

Resource Conceptual Models of Volcano-Hosted Geothermal Reservoirs for Exploration Well Targeting and Resource Capacity Assessment: Construction, Pitfalls and Challenges

William Cumming

Cumming Geoscience, Santa Rosa CA
wcumming@wcumming.com

Keywords

Exploration, conceptual model, geophysics, geochemistry, resource risk assessment

ABSTRACT

Building geothermal resource conceptual models to support assessments of well targets and resource capacity is a widely recommended geothermal industry best practice, with potentially serious pitfalls if important data is collected without adequate consideration of its conceptual context and uncertainty. The process is illustrated by a detailed step-by-step example of the construction of an exploration conceptual model for a synthetic volcano-hosted geothermal reservoir using a representative data set including the geochemistry of hot springs and fumaroles, maps of surface geology and structure, and images of the low resistivity clay cap using magnetotelluric (MT) surveys. A range of conceptual models representative of both data and conceptual uncertainty supports well targeting and resource capacity risk assessments. Well targeting failures in recent geothermal exploration and development projects have highlighted pitfalls in the conceptual model approach and also its resilience in identifying remedies and focusing attention on unresolved challenges. For example, MT surveys typically avoid incised drainages and so may fail to detect extensive outcrop of propylitic alteration that implies a higher probability of encountering relict alteration that is relatively cool and low in permeability. As prospects that fit the exploration assessment methods outlined in this paper are drilled, the remaining prospects are a poorer fit to the paradigm. Whatever alternative data sets are gathered to reduce risk in the remaining prospects, it is likely that they will more effectively address well targeting and resource capacity risk using a conceptual model approach.

Introduction

The immediate impetus for this paper was to support workshops on developing conceptual models of geothermal systems, supplementing an earlier tutorial (Cumming, 2009) by providing greater detail on the conceptual elements of volcano-hosted reservoirs and a more step-by-step illustration of the exploration process used to produce a conceptual model. In recent years, the conceptual model approach to geothermal resource assessment has been widely promoted as a geothermal best practice, for example, in IGA Service GmbH (2014), Young et al. (2012) and US DOE (2014). Alternative approaches to geothermal resource decision making like anomaly hunting and statistical data correlation can be effective for tasks like screening of regional data for prospect leads (Dipippo, 2016). Lower value decisions like locating initial measurement points for surveys are more efficiently made by experts inspecting available information and applying rules-of-thumb developed through experience with geothermal conceptual model principles, but without building elaborate models. The investment in building conceptual models is justified by high value decisions like assessing resource capacity or targeting wells.

Research on decision making indicates that success in making complex high value decisions based on uncertain data requires that the decision analysis be directed at fundamental processes and not just the statistics of data matched to outcomes (e.g. Klein, 2009; Silver, 2012). This has been highlighted many times in finance, for example in 2008 by the

differences in outcomes for those analyzing fundamentals versus those using elaborate statistical models to predict the value of mortgage securities based on historic mortgage failure rates in a fundamentally different mortgage market. In a geothermal context, this is analogous to targeting resource conceptual models versus targeting data (targeting data is often called “anomaly hunting” in the geosciences). Besides emphasizing fundamentals, a reliable decision process must accommodate uncertainty, typically starting with a conceptual model hypothesis, testing its consistency with available information, adding missing information expected to be particularly decisive, and updating a range of conceptual models representative of uncertainty. Decision research also highlights the need for practice in making decisions under uncertainty. Practice is needed in both the process used to choose data and build conceptual models and in the process used to analyze decision outcomes to understand if the decision process was flawed or the outcome was merely consistent with acknowledged decision uncertainty.

Challenges in applying a conceptual model approach to geothermal decision making include assimilating sufficient background information and providing geoscientists sufficient opportunities to practice making high value decisions. Many conceptual model case histories can be found online in the International Geothermal Association (IGA) geothermal conference database. Underlying research reports and much source data can be found in the US DOE databases summarized in Young et al. (2014). The United Nations University (UNU) in Reykjavik provides lecture notes and tutorial publications not included in the IGA or US DOE data bases. However, despite the rapid improvement in access to sources of geothermal background information that can provide context for decisions, geothermal developers are likely to face increasing challenges in making decisions that balance risk and opportunity.

- Publications usually focus on particular technical analyses or data sets and the resource conceptual model and related data are summarized only to the extent they are relevant to the narrow context of that topic.
- Most publications that include conceptual models present a single model as a “just so story”, providing little guidance on the process used to develop the starting model or the range of models used to assess uncertainty and risk.
- In relation to their prevalence, very limited information is published on application pitfalls, improbable conceptual models, ineffective decision processes and similar failure case histories, except in incomplete introductions to improvements.
- Because of the boom-bust cycle of the geothermal industry and the limited number of projects that most geothermal professionals have an opportunity to investigate, few geothermal geoscientists have extensive experience in building realistic conceptual models, researching worldwide analogies to assess the likelihood of conceptual model options, making high value decisions based on conceptual models, and analyzing outcomes to assess the effectiveness of the decision process.
- The boom-bust cycle has also led to a steep decline in the availability of expert mentors who can coach less experienced staff through technical and decision processes.

Although geothermal developers can improve decision-making by ensuring that geoscientists have sufficient time and resources to investigate a range of case histories relevant to their projects, this does not address the need for practice in supporting and making high-value geothermal decisions. Experience suggests that an incomplete but still significant part of the necessary experience can be synthesized in workshops that attempt to realistically simulate parts of the geothermal exploration and development analysis and decision process based on case histories of developed geothermal fields.

Because this publication has been prepared to support a workshop on building conceptual models, it uses simplified generic models to make points more clearly and to illustrate mistakes and pitfalls without client objections. The references highlight the sources of figures used in the workshop presentations; hence the focus on my own papers. DiPippo (2016) provides an overall context for geothermal assessment. Cumming (2009) reviews different geothermal resource evaluation approaches and illustrates the conceptual model approach for an almost hidden non-magmatic geothermal system hosted in sediments. Cumming and Powell (2010) reviews the geochemistry tools used to illustrate the construction of the conceptual model. Muñoz (2014), Ussher et al. (2000) and Arnason et al. (2000) review the reasons for the focus on resistivity methods, and MT in particular, in geothermal geophysics. A tutorial on the thermodynamics of isotherms in geothermal systems and the interpretation of well temperature data has been delayed, but look for such a paper by John Murphy soon. As a planned companion to this paper, Cumming (2016) reviews resource capacity assessment issues and provides details on the lognormal power density approach used in the workshops. Because this is a tutorial rather than a foundational paper, I recommend that geothermal practitioners follow the progress of the International Geothermal Association projects currently directed at updating best practices and standards for assessing and reporting geothermal resources.

An outline of the typical elements used to constrain a geothermal resource conceptual model introduces a step-by-step synthetic example of the development of a resource conceptual model and an assessment of resource capacity and well targets. Following a conventional analysis of the model uncertainty and the implications of this for well targeting and resource capacity risk, the challenges in this approach are illustrated by synthetic failure cases that are closely

analogous to real geothermal well targeting failure cases (that are, unfortunately, unlikely to be published). The common theme among these failures highlights a pitfall of the conceptual model approach; although its use can improve decision-making, until practitioners accumulate a broad range of experience, they tend to be overconfident regarding the models and related predictions.

Elements of Volcano-Hosted Geothermal Conceptual Models

The conceptual models in Figure 1 illustrate the basic elements of two variations on volcano-hosted natural state geothermal conceptual models. These are conventional geothermal reservoirs that have sufficient permeability that heat is mainly transmitted by buoyant flow of hot water (Grant and Bixley, 2011). It is often helpful to categorize the conceptual model elements according to whether they are primarily related to the hydro-thermodynamic “fluid” elements or the “rock” elements that host the fluid. The essential hydro-thermodynamic “fluid” elements are listed first.

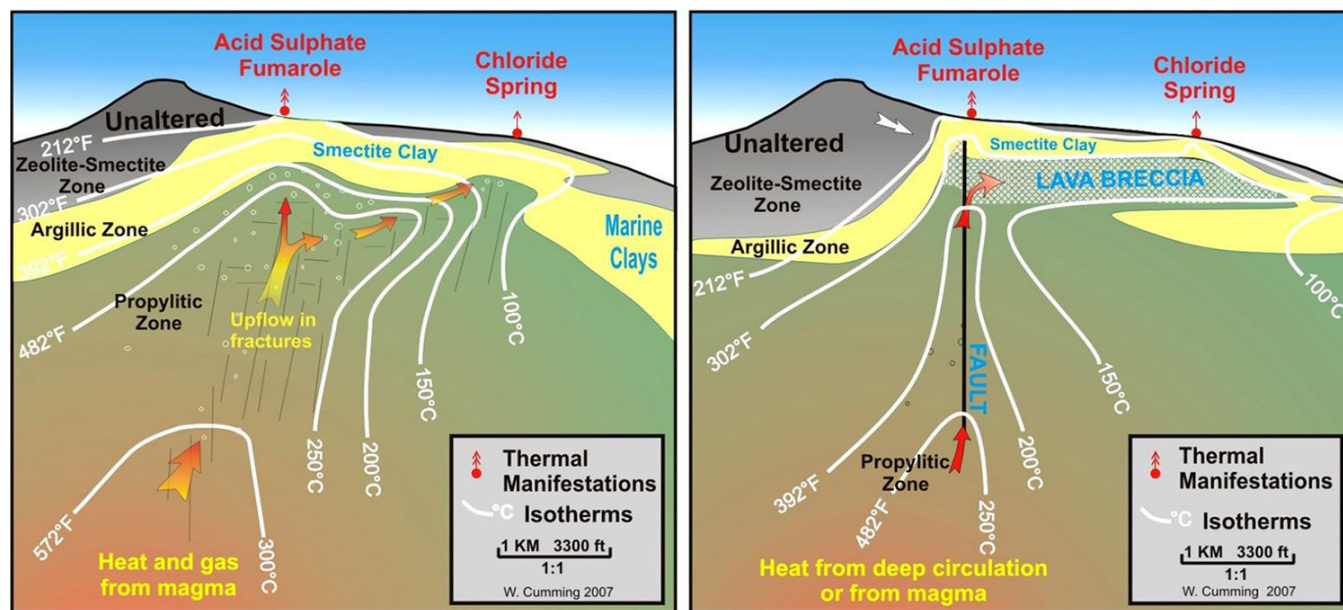


Figure 1. Volcano-hosted geothermal resource conceptual model cross-sections. The reservoir at left is hosted in distributed permeability in recent volcanics extending to over 3000 m depth whereas the resource at right has an upflow that is confined to a narrow fault-zone where it traverses much older metamorphosed volcanics and sediments that tend to resist forming distributed permeability. The reservoir at left is probably developable at 250 to 300°C in the recent volcanics from 1000 to 3000 m depth. The resource at right might be developed at 150 to 200°C, mainly in the easily targeted formation permeability associated with the lava breccia. In both models, the water table is at the elevation of the chloride spring.

Water Table: Unless wells are available, the pressure regime for the prospect is usually based on an assumption of a hydrostatic pressure gradient below a deep water table most commonly inferred from spring chemistry. The pressure constrains the maximum temperature that is consistent with any given elevation, generally less than the boiling point temperature at that pressure. Although the water table is a crucial starting point in building a geothermal conceptual model, it is often omitted in final models to avoid clutter, in which case, its elevation should be identified in a caption. In both models in Figure 1, the deep water table is an almost flat surface at the elevation of the chloride spring.

Spring chemistry, shallow wells and resistivity are typically used to constrain the elevation of the deep water table prior to drilling exploration wells at volcanic geothermal prospects. Chloride springs like those shown in both models in Figure 1 are likely to be at or below the water table. Acid-sulphate fumaroles are typically found above the water table, heated by steam and gas leaking through the vadose zone between the deep water table and the surface. A hot spring with neutral chloride chemistry found at the elevation of the fumarole would suggest that the volcano might have a pressure regime much higher than surrounding aquifers, implying at least a low permeability barrier between them, and perhaps also generally low permeability associated with the volcano. When analyzing the implications of pressure in a conceptual model, it is sometimes helpful to sketch the pressure profile that would be measured in wells drilled at conceptually different parts of the model.

Isotherms: The natural state isotherm pattern is the most important element of the conceptual model of a permeable geothermal resource because it provides the most effective overall constraint on the resource properties that affect capacity assessment and well targeting (Grant and Bixley, 2011). After wells are tested, reservoir engineering best practice emphasizes matching the natural state temperature pattern as an overall constraint on numerical simulations of geothermal

reservoir production performance. At the exploration stage prior to drilling, the isotherm pattern is more uncertain but that uncertainty is important to drilling and capacity risk assessment. Fortunately, the thermodynamic principles of fluid flow in rocks provide effective constraints on the isotherm pattern based on seemingly sparse information from geochemistry, geology and geophysics surveys.

Prior to deep drilling, sketches of isotherms in volcanic geothermal models begin with temperature estimates inferred from water and gas chemistry of springs and shallow wells and from active surface alteration like sinter (Powell and Cumming, 2010; Cumming, 2009). Based on the topography and very basic thermal manifestation chemistry shown in Figure 1, an initial guess could have been made of the geometry of the reservoir upflow, boiling and outflow zones that are common to both models. The differences between the models would be refined by completing a range of geoscience surveys that will vary depending on the situation but most commonly includes detailed geology and structure mapping, gas and water chemistry and a magnetotelluric (MT) resistivity survey. The procedure for building an isotherm model consistent with exploration data is illustrated by a synthetic case history in this paper.

As noted above, a prerequisite for sketching the isotherm pattern is an estimate of the water table, which constrains the pressure and the associated boiling point versus depth (BPD) limit of subsurface temperatures. Except in special cases like transient pressure and temperature changes near eruptions or near magma, temperature is unlikely to exceed the boiling point of water, which mainly depends on pressure and gas content in a geothermal context. As pressure increases at a hydrostatic rate below the water table, the maximum temperature to be considered when drawing isotherms at that depth increases according to the BPD relationship. At vigorous fumaroles, temperature is sometimes slightly superheated relative to the boiling point at that altitude, but 100°C is rough maximum. As an aid to sketching geothermal conceptual models, geoscientists sometimes find it helpful to memorize a few approximate temperature-depth pairs for BPD; 150°C-50 m, 200°C-200 m, 250°C-500 m, 300°C-1000 m, and 350°C-2500 m. These pairs indicate the minimum depth below the water table for the corresponding temperature; that is, the isotherms corresponding to these temperatures can be much deeper but not shallower in a geothermal conceptual model.

Further rules of thumb for interpreting isotherm patterns, aside from the BPD constraint, can be derived from the principles of thermodynamic flow of water in rock. To ensure that interpreted isotherm patterns are plausible, it is useful to compare isotherms sketched for exploration conceptual models to the isotherm patterns measured and simulated in potentially analogous drilled geothermal reservoirs. It is also useful to sketch the temperature-pressure patterns expected for wells at various locations in exploration conceptual models in order to compare them to potentially analogous wells in developed reservoirs. The generic models in Figure 1 illustrate the basic rules of thumb for interpreting or sketching isotherms.

- In impermeable rock, isotherms will be evenly spaced and smooth. Although the thermal conductivity of rocks can affect the isotherm pattern, at the exploration stage in a volcano-hosted resource area, this is a secondary effect and so it is not considered. A well drilled through such a zone will have the linear temperature gradient characteristic of thermal conduction. A group of wells that have a similar linear temperature gradient would define a large volume of impermeable rock.
- In permeable rock, the thermal gradient will be much lower in the direction of flow, subject to maintaining a sufficient temperature-pressure gradient to drive buoyant thermal flow.
- A high linear gradient implies that a low permeability barrier (like a clay cap or a fault full of gouge) separates two permeable zones, one with cooler water (like cold meteoric gravity flow above a clay cap) and the second with hotter water (associated with the reservoir). For example, the isotherms are close together in the impermeable clay cap shown in yellow in both models of Figure 1.
- Thick impermeable zones separating the same permeable zones will have a lower temperature gradient, like the shallow unaltered zone and clay cap on the left side of the distributed permeability model in Figure 1.
- On the left side of the fault-hosted upflow model in Figure 1, the shallow volcanics are more permeable and, because they are above the cap and connected to the surface, they host cold water down-flow. Formations with significant primary permeability like rhyolite lava breccias are sometimes encased by impermeable formations like lake beds so that they channel cold water from a relatively high pressure surface source like a lava dome through high temperature geothermal reservoirs, resulting in complex models that have been effectively targeted despite the complexity (Boseley et al., 2010).
- Fluid that is in a permeable zone and is hotter than overlying fluid will flow upward by thermal buoyancy. Where such a flow encounters an impermeable cap, it will flow updip beneath the cap, extending the isotherms updip in that direction (that is, the base of the clay cap in Figure 1 guides the outflow in an updip direction). If an upflow or outflow is trapped beneath a cap, it might form a local convection cell. Importantly, geothermal outflows below the flanks of volcanoes flow buoyantly updip beneath the clay cap, not by gravity flow down the slope of the volcano, as conventional hydrologists commonly assume.

- Cold fluid generally flows down dip by gravity flow, as in conventional hydrology. At the top of the water table, water as hot as 100°C can flow by gravity down dip.
- Hot or cold zones that are isolated in three dimensions cannot exist in the natural state except as transients. However, in a 2D representation of a reservoir such as a map or cross-section, closed contours can exist, implying flow in or out of the plane of the plot. Closed isotherms should be labeled to indicate the sense of fluid motion.

Hot and Cold Flow Arrows: Flow direction arrows clarify implications of isotherms and the water table (temperature and pressure); they are constrained by the same data as the isotherms. These arrows show the buoyant flow path of hot water from the bottom of the permeable reservoir to the outflow zones (so the deepest arrow may be far above the magmatic heat source). Flow arrows are essential in the common circumstance where flow is oblique to the cross-section, in which case it is shown as a circle and dot (an arrow point) if it is coming out of the cross-section toward the viewer and a circle with an “x” (an arrow tail) if it is going into the cross-section. However, arrows cannot replace isotherms in representing a conceptual model because the isotherms better illustrate how the model is constrained by thermodynamics.

Cold meteoric influx zones moving by gravity flow of conventional hydrology rather than the buoyant flow of hydrothermal systems are illustrated by the isotherms and can be emphasized using arrows, e.g., by the white arrow in the model in the right panel of Figure 1.

Boiling Zones, Steam Caps, Mixing Zones and Zones of Gas Loss: These elements should be graphically illustrated and must be consistent with the boiling point versus depth constraint. Such features are mainly constrained by the surface manifestation chemistry, exposed alteration and resistivity geometry.

A volcano-hosted, steam-dominated reservoir like Darajat (Whittome and Salveson, 1990) is a special case in which the pressure-carrying phase in the reservoir is steam (Grant and Bixley, 2011). The usual metaphor is that the matrix porosity probably still contains 50 to 90% water but the higher permeability fractures contain only steam. The permeable part of the reservoir is at much lower pressure than adjacent hydrostatically pressured aquifers and so the reservoir must be completely sealed off from its surroundings by hydrothermal alteration, mineral deposition or impermeable rocks like shale. Because such reservoirs are rare, significant supporting evidence would be needed to support the choice of such a conceptual model for a prospect prior to drilling.

Deep Fractured Upflow Zone(s): It is conceptually important to understand the general properties of the deep upflow zone(s); that is, whether it is likely to be associated with recent magmatic activity or deep fluid circulation. This can usually be inferred from geochemistry. However, specific details of the connection between the heat source and the producible reservoir are usually omitted because they are poorly constrained. In both of the models in Figure 1, the heat source is several km deeper than the base of the deepest arrows. This is consistent with most numerical reservoir simulations where the base of the reservoir is defined by boundary conditions for thermal conductivity, temperature and fluid mass flow associated with the upflow zone(s). Exceptions include basalt-hosted reservoirs like those in Iceland, Hawaii and the East Africa Rift System where the base of the reservoir may be constrained by magma as shallow as 2 or 3 km.

The “rock” elements of the conceptual model are typically customized more than the “fluid” elements but important themes include the susceptibility of the geological formations to forming open space fracture permeability, the faults and stress state that create the upflow permeability, and the smectite clay cap that is the most diagnostic part of the reservoir, both because it is easiest to detect using geophysics (based on its low resistivity) and because its base typically conforms to the upper reservoir that will likely be the initial target (Árnason et al., 2000; Ussher et al., 2000; Muñoz, 2014).

Cap: The low permeability clay cap is shaded yellow in the models in Figure 1. All developed geothermal reservoirs over 100°C are capped and a cap is probably a thermodynamic necessity for all hidden geothermal resource models with temperature over 100°C (Cumming, 2009). The cap prevents the buoyant flow in a >100°C reservoir from producing water or steam to the surface at the full capacity of the reservoir, limiting losses to relatively minor leaks at thermal manifestations (Facca and Tonani, 1967). The cap also impedes catastrophic cooling by surface water influx when the reservoir pressure drops during commercial production. Models of breached caps, for example at Karaha Telaga-Bodas (Moore, 2012), suggest that the cap also helps maintain high permeability in the reservoir by maintaining thermodynamic and chemistry conditions that prevent precipitation of silica, calcite and similar minerals. In a vapor-dominated reservoir the cap completely isolates the pressure regime of the reservoir from surrounding aquifers whereas a liquid dominated reservoir is likely to outflow beneath an extended cap. When the upflow of hot water in a liquid-dominated geothermal reservoir is intercepted by its impermeable clay cap, the buoyant flow is directed laterally updip, following the base of the cap.

In almost all developed volcano-hosted geothermal reservoirs, most of the cap consists of hydrated smectite or mixed-layer clay (smectite-illite in andesite, smectite-chlorite in basalts). In volcanic rocks, the geothermal system can generate a clay cap by hydrothermal alteration of overlying precursor minerals (Ussher et al., 2000; Árnason et al., 2000). Rocks containing smectite tend not to form open space permeability when fractured, an essential property of a material that can effectively cap a fractured reservoir (Hickman and Davatzes, 2010; Lutz et al., 2011). Importantly, hydrated smectite alters to more brittle illite clay at a rate controlled by both temperature and permeability, and so hydrated smectite can be found

capping geothermal reservoirs at temperatures from 60°C to as high as 240°C. Because of the conceptual importance of the cap and the exceptionally low resistivity of hydrated smectite clay, resistivity methods dominate geothermal geophysics. In basalt and andesite rocks, the resistivity of the clay cap is typically 2 to 10 ohm-m. Isotherms are crowded closer together through the impermeable, low resistivity cap and, in the typical cases where the top of the permeable reservoir conforms to the geometry of the base of the smectite clay cap, buoyant thermal flow is directed updip below the base of the cap imaged as a low resistivity zone.

Although almost all commercial geothermal reservoirs are at least partially capped by low resistivity smectite clay, other types of impermeable cap exist. As temperature increases at greater depth in the cap over a reservoir, the smectite alteration transitions to mixed-layer smectite-illite or smectite-chlorite clay that is low in permeability but can have intermediate resistivity (Boseley et al., 2010). In some reservoirs, the base of the low resistivity smectite cap is generally conformable to the top of the reservoir but separated from it by an impermeable zone containing higher resistivity illite, is sometimes called a phyllic cap (Stimac et al., 2008). The precipitation of minerals like silica, anhydrite and calcite can also create a low permeability part of the reservoir that functions as a cap that will be electrically resistive. Dense unaltered lava can cap buoyant geothermal flow, although this tends to be short term since only one crack is needed to make a lava leak, whereas clay alteration is self-healing and can act as a cap through geologic time.

Volcanic rocks that lack the magnesium needed to form smectite, like the trachyte and phonolite lavas and tuffs commonly found in the East African Rift System, still usually alter to form a clay cap, but it usually contains less smectite. The resistivity is still relatively low but not as low as the 2 to 10 ohm-m common in andesites and basalts. On the other hand, meteoric water in very porous trachyte and phonolite tuffs can provide enough magnesium to support the formation of abundant smectite.

The variations in composition of the clay cap in volcanic prospects complicate the interpretation of resistivity to the extent that it is seldom possible to reliably associate a particular resistivity with a particular isotherm. However, despite these complications, the pattern is usually consistent. High resistivity is ambiguous; it could be hot or cold, permeable or impermeable and so it must be interpreted in context. However, low resistivity is less ambiguous. In andesitic or basaltic rocks, a layer imaged as under 10 ohm-m shallower than 2000 m depth is very likely to be impermeable due to elevated smectite clay content. However, without supporting geochemistry, surface alteration or borehole data, detecting a low resistivity zone that could act as a cap is not a reliable indicator of a geothermal system. Without a low resistivity cap, it is unlikely that a volcano-hosted commercial geothermal reservoir exists; with a clay cap, more information is needed to confidently predict that a geothermal resource exists since it could be relict, it could be sedimentary, it could be generated by volcanic degassing, and so on.

Some volcano-hosted geothermal reservoirs include sediments associated with lakes (e.g. Boseley et al., 2010). The clay cap model applies to clay-bearing sediments, except that the clay is deposited rather than being created by the geothermal system, and the buoyant flow conforms to the pattern of permeability imposed by the sediments. Clay-rich sediments can be imaged using the same resistivity methods used for volcanic formations. Because sediments like mudstone usually contain smectite, they will be low resistivity but, because a mudstone cap over a hot reservoir will have elevated temperature and precursor minerals will be altered to smectite, the resistivity of the capping formation is typically lower over a geothermal reservoir, unless the temperature exceeds 200°C or so, in which case the clays will be converted to more resistive illite.

Deep Fractures: Below about 2500 m depth, rock properties and stress state favor localized geothermal upflow associated with near-vertical fractures. For example, a deep upflow may be located where vertical permeable conduits are created through otherwise impermeable formations by intrusive necks, a complex fault and stress geometry, or a breccia created during a complex fault slip event at temperature near the boiling point (Davatzes and Hickman, 2010; Lutz et al., 2011; Hickman and Davatzes, 2010).

Formation-Mediated Fracture Permeability: From about 250 to 2500 m depth, buoyant geothermal upflow and lateral outflow are typically in formation-mediated fracture permeability. The host rock properties are as important to the open space fracture permeability as are the fault geometry and stress state. (Lutz et al., 2011).

Formation Permeability: From the surface to about 500 m depth, despite the general dominance of fracture permeability in geothermal reservoirs, some formations resist compaction and alteration and have sufficient primary permeability to locally dominate thermal flow. This includes conventional aquifers like gravels. Some formations like rhyolite lavas or carbonate rocks can maintain high formation permeability at great depth.

Fault Barriers: Faults commonly create flow barriers within fields (Sewell et al., 2015) and many field edges are fault-controlled. For example, although extensional step-over zones associated with major strike-slip faults host several of the world's largest geothermal fields, the strike-slip faults themselves are more likely to be boundaries than conduits, although some faults both localize permeability near the fault and bound a permeable reservoir. Spring hydrology sometimes provides the most definitive constraints on the interpretation of deep hydrologic barriers. Because springs commonly align along faulted field margins, they are often mistakenly interpreted as permeable conduits, rather than as barriers to flow.

Younger Volcanic Rocks Versus Older Rocks: In younger (say Holocene-Pleistocene) mixed lavas and tuffs, rock properties are typically more heterogeneous than in older rocks that have been more highly indurated. Faulting is more likely to create a distributed network of open fractures in younger volcanics because of their greater heterogeneity, like in the model in the left panel of Figure 1.

The discovery of outcrops of much older (say Mesozoic) metamorphosed volcanics at relatively high elevation near a volcano will favor a resource geometry like the right panel of Figure 1. In this case, the upflow is focused along a relatively small volume path associated with a fault breccia that penetrates the more uniformly indurated metamorphosed rocks that are unlikely to host the distributed permeability that is characteristic of younger volcanic rocks.

Heat Source: The largest developed geothermal reservoirs and the majority of geothermal power generation are associated with volcanoes and are considered to have a magmatic heat source with varying degrees of magmatic affinity (Stelling et al., 2016; DiPippo, 2016). This is not to say that fault-hosted systems with minimal magmatic input, like many fields in the US Basin and Range, cannot exist near volcanoes but, if detected based on geochemistry or drilling, such systems have been given lower priority until the prospects with magmatic indications of higher temperature and capacity have been explored (DiPippo, 2016). Most developed geothermal reservoirs with average production temperatures over 230°C are magmatically heated and are associated with fumaroles and/or hot springs, at least some of which typically provide indicative water and/or gas geochemistry. Moreover, because fluid and gas reaching the surface with chemistry compatible with commercial temperature and pH implies that a permeable path to such a resource must exist, geothermal assessments in volcanic terrain have emphasized the geochemistry of surface manifestations in the context of the geology as the primary constraint on the three most commonly used existential risk categories for geothermal resource exploration, temperature, permeability and benign chemistry (Cumming 2016).

If the geochemistry of surface manifestations provides sufficient confidence in the existence of a geothermal resource to proceed with geophysical surveys, then the details of the deep heat source are usually given much less emphasis because of their much greater uncertainty. However, if a preliminary microearthquake monitor detects significant local seismic activity and a local array detects a pattern of seismicity consistent with shallow magma movement, then this should be included in the resource model. Deep low resistivity zones detected by MT are sometimes also interpreted as magma, although confirmation using earthquake results would increase confidence in such challenging analyses. Basalt, trachyte and phonolite magma can coexist in close proximity to a neutral geothermal reservoir and, therefore, it is an important conceptual element constraining the base of the productive reservoir and the isotherm pattern, with the 400°C isotherm close to the magma and the 350°C isotherm below the base of the conventional reservoir. Moreover, as indicated by Gudmundsson and Mortensen (2015), shallow magma at Krafla is associated with chemical and thermodynamic compartmentalization in the field. Given this complexity, even where the interface between the magma and reservoir has been drilled, the resource assessment has focused on the relatively isolated neutral fluid system that supports the commercial production. For geothermal prospects hosted in andesite or rhyolite volcanics, shallow swarm seismicity correlated with increases in CO₂ flux might be considered indicative of an eruption hazard. However, in most cases, the details of the magmatic heat source and the deep connection from the heat source to the reservoir are not well constrained and so isotherms over 350°C are usually omitted from the conceptual model, as in Figure 1.

Surface geological observations related to the underlying magmatic heat source, like the volume of the erupted volcanics or the eruption of specific types of magma have sometimes been proposed as indicators of resource likelihood or capacity but, at least for arc volcanoes, this is not supported by statistical studies of developed geothermal fields (Stelling et al., 2016). However, for a particular geologic trend, geoscience analyses such as volcano morphology, geobarometry, magma genesis modeling, volatile gas analyses and earthquake seismology may consistently indicate that the magmatic sources of the recent volcanic rocks are generally deep and that only a relatively small volume of magma has been intruded into the upper few km of crust. Such analyses can provide a genetic explanation for areas that include recent volcanic rocks but have thermal manifestation geochemistry more consistent with the fault-hosted geothermal reservoirs of the US Basin and Range than the volcano-hosted reservoirs with more magmatic influence in the Philippines or Kenya.

Conceptual Model Development

The conventional procedure for building a conceptual model of a volcano-hosted geothermal exploration prospect is illustrated in Figures 2 to 8 using an imaginary data set consisting of those types of data that have demonstrated the greatest relevance and reliability in geothermal decision risk assessments for this type of prospect. Some supporting data sets are assumed to have been used if needed. For example, prior to beginning field work, georeferenced surface images with a pixel size of under 0.5 m ground distance should have been acquired, if they are not already available from Google Earth. If MT static distortion introduced significant uncertainty in the resistivity imaging, a TEM survey is assumed to have been acquired to address this issue (Cumming and Mackie, 2010). Other data sets that sometimes add value in specific circumstances like detailed CO₂ flux, gravity, magnetics and earthquake monitoring are assumed to be

less relevant in this case since the focus is on the conceptual model development process, not the potential contribution of every data set.

The map in Figure 2 shows a typical geothermal geoscience reconnaissance data set including a basic geochemistry analysis of the hot springs and fumaroles shown in Figure 3 and an initial hypothesis regarding the conceptual elements inferred from them in the cross-section at right in Figure 2. A 300 year-old regional tuff blankets the map area except in a few drainages where a thousand year old tuff from the local summit is exposed. As commonly occurs in volcanic geothermal prospects, these recent tuffs obscure the surface expression of all but the most prominent structures. In conventional geothermal risk assessments, the extensive spring and fumarole geochemistry data is given the greatest emphasis in establishing the likely existence of a commercial geothermal resource and guiding the design of the geophysical surveys, with the structural model setting limits and the overall context for the existence and extent of a resource.

In the right hand panel of Figure 2, the water table inferred from the chloride spring provides the pressure constraint, the gas and water geothermometry indicate a likely 250°C temperature in liquid near the top of the reservoir and the BPD

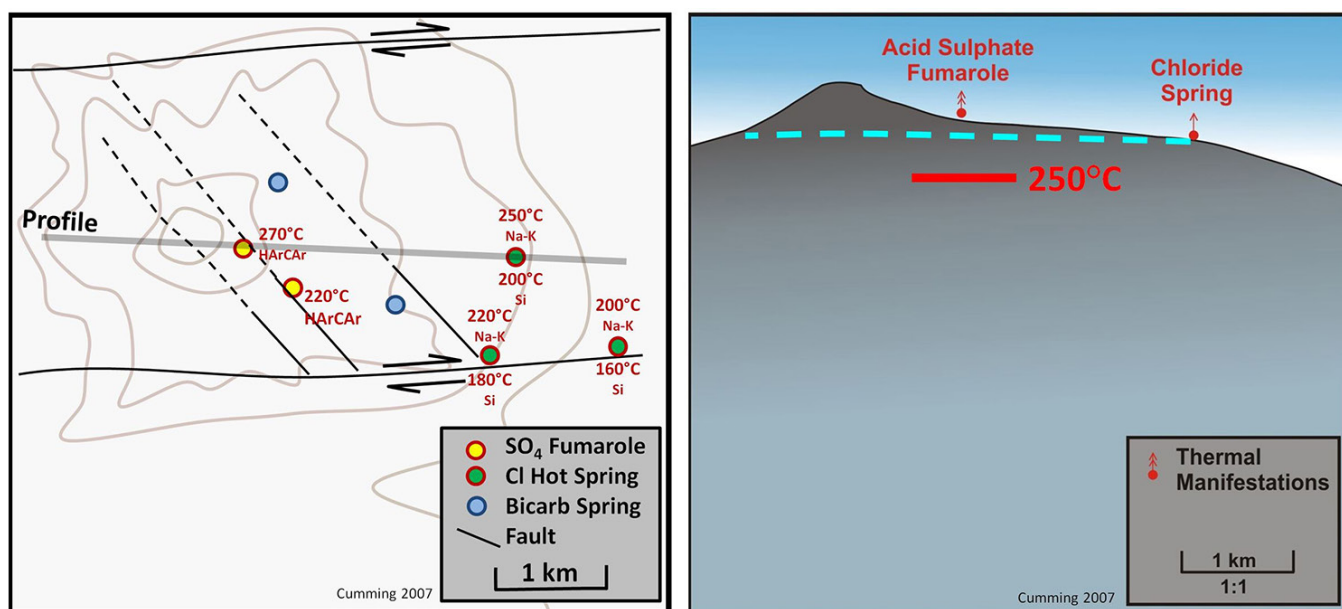


Figure 2. A prospect map showing topography, structure and thermal manifestations (all exposures are andesite tuff) together with a conceptual cross-section at right showing the water (blue dashed) table and an initial temperature (red solid line) consistent with the implied hydrostatic pressure. The temperatures are from gas ratio geothermometry of fumaroles (HArCAr), and cation and silica geothermometry of chloride hot springs (Na-K, Si) as described in Powell and Cumming (2010). Because it is a synthetic example, this map omits coordinates and the map datum and projection, inconsistent with best practice standards.

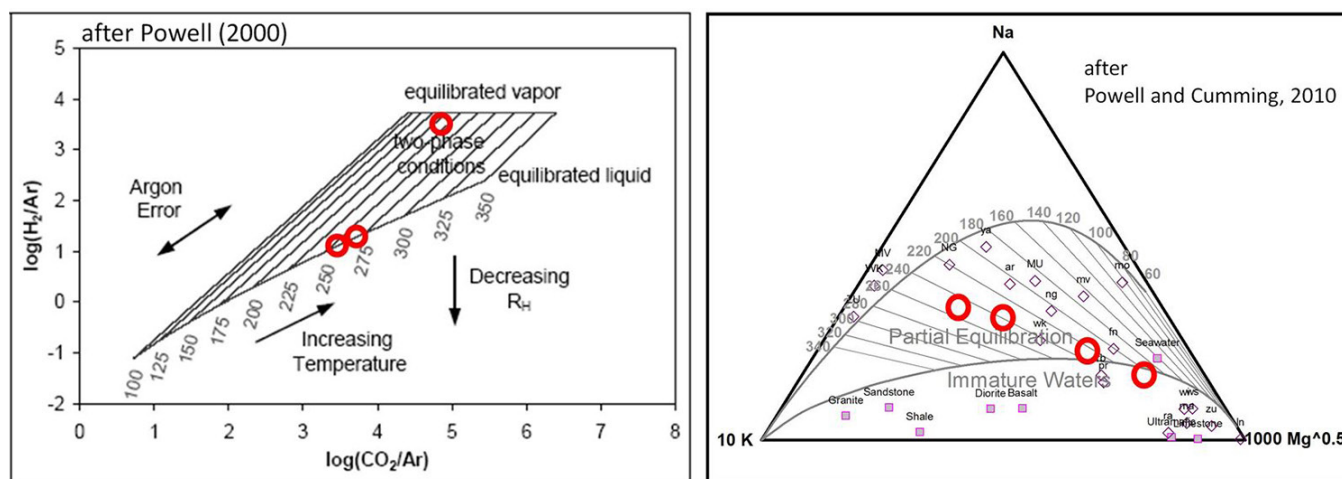


Figure 3. Water and gas geochemistry plots based on the spreadsheets from Powell and Cumming (2010). On the left, a gas ratio plot for the fumaroles labeled HArCAr in Figure 2 suggests that boiling occurs in a steam cap at >230°C, with deeper temperatures in water >270°C. The water chemistry shown in the Na-K-Mg ternary plot for the chloride springs in Figure 1 shows a meteoric mixing or a re-equilibration trend to a temperature of 250°C.

constraint provides a minimum depth below the water table for that temperature. Other conceptual models might assume that 250°C would be deeper, depending on how this fits other evidence, like the resistivity pattern.

If the geothermal system was more likely to be fault-hosted and/or the thermal manifestations were sparser than in Figure 2, the lack of geological exposure would be problematic. Targeting risk for fault-hosted prospects is significantly reduced by conducting detailed structural analyses based on high resolution remote sensing and ground confirmation of fault properties including pattern, age, slip rate, stress state and tendency to slip or dilate based on their orientation in the regional stress field (Faulds and Hinz, 2015). In the case shown in Figure 2, the reliably interpreted geological elements are the recent local eruption center in a zone of dextral shear between two prominent regional strike-slip faults. No active alteration is detected except at the fumaroles. Active (warm) alteration can be treated as a thermal manifestation that lacks geothermometry. Permeability is expected to be related to structural complications associated with the secondary faults between the strike-slip faults, but this is obscured by recent tuff. The hints of structure that are available are consistent with the shear fault sets typical of this setting, but the information is too sparse to build more than a very general targeting model.

Figure 4 shows an MT survey design based on the expectation that the top of the reservoir may be as shallow as 700 m depth (200 m to the water table and ~500 m to 250° based on BPD for pure water). The MT stations are about 500 m apart near the fumarole and spread farther apart in areas farther from the features of most interest. The map shows that the MT stations are located closer together along the line-of-section labeled “Profile” that connects the fumarole with the highest gas (HArCAr) geothermometry to the hot spring with the highest cation (Na-K) geothermometry (Powell and Cumming, 2010).

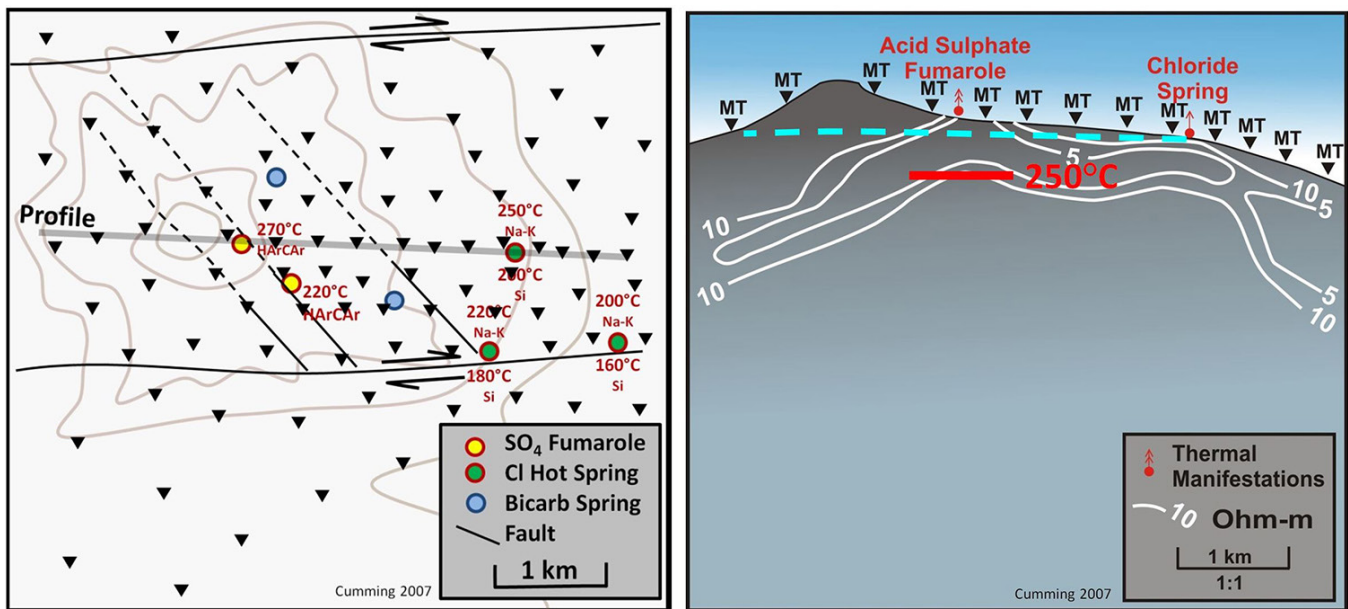


Figure 4. The map at left illustrates the layout of an MT (and perhaps a collocated TEM) survey designed to produce resistivity cross-sections like that at right. A resistivity of less than 5 ohm-m is typical for a clay cap on the flank of an andesitic volcano, whereas a resistivity over 20 ohm-m is typical of the base of the clay cap, in some cases corresponding to the top of the reservoir.

The map in the left panel of Figure 5 illustrates an interpretation of the elevation of the base of the smectite clay cap (the acronym BoC is used for base of conductor or base of clay). The dashed line in the cross-section indicates the interpreted base of the clay cap. It is not aligned with a particular resistivity contour because the resistivity at the BoC may vary. For example, a <3 ohm-m smectite cap might directly overlie a >20 ohm-m geothermal reservoir near the apex of the permeable reservoir, whereas a thicker but more resistive <10 ohm-m mixed-layer smectite-illite clay zone might cap the deeper outer edge of the >20 ohm-m reservoir. To allow for changes in clay cap properties, the BoC is commonly interpreted as corresponding to the highest gradient to increasing resistivity. In the synthetic case, the maximum gradient is generally between 5 and 10 ohm-m.

Because hot water trapped below a clay cap will flow buoyantly updip, the map of the elevation of the interpreted BoC shown in Figure 5 is a standard plot used to interpret the likely outflow direction from a geothermal upflow. Steam-dominated reservoirs do not have a reservoir outflow (they must be sealed) and so a BoC plot will typically make a *bulls-eye* pattern at the shallowest part of such a reservoir. With significant caveats, this sometimes also applies to local parts of water-dominated reservoirs. Therefore, Anderson et al. (2000) strongly advocated using maps of the BoC for well targeting.

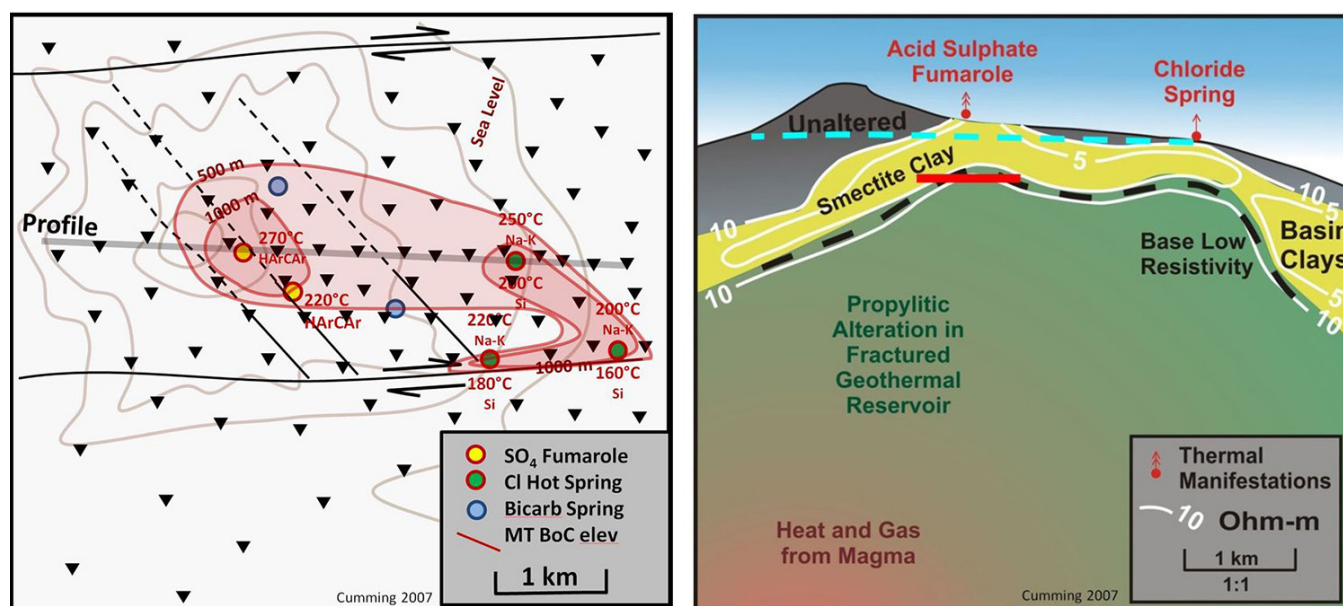


Figure 5. The resistivity pattern mapped from the MT survey is interpreted as a clay cap in the cross-section. The black dashed line across the cross-section illustrates the elevation at which resistivity is contoured in the map on the left of Figure 5.

In Figure 5, there are two areas enclosed by 1000 m rsl contours in the elevation of the BoC that, when integrated with the geochemistry would have significantly different conceptual interpretations and implications for well targets. For example, most interpreters would locate the upflow near the 1000 m rsl BoC contour that outlines the fumarole with the

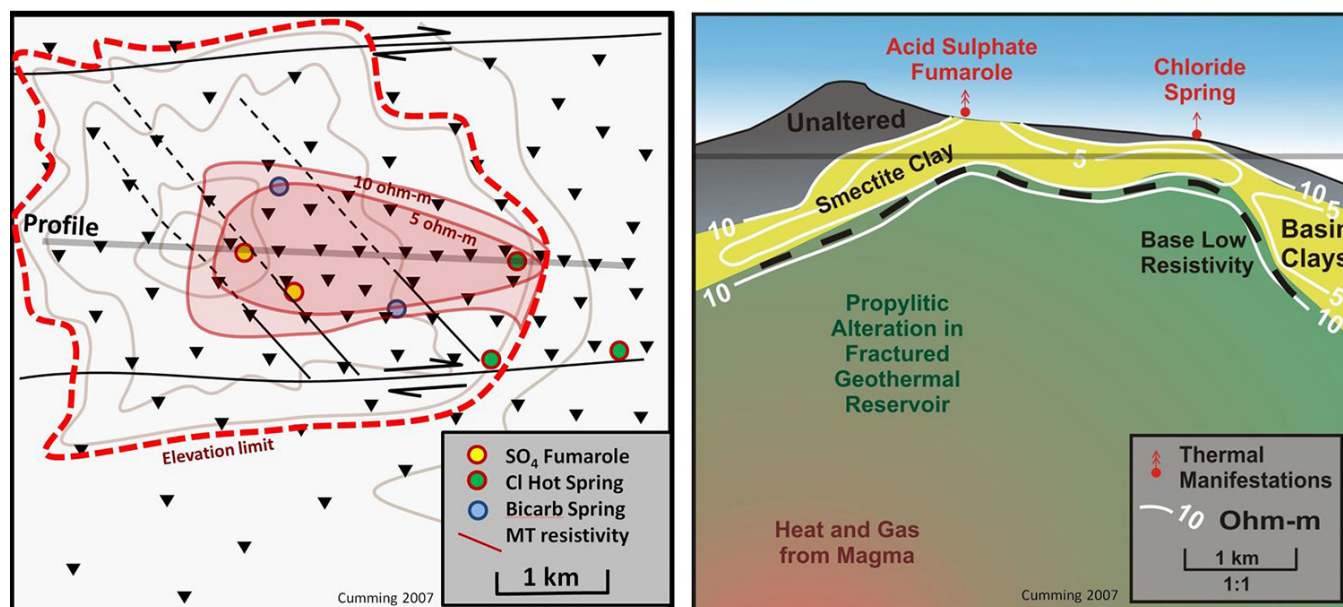


Figure 6. A map of MT resistivity at the elevation shown as a grey transparent line in the cross-section at right. A dashed line indicates the limit of the data; outside this line, the horizontal map slice is above the surface elevation. The <10 ohm-m low resistivity zone shaded red in the map at left is interpreted as smectite clay (shaded yellow) in the cross-section at right. When interpreted in the context of the thermal manifestation geochemistry, most of the smectite is zone is likely to be a hydrothermal clay cap over a geothermal reservoir, although the very thick low resistivity zone to the right is interpreted as clays in a sedimentary basin.

highest 270°C gas geothermometry, while associating the 1000 m rsl contour that encloses the chloride spring with a much cooler outflow that has liquid geothermometry that remembers its 250°C origin (Powell and Cumming, 2010). However, from an anomaly hunting perspective, the 1000 m rsl contours are the same, except that the best resolved fault in the region can be targeted from a location near the chloride springs and, because it is on the lower flank of the volcano, it would be close to roads, whereas a road to the fumarole might cost as much as a well. This is a surprisingly common scenario and, in a surprising number of cases, the management appeal of the lower cost road together with the BoC *anomaly* and the

well-defined fault near the chloride springs has resulted in a significant number of very disappointing wells. A more systematic use of a conceptual model and risk assessment approach supported by case histories would likely have provided a better appreciation of the risk that the wells near the chloride springs would be on a $<200^{\circ}\text{C}$ outflow.

The interpretation of the MT resistivity pattern is mainly done in cross-sections because the focus is on drawing isotherm contours consistent with buoyant flow, which is much easier to do on a cross-section. The maps are used to extrapolate the resource interpretation that is developed on cross-sections to a 3D model in map and section view.

Beginning with the 250°C isotherm in Figure 5, these plots provide sufficient information to begin developing a conceptual model based on the rules of thumb that constrain the thermodynamics of hot buoyant fluid flow in rocks, listed in the conceptual model entry on isotherms. Figure 8 shows a plausible isotherm interpretation and a conceptual element outline in map view. Since hotter flows toward colder, the flow is likely to be up near the fumarole with the highest geothermometry and out toward the chloride spring. Based on the 250°C below the cap at the fumarole and less than 100°C

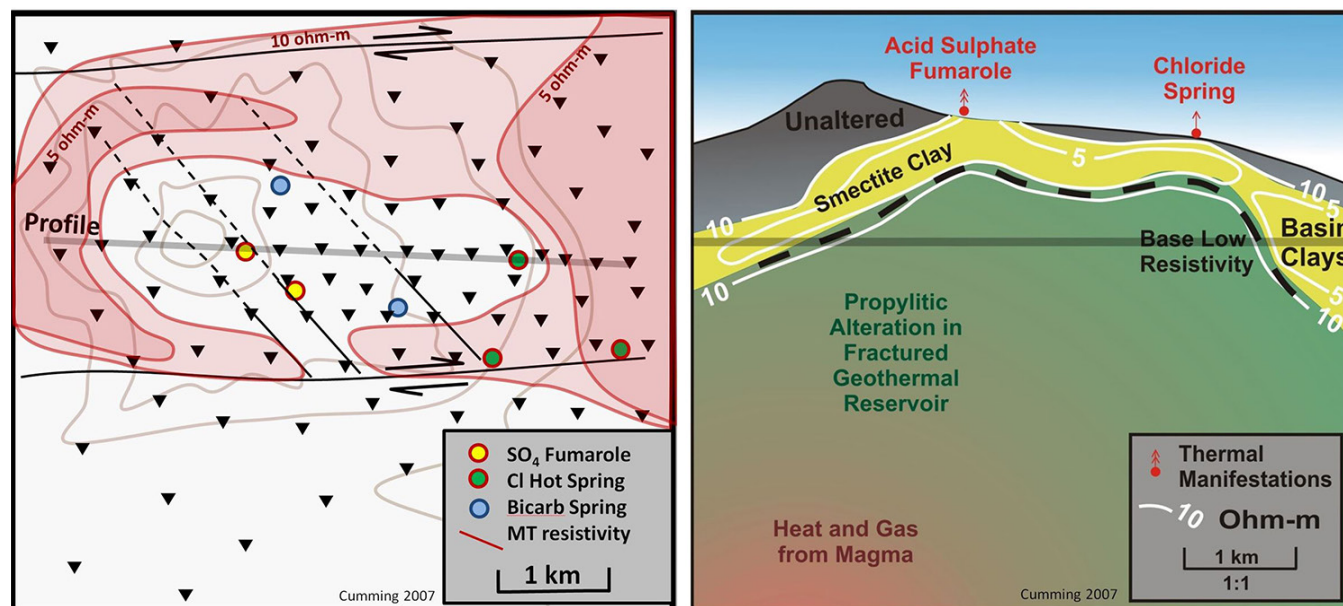


Figure 7. A map of an MT resistivity slice at 700 m lower elevation than the map in Figure 6. The elevation of the slice is shown as a grey transparent line in the cross-section at right. Because the horizontal slice cuts through the relatively resistive reservoir, as shown in the cross-section at right, the low resistivity shaded red has the “hole in a donut” pattern characteristic of many geothermal reservoirs, for instance Glass Mountain (Cumming and Mackie, 2010).

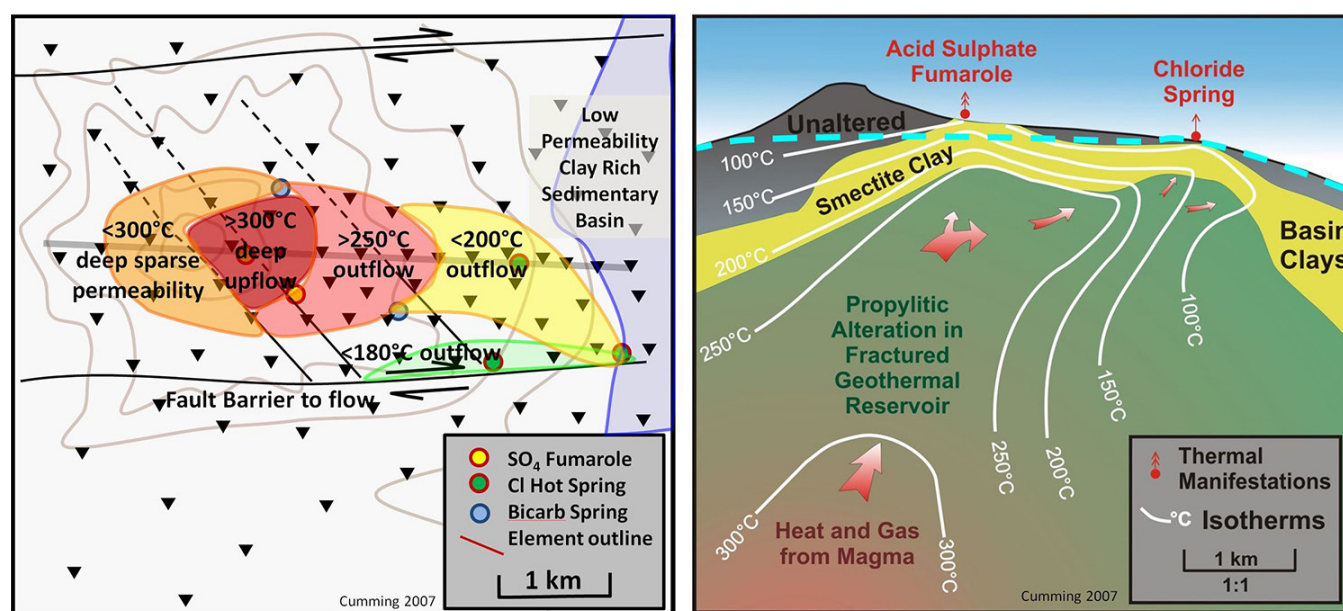


Figure 8. The conceptual elements map illustrates the map geometry of the conceptual model features indicated by the isotherms in the cross-section at right.

at the fumarole, isotherms can be crowded in the clay cap assuming meteoric water cooling to the top of the cap. The proposed thermal gradient in the reservoir should be low to be consistent with high permeability, although the gradient shown could be compared to measured or simulated temperatures in reservoirs to check if this is reasonable. The upflow must be redirected by the clay cap to flow updip toward the chloride springs. The extent and thickness of the outflow is the main source of uncertainty in this particular conceptual model.

Conceptual Model Uncertainty and Targeting Risk

The conceptual model shown in Figure 8 could be used as a median (P50) model needed to prepare a lognormal power capacity distribution for this resource, following the example in the companion paper Cumming (2016). Figure 9 shows the 250°C isotherm for two additional conceptual models corresponding to the 10 and 90% confidence models of the lognormal distribution of areas outlined in the map in Figure 9. The areas are drawn for the same confidence levels from three additional cross-sections along the profiles shown in Figure 9 and interpolated based on the maps in Figures 5 to 8 (the cross-sections for Profiles 2 to 4 are not shown). The resource areas are not based on any particular geophysical feature or mapped parameter. One definition is that the resource area outlines the part of the conceptual model that is likely to support commercial production at a particular level of confidence. More elaborate definitions that exclude injection areas and/or make other adjustments exist but are usually practical to apply at the exploration stage.

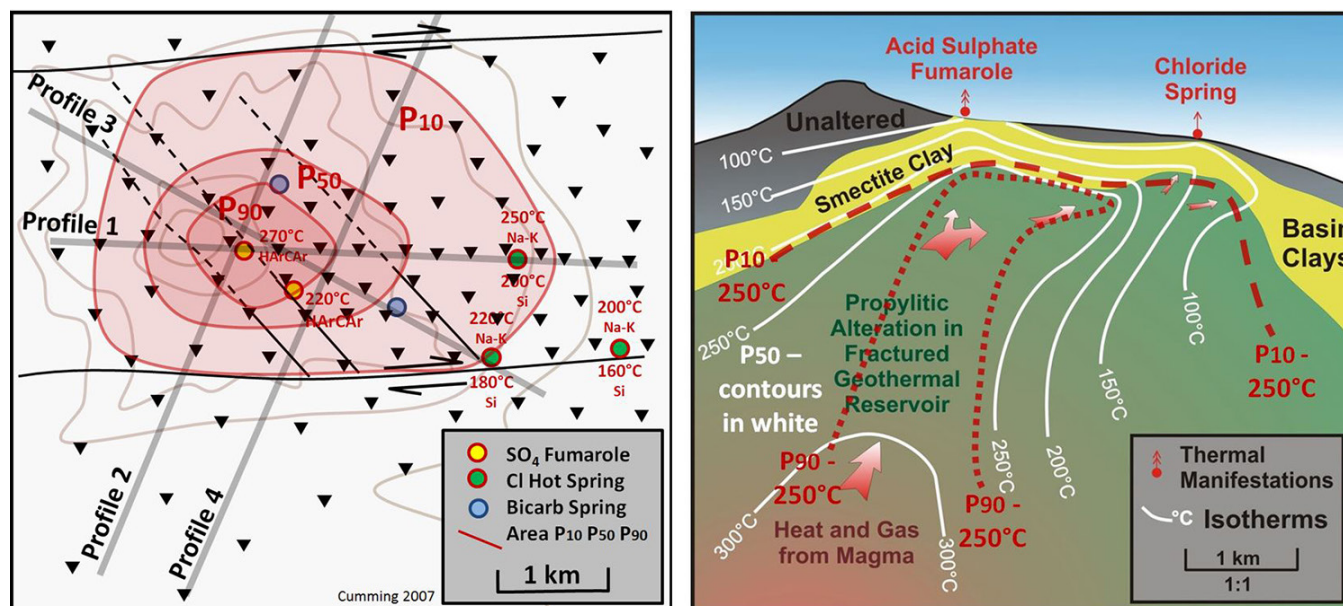


Figure 9. Conceptual model variations shown by sketching the 250°C isotherm at 10 and 90% confidence levels in dashed red lines in the cross-section at right. The related projected areas of the producible resource are shown in the map at the 10, 50 and 90% levels of confidence that fit a lognormal area distribution.

The power density method in Cumming (2016) requires that a power density distribution be estimated based on analogous fields. For convenience, a cross-plot of power density, resource temperature and geologic setting for named fields is provided based on Wilmarth and Stimac (2015). A range can also be estimated based on the general geological settings or a knowledge of fields or groups of fields that are likely to be comparable.

The assessment of geothermal power capacity in Cumming (2016) includes an overall exploration probability of success (POSexpl). This is sometimes interpreted as the probability that the lognormal geothermal capacity distribution is representative of the prospect but, to provide a closer fit to the experience of geothermal experts, it is usually defined the probability that an exploration program of several wells would discover at least one well with commercial deliverability in MW based on considering the probability of adequate temperature, permeability and benign chemistry. Note that POSexpl is not the same as the probability that a particular well succeeds but the probability that an exploration program, perhaps including several wells, could discover a commercial well. In the synthetic example described in this paper, there are several developed field case histories that are reasonably close analogs. The other approach is to assemble experts and ask them to assess the three essential qualities, temperature, permeability and neutral chemistry. A useful check on POSexpl is to complete *pre-mortem analyses*, that is, if the exploration program fails, what are the most likely reasons, and what is the probability of that occurring.

The conceptual models developed for the capacity assessment can be adapted to well targeting assessment. Experience suggests that geoscience teams can use the conceptual models to weight relative chance of success among candidate targets more realistically than they can estimate a realistic probability of success. A pre-mortem analysis can help make the overall assessments more realistic but specific probabilities requires extensive experience and careful checking of actual performance. The number of people in the geothermal industry who have done this type of work in a wide variety of settings is small but a few papers provide some perspective on what base rates might apply to specific regions (Wall and Dobson, 2016).

Recent Failure Cases in Targeting Wells Based on Conceptual Models

Veneer of Recent Volcanics on Metamorphic Rocks: Some exploration programs focus on geochemistry, structure and MT resistivity and have failed to consider the implications of widespread exposures of metasediments around the lower flanks of the target volcano. Such rocks are unlikely to form open-space permeability when fractured. A reservoir encountered below the recent volcanic rocks is much less likely to host distributed permeability. The common theme in these failures has been too narrow a view of how data is likely to constrain a geothermal resource conceptual model.

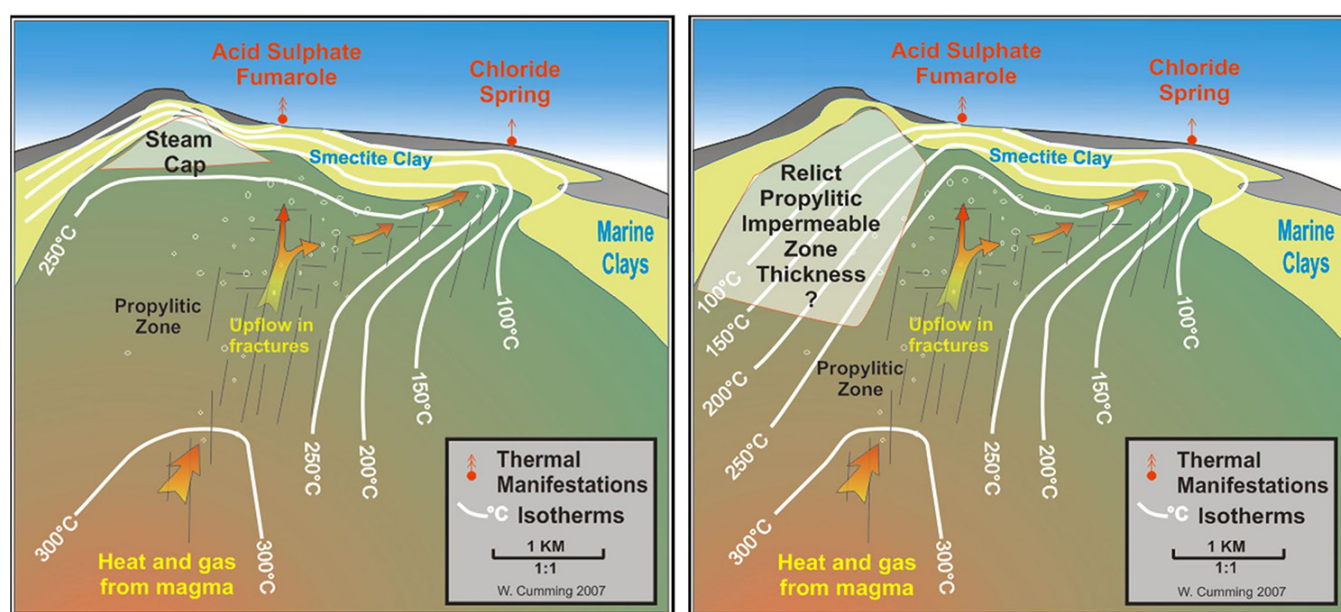


Figure 10. A conceptual model failure case with the overly optimistic drilling model at left and the actual case at right, a relict low permeability alteration zone.

Relict Low Permeability Alteration: Another pitfall that has been encountered when following an approach like that illustrated in Figures 2 to 9 is illustrated in Figure 10. In the case on the left, the clay cap is much thinner at the volcanic center, a feature that had been attributed to a steam cap above the water table (the pressure of the steam cap should depress the water table somewhat). However, the pressure of a 240°C steam cap would be close to the failure pressure of rock at 200 m depth, and almost surely would exceed the strength of rock altered to clay, and yet there are no thermal manifestations associated with the proposed steam cap. After wells have been drilled on such features, most have been revealed to be zones of relict high temperature alteration, now cold and low permeability, as illustrated at right.

Aside from the inconsistency of having a high pressure steam cap trapped beneath a thin clay cap that does not leak, in several reviews of such targets, an examination of deeply incised stream beds on the volcano have discovered exposed high temperature propylitic alteration that does not leak steam or hot water, consistent with the model at right in Figure 6. The MT typically images a continuous clay cap in such situations because the MT stations are acquired on the more accessible ridges where the cap is preserved, not in deeply incised drainages. In these cases, the geology could have provided the decisive information that would have changed the assessment of targeting risk. Sometimes exposures of high temperature propylitic alteration at the surface are thought to be a positive indicator, but the current temperature of the exposed rock is much lower than its mineralogical temperature and the most likely outcome would be that this relict alteration extends into the subsurface.

Prospects That Do Not Fit the Paradigm: Many volcanic geothermal prospects lack indicative spring or fumarole chemistry, even though the heat flow through all of the thermal manifestations may be large. For example, there are many

volcanic prospects with a summit fumarole and widely dispersed bicarbonate hot springs that are not reliably diagnostic of a geothermal resource based on case histories. One viable model for these prospects is that a central hot core is conductively heating surrounding meteoric aquifers to about 100°C. MT resistivity surveys image a clay zone mantling many of these volcanoes, but these zones may be only alteration related to the degassing of an active volcano. It could be that none of these prospects have an associated geothermal field but, given their high heat flow, this seems an unreasonably pessimistic conclusion. It may be that research outside the industry is needed to establish whether any of these prospects is likely to host a geothermal reservoir.

Conclusions

The geothermal resource conceptual model is an information organizing principle that depicts those aspects of the geothermal reservoir that are most relevant to high value economic decisions like well targeting and capacity assessment and provides a scientific hypothesis that a well will confirm or refute. For example, the isotherm pattern is directly relevant to the two most important direct constraints on cost and value, the enthalpy of the production and the permeability. The isotherm pattern constrains permeability at two relevant scales – it directly constrains the overall permeability of the reservoir that most affects the resource capacity assessment and it is thematically relevant (at lower resolution) to locating the specific permeable zones that will be targeted by wells.

The conceptual model process presented in this paper supports the assessment of the capacity distribution more directly than it supports the estimate of the probability that a reasonable exploration program would discover a potentially commercial resource.

Based on decision research popularly summarized by Klein (2009) and Silver (2012), geoscientists and engineers who have more practice in building conceptual models, making decisions based on them and reviewing the outcomes for geothermal exploration and development will make more effective decisions. Reading about it is entirely different than making a decision and reacting to the consequences. Workshops that synthesize this experience based on realistic case histories.

Well targeting failures in recent geothermal exploration and development projects have highlighted pitfalls in the conceptual model approach and also its resilience in identifying remedies and focusing attention on unresolved challenges.

As prospects that fit the exploration assessment approach outlined in this paper are drilled, the remaining prospects are inevitably a poorer fit to the paradigm and therefore are assessed as having higher risk. To distinguish which of these is more likely to host a commercial geothermal reservoir, the alternative approach most often proposed is low-cost slim-hole drilling directed at measuring temperature in the clay cap or the temperature and water chemistry of a shallow outflow aquifer.

References

- Anderson, E., Crosby, D. and Ussher, G., 2000. "Bulls-eye! – Simple resistivity imaging to reliably locate the geothermal reservoir." Proceedings World Geothermal Congress, Kyushu-Tohoku, Japan, p. 909-914.
- Árnason, K., Karlsdóttir, R., Eysteinnsson, H., Flovenz, O.G. & Gudlaugsson, S., 2000. "The resistivity structure of high-temperature geothermal systems in Iceland." Proceedings World Geothermal Congress, 2000, p. 923-928.
- Boseley, C., Cumming, W., Urzúa-Monsalve, L., Powell, T., Grant, M., 2010. "A resource conceptual model for the Ngatamariki Geothermal Field based on recent exploration well drilling and 3D MT resistivity imaging." Proceedings of the 2010 World Geothermal Congress, Bali, Indonesia, 7 p.
- Cumming, W., 2009. "Geothermal resource conceptual models using surface exploration data." Proceedings 34th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.
- Cumming, W. and Mackie, R., 2010. "Resistivity imaging of geothermal resources using 1D, 2D and 3D MT inversion and TDEM static shift correction illustrated by a Glass Mountain case history." Proceedings World Geothermal Congress, Bali 2010.
- Cumming, W., 2016. "Resource capacity estimates using log normal power density from producing fields and area from resource conceptual models: Advantages, pitfalls and remedies." Proceedings 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.
- Davatzen, N. and Hickman, S., 2010. "The feedback between stress, faulting, and fluid flow: Lessons from the Coso Geothermal Field, CA, USA." Proceedings of the 2010 World Geothermal Congress, Bali, 12 pp.
- Dipippo, R., 2016, "Geothermal Power Generation." Ron Dipippo (ed.). Elsevier, 2016, 654 p.
- Facca, G. and Tonani, F., 1967. "The self-sealing geothermal field." Bulletin Volcanologique, 30-1, p. 71-273.
- Faulds, J., and Hinz, N., 2015. "Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA: Proxies for discovering blind geothermal systems," Proceedings World Geothermal Congress, Melbourne, Australia, 6 p.
- Gudmundsson A. and Mortensen, A., 2015. "Well Locations Consideration of Purpose, Objectives and Achievement with Emphasis on Recent Drilling in the Krafla Geothermal Area." Proceedings World Geothermal Congress, Melbourne, Australia, 10 p.
- Grant, M., and Bixley, P., 2011. "Geothermal Reservoir Engineering." Academic Press. 378 p.

- Hickman, S. and Davatzes, N., 2010. "In-situ stress and fracture characterization for planning of an EGS stimulation in the Desert Peak Geothermal Field, NV." Proceedings 35th Workshop on Geothermal Reservoir Engineering, Stanford University, California, 11 p.
- IGA Service GmbH, 2014. "Best Practice Guide for Geothermal Exploration." Report written by GeothermEx Inc for International Finance Corporation, edited by Dr. Colin Harvey for IGA Service GmbH. 196 p.
- Klein, 2009. "Streetlights and Shadows: Searching for the Keys to Adaptive Decision Making." MIT Press, 480 pp
- Lutz, S.L., Zutshi, A., Drakos, P., and Robertson-Tait, A., Zemach, E., 2011. "Lithologies, Hydrothermal Alteration, and Rock Mechanical Properties in Wells 15-12 and BCH-3, Bradys Hot Springs Geothermal Field, Nevada." Geothermal Resources Council Transactions 35, p. 470-476.
- Moore, J., 2012. "The evolution of a partially vapor-dominated geothermal system at Karaha-Telaga Bodas, Indonesia: insights from mineral distributions and fluid inclusion measurements." Proceedings New Zealand Geothermal Workshop. 8 p.
- Muñoz, G., 2014. "Exploring for Geothermal Resources with Electromagnetic Methods." Surveys in Geophysics. 35, 1, p. 101-122.
- Nicolson, K., 1993. "Geothermal fluids: Chemistry and exploration techniques." Springer-Verlag, 263 p.
- Powell, T., and Cumming, W., 2010. "Spreadsheets for geothermal water and gas chemistry." Proceedings of the 35th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-188.
- Robertson-Tait, A., 2013. "Conceptual Modeling: Data Integration and Presentation." IFC Best Practice Best Practices Launch Event, İstanbul, 27 March 2013. http://www.geothermal-energy.org/ifc-iga_launch_event_best_practice_guide.html.
- Sewell, S., Cumming, W., Winick, J., Quinao, J., Bardsley, C., Wallis, I., Sherburn, S., and Bourguignon, S., 2015. "Interpretation of microseismicity at the Rotokawa Geothermal Field, 2008 to 2012." Proceedings of the 2015 World Geothermal Congress, Melbourne, Australia, 10 p.
- Silver, N., 2012. "The signal and the noise: Why so many predictions fail--but some don't." Penguin Books, 560 p.
- Ussher, G., Harvey, C., Johnstone, R. & Anderson, E., 2000. "Understanding the resistivities observed in geothermal systems." Proceedings World Geothermal Congress, Kyushu-Tohoku, Japan, May 28 - June 10, 2000.
- US-DOE, 2014. "Best practices for Risk Reduction Workshop Follow-up Manual." Published 8-Jul-2014. 40 p.
- Wall, A. and Dobson, P., 2016. "Refining the Definition of a Geothermal Exploration Success Rate." 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.
- Whittome, A. and Salveson, J., 1990. "Exploration and Evaluation of the Darajat Geothermal Field, West Java, Indonesia." Geothermal Resources Council Transactions 14, pp. 999-1005.
- Wilmarth, M. and Stimac, J., 2015. "Power Density in Geothermal Fields," Proceedings, World Geothermal Congress, Melbourne, Australia.
- Young, C., Reber, T., and Witherbee, K., 2012. "Hydrothermal exploration best practices and geothermal knowledge exchange on OPENEI." Proceedings 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California, 13 p.
- Young, C., Bennett, M., Atkins, D., 2014, "Geothermal Exploration Case Studies on OpenEI." Proceedings 38th Workshop on Geothermal Reservoir Engineering, Stanford University, California, 11 p.

