

# AKUTAN GEOTHERMAL PROJECT

## Preliminary Technical Feasibility Report



**Prepared for the City of Akutan**

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by

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Cover page photo: Hot Springs Bay Valley in May. Photo by Amanda Kolker, 2009.

## Executive Summary

The geothermal system at Akutan Island has not been drilled, but exploration data indicate a viable resource that could feasibly support planned development for power production and direct use applications. The resource capacity, and the probability of exploration and development success, are all dependent on the target. A shallow geothermal resource of 155-180 °C (i.e., “outflow zone”) is likely to be accessible for development at Akutan. A deeper, hotter resource of >220 °C (i.e., “upflow zone”) has a greater access risk but will be targeted because of its potentially lower development cost. Two slim-hole exploratory wells are targeted to verify the existence of these aquifers, and determine their potential for development. Two follow-up wells would characterize the potential for an outflow zone that has greater resource risk but a potentially larger access area.

# **I. Introduction**

## **Project description and location**

Akutan Island is located 790 miles southwest of Anchorage and 30 miles east of Dutch Harbor. As a volcanic island with accessible hot springs, it has been the subject of geothermal resource studies since 1979. The City of Akutan (COA) is incorporated as a 2<sup>nd</sup> class city, with a total estimated population of 859 in 2007, including resident fishery workers of Trident Seafoods. The COA encompasses 148 square miles, covering most of the island, including likely sites of the proposed geothermal development. The City and Trident Seafoods are entirely dependent on diesel fuel imported into the area for power and heat—with an average total demand of 4.3 MW (~7-8 MW peak). In 2008, the base cost of power in the City of Akutan was \$0.323/kWh (Kolker and Mann, 2009).

The geothermal system on Akutan Island is considered one of the most promising high-temperature sites in Alaska for geothermal resource development (Motyka et al., 1993, Kolker 2007), but until recently only reconnaissance level exploration had been completed at the site. The City of Akutan plans to develop its geothermal energy resource as part of a long-term comprehensive renewable energy strategy. In 2009, the City applied for and received energy grant and loan funds totaling \$3.7 million from the state of Alaska. Part of these funds was used to conduct exploration activities in summer 2009 in order to better characterize the geothermal resource and to target exploratory wells. The remainder of the funds will be used to support exploratory well drilling in summer 2010.

## **Context and Objective of Study**

This report is a preliminary assessment of the technical feasibility of developing Akutan's geothermal resource. The discussion is preliminary in nature because it is based solely on surface exploration data, as no wells have been drilled on Akutan to date. A commercial project financing feasibility study is not possible until exploratory wells are drilled and tested in order to establish resource parameters such as temperature, well deliverability, fluid composition, resource capacity, location and accessibility of the geothermal resource.

The objective of this study is to provide a preliminary technical discussion that will be combined with economic findings into a preliminary feasibility study of the type used to justify equity investment for preliminary exploration drilling. Because of the relatively high cost of operations in remote areas of Alaska like Akutan, this study presumes that initial slim-hole wells would be drilled using a rig that could be helicopter supported. Such wells could establish the temperature and fluid properties of the accessible resource before a road was constructed so that larger rigs could be mobilized to drill exploration wells capable of testing productivity.

## Methods and Scope

This preliminary technical feasibility study draws primarily from three datasets in order to conceptualize the geothermal resource at Akutan and draw conclusions from that model. Those datasets are, in order of importance: 1) Previously recorded fluid chemical compositional data (see Motyka and Nye, 1988); 2) Data from the 2009 MT survey (see Kolker et al., 2010); and 3) Soil gas chemical data (see Kolker et al., 2010). The fluid chemistry data is significant because it provides reservoir temperature estimates via chemical geothermometry and information about the likely conceptual geometry of the resource. The MT data indirectly “images” geologic features associated with the geothermal reservoir. The soil gas chemical data constrains the outflow geometry of the geothermal fluids. By means of these datasets, we are able to assess the likely size, temperature, location, and geometry of the yet-undiscovered geothermal resource.

There are a variety of methods for estimating the production capacity of a geothermal resource. Statistical methods such as “volumetric-heat-in-place” assessments are sometimes done at this stage when surface methods indicate that resource parameters suitable for a geothermal development are likely but no direct reservoir measurements are available from wells. However, such methods commonly lead to unrealistic expectations of capacity and do not lend themselves to an evaluation of the accessibility of that capacity, an issue likely to be significant at Akutan. To address this in a practical manner, this assessment compares and contrasts Akutan to roughly analogous existing geothermal fields. This approach addresses not only a plausible range of resource size but also the probability of exploration success and development design in the context of access limitations.

## Assumptions

The Akutan Geothermal Project was originally envisioned as a combined power and direct use project (Kolker and Mann, 2009) and, in this study, the phrase “geothermal development” includes power production *and* direct use applications.

Based on the estimated cost of current electric energy production, the Geothermal Energy Demand & Stakeholder Assessment (Information Insights, 2010) found that a geothermal project would be viable if it can produce energy for less than \$0.21 per kWh. In addition to current energy demand, there are planned and potential projects that will substantially increase the energy demand load. These include a planned small boat harbor and airport, and a potential expansion of cold storage at the fish processor (Information Insights, 2010).

The Akutan geothermal area is roadless. While exploratory drilling activities will be supported by helicopter, it is assumed that roads required for production well drilling and all subsequent construction activities will be constructed.

## II. Geothermal Resource

### Background

A state-funded geothermal exploration program was carried out in Akutan Island in the early 1980s (see Motyka and Nye, 1988). The program was limited to the immediate hot springs area and included detailed geologic mapping, shallow (<150m) geophysical surveys, soil and fluid geochemical studies, and hydrologic investigations. No drilling has yet occurred at Akutan.

In summer 2009, the COA executed a follow-on exploration program to better characterize the geothermal resource on Akutan Island. The 2009 program included practical access assessments, a geologic reconnaissance field study, soil and soil gas geochemical surveys covering a broader area than the 1988 study, a remote sensing study using satellite data, a review of existing hot springs geochemistry data, a magnetotelluric (MT) survey, and a conceptual model analysis. A report on 2009 exploration activities was prepared for the COA by Kolker et al. (2010), which presents the results of the exploration program and implications for geothermal development. The next stage of exploration includes access analysis, fumarole sampling and analysis, and the drilling of slim-hole (non-production) exploratory wells.

### Geology and Geochemistry

Akutan volcano is part of the Aleutian Volcanic Arc, which is Alaska's most promising setting for geothermal energy. Akutan volcano is one of the most active volcanoes in the Aleutians, with 32 historic eruptions (Simkin and Siebert, 1994). An initial volcanic hazard review indicated that the proposed geothermal development area was unlikely to be directly impacted by eruption activity consistent with the previous 1500 years, excepting ash fall that might cause temporary closure. Several thermal springs are located in Hot Springs Bay Valley, about 6 km from Akutan village (Fig. 1). Due to the frequent eruptions of Akutan volcano, there is likely to be a magmatic vent system and possibly an acid-core zone associated with gas rising from a persistent magma system (e.g. Reyes et al., 1993). However, the neutral cation geochemistry of the hot springs is strong evidence that a neutral system exists. Case-histories suggest that an acid-core zone would isolate itself from a neighboring neutral geothermal system by a 'rind' of impermeable rock, typically created by silica and anhydrite deposition where incompatible acid and neutral fluids interact (Wood, 1994). Conduction through the impermeable rind or above episodic dike intrusions on the flank of Akutan volcano could provide heat for a neutral chloride geothermal convection system adjacent to the active vent system. This is consistent with the rifting model of Lu et al., (2000) who conclude that Akutan's magmatic system is associated with island-wide extension and related dike emplacement.

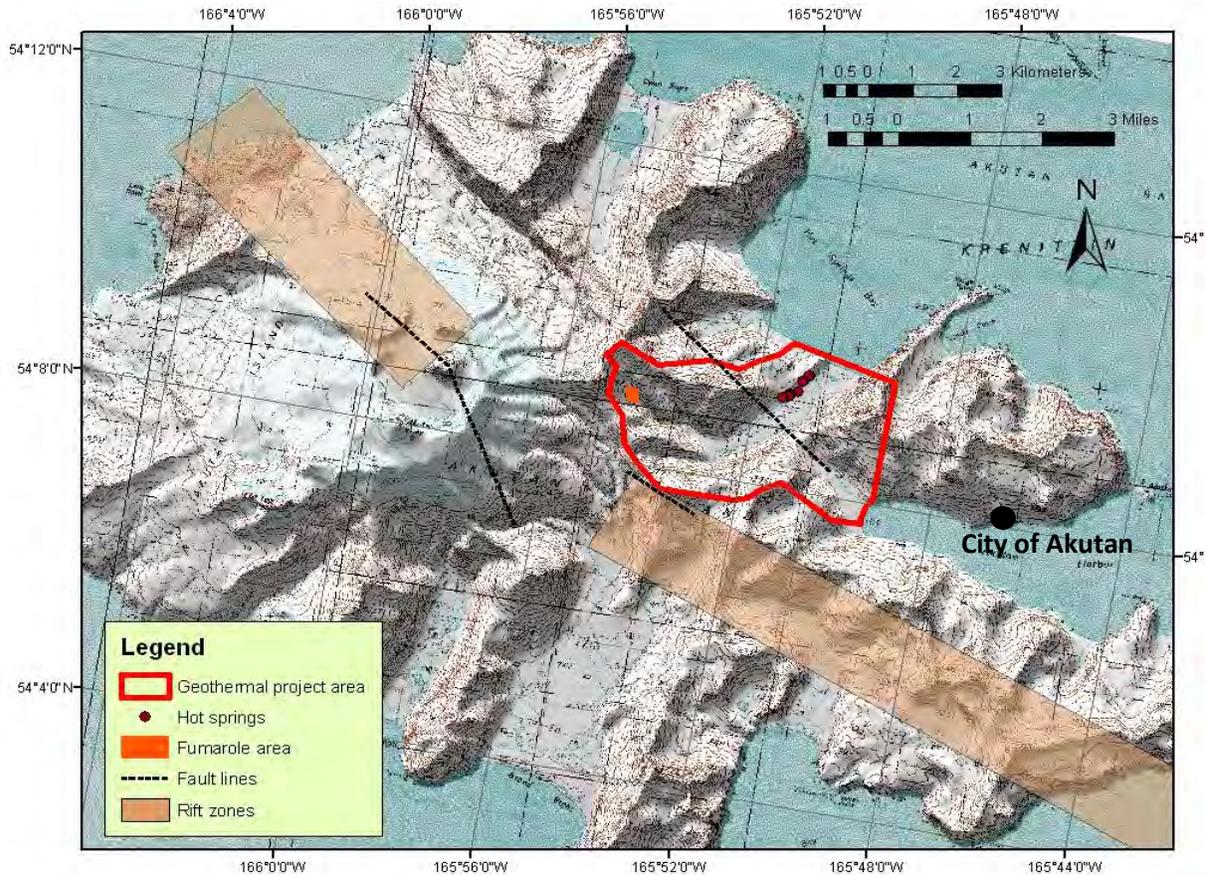


Figure 1. Map of Akutan Island, showing the geothermal area and pertinent geologic features. Faults and rift zones are identified from seismic data (J. Power, pers. comm.)

Five groups of hot springs with about ten vents have been identified, including tidewater springs on Hot Springs Bay beach that are only exposed at low tide. Temperatures range from 54-94 °C. The hottest springs are HS8 and HS9 (groups A and B), with measured temperatures of 94°C (Fig. 2).

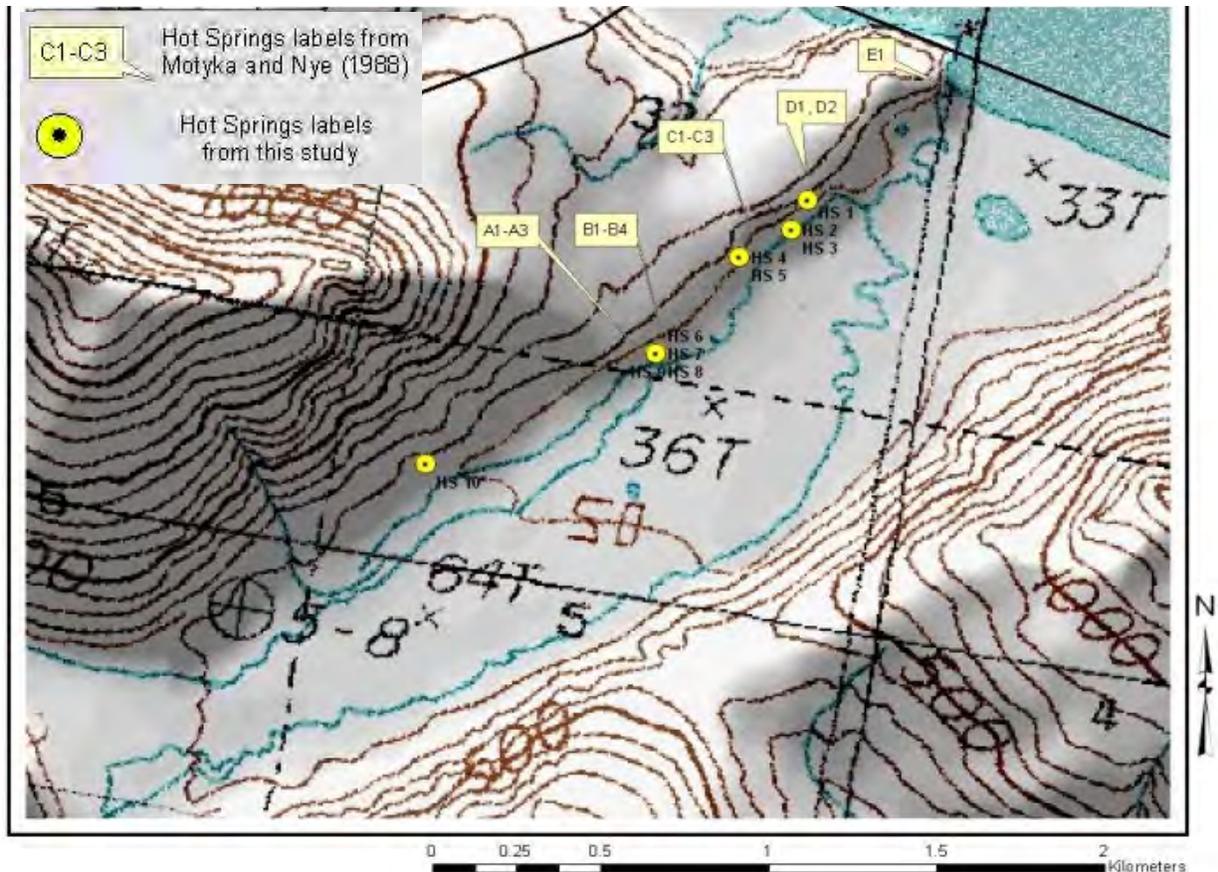


Figure 2. Hot spring locations in Akutan's Hot Springs Bay Valley.

Most of the hot springs fluids are a dilute chloride to chloride-bicarbonate type (Fig. 3). The unusually low dissolved solids concentration, relative to springs at the margins of many other geothermal systems, could indicate that they do not originate from a well-equilibrated geothermal reservoir. For example, they might originate from partially equilibrated steam-heated surface water in a relatively small aquifer. Alternatively, a high flux of meteoric water might result in a reservoir water with low dissolved solids that is further diluted in its path to the surface springs by mixing with cold groundwater. The fact that Cl is the dominant anion in Akutan hot springs fluids indicates that the source of their hot water is likely to be a hydrothermal system since steam-heated groundwater is likely to contain more  $\text{SO}_4$  and groundwater typically contains more  $\text{HCO}_3$  (Fig. 3). Although Cl is also a dominant anion in sea water, only the low elevation hot springs near the coast (in group E) have the relatively high Mg expected for such water. Therefore, the chemistry of the hot springs is likely to primarily reflect their geothermal origin, with some ambiguity regarding whether they come from a primary upflow or from a partially equilibrated shallow reservoir heated by steam.

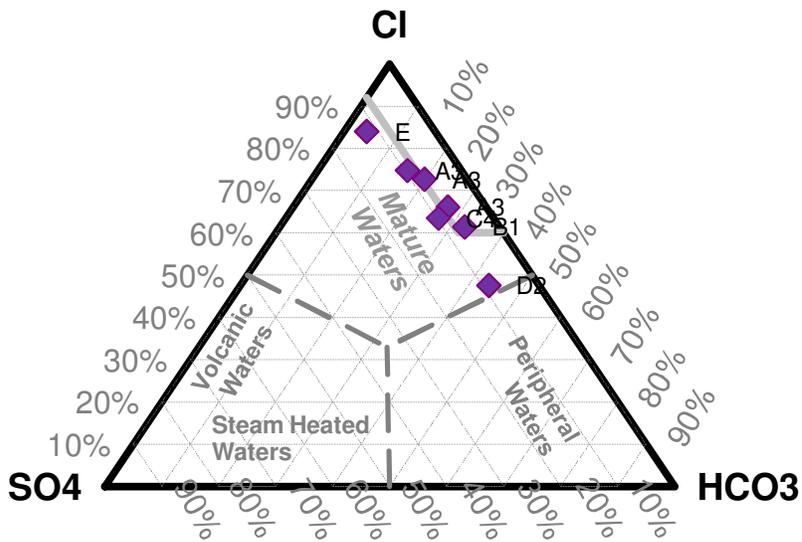


Figure 3. Ternary plot showing relative concentrations of the anions chloride (Cl), sulfate ( $\text{SO}_4$ ), and bicarbonate ( $\text{HCO}_3$ ). Fluids from groups D and E should be evaluated with caution due to likely seawater contamination. Compositional data are from Motyka and Nye (1988). Plot has been generated using Powell and Cumming (2010).

Reservoir fluid temperatures can be indirectly estimated from chemical geothermometry. This is based on the principle that, when water is given enough time to reach equilibrium with the rock it is saturating, the relative concentration of chemical species in the water will be characteristic of the temperature at which it equilibrated, usually implying a significant mixed volume of water. As some fluid in this equilibrated reservoir escapes and rises to a hot spring through thermal buoyancy, it will usually be cooled by conduction and mixing faster than it will chemically re-equilibrate. Because some chemical species, like silica, equilibrate faster than others, like sodium and potassium, the chemical composition of hot springs can be used to interpret the temperature and mixing history of a fluid in its path from the reservoir to the surface. The most widely used liquid geothermometers involve silica concentration and relative concentrations of the cations Na, K, Mg and Ca. Geothermometry calculations were applied to the 1988 chemical analyses of the Akutan hot springs using the Microsoft Excel liquid chemistry spreadsheets from Powell and Cumming (2010). Table 1 shows values for the common silica (quartz) and cation (Na/K and Na/K/Ca/Mg) liquid geothermometers as applied to Akutan geothermal fluids.

Sample	Temp. °C	Quartz Cond.	Na-K-Ca	Na-K-Ca Mg corr	Na/K (Fournier)
Akutan HS A3	84	159	189	169	205
Akutan HS A3	84	155	185	162	198
Akutan HS A3	nd	157	178	162	185
Akutan HS B1	47.4	139	179	138	211
Akutan HS C4	73.4	155	171	137	196

Table 1. Geothermometer calculations for Akutan hot springs waters from groups A-C. Groups D and E are omitted due to likely seawater contamination. Compositional data are from Motyka and Nye (1988) and the geothermometers have been generated using Powell and Cumming (2010), based on Giggenbach (1991) and Fournier (1989).

The Na-K-Mg ternary plot in Fig. 4 shows the sodium-potassium (Na-K) geothermometer along with the potassium-magnesium (K-Mg) geothermometer (after Giggenbach, 1991) to highlight reservoir processes and trends. This plot suggests that Akutan hot springs waters are poorly to partially equilibrated and/or mixed. Samples B1 and A3 appear to be the closest to equilibrium, as expected given their location farthest up-valley, closer to the volcano flank. The trend among the samples in Figure 4 is toward an equilibrium cation temperature of 200 to 220 °C. Because the cations equilibrate more slowly than silica, higher geothermometry from cation than from silica concentrations is consistent with an interpretation of a geothermal reservoir where the water equilibrated with the rocks at >210 °C farther than 500 m from the hot springs. While the cation geothermometry indicates that a geothermal reservoir of >210 °C probably exists at Akutan, the silica geothermometry of ~160 °C indicates that the resource close to the hot springs that is easily accessible (<500 to 1000 m distance and depth) is likely to be 160 to 180 °C. This is consistent with the active silica sinter deposition at hot springs groups A-C, which is typically associated with nearby aquifer temperature close to 180 °C.

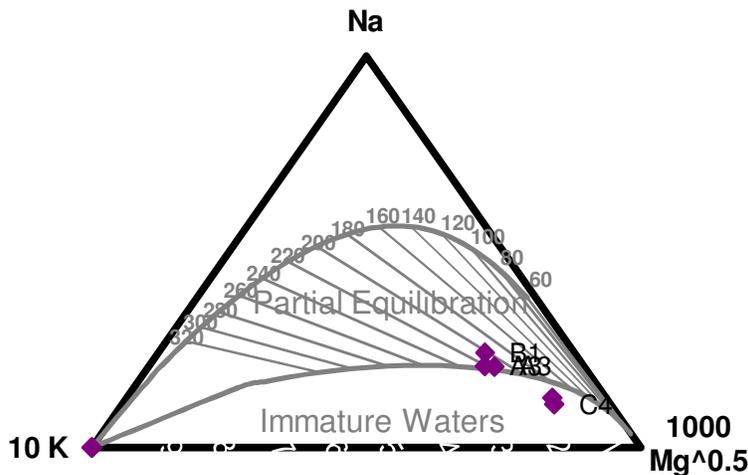


Figure 4. Ternary plot showing relative concentrations of Na, K, and Mg, and the Na-K and K-Mg geothermometers (Giggenbach, 1986). Compositional data are from Motyka and Nye (1988) and the plot has been generated using Powell and Cumming (2010).

The fumarole field located at an elevation of 350 m on the flank of the volcano is likely to have significantly different properties from the summit fumarole associated with the active volcanic vent. The flank fumarole occurs near the head of Hot Springs Bay valley about 3.5 km southwest of the lower valley hot springs (Fig. 1). The fumarole field consists of a series of low- to moderately-pressured steam vents with temperatures of 99 °C, steaming ground, and boiling acid-sulfate springs covering an area of about 5,000 m<sup>2</sup> (Motyka and Nye, 1988). Akutan fumarole gasses have been sampled as part of the initial geothermal exploration study (Motyka and Nye, 1988), and again in 1996 in a USGS study (Symonds et al., 2003). Unfortunately, both sets of data are not of sufficient quality to be used for reliable gas geothermometry.

## MT Resistivity

The 2009 MT survey detects a resistivity pattern typical of most economically viable geothermal reservoirs where a low resistivity, low permeability hydrothermal smectite clay cap “caps” a higher temperature, permeable geothermal reservoir, as illustrated by the resistivity map in Fig. 5 and the cross-section CM1 in Fig. 6. Cross-section CM1 has a bend in it to follow the MT station coverage from the fumarole to the hot springs. It shows a relatively low resistivity (green) layer that forms a cap over a higher resistivity (blue) zone. Unfortunately, because of difficult access by foot, MT stations were not located near the fumarole or in much of the area between the fumarole and the hot springs. Therefore, the pattern in this crucial area is largely inferred rather than directly imaged by the MT. With this caveat, the overall resistivity pattern can be interpreted in a geothermal context as illustrated by the more complete set of cross-sections and maps in WesternGeco (2009). The map of resistivity at -400 m elevation in Fig. 5 shows a tongue of high resistivity trending from the fumarole to the hot springs that is consistent with a path from a >220 °C upflow near the fumarole to a <180 °C outflow extending at least as far as the hot springs, as shown in the conceptual model in Fig 9.

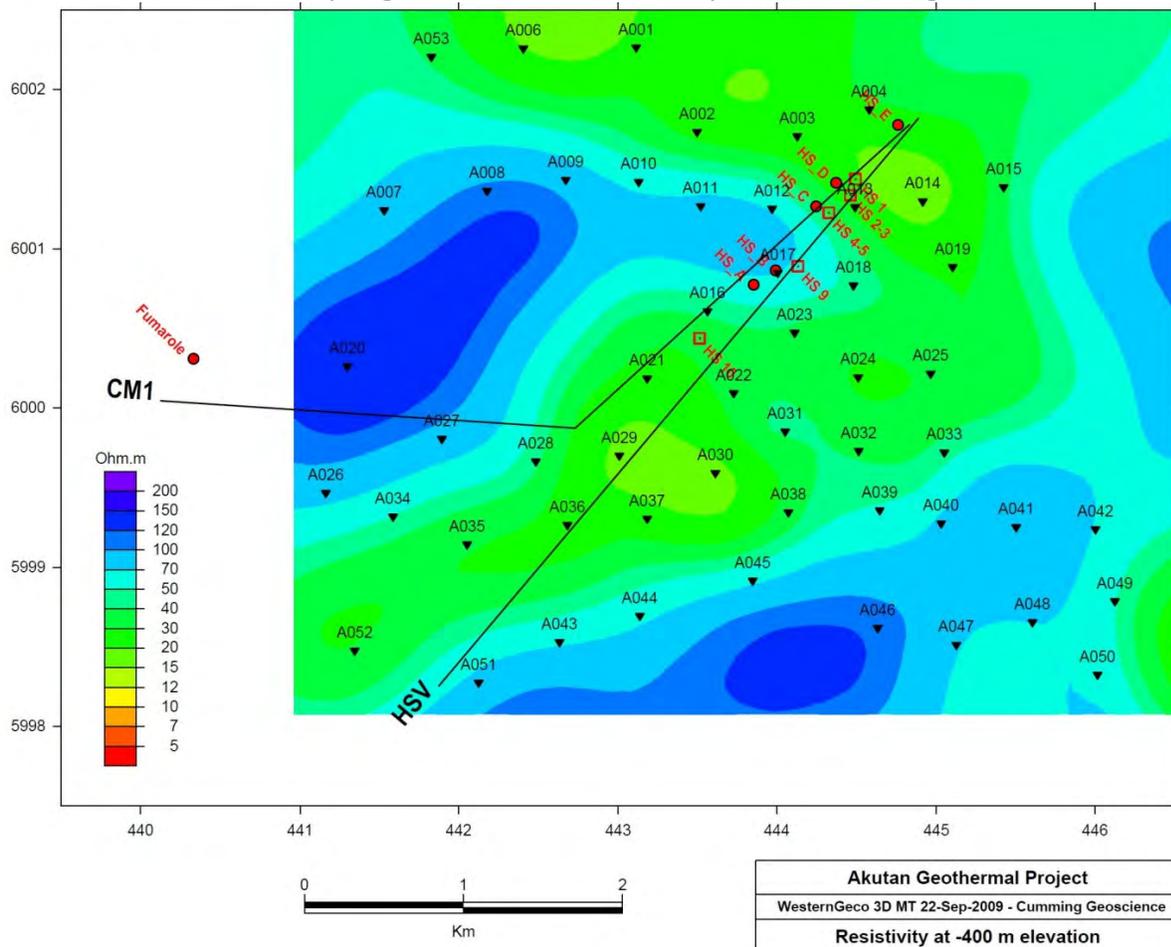


Figure 5. Map of 3D MT resistivity at -400 m elevation with cross-section lines used to illustrate the conceptual model (CM1) and the geometry of shallow aquifers in Hot Springs Bay Valley (HSV). The conductive clays in Hot Springs Bay Valley are lower resistivity (green) than the more resistive (blue) area around the fumarole. The trend between the fumarole and the springs is suggested rather than resolved by the widely spaced stations.

Besides the ambiguity related to the poor MT coverage of the interpreted upflow zone near the fumarole, the most serious risk indication in the interpreted upflow and outflow path is the 20 ohm-m resistivity of the clay cap. A hydrothermal clay cap is typically less than 10 ohm-m. A clay cap resistivity 20 ohm-m implies an unusually low intensity of clay alteration for a zone overlying a geothermal reservoir, although this is sometimes observed in parts of geothermal clay caps where an unusually high proportion of dense lava or intrusive rocks inhibit alteration or where an earlier, much hotter episode of hydrothermal activity produced more resistive shallow alteration more typical of the deep reservoir.

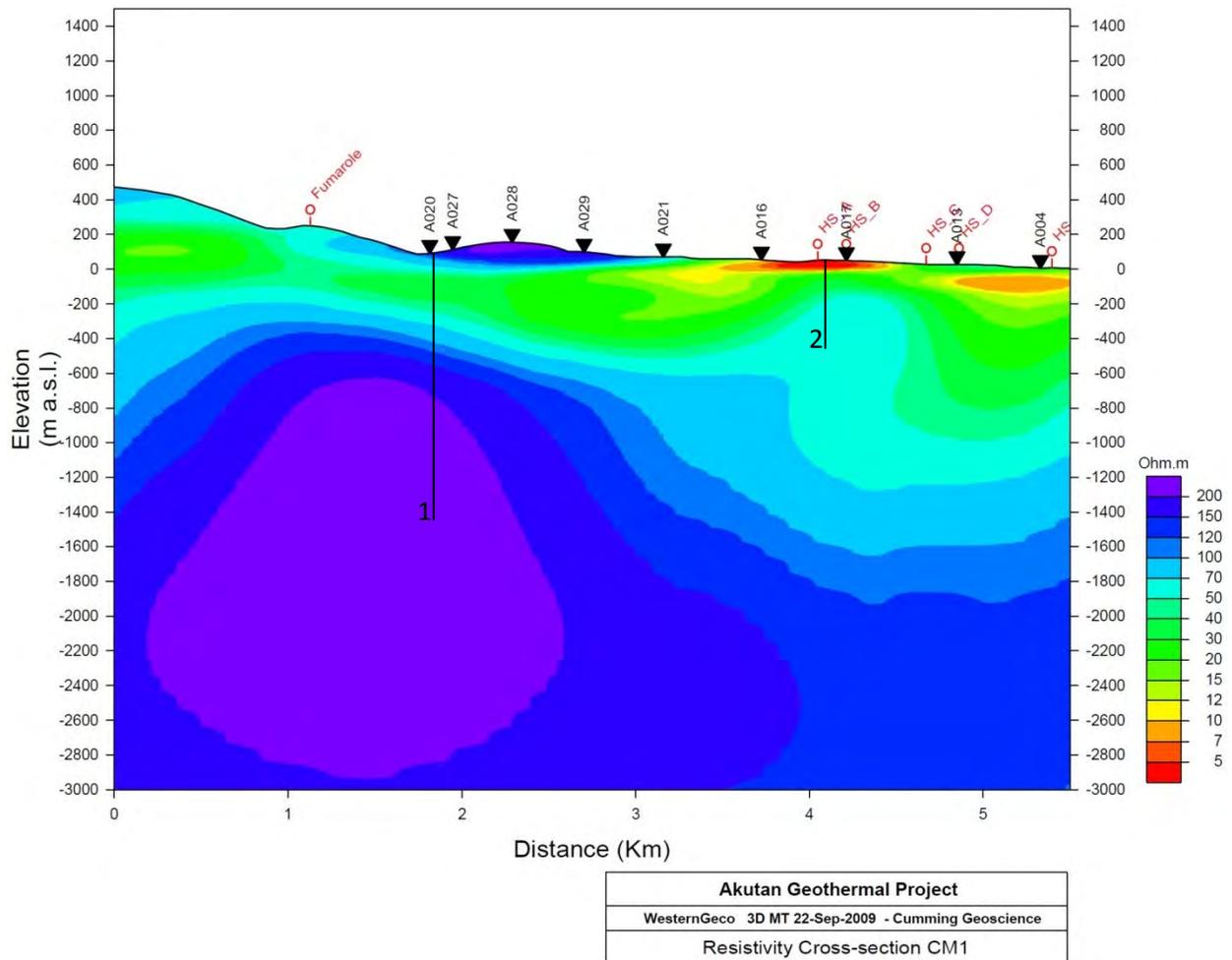


Figure 6. MT resistivity cross-section from a 3D inversion of the MT stations in a bent profile extending from the fumarole to the springs in Hot Springs Bay Valley. The relatively low resistivity clay cap is green while the high resistivity, high temperature zone will be in the blue shaded zone. The much lower resistivity clay cap (red) over the very shallow aquifer that feeds the hot springs is red. A corresponding resource conceptual model is in Fig. 10. Proposed locations of exploration wells are projected onto the plane of the cross section (numbered black lines).

The pattern of resistivity within Hot Springs Bay Valley suggests that at least one geothermal aquifer exists in the valley and supplies the hot springs. According to Motyka and Nye (1988), the Hot Springs Bay Valley is flooded by a debris flow which is acting as an impermeable cap

over the subsurface hydrothermal system. From very shallow 1988 electrical resistivity and seismic refraction surveys, they interpret this “cap” to be 30-40 m thick. In the cross-section shown in Fig. 7, the 2009 MT stations A016, A037 and A013 span the A and B hot springs that have the highest geothermometry and measured temperature. The 1D MT inversions shown in Fig. 7 for these stations have higher resolution at shallow depth than the 3D MT inversion (Cumming and Mackie, 2010) and appear to resolve a relatively resistive zone at about -20 to -120 m, most likely corresponding to an aquifer with a temperature between 100 and 160 °C. Although potentially productive, this very shallow aquifer is unlikely to sustain the high flow rates required for long-term commercial generation of more than a MW.

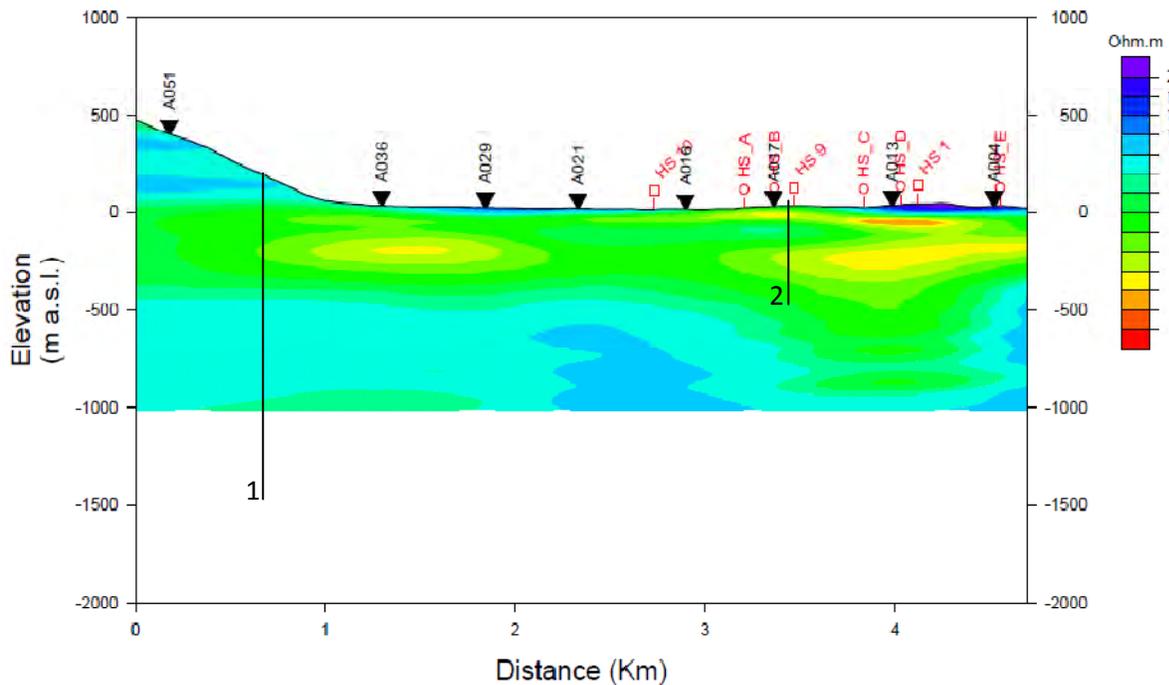


Figure 7. Resistivity cross-section HSV showing a 1D inversion of MT data along Hot Springs Bay Valley. A very thin clay cap shallower than 50 m is 5 to 15 ohm-m resistivity, shaded orange to light green and yellow over an aquifer in green at about 50 m depth. Another zone of high clay content extends to 350 m depth. Proposed locations of exploration well locations are projected onto the profile line. Well #1 projects higher on the hill than its actual location.

Near the hot springs, the MT also resolves a low resistivity clay zone below -120 m elevation that extends down to about -350 m elevation. This low resistivity is consistent with a clay cap over a <180 °C outflow in a tabular aquifer below -350 m elevation that locally upflows to a shallower ~100C aquifer at about -60 m elevation. The low resistivity zone at -120 to -350 m elevation near the hot springs thickens near the shore at the end of the profile in Fig. 7 and to the southeast side of the valley as shown in several cross-sections in WesternGeco (2009). The geothermal manifestations are limited to the NW side of the Hot Springs Bay Valley, consistent with the very low in resistivity and thin cap at that margin.

Because the low resistivity clay extends from the hot springs across the valley and becomes thicker to the southeast, it is possible that the hot aquifer also extends across the Hot Springs Bay Valley, at greater depth to the southeast. However, hot springs do not appear where the clay is truncated against the resistive rocks on the southeast margin of the valley. The high resistivity rocks on the southeast cliff face host numerous unaltered or weakly altered dikes that seem likely to be permeable. The high resistivity on the elevated southeast margin extends from the surface to -300 m elevation in profile A-5 of WesternGeco (2009) and seems likely to promote cold downflow that might penetrate the clay alteration into the deeper rocks. Therefore, this margin of the valley is a relatively high risk target despite the thick low resistivity clay cap within the valley itself that appears to extend at greater depth to the southeast.

The low resistivity alluvial fill in the valley may act as an impermeable barrier at depth, channeling an outflow from the area of the fumarole along the northwest margin of the valley. In this model, the valley would not host a developable tabular reservoir. In a more optimistic model, compatible with the higher resistivity zone imaged below -350 m elevation in the valley, the interpreted >160 °C outflow intersects the Hot Springs Bay Valley and extends into the valley at -350 m elevation and leaks upwards to a ~100 °C aquifer that supplies the hot springs. The deeper >160 °C aquifer is a relatively accessible exploration target that might support pumped production for a binary power plant.

#### **Other Data**

Soil geochemical anomalies are clustered at three locations in Hot Springs Bay Valley. Arsenic (As), mercury (Hg), and carbon dioxide (CO<sub>2</sub>) all appear in anomalously high concentrations near the hot springs, which is not surprising. However, mercury (Hg), and carbon dioxide (CO<sub>2</sub>) are also anomalously high at the junction of the Fumarole Valley and the Hot Springs Bay Valley (Fig. 8). This indicates that Hg is likely being lost from a reservoir due to boiling and steam loss, probably northwest of the junction. However, the location need not be close to the junction of the valleys since the Hg could be carried in alluvium from farther up Fumarole Valley. Nevertheless, the presence of the Hg anomaly is a favorable indication for targeting a well northwest of the valley junction.

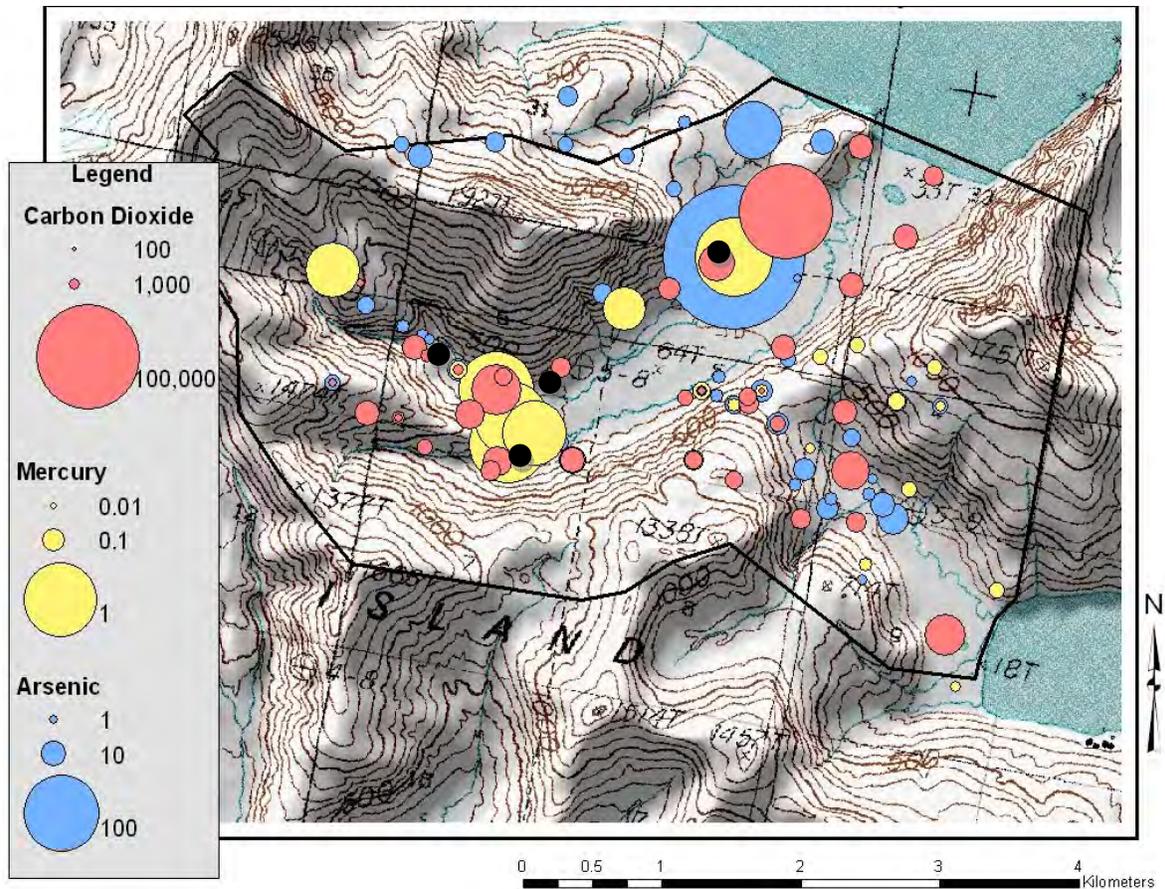


Figure 8. Map showing anomalous concentrations of CO<sub>2</sub>, Hg, and As in Akutan soils. All concentrations in ppm. Black circles indicate proposed exploration well locations (see Fig. 12).

## Conceptual Models

Two conceptual models were prepared to illustrate targets that could be reached from accessible locations (Fig. 9). The conceptual elements common to these models include a magmatic core and/or an acid-core of the volcano, a hydrologic barrier between magmatic/acid core and neutral reservoir, a neutral chloride upflow at >220 °C, and a neutral chloride outflow. Although all models have a neutral chloride upflow, its location, lateral size, vertical extent, and temperature are not well determined by the available data and so it is assumed to be centered under the fumarole. The heat source is conduction from the volcano or from deeper dikes under the fumarole area causing convection. Although gas geochemistry has not been successfully sampled at the fumarole, the extensive alteration zone and minor sulfur sublimation suggests that it is likely to be associated with a >270 °C upflow, whereas the modest rate of sulfur deposition suggests that the upflow is likely to be neutral chloride.

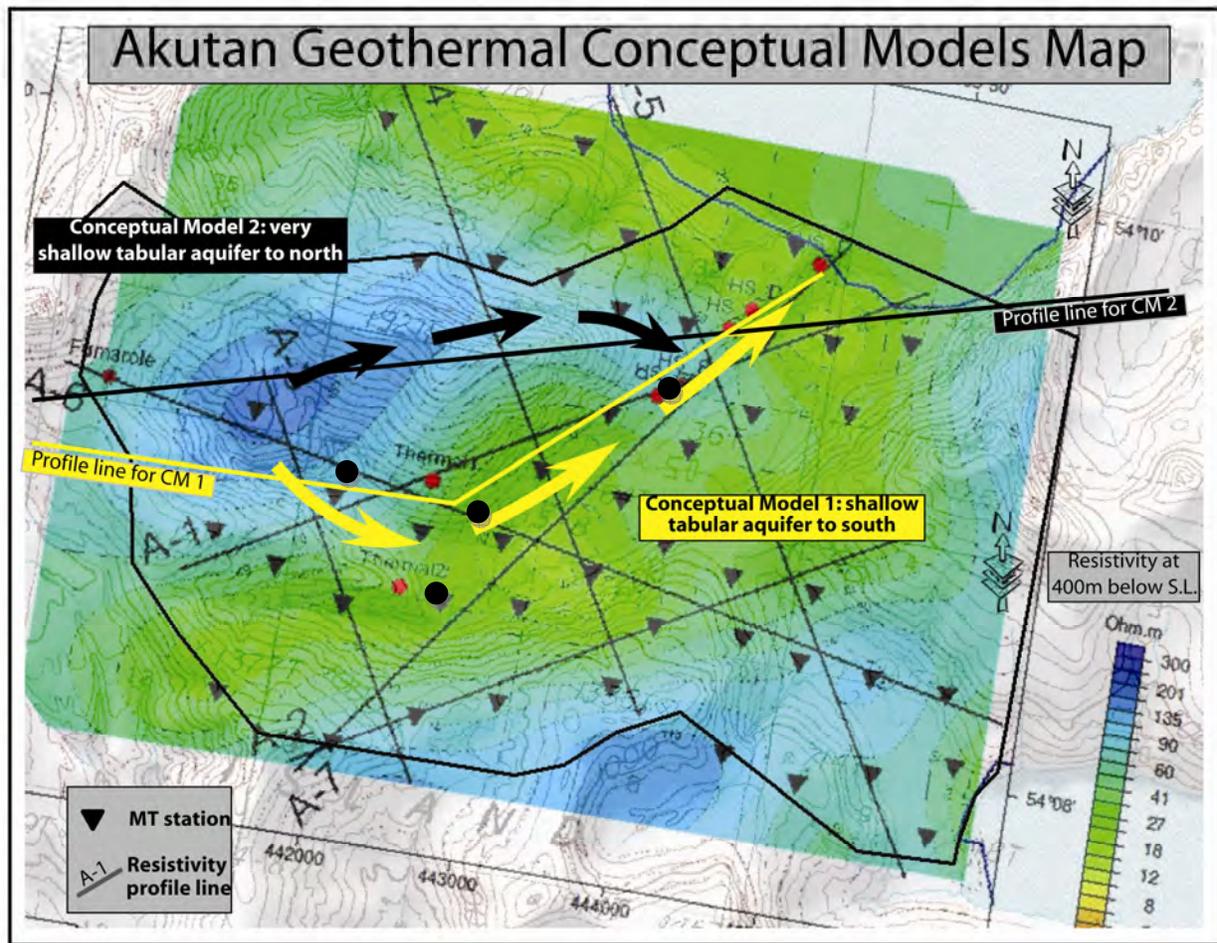


Figure 9. Map view of water flow for conceptual model cross sections presented in figures 9 and 10. Shading reflects resistivity at -400 meters a.s.l., draped over the topographic map of the area. Yellow (model 1) and black (model 2) arrows indicate the direction of shallow water outflow, respectively. Red circles indicate the location of hot springs. The upflow region is near the start of the outflow arrows just east of the fumarole field.

The size of the outflow cannot be constrained due to data limitations associated with poor access beyond the valley floor. However, the minimum size of outflow system appears to be about ~1000 x 500 m.

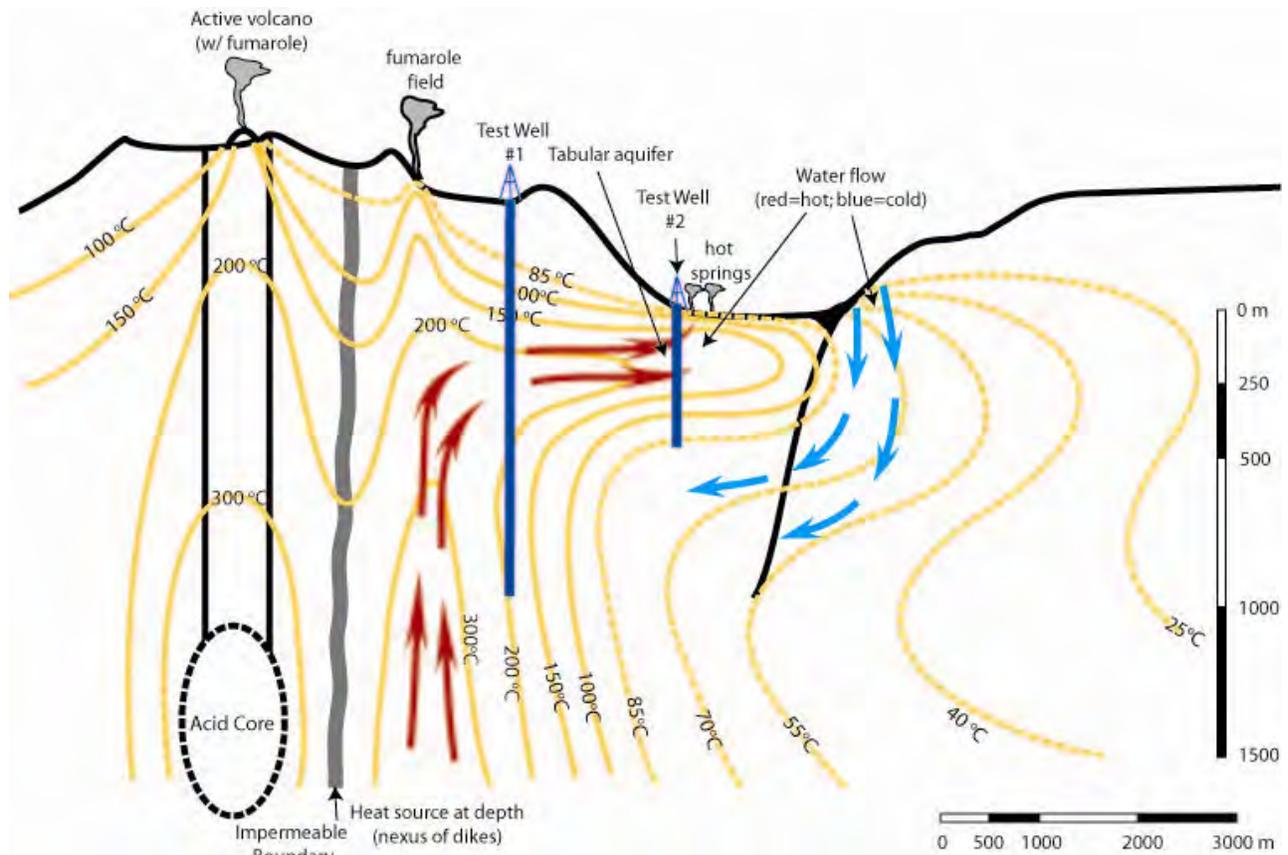


Figure 10. Conceptual Model 1 for the Akutan geothermal system. In this model, shallow outflow occurs in Hot Springs Bay valley, confined by structural features and clay aquitards. An impermeable barrier (vertical gray line) exists between the acid core of the main volcano and the geothermal system. Heat source is likely a region repeatedly injected with magmatic dikes at depth; recharge occurs through fractured rock exposed in the valley walls. Red arrows indicate the flow of heated water; blue arrows indicate cold water flow. Proposed exploration well locations are projected onto the profile line; note that well #1 falsely projects on top of a hill. Well #1 will be on the valley floor.

In Conceptual Model 1 (Fig. 10), the upflow is located near the fumarole and supports outflows to and along the valley. Outflow occurs primarily as one or more tabular aquifers in the subsurface. One aquifer appears to lie at a depth of <100 m and another at a depth of ~500 m, beneath an aquitard of low resistivity impermeable clay. The outflow follows the surface trend of the valley, that is, initially flowing SE and then making an abrupt 90° turn to the NE.

In Conceptual Model 2 (Fig. 11), outflow does not follow any surface morphology but a concealed subsurface structure or formation to flow ENE from the fumarole field towards the NE margin of the valley. This case implies greater risk because the outflow is less accessible and may not be available for development.

Both of the interpreted outflow trends may be available to development. If both exist, they are likely to constitute a single interconnected aquifer. Many other conceptual model possibilities exist but the most significant affect risk but not the choice of well targets.

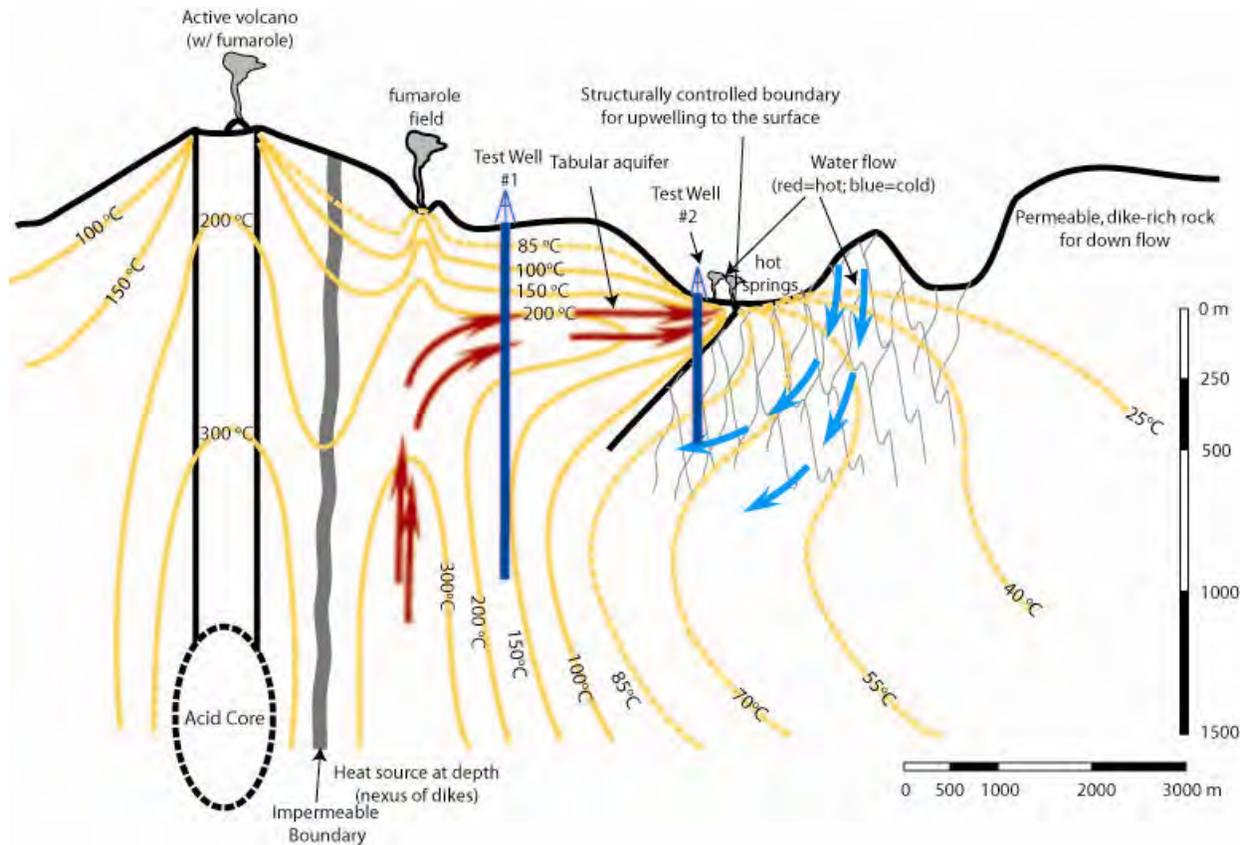


Figure 11. Conceptual model 2 for the Akutan geothermal system. In this model, a very shallow tabular outflow extends north of Hot Springs Bay Valley until water interacts with a concealed structural barrier and is forced to the surface. As in model 1, an impermeable barrier (vertical gray line) exists between the acid core of the main volcano and the geothermal resource. Heat source is likely a region repeatedly injected with magmatic dikes at depth; recharge occurs through fractured rock exposed in the valley walls. Red arrows indicate the flow of heated water; blue arrows indicate cold water flow. Proposed exploration well locations are projected onto the profile line; note that well #1 falsely projects on top of a hill. Well #1 will be on the valley floor.

### III. Targeting Implications

The exploration data suggests that the likely upwelling location is in the general vicinity of the fumarole field. However, the fumarole field is located on an extremely steep hillside at about 350 m elevation. This poses severe limitations in terms of access that would require very high cost road construction, perhaps comparable to the project cost. Much of the rest of the Akutan geothermal area has difficult access as well (Fig. 12). Hence, well locations and drilling targets will have to be designed as a compromise between resource target risk and accessibility.

We propose to drill two to four slimholes at locations given in Fig. 12, the locations of which are based on an analysis of access limitations and on the conceptual models of the Akutan geothermal reservoir presented in Figs. 10 and 11. These wells will provide temperature gradient measurements that will illustrate whether an accessible geothermal resource is likely to exist at Akutan and will help design larger scale wells capable of production. The initial two to four wells will be designed so that, if a permeable hot aquifer is encountered, it will usually be possible to induce temporary flow so that fluid samples uncontaminated by drilling fluids can be taken for geochemistry analyses. The focus of this will be analyses of the likely temperature of the deep source of the thermal fluids, not representative production testing of the resource. Production testing requires a much more expensive well design and a larger drilling rig and, hence, road construction. Due to the roadless and rugged terrain on Akutan geothermal area, drilling rigs for this exploration phase of the project will have to be mobilized and largely supported by helicopter, limiting the economically feasible well design to small-diameter (“slim-hole”) wells.

The Well 1 target, located in Fumarole Valley ~1200 m southeast of the fumarole will be drilled to a TVD of 1500 m (3500 ft.). This is a higher priority well as it appears to be the accessible location closest to the high resistivity zone interpreted as a high temperature upflow zone associated with the fumarole. One significant risk issue is its 1200 m distance from the fumarole. Also, mercury anomalies tend to be highest on the periphery of a high temperature zone, not over it. However, if this well encounters >250 °C and evidence of permeability, the likelihood of generating >20 MW with three production wells would be much higher than it would be for 3 wells targeting the lower temperature outflow. Follow-up full-sized production wells could be drilled directionally toward the fumarole to the northwest.

Well 2, near hot springs group A, will be drilled to 500 m (1500 ft.). This well target has a higher probability of encountering a permeable reservoir than Well 1 but the reservoirs below Well 2 are likely to be lower temperature outflows. The site appears to be located where a 160 to 180 °C tabular outflow from the higher temperature upflow located to the southwest intersects Hot Springs Bay Valley. The geophysics suggests that two tabular aquifers could be penetrated at relatively shallow depths, although only the deeper aquifer would be expected to be capable of >1 MW sustained production. This well will be drilled in stages designed to make induced flow from the aquifers feasible, in order to provide geochemistry constraints on the properties of the shallow and deep aquifers.

Optional wells 3 and 4 will also be drilled to 500 m (1500 ft.). These wells, drilled at the intersection of the Fumarole Valley and the Hot Springs Bay Valley, are targeted on the projected outflow zone described in Conceptual Model 1. If one or both of these wells should penetrate the outflow zone, it will likely be hotter than outflow fluids near Well 2 in Hot Springs Bay Valley and they could prove a larger area accessible for targeting the tabular outflow.

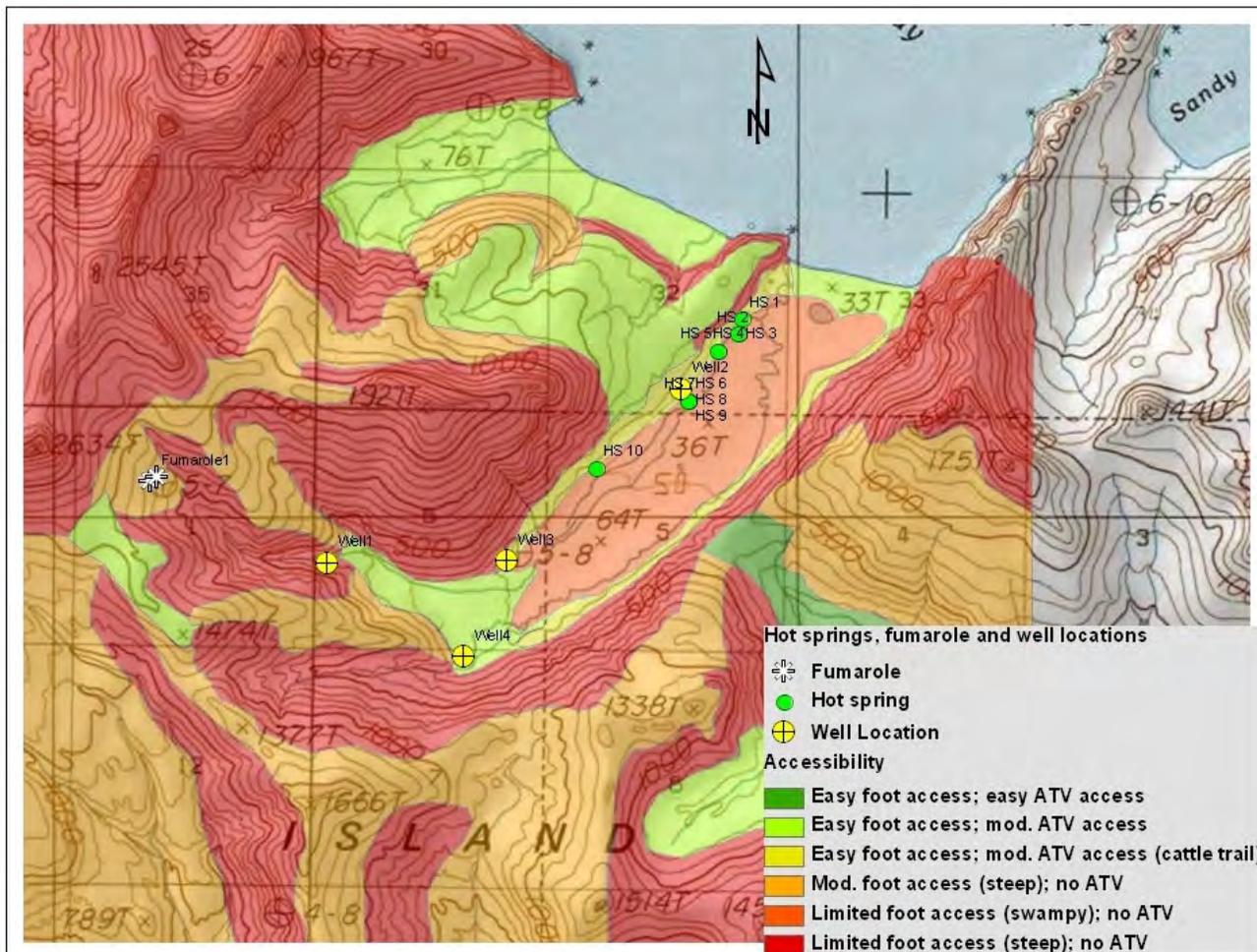


Figure 12. Map showing accessibility in and around the Hot Springs Bay geothermal area; and proposed locations and depths of exploration wells. Any all-terrain vehicles (ATV's) will have to be transported to the field site by skiff or helicopter. Green areas indicate easy walking and ATV driving, with light green areas indicating moderate ATV driving conditions or regions in which ATV's would have to be dropped into place by helicopter. Helicopter landing is excellent in green areas, moderate in swampy or inclined regions (in orange), and limited to specific sites in the steepest terrain (red).

## IV. Feasibility Assessment

A preliminary feasibility study to support the exploration of a potential geothermal resource like that at Akutan must necessarily accommodate significant uncertainty while establishing the essential plausibility of the project. A more specific project feasibility study that considers power plant and field design and operation will be conducted when the results of the exploratory drilling and testing program are completed.

### Issues Affecting Resource Existence and Capacity

For the following reasons, the preliminary surveys indicate that there is a high probability that a hydrothermal system exists at Akutan.

- The chemistry of the hot springs strongly suggests the existence of a neutral chloride reservoir with economically interesting temperature. The fluid geothermometry tells a consistent story, with the longer memory cation geothermometry detecting a >210 °C reservoir temperature and the short memory silica geothermometry and presence of sinter suggesting that 160 to 180 °C exists close to hot spring B. This pattern is typical of volcanic geothermal systems.
- The flank fumarole field appears to have high heat flow and is surrounded by extensive hydrothermal alteration. It is not depositing large quantities of sulfur and, therefore, appears to reflect leakage from a geothermal reservoir rather than from a shallow magmatic source or acid-core system.
- The MT resistivity pattern indicates that a hydrothermally altered clay cap exists near the fumarole and probably overlies an outflow connection from the fumarole to the highest temperature hot springs.
- Anomalous measurements of mercury and arsenic in soil are consistent with the presented conceptual model and suggest that an upflow near the fumarole may extend over 1000 m to the southeast.
- Supporting data sets including geological structure and rock types are consistent with the existence of a permeable reservoir associated with structural extension.
- Although Akutan is an active volcano with frequent historical eruptions, the most attractive target areas near the thermal manifestations (fumaroles and hot springs) are over 3 km from the active volcanic vent in a location where lava and significant ash flows have probably not reached for >1500 years.

While a hydrothermal system very likely exists at Akutan, the preliminary exploration program identified several risk issues as being particularly significant.

- The relatively dilute dissolved solid content of the hot spring water waters could indicate that they originate from steam-heated ground water that is only partially equilibrated, which would most likely imply a relatively small reservoir.
- While the resistivity pattern is typical of a hydrothermal clay cap between the fumarole and the hot springs, its 20 ohm-m resistivity is not as low as is typical of hydrothermal

clay alteration over most permeable geothermal reservoirs. The 2 to 10 ohm-m resistivity of the alluvium in Hot Springs Bay is more typical of hydrothermal alteration. It is possible that, closer to the fumarole, alteration is more intense and resistivity is more typical of a clay cap, but no MT stations image that area because of the difficult access.

- Although the fumarole does not appear to be magmatic, the existing gas samples are unreliable and so there remains some risk that fumarole gases would indicate that the underlying reservoir was not an equilibrium chloride convection system. This would make Well 1 a more risky target. In addition, if the upflow associated with the fumarole was not an equilibrium chloride reservoir, the cation chemistry of the hot springs would then more likely be interpreted as being related to a relatively low volume of partially equilibrated steam-heated ground water. Therefore, the chance of exploration success of Well 2 would not necessarily change but the likely capacity of the outflow resource targeted by Well 2 would be smaller.
- The lack of fumarole gas composition measurements might be addressed by re-sampling, but this is itself risk-prone because two earlier attempts have been unsuccessful. Photographs of earlier fumarole sampling at Akutan suggest that accessible vents may be in deep cracks that are difficult to seal from air contamination. A specialized sampling approach specific to weak geothermal features is probably required, involving the use of a wet clay pack to isolate the sampling orifice from air. High winds and freezing conditions would make it less likely that a reliable gas sample could be obtained using such an approach.
- The flank fumarole field is the most likely indication of an underlying high temperature upflow zone but it is very difficult to access due to steep topography. Data from that area is therefore limited, making the resource models and this assessment more tentative. For example, the area immediately around the fumarole was not surveyed by MT due to challenging access but, if it is lower resistivity, that might indicate that the >220 C upflow reservoir is limited to an area inaccessible to drilling. This risk would be substantially mitigated if successful fumarole sampling and promising temperature and alteration results from Well 1 were followed up with a subsequent deep well drilled directionally ~1200 m northwest from the Well 1 location to a target beneath the fumarole using a heavy road-based rig. Although this is technically feasible for a well drilled to over 3000 m depth, there is a relatively low likelihood of reaching the full step-out distance with an initial well. Such a well would be expensive.
- The 160 to 180 °C outflow from the area of the fumarole might terminate at the northwest edge of Hot Springs Bay Valley so that only a thin 100 to 160 °C aquifer at about 100 m depth would be accessible from Hot Springs Bay Valley. Such an aquifer would be difficult to reliably exploit for more than a MW since pump depths would be very shallow. In addition, cold water influx from the surface aquifer or from injection would be more likely.
- Extensive hydrothermal alteration exposures were not observed between the fumarole and the hot springs and do not occur in Hot Springs Bay Valley except in the immediate area of the hot springs. This is not unusual for a geothermal system with a well-developed clay seal which the resistivity suggests may exist in the valley. However, it is

more ambiguous between the fumarole and the hot springs. Because of the lack of high resolution air or satellite images at Akutan, it is possible that undetected alteration exists northwest of Hot Springs Bay Valley, between the fumarole and the hot springs.

### **Resource Existence and Size**

Resource risk assessment approaches commonly divide the assessment into two parts; 1) an assessment of confidence in the existence of a resource as a percent probability, and, 2) assuming the resource exists, an assessment of its size, usually as a statistical distribution (e.g. Newendorp and Schuyler, 2000). The probability of existence is sometimes restated as the probability of exploration success; i.e., the probability that an exploration drilling program would discover at least one economically productive well. In many published geothermal resource assessments, the assessment of existence is often not explicitly evaluated but nominally included in the size distribution, for example, in the Western Governors' Association Clean and Diversified Energy Initiative Geothermal Task Force Report (2006). In the Western Governors' Association report, many geothermal prospects in the western USA with poorer indications of temperature over 220 °C and much lower surface heat flow than Akutan are assessed as having over 20 MW potential.

### **Confidence in Resource Existence**

The most common method of estimating the probability of existence for a resource is to arrange for a group of experts to review the available data and, based on analogous experience with other geothermal prospect areas, estimate the confidence (as a probability) that the necessary components of a resource exist together. For volcanic prospects that have hot springs with cation geothermometry similar to Akutan's and an apparently non-magmatic fumarole, few failure cases exist in which the most attractive target was drilled. The numerous success cases differ in detail, particularly with respect to the geology and very dilute chemistry characteristic of Akutan. For example, in the western USA, there are two developed geothermal fields in volcanic systems with different geologic settings but broadly similar geochemistry, the 160 to 175 °C, ~40 MW Casa Diablo field at Long Valley (Sorey et al., 1991) and the 160 to 180 °C, 45 MW Steamboat Springs Field near Reno (Mariner and Janik, 1995). In both of these systems, it is entirely or mainly the lower temperature outflow that has been developed. At Akutan, the combination of an apparently non-magmatic flank fumarole, a trend in cation geothermometry to >210 °C, and silica geothermometry over 160 °C with sinter deposition support the existence of a convecting geothermal resource on Akutan with a high confidence of 80%. The confidence that a >210 °C upflow or a >160 °C outflow exists and is accessible to drilling is addressed in a separate section.

### **Probable Resource Capacity**

The capacity of the geothermal resource at Akutan in terms of electrical power can be assessed using analogies, both the rough comparisons to the prospect estimates provided in the Western Governors' Association report and the analogs to the 40 to 45 MW Casa Diablo

and Steamboat Springs developments. Because of the dilute outflow chemistry, handicapping the Akutan likely 160 to 180 °C resource by 50% relative to these developed reservoirs would be reasonable, giving an analogous low temperature resource capacity estimate of 20 MW with an 80% probability. Because a high temperature resource might exist, a more optimistic capacity estimate for the entire system would be as high as 100 MW, using the Western Governors' Association report assessments as analogs.

The initial drilling will provide more concrete resource parameters, including geothermal fluid temperature, fluid and gas chemistry, rock properties and locations for follow-up production test wells. The subsequent production wells would confirm fluid flow rate, reservoir pressure, and fluid and gas composition. For a power plant design, the location of geothermal production wells, site logistics, cooling temperature (air or cold water sink) and similar issues would be specified.

### **Probability of Exploration Success**

#### ***Upflow Target***

The probability of exploration success in this case includes access constraints on exploration well targeting. Upflow appears to occur directly beneath or slightly north/northeast of the fumarole field beneath very steep terrain. The extent of the permeable zone, including in the direction of location 1, is poorly constrained by the scant MT coverage. Because wells deviated more than 1200 m may be required to intersect the permeable upflow, exploratory boreholes will more likely penetrate the margin of the deep upflow. The margins are more likely to be hot than permeable. Hence, although a well that actually extends past the fumaroles has a high probability of achieving over 5 MWe equivalent productivity, perhaps 70%, the probability of achieving this in two wells drilled from location 1 would be less than 35%. The probability of a 1500 m vertical hole at location 1 encountering economically significant permeability at >220°C would be less than 15%.

#### ***Outflow Target***

On the other hand, initially targeting the outflow system appears to be relatively straightforward. The outflow occurs in low-lying valley topography, so access is not as difficult as in the upflow zone. One significant concern is limited area for practical occupancy due to the swampy nature of the valley floor, which could pose a problem for achieving an adequate well spacing for development or for accessing the outflow if it is mainly located beneath the valley floor. Despite these potential risks, the probability of a successful initial exploration well is high, perhaps 80%.

### **Probability of Development from Accessible Area**

A major risk for the Akutan geothermal project is accessibility. Typically, an initial exploration well would be directed beneath a fumarole if the gas geochemistry suggested >270 and <330 °C temperature and neutral chemistry and the resistivity showed that such a well would test a conceptually attractive upflow. The likelihood of penetrating a high-enthalpy resource at

Akutan is highest nearer the fumarole, even though the gas chemistry is not available to confirm this. As noted above, although technically feasible, deviating a well laterally ~1200 m from location 1 to the fumarole would be expensive and prone to result in an incomplete deviation. If, however, the initial vertical exploration slim-hole implies that the upflow zone extends a significant distance to the southeast of the fumaroles, the directional drilling option will be much more attractive.

Alternatively, the lower temperature outflow could be developed but this requires more wells. These relatively shallow wells would not be drilled directionally and so they would be spread out over a larger surface area. If a very permeable zone was encountered below 400 m depth, like at the Casa Diablo field, the 20 MW might be produced from an area smaller than 1 km<sup>2</sup>, assuming pressure support from a larger area. Development in the outflow zone on the valley floor is associated with some risks that are higher than is the case for the higher temperature system targeted by Well 1. There may be a higher probability of cold water influx from shallow or adjacent cooler aquifers. Due to the swampy nature of the valley floor, construction of the greater number of well pads may limit much of the development to the ridge northwest of the valley, requiring deeper wells and increasing well targeting risk by decreasing targeting flexibility. These potential risks are tabulated in Table 3.

<b>MODEL and Well</b>	<b>MW CAPACITY RANGE</b>	<b>ADVANTAGES</b>	<b>DISADVANTAGES</b>
Upflow and Well 1	20-100	High-enthalpy	Lack of fumarole gas sampling increases risk of low permeability, high gas, or corrosive conditions
		Single pad production for 20 MW	Poorly imaged target geometry due to lack of MT coverage
			Longer transmission lines
			Initial straight hole unlikely to directly test a small or medium sized reservoir
Outflow and Wells 2-4	2-20	Better constrained by geochemistry	180 °C requires more wells and 160 °C many more wells
		Better constrained resistivity geometry	
		Shallower cheaper wells	
		Shorter transmission lines	More reinjection wells required
			Greater probability of injection breakthrough
			Greater possibility of surface cold water influx
			Swampy nature of valley could hinder exploration and construction activities

Table 3. Potential advantages and disadvantages associated with the development of the two major Akutan geothermal resource models.

In some geothermal systems, particularly those with lower enthalpy, pressure in the system is maintained by injecting produced fluid back into the reservoir. This eventually causes resource decline as temperatures are reduced. If managed appropriately, more than 30 years of operation should be feasible. Injection for a high temperature system is likely to require a

customized solution depending on the thermodynamic state of the system and the available permeable zones for injection.

## **Plausible Design for Power and Heat Utilization**

### **1. Power production**

There are three major technologies commonly used to generate electricity from geothermal resources. Which technology is appropriate for Akutan will be determined once the resource is better constrained. The three types of plants are:

Dry steam: uses geothermal steam directly from a geothermal reservoir that has a fracture system that is entirely steam. The reservoir steam temperature is typically 220 to 245° C. This is the lowest cost system to develop but reservoirs that can support this development are rare. A dry steam system is unlikely given the chloride hot springs.

Flash: geothermal steam is separated from hot water at the surface. The steam is delivered to a steam turbine, while water phase is re-injected into the geothermal reservoir. The reservoir fluid temperature is typically 200 to 330 °C and so this might be feasible at the Well 1 location.

Binary cycle: uses a secondary ‘working’ fluid (i.e., “binary” fluid) with a lower boiling temperature than water, such as ammonia. Heat from the geothermal fluid causes the binary fluid to flash to vapor via a heat exchanger, and the binary vapor is sent through the turbine to generate power.

Until recently, the minimum temperature for binary plants was ~120°C. United Technologies Corporation (UTC) developed a binary geothermal power plant currently operational at Chena Hot Springs which produces power from geothermal fluid at 80 °C, made feasible by the very low temperature fluids available for the cooling cycle. However, there are several problems with the UTC system at Chena. The power plant has experienced multiple shutdowns since inception in 2006. Many of these have been explained by factors unrelated to the geothermal resource, such as an electrical fire in the plant building (Gwen Holdmann, pers. comm.). However, it is unknown whether some of the shutdowns are due at least in part to resource issues. For these reasons, it may be too risky to use a UTC-type plant for power generation in a remote community such as Akutan.

Of these options, at Akutan, two are plausible designs for power production. Either a flash or binary plant might be feasible at the head of the valley, with production wells targeted towards a high temperature upflow zone near the fumarole. Given the lower temperatures likely in Hot Springs Bay Valley, a binary power plant is most likely. Beyond temperature, there are several other reasons why a binary system may be a more attractive option for Akutan. The construction time on site is shorter for binary plants because they are more modular and can be

barged to the island in large sections. Binary systems that use air-cooled condensers operate more efficiently in cool climates and so that is not the handicap that it can be in other areas. Depending on the cooling system efficiency and design, the footprint of binary systems can be smaller than that of flash plants, which would also be advantageous at Akutan.

A variety of sources including Lovekin et al. (2006) and the Western Governors' Association Clean and Diversified Energy Initiative Geothermal Task Force Report (2006), indicate that a reasonable average cost estimate for a new geothermal power development including exploration, drilling, facilities and power plant is about \$3500/kWe. For new *small-scale* geothermal power plants (<1 MW) in remote parts of Alaska, Kolker (2008) estimated average costs to be \$7850/kWe. This estimate is too high for Akutan because the likely larger power plant size would reduce capital costs due to economies of scale; however, it is useful to consider in the context of the remoteness of Akutan's location. At the stage of development at Akutan, before the resource properties are known, a reasonable assumption for the cost of development might be an average of the two estimates, at \$5540/kWe.

Estimates for the corresponding levelized cost of power vary from \$70 to \$90/MWh depending on assumptions used (e.g. Western Governors' Association Clean and Diversified Energy Initiative Geothermal Task Force Report, 2006). Again, at Akutan some premium should be added for the remoteness of the location.

## **2. Direct use applications**

The use of geothermal fluids for space heating is very important for Akutan, as it will further reduce the diesel fuel consumption of village residents. Other applications include cold storage for fish processing, greenhouse agriculture, resort development, the production of alternative fuels for transportation, and others (see Information Insights, 2010).

In most geothermal fields that emphasize production of both heat and power, there are dedicated well(s) for each application so that they can be independently managed based on their own demand. In any case, however, there will be at least a partial non-geothermal backup system for heat and power. To provide a higher security of supply, a typical rule of thumb is that geothermal fields have at least one more production and injection well than are needed at any given time. There might be an option to provide a mixed system with one spare well that would back up both the heat and power applications.

Whether a separate district heating system makes economic sense for Akutan cannot be assessed before the location, temperature, and composition of the geothermal resource is known. Beyond fixed costs such as the well, heat exchanger, and other hardware, the cost of a district heating system is largely a function of two factors: (1) pumping and piping costs over the distance between resource and users (hence location of the production well needs to be constrained); and (2) the costs of processing to prevent scaling (hence, the temperature and composition of the production fluids need to be constrained).

### **3. Whole-system design**

Another possibility for development is a 'cascaded-use' approach. In a 'cascaded-use' scenario, fluids from one production well would be used for multiple purposes. Fluids would first be utilized onsite for power production. Spent fluids from the power plant would then be piped to the village for direct use, and piped back to the 'reservoir' area for reinjection. This would likely require fluids that are above ~240 °C and have relatively low concentrations of total dissolved solids (TDS) to prevent scaling problems.

The difficulty with the cascaded-use approach is that the heat supply is complicated by all the power plant issues as well as the heating issues; for example, a particular power plant scale or corrosion mitigation option may be precluded by the need to service the heating system. Therefore, combining the systems increases uncertainty for both. The geothermal heat supply is likely to be more secure if it utilizes a dedicated well for direct use applications, divorced from power production activities except for possible shared backup. While it is more expensive, the economics might be attractive due to avoided fuel costs. On the other hand, the cascaded-use approach could work for Akutan, since the City already has a working heating system in place that could serve as a backup.

## V. Conclusions and Next Steps

The feasibility of geothermal development at Akutan, and the type of development, is dependent on the results of the exploratory drilling program. Exploration drilling will provide necessary resource parameters that can now only be estimated from surface data.

Based on conceptual models built primarily from MT and geochemical datasets, it appears that development of the Akutan geothermal resource for power and/or direct use may be feasible. These datasets point to a shallow, tabular aquifer(s) of 155-180 °C (i.e., “outflow zone”) and a deeper, hotter resource of >220 °C (i.e., “upflow zone”) that will be targeted because of the potentially lower cost and lower land access required to develop >20 MWe. The initial exploratory wells will attempt to verify the existence of these aquifers, and determine their potential for development.

The probability of resource existence at Akutan is relatively high. The most likely range of geothermal reservoir conceptual models include a high-enthalpy upflow zone and a lower enthalpy outflow zone. Both these zones might be developable for geothermal heat and/or power. The resource capacity and the probability of exploration and development success are dependent on the target.

Due to difficult access, the upflow targeted by Well 1 is poorly imaged and, for the same reason, only the periphery of the likely upflow is accessible using a vertical test well. As a result, the probability of encountering a resource using a vertical well at this location is lower than at the outflow target, although fewer wells and much less fluid handling would be required to develop a higher temperature system.

Well 2 on the outflow zone has a higher probability of encountering a productive resource, albeit still constrained by access. However, more wells would be required to develop a 20 MWe capacity.

Because of the modest demand at Akutan, either the upflow or the outflow resource might be adequate.

A few additional exploration activities should be conducted prior to or during the drilling of exploratory wells to reduce uncertainty in the well target expectations and improve the assessment of the well results. These activities include: (1) Sampling the fumaroles for gas using modern geothermal industry oriented sampling and analytical methods; (2) Acquiring high-resolution satellite imagery over the geothermal area; and (3) Further field tests to follow up on the remote sensing results (see Kolker et al., 2010).

## VII. References and Bibliography

- 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 2010.
- Fournier R.O., 1981. Application of water geochemistry to geothermal exploration and reservoir engineering. *In: Geothermal Systems: Principles and Case Histories*, Ryback and Muffler eds., John Wiley and Sons, NY, 109-143
- Fournier R.O., 1989. Lectures on geochemical interpretation of hydrothermal waters. UNU Geothermal Training Programme, Reykjavik, Iceland. Report 10, 1989. [www.unugtp.is/solofile/33667](http://www.unugtp.is/solofile/33667)
- Giggenbach, W., 1991. Chemical Techniques in Geothermal Exploration. *In: The Application of Geochemistry in Geothermal Reservoir Development*, F. D'Amore Ed. 1991 UNITAR/UNDP Guidebook.
- Information Insights, 2010. Akutan Geothermal Energy Demand and Stakeholder Assessment. Unpublished report to the City of Akutan and the Alaska Energy Authority, 34p.
- Kolker, A., 2008. Geologic Setting of the Central Alaskan Hot Springs Belt: Implications for Geothermal Resource Capacity and Sustainable Energy Production. Ph.D. Dissertation, University of Alaska Fairbanks, 203p. Available Online at: <http://www.uaf.edu/rap/students/Alumni/Kolker-dissertation-2008.pdf>
- Kolker, A., and R. Mann, 2009. Heating Up The Economy With Geothermal Energy: A Multi-Component Sustainable Development Project at Akutan, Alaska. *Geothermal Resource Council Transactions*, 33
- Kolker, A., P. Stelling, B. Cumming, A. Prakash, and C. Kleinholt, 2010. Akutan Geothermal Project: Report on 2009 Exploration Activities. Unpublished report to the City of Akutan and the Alaska Energy Authority, 37p.
- Lovekin, J., Sanyal, S. and Sener, A., 2006. Potential Improvements to Existing Geothermal Facilities in California. *GRC Transactions*, 30.
- Lu, Z., C. Wicks, D. Dzurisin, W. Thatcher, and J. Power, 2000. Ground Deformation Associated with the March 1996 Earthquake swarm at Akutan Volcano, Revealed by Satellite Radar Interferometry. *Journal of Geophysical Research*, v. 105, No. B9, p. 21483-21495.
- Mariner, R. and Janik, C., 1995. Geochemical data and conceptual model for the Steamboat Hills Geothermal System, Washoe County, Nevada. *Geothermal Resources Council Transactions*, 19, 191-200.

- Miller, T.P., G. McGimsey, D. Richter, J. Riehle, C. Nye, M. Yount, and J. Dumoulin, 1998. Catalog of the historically active volcanoes of Alaska. USGS Open-file Report 98-582.
- Motyka, R., and C. Nye, eds., 1988. A geological, geochemical, and geophysical survey of the geothermal resources at Hot Springs Bay Valley, Akutan Island, Alaska. Alaska Division of Geological and Geophysical Surveys (ADGGS), Report of Investigations 88-3.
- Motyka, R.J., S. Liss, C. Nye, and M. Moorman, 1993. Geothermal Resources of the Aleutian Arc. ADGGS Professional Paper 114.
- Newendorp, P. and Schuyler, J., 2000. Decision Analysis for Petroleum Exploration, Second Edition. Planning Press, pp. 618.
- Newhall, C.G., and D. Dzurisin, 1988. Historical unrest at large calderas of the world. USGS Bulletin 1855.
- Powell, T., and W. Cumming., 2010. Spreadsheets for Water and Geothermal Gas Chemistry. Proceedings of the Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-188.
- Reyes, A.G., Giggenbach, W.F., Saleras, J.R., Salonga, N.D., Vergara, M.C., 1993. Petrology and geochemistry of Alto peak, a vapor-cored hydrothermal system, Leyte Province, Philippines. *Geothermics*, 22, 479-519.
- Richter, D.H., C.F. Waythomas, R.G. McGimsey, and P.L. Stelling, 1998. Geology of Akutan Island, Alaska. USGS Open-File Report 98-135, 1 sheet, 1:63,360 scale
- Simkin, T., and Siebert, L., 1994, *Volcanoes of the World*, 2nd edition: Geoscience Press in association with the Smithsonian Institution Global Volcanism Program, Tucson AZ, 368 p.
- Sorey, M.L., Suemnicht, G.A., Sturchio, N.C., and Nordquist, G.A., 1991. New evidence on the hydrothermal system in Long Valley caldera, California, from wells, fluid sampling, electrical geophysics and age determinations of hot spring deposits. *Journal of Volcanology and Geothermal Resources*, 48, pp. 229-264.
- Symonds, R. B., R. Poreda, W. C. Evans, C. J. Janik, and B. E. Ritchie, 2003. Mantle and crustal sources of carbon, nitrogen, and noble gases in Cascade-Range and Aleutian-Arc volcanic gases. USGS Open-File Report 03-436.
- WesternGeco, 2009. Magnetotelluric Survey at Hot Springs Bay Valley, Akutan, Alaska: Final Report – 3D Resistivity Inversion Modeling. Unpublished report prepared for the City of Akutan, Alaska, GEOSYSTEM/WesternGeco EM, Milan, Italy, 27p.
- Wood, C.P, 1994. Mineralogy at the magma-hydrothermal system interface in andesite volcanoes, New Zealand. *Geology*, 22, 75-78.