT drill target models (i.e. [25]). Over 200 MT sounds and over 300 gravity stations were employed in the exploration program leading up to the deep target identification. Shallow low electrical resistivity lenses, popularly interpreted as “clay cap” alteration were proven to be clay alteration of volcanic vent pyroclastic infill with no affiliation with warm water. The smoothing effects of 3-D MT data processing removed all small perturbations in the resulting data presentation, and provided no substantive contribution to the exploration process. Subsequent 2-D slice processing (figure 16) provided valuable shallow (0-2 km) structure of the volcano flank, but was unable to provide the deeper detail needed for identifying a drill target. Gravity data provided the structural insight that was used to identify the two deep drill targets, based on the local geometry. The major change in the exploration risk management strategy leading to the discovery well was employing exploration tools with the curiosity of ‘How can the data be integrated into the total exploration program, and what might the data contribute in this specific location?’ rather than following the popular practice of ‘We will use this one tool and it will tell us where to drill in all locations.’
Figure 15. The Newberry Volcano topographic map. MT sounds locations are identified as red and black triangles, Geothermal discovery well 46-16 (yellow square) and well 55-29 (blue square) are shown.

Figure 16. The 2-D MT slice [26] running north-south and intersecting both wells 55-29 (blue in figures 14 and 15) and 46-16 (yellow in figures 14 and 15) clearly does not identify a “bulls-eye” [25] drill target, and shows no evidence of the geothermal resource intersected by well 46-16.
4. Discussion
Effective exploration strategies for geothermal resources in volcanic terrains requires an understanding of the wide range of both size and geometry of the systems. The scale and geometry of geothermal resources should be one of the major considerations when designing an exploration program. The types of exploration tools, and the interpretation of data provided by the various tools should change markedly for a kilometer-scale stockwork-type target from that of a dilation upflow conduit that may be only a few hundreds of meters across at depth.

The large stockwork-type of fractured pluton-hosted geothermal resources are associated with active volcanism and typically have some surface evidence of underlying heat, such as fumaroles, geysers, hot springs or expansive areas of alteration mineralogy. The broad subsurface resource area is of square kilometers and therefore easily identified by temperature gradient and electrical resistivity surveys [25]. Due to the size and geometry of these resources they pose lower risk exploration and development targets.

Both the regional groundwater hydrology and the shallow geothermal dispersion plume need to be understood when assessing and exploring the economic potential of dilation structure resources. The shallow discharge zone will show a broad lateral plume of geothermal water flowing outward and becoming integrated into the shallow groundwater system. Temperature gradient measurements in the discharge plume will show a shallow high temperature gradient and a reversal or negative gradient underlying the outflow zone. The economic drilling target is the much narrower and higher temperature stem or conduit hosting the geothermal upflow. The narrow geometry of the conduit makes it extremely difficult to be identified with some of the geophysical exploration tools, particularly electrical resistivity techniques such as MT. This problem is compounded when applying 3-D smoothing programs, which are designed to remove small subtle aspects of the dataset. This resource geometry can lead to very poor risk management strategies if an exploration model formula that is adequate for a large fractured stockwork geothermal target [25] is assumed to work equally as well for narrow dilation conduit geothermal targets.

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